DIAGNOZA - GENEZA - PROGNOZA => PODSTAWA KAŻDEJ DECYZJI

POLSKIE TOWARZYSTWO DIAGNOSTYKI TECHNICZNEJ

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Wszystkie opublikowane prace uzyskały pozytywne recenzje wykonane przez dwóch niezależnych recenzentów. Obszar zainteresowania czasopisma to problemy diagnostyki, identyfikacji stanu technicznego i bezpieczeństwa maszyn, urządzeń, systemów i procesów w nich zachodzących. Drukujemy oryginalne prace teoretyczne, aplikacyjne, przeglądowe z badań, innowacji i kształcenia w tych zagadnieniach.

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Słowo wstępne

W niniejszym wydaniu Diagnostyki 3(47)/2008 prezentowane są prace, na których podstawie zostaną wygłoszone referaty w 11 sesjach plenarnych IV Międzynarodowego Kongresu Diagnostyki Technicznej w tym referaty wygłoszone z okazji 70 rocznicy urodzin prof. Czesława Cempla.

W kongresie udział wezmą przedstawiciele z następujących krajów: Anglii, Australii, Białorusi, Grecji, Hiszpanii, Kolumbii, Litwy, Nepalu, Niemiec, Rosji, Słowacji, Ukrainy, USA oraz z Polski.

Przedstawione publikacje w tym wydaniu Diagnostyki obejmują podstawowe i kluczowe zagadnienia na obecnym etapie rozwoju diagnostyki technicznej w zakresie: budowy modeli, nowych metod i środków diagnostycznych. Począwszy od określenia kierunków rozwoju diagnostyki, roli i znaczenia modeli dynamicznych w budowie systemów monitorowania maszyn, mechatroniki w diagnostyce, dynamikę powstawania symptomów we wnioskowaniu, metod i algorytmów diagnozowania wybranych układów i zespołów maszyn oraz pojazdów.

Pierwsze cztery prace poświęcone są Jubilatowi – prof. Czesławowi Cempelowi. Zestawiony dorobek naukowy Jubilata jest imponujący, zarówno w liczbach publikacji jak i osiągnięciach naukowych w zakresie:

- dynamiki i wibroakustyki maszyn i systemów,
- diagnostyki wibroakustycznej maszyn,
- energetycznej teorii ewolucji maszyn,
- koncepcji wielowymiarowej informacji diagnostycznej w ujęciu symptomowej macierzy obserwacji,
- zastosowaniu teorii szarych systemów do prognozowania.

Prof. Czesław Cempel posiada wyjątkową osobowość i talent organizowania licznej rzeszy uczonych do rozwiązywania istotnych problemów badawczych. Tak zrodziła się polska szkoła diagnostyki technicznej w latach siedemdziesiątych XX wieku i Informator Polskiego Towarzystwa Diagnostyki Technicznej pt. „DIAGNOSTA".

W pierwszym numerze z 1990 roku ówczesny Prezes Czesław Cempel tak pisał (...) zainteresowanie diagnostyką techniczną w kraju sięga 1977 roku, kiedy to liczna grupa entuzjastów nowo powstałej dziedziny zebrała się w Białym Borze (...). Zatem celem działania PTDT, skupiającego naukowców, praktyków i wytwórców przyrządów diagnostycznych, jest rozpoznawanie znanych i sprawdzonych metod i środków diagnostycznych, a także stymulacja opracowań nowych. W zadaniach tych niebagatelną rolę będzie odgrywał Informator, jako płaszczyzna wymiany myśli między twórcami metod diagnostycznych, środków diagnostycznych a użytkownikami (...).

Tak wówczas pisał Jubilat na łamach DIAGNOSTY jako informatora liczącego 8 stron maszynopisu formatu B5, którego głównym mottem było „diagnoza–geneza–prognoza – podstawą każdej decyzji".

Następnie z inicjatywy Jubilata począwszy od nr 23(2000r.) Informator DIAGNOSTA został przekształcony w czasopismo naukowo-techniczne **DIAGNOSTYKA.**

Zasługi Jubilata, jako przewodniczącego rady programowej czasopisma są nieocenione, w sensie merytorycznym i koncepcyjnym. Do redakcji Diagnostyki Jubilat stale zgłaszał nowe propozycje w zakresie treści i formy czasopisma. Pozwoliło to osiągnąć wysoki poziom i uznanie w środowisku naukowym między innymi wyrażone 4 punktową ocena Diagnostyki na liście MN i SW.

To wyjątkowy Jubilat,
Rozpatrując dynamikę i akustykę,
Z zapałem wtargnął w diagnostykę,
By symptomowe toczyć boje,
Osiągnął wyżyny energetycznej ewolucji maszyn.
Co zaś się tyczy Jubilata,
To tu wyznać muszę szczerze,
Że to jest wyjątkowy naukowiec,
Bo w to co robi – wierzy szczerze.
A że w nauce zrobił wiele,
To nikt tutaj nie zaprzeczy,
Że to wszystko ma sens i jest do rzeczy.
Czesławie – Tyś wielki w Wibroakustyce
i Diagnostyce.
Boś wiele zrobił na tym polu,
Brawo Ci za to – Jubilacie, w imieniu własnym
i przyjaciół wielu,
Abyś nadal trzymał szyk i styl przez następnych
wiele, wiele lat.

Redaktor naczelny

Ryszard MICHALSKI

KU WYŻYNOM NAUKI – PORTRET PROFESORA
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Są takie chwile w życiu człowieka, kiedy zupełnie nieoczekiwanie pojawia się okazja, by dokonać okresowego podsumowania dokonań kogoś bliskiego, zaufanego i prawego w każdej sytuacji. Mam taką przyjemność i zaszczyt jako uczeń Profesora sprawozdać pokrótce o dokonaniach Mistrza, co wiąże się z Jego 70 – rocznicą urodzin.

1. Dane biograficzne

Profesor Czesław CEMPEL urodził się dnia 22 lipca 1938 roku w Biskupicach Zabarycznych koło Ostrowa Wielkopolskiego, na zapadłej wsi w Wielkopolsce – jak pisze sam Profesor. Dom z 1812 roku, pokryty słomą, szkoła podstawowa z językiem angielskim, pierwsze badania łączenia rabarbaru z łopianem, to tylko wyrwane wątki wspomnień tamtych miejsc i lat.

I tak to się zaczęło…

Studia wyższe odbył na Wydziale Matematyki Fizyki i Chemii Uniwersytetu Adama Mickiewicza w Poznaniu uzyskując w roku 1962 stopień magistra fizyki w zakresie Drgania i Akustyka. Młodzieńcze lata studiów przeplatane były różnymi epizodami, najczęściej wytężoną pracą, także wojskiem jak i odpoczynkiem. Był to trudny okres dla młodego człowieka, naznaczony wieloma wyzwaniami, co do miejsca pobytu, czasu historii trudnych losów naszego kraju, jak i poszukiwania sposobu na przyszłe, godziwe życie. Wizja swojego rozwoju wyniesiona z domu, ukształtowana przez Rodziców Profesora to drogowskaz postępowania, który dzięki uporowi, czasami na przekór chwilowym trudnościom, widokom i opcjom dała oczekiwane, a nawet niespodziewanie większe efekty.

Po studiach w latach 1962 - 64 pracował jako asystent prof. M. Kwieka i prof. E. Karaśkiewicza w Katedrze Akustyki i Teorii Drgań Uniwersytetu. Tu zdobywa pierwsze doświadczenia dydaktyczne i badawcze, co zwielokrotnione dalej wytężoną pracą są możliwe do obserwacji na drodze rozwoju naukowego.

Studia przeplatane wojskiem…

Od roku 1964 pracuje w **Politechnice Poznańskiej**, na początku w Katedrze Mechaniki będąc asystentem prof. E. Karaśkiewicza, a po reorganizacji do chwili obecnej w Instytucie Mechaniki Stosowanej. Były to trudne lata pracy, początki badań naukowych, nowe i trudne wyzwania zajęć dydaktycznych, karkołomne problemy organizacji laboratoriów – z czym młody pracownik zmierzył się z dużym zapałem i dobrymi efektami.

Wytężona praca i niekiedy wypoczynek młodego…

Stopień naukowy doktora nauk technicznych nadała mu Rada Wydziału Budowy Maszyn Politechniki Poznańskiej na podstawie **rozprawy doktorskiej** p.t.: ***Drgania układów prętowych z nieliniowymi warunkami brzegowymi*** w roku 1968. Tutaj też w marcu roku 1971 obronił **rozprawę habilitacyjną** na temat ***Okresowe drgania z uderzeniami w dyskretnych układach mechanicznych***. Od roku 1972 jest docentem w Instytucie Mechaniki i tworzy tam Laboratorium Drgań i Hałasu, a w roku 1974 zostaje mianowany **wicedyrektorem** Instytutu i Kierownikiem Zakładu Dynamiki i Wibroakustyki Maszyn, w skład którego wchodzi utworzone poprzednio Laboratorium, (*obecnie Zakład Wibroakustyki i Biodynamiki Systemów*). Profesor Cempel pełnił funkcje zastępcy dyrektora Instytutu przez wiele kadencji, będąc również jego **dyrektorem** w kadencji 1987-90.

W latach 1993 – 99 był **dziekanem** Wydziału Budowy Maszyn i Zarządzania, naonczas wydziału o 6 -ciu kierunkach studiów, czterech jednostkach wydziałowych. Zreformował on w tym czasie strukturę organizacyjną Wydziału i wprowadził dwie nowe specjalności; Studia Techniczno Handlowe oraz **Mechatronika,** obie finansowane przez program europejski TEMPUS. Przeprowadził także bezpiecznie Wydział przez rafy zmian organizacyjnych, zmiany nazwy oraz wprowadził na wydziale skuteczną reformę finansowania, czyniąc Wydział samowystarczalnym, na drodze do obecnej rentowności.

Pewne doświadczenia z tego obszaru ekonomii zdobywał Profesor na niwie życia prywatnego, gdzie wspomagany i zachęcany przez żonę Krystynę (związek małżeński zawarto w 1963r.) postawił dom letniskowy wraz z rodziną, zadbał o parking dla pierwszego własnego pojazdu i odpoczywał tanio nad polskimi jeziorami.

Profesor Cempel uzyskał **tytuł profesora** nadzwyczajnego w roku 1977, a zwyczajnego w roku 1985. W roku 1991 został wybrany do **Komitetu Badań Naukowych**, a ponownie na drugą kadencję w roku 1994 z reelekcją na lata 2000 – 2004. W roku 1994, w uznaniu dorobku naukowego zostaje wybrany członkiem korespondentem **Polskiej Akademii Nauk**. W uznaniu zasług naukowych i dobrej współpracy z Politechniką Szczecińską, Uczelnia ta nadaje mu w roku 1996 godność **doktora honoris causa**. Natomiast w uznaniu zasług na polu innowacyjno wdrożeniowym (14 patentów) i osiągnięć w zakresie diagnostyki maszyn w 1998 roku zostaje wybrany jako członek **Akademii Inżynierskiej w Polsce**. W roku 2005 Akademia Górniczo Hutnicza nadaje mu również godność doktora honoris causa.

Publikowany dorobek profesora Cempla liczy ponad 400 prac opublikowanych w czasopismach krajowych i zagranicznych (http://neur.am.put.poznan.pl).

O licznych, doniosłych osiągnięciach i zasługach Profesora świadczy już ten krótki rys danych osobowych, z którego wynika, że mamy do czynienia z Człowiekiem o dużym formacie uczonego, uznanego w środowisku naukowym i od początku związanym z Politechniką Poznańską. Wymienione poniżej odznaczenia są tylko dowodem na to, że mamy do czynienia ze wspaniałym badaczem i wybitnym uczonym jednoczącym wiele dziedzin nauki i wiele spojrzeń na współczesne problemy nauki i życia. Te główne wyróżnienia to:

- Krzyż Kawalerski Orderu Odrodzenia Polski 1983 r.;
- Medal Komisji Edukacji Narodowej 1990r.;
- Krzyż Oficerski Orderu Odrodzenia Polski 2000r.

Oczywistym jest, że trudne chwile mozolnej i wyróżniającej pracy Profesora mieszają się ze sporadycznymi epizodami wesołego życia towarzyskiego z przyjaciółmi i rodziną.

Za wyróżniającą pracę Profesor otrzymał 12 nagród Ministra Nauki Szkolnictwa Wyższego (*lub Edukacji w stosownym czasie zmienionego nazewnictwa*) indywidualnych i zespołowych.

2. OSIĄGNIĘCIA NAUKOWE

Obszar badań i osiągnięć badawczych profesora Cempla można zaliczyć do **Dynamiki i Wibroakustyki Systemów** z głębokimi implikacjami i aplikacjami w Dynamice i Eksploatacji Maszyn, Analizie Sygnałów Wibroakustycznych, Diagnostyce Maszyn i Systemów Technicznych, Teorii i Inżynierii Systemów i Ekologii, oraz Metodologii Badań. Celem systematycznego przedstawienia tych osiągnięć warto je podzielić na kilka obszarów.

Akustyka maszyn i środowiska

Ten obszar badań otwiera pierwsza publikacja prof. Cempla z roku 1964, gdzie wykryto różnice w składzie widmowym hałasu młyna kulowego do przemiału cementu w zależności od jego zapełnienia i stopnia przemiału i zaproponowano wykorzystanie tych cech do regulacji młyna. Ogólnie do najważniejszych osiągnięć należy tu opracowanie korelacyjno - koherencyjnej metody identyfikacji źródeł hałasu i akustycznych własności pomieszczeń produkcyjnych. Zwieńczeniem badań w tym obszarze było wydanie krajowej monografii WIBROAKUSTYKA STOSOWANA w roku 1978r, przez PWN (II wydanie 1985r), a potem ponownie z całkowicie zmienioną zawartością w 1989r. Można powiedzieć, że książka ta pomogła wykreować dziedzinę Wibroakustyki lansowanej wtedy przez autora wspólnie z profesorem Z. Engelem z AGH.

Wibroakustyka narzędzi pneumatycznych

Na początku lat 70–tych w zespole prof. Karaśkiewicza w Politechnice Poznańskiej rozpoczęły się pionierskie badania identyfikacyjne zagrożenia drganiowego związanego z użytkowaniem młotków pneumatycznych, źródłem choroby wibracyjnej w przemyśle. Zespołowa kontynuacja tych badań wspólnie z M. Dobrym (*obecnie prof. nzw. Politechniki Poznańskiej*), pozwoliła zwolna pokonać te trudności i opracować nieliniowy wibroizolator nie przenoszący sił dynamicznych narzędzia z dokładnością do sił tarcia w jego konstrukcji.

Poszukiwania ciszy i należnego spokoju po wyczerpującej tematyce drgań i hałasu od zawsze towarzyszą Profesorowi.

Żmudna zmiana nocna…

Wibroizolator wraz z nowym narzędziem opatentowano w wielu krajach świata i rozpoczęto produkcję seryjną narzędzi, które jako jedyne w świecie spełniają drganiowe normy bezpieczeństwa ISO. Stąd też miedzy innymi biorą się źródła Bio – Dynamiki uprawianej od dawna w Zakładzie.

Niekończące się dysputy z Kolegami…

Dynamika układów z wibrouderzeniami

Uderzeniowy charakter pracy wielu maszyn technologicznych i brak teorii dynamiki takich układów ściągnęły uwagę i inicjatywę badawczą prof. Cempla. Badając te układy zaproponował wpierw dystrybucyjny sposób opisu i rozwiązania równań ruchu układów z uderzeniami już w roku 1969.

W dalszych pracach z tej dziedziny skupił się na tzw. wielomasowych uderzeniowych eliminatorach drgań. Badając je zaprezentował w roku 1979 w Journal of Sound and Vibration efektywną i zgodną z eksperymentem 'koncepcję **siły równoważnej'** reprezentującej ruch wielu mas w pojemniku wielomasowego eliminatora drgań. Badając później z H. G. Natke (Uniw. Hannover) śrutowy eliminator drgań zaprezentował równoważne **podejście energetyczne** reprezentujące ruch i oddziaływania śrutu i umożliwiające dodatkowo badanie oddziaływań i efektywności eliminatora śrutowego. Najnowsza koncepcja, która wykluła się na kanwie tych badań to zastosowanie automatów komórkowych do modelowania tych zagadnień. Bowiem zwykłe systemy symulacyjne, np. Matlab®, zawodzą w obliczu takiej złożoności i nieliniowości.

Diagnostyka wibroakustyczna maszyn

Badania w tym obszarze rozpoczęły się w zespole prof. Cempla we wczesnych latach 70-tych i były prowadzone szerokim frontem, o czym szczegółowo mówi prof. Z. Engel w następnym artykule.

Ta redundancja, optymalizacja, kumulanty i inne wypracowane często po nocach w samotności, często po długich dyskusjach spacerowych z przyjaciółmi wyzwalają w Profesorze potrzebę relaksu na łonie natury.

Natura, żona i nowe pomysły…

Pionierskie prace Profesora z tego obszaru zyskały uznanie światowe w postaci referatów plenarnych wielu konferencji i czasopism naukowych.

Idąc tak szerokim frontem badań zaproponował on ogólną Metodologię Wibroakustycznej Diagnostyki Maszyn zawartą w monografiach: **Podstawy wibroakustycznej diagnostyki maszyn – WNT 1982, a szczególnie w Wibroakustyczna diagnostyka maszyn – PWN 1989,** z tłumaczeniem niemieckim i angielskim. To przejście od sztuki pomiaru i intuicji w diagnostyce do nauki i technologii diagnozowania widać wyraźnie w pracy zbiorowej **Diagnostyka Maszyn – Zasady Ogólne i przykłady zastosowań**, Wyd. ITE. 1982, której idea wydania, współautorstwo i współredakcja jest jego pomysłu. Przez długie lata była ona jedynym kompendium wiedzy teoretycznej i praktycznej w tej szerokiej dyscyplinie. A dopiero niedawno wspólnie z prof. B. Żółtowskim opracował – również w ramach pracy zbiorowej **Inżynierię Diagnostyki Maszyn,** Wydawnictwo ITE, Radom 2005, str. 1111**.**

Energetyczna Teoria Ewolucji Maszyn i Systemów

W pracach profesora Cempla nad modelem ewolucji stanu maszyny, niezbędnego w diagnostyce, wyłoniła się koncepcja potraktowania rosnących uszkodzeń materiału, elementów i podzespołów maszyny jako zdyssypowaną i zakumulowaną wewnętrznie energię a potem koncepcja powiązania tej energii z dynamiką i drganiami obiektu. Tak powstał w roku 1985 model Tribo – wibroakustyczny opublikowany pierwotnie w WEAR w Anglii, następnie w bardziej dojrzałej formie w Biuletynie PAN, a potem ulepszony w Journal of Mechanical Systems and Signal Processing, i innych. Współpracując w tym obszarze wspólnie z prof. Natke z Hanoweru i Dr Winiwarterem z Bordalier Institute – Francja, udało się model ten znacznie uogólnić na inne systemy mechaniczne, a także na inne typy systemów działaniowych. Dla mechanicznych procesorów energii (*materiały, maszyny, konstrukcje*) można pokazać, że bezwymiarowy czas życia systemu to wprost odpowiednik prawa Palmgrena – Minera, Odkwista – Kaczanowa i odpowiednich praw dla innych form zużywania się.

Koncepcja procesora energii doprowadziła do sformułowania pojęcia **czasu życia** i czasu **przeżycia** (awarii) procesora, jako miary zdyssypowanej wewnętrznie energii, mierzonej od urodzenia systemu aż do jego śmierci. Umożliwiło to z kolei wprowadzenie czasu życia innych systemów działaniowych, w ramach, którego następuje ewolucja własności systemów (*np. zmiana masy, sztywności, tłumienia*) na skutek pracy systemu. Dało to narzędzie do sformułowania Holistycznej Dynamiki Systemów Mechanicznych, dynamiki ujmującej dwa czasy; ewolucję własności systemów w czasie ich działania (życia) makro czas, a także zjawiska dynamiczne i drgania w systemie-mikro czas. Tak rozumiana holistyczna dynamika systemów jest podstawą książki opublikowanej wspólnie z profesorem Natke pt. **Model – aided diagnosis of mechanical systems**, Springer Verlag 1997. Dalszy rozwój tej koncepcji to systemy złożone z procesorów energii różnego przeznaczenia, co może być podstawą systemów samodzielnych z reutylizacją energii, jak np na stacji kosmicznej lub platformie wiertniczej. Narodził się tu również nowy pomysł procesora energii z podukładem samo regeneracji, na podobieństwo tego jak to się odbywa w systemach ożywionych.

Diagnostyka wielouszkodzeniowa

Hardwarowe i softwarowe postępy w metrologii w przestrzeni zjawiskowej maszyny pozwalają zmierzyć praktycznie każdy proces mogący charakteryzować stan maszyny; temperatura, drgania, moc zasilania, itd. Mamy tu zatem, dostępną pomiarowo przestrzeń możliwych symptomów do charakterystyki pracy i ewolucji uszkodzeń nadzorowanej maszyny. Jeśli skojarzyć to jeszcze z obecną łatwością obliczeń, dekompozycji i transformacji dowolnych macierzy, to mamy możliwość ekstrakcji niezależnej informacji uszkodzeniowej; wychodząc z nowo zdefiniowanej **symptomowej macierzy obserwacji** obiektu i uogólnionych symptomów uszkodzeń. Ta koncepcja ekstrakcji wielowymiarowej informacji diagnostycznej z symptomowej macierzy obserwacji, w skojarzeniu z układami samouczącymi może ułatwić zaprojektowanie agenta diagnostycznego, jako elementu samo diagnostyki systemów mechanicznych i mechatronicznych. W ostatnim jednak czasie stała się aktualna w Europie chińska metodologia związana z teoria szarych systemów. Daję ona również dobrą metodę prognozowania, co profesor Cempel pokazał ostatnio w swych pracach.

Inżynieria systemów i ekologia

Inżynieria systemów społecznych, to również wiedza o społecznym przetwarzaniu i tworzeniu wiedzy, co nabiera niezwykłej wagi w obliczu wchodzenia w **gospodarkę wiedzy.** Przemyślenia swoje w tym względzie profesor Cempel zawarł w kilku publikacjach i w serii wykładów dla różnych Szkół Wyższych po serii spotkań z różnymi ludźmi, różnymi faktami i osobami.

Szerokie zainteresowania profesora Cempla i umiejętność syntezy ujawniły się ostatnio w publikacjach i wykładach popularnych na temat **Ekogospodarki** przyszłości i wynikających stąd wyzwaniach stojących przed szkolnictwem wyższym. Bowiem stojąca przed nami zmiana paradygmatu gospodarowania, z obecnego **środowisko jest zasobem gospodarki,** na nowy **gospodarka to część środowiska**, musi być poprzedzone **zmianą mentalności** kadry naukowej, inżynierskiej i zarządzającej kształconej w szkołach wyższych.

Zainteresowania procesorem energii popchnęły prof. Cempla w zagadnienie przetwarzania energii w środowisku i do koncepcji **emergii** wprowadzonej w latach 80 tych przez Odum'a. Nowa ekogospodarka, a zatem gospodarka energetyczna i materiałowa musi być oparta na takim bilansowaniu pierwotnie włożonej energii słońca, czyli emergii. Z takiego rachunku bilansowego można wyciągnąć wiele konkluzji, np. ile ludzi może utrzymać nasza geobiosfera.

3. UDZIAŁ PROFESORA CEMPLA W ROZWOJU NAUKI

Ukazanie się w roku 1978 książki profesora Cempla pt.: **Wibroakustyka stosowana,** pierwszej książki z tego obszaru w piśmiennictwie polskim, ugruntowało potrzebę i przyspieszyło rozwój i formułowanie się nowego obszaru badań **Wibroakustyki Maszyn**. Można z całą otwartością stwierdzić, że w kraju obszar ten został wypromowany wspólnie z profesorem Engelem z AGH. Podobnie ma się historia z wykreowaniem kształcenia o specjalności Diagnostyka Maszyn w latach 80 tych, jako pokłosie wielu prac z tego zakresu, a także ówczesnego zapotrzebowania na tę wiedzę i umiejętności przez przemysł.

Koncepcje te znalazły uznanie środowisk naukowych i społeczności akademickiej, co dało pierwsze zaszczyty honorowe.

Honoris Causa dla Profesora …

Nowa koncepcja równań ruchu układów z uderzeniami opracowana przez profesora Cempla, a następnie koncepcja energetycznie równoważnej siły dla wielomasowego eliminatora drgań z uderzeniami jest wielokrotnie cytowana przez różnych autorów. Dało to nową znacznie prostszą możliwość analizy układów z wibrouderzeniami, gdyż podejście ekwiwalentnej siły zwalnia z rozwiązywania dziesiątków nieliniowych równań różniczkowych.

Osiągnięcia profesora Cempla w wibroakustycznej diagnostyce maszyn są widoczne zarówno w kraju jak i zagranicą.

Energetyczna teoria ewolucji stanu maszyn i systemów to najświeższe i międzynarodowo znane osiągnięcie profesora Cempla, a rozpropagowane w ostatniej współautorskiej monografii: **Model – Aided Diagnosis of Mechanical Systems** (Springer 1997). Zaczęło się to od prostego modelu Ewolucji stanu maszyny sformułowanego przez prof. Cempla w WEAR w 1985, a zaowocowało modelem ewolucji Procesora Energii jako modelu systemu działaniowego przetwarzającego dowolna energię, ze zdefiniowanym czasem życia poprzez energię dyssypacji, z potencjałem destrukcji (*damage capacity*) i niezawodnością symptomową. W końcu posłużyło to do sformułowania holistycznej dynamiki układów mechanicznych, umożliwiającej badania i symulację zachowania się obiektu w całym cyklu jego życia, od wytworzenia aż do kasacji i reutylizacji.

To o tym rozprawiał Profesor na jednym z ostatnich Kongresów międzynarodowych, poszukując przy tym kawy, dyskusji i spokoju.

Ciągle konieczne wyjazdy naukowe – tu Chiny, Czeng Du …

4. WSPÓŁPRACA NAUKOWA

Od wczesnych lat 70–tych, tuż po habilitacji, profesor Cempel podejmuje współpracę naukową i organizacyjną z liczącymi się ośrodkami naukowymi w kraju i zagranicą. Na gruncie krajowym jest to przede wszystkim Instytut Podstawowych Problemów Techniki, z prof. S. Ziembą i doc. A. Muszyńską na czele. Na ich prośbę prof. Cempel podjął się organizacji Międzynarodowego Kongresu Drgań Nieliniowych w Poznaniu w 1972 roku. Była to wielka promocja nauki polskiej a jednocześnie okazja do nawiązania roboczych kontaktów z uczonymi całego świata. Od tego też czasu datowała się współpraca profesora Cempla z prof. S. H. Crandal'em z MIT – USA, a potem z profesorem R. H. Lyon'em z tej samej uczelni. Kolejny współpracujący ośrodek to Politechnika Warszawska z prof. Z. Osińskim i M. Dietrichem na czele, zwłaszcza przy organizacji Letnich Szkół z Dynamiki Maszyn, gdzie prof. Cempel był wielokrotnie wykładowcą, a materiały wykładowe były publikowane przez Ossolineum. Z tego też kręgu wyszła bardzo cenna inicjatywa nowego czasopisma Machine Dynamics Problems, gdzie prof. Cempel jest w radzie redakcyjnej a przewodniczył jej prof. Z. Osiński. Po Jego śmierci współpraca dalej trwa z jego wychowankami, profesorami Zb. Dąbrowskim i St. Radkowskim. Efektem tego są między innymi proszone wykłady na Studium Doktoranckim Wydziału SIMR.

Kolejnym ośrodkiem intensywnej współpracy prof. Cempla był Instytut Mechaniki i Wibroakustyki obecnego Wydziału Inżynierii Mechanicznej i Robotyki AGH. Dotyczy to szczególnie jego twórcy prof. Z. Engela i jego zespołu. Zespól ten tworzy obecnie trzon kierowniczy kilku katedr powstałych po podziale Instytutu w latach 90 tych. Ta wczesna współpraca zaowocowała całym szeregiem wspólnych tematów badawczych w ramach Centralnych Programów Badawczych, raportów i publikacji i innych materiałów, dając nowe impulsy rozwojowi Wibroakustyki i Diagnostyki i w kraju.

Podróże, podróże, podróże i coś przy okazji …

Współpraca ta trwa do chwili obecnej a jej rozmiar wystarczy zilustrować liczbami, na około 200 recenzji dorobku, prac na stopień i monografii, około 40 dotyczy Wydziału Inżynierii Mechanicznej i Robotyki AGH.

Politechnika Szczecińska to następny ośrodek współpracy w zagadnieniach Dynamiki Maszyn w szczególności. Tutaj w nowych doktoratach i habilitacjach zostały przetestowane niektóre koncepcje profesora Cempla, jak np. podatność szerokopasmowa jako miara dynamiczności układu mechanicznego będącego modelem konstrukcji, miary wibroizolacji systemów, nowych definicji symptomów w diagnostyce maszyn, i inne.

Profesor Cempel był i jest zapraszany do członkostwa różnych rad naukowych; poprzednio OBR łożysk Tocznych, Wyższa Szkoła Oficerska – Piła, KNIPT Zespół XIII, Zespół Dydaktyczny Mechanika przy MEN (1 kadencja), Instytut Akustyki UAM Poznań, Instytut Obróbki Plastycznej – Poznań, a obecnie Instytut Maszyn Przepływowych PAN w Gdańsku.

5. WSPÓŁPRACA ZAGRANICZNA

Po powrocie ze stypendium British Council w roku 1981 i zakończeniu stanu wojennego, prof. Cempel zaczął wyjeżdżać za granicę nie tylko na konferencje, ale był zapraszany również na wykłady lub cykle wykładów oraz dalsze stypendia, w szczególności DAAD. Ilustruje to poniższe wyliczenie – **wykłady**: RWTH – Aachen 1982 i 1983, Instytut Mechaniki AN NRD w Chemnitz 1985 i 1987, Politechnika w Birmingham 1985; Uniwersytet Kaiserslautern 1986, 1988 i 1990; Uniwersytet Hanower 1986–1995 (corocznie), 2001; MIT – Cambridge 1987; Hawana 1985 i 1987; Shenyang Chiny 1988; Leningrad - Moskwa – Gorki 1989; Oulu Finlandia 1992; Uniwersytet w Paryżu 1991; Bordalier Institute Francja 1991; Instytut Inżynierii Mechanicznej CETIM Francja 1991, 1992 i 1995, Techn. Universitaet Braunschweig 1998 do 2002, corocznie.

Poszukiwania dyskusji naukowej i spokoju, też za granicą …

Stypendia: Britiish Council w Loughborough Uniw. 3 miesiące; DAAD Hannover Uniw. po 2 mieś.: 1987, 88, 89, 92, 93, 94, 95 (5 miesięcy) i aż do roku 2001 po 1 miesiąc w roku. Profesor Cempel uzyskał również stypendium TEMPUS w 1991 we Francji na uogólnienia swego **procesora energii** i drugie stypendium TEMPUS w Ilyvieska Institute of Technology (*Finlandia 1995*) dla pogłębienia studiów inżynierii systemów.

Prof. Cempel jest członkiem szeregu towarzystw naukowych i technicznych, krajowych i międzynarodowych – łącznie 25.

Dzięki swemu autorytetowi jest zapraszany do komitetów organizacyjnych konferencji krajowych i zagranicznych. Jest członkiem rad redakcyjnych wielu czasopism krajowych i międzynarodowych, między innymi: Zagadnienia Eksploatacji Maszyn, Machine Dynamics Problems, Mechanical Systems nad Signal Processing, Maintenance Management – COMADEM, Engineering Mechanics i przewodniczy radzie programowej czasopisma naukowo technicznego Diagnostyka.

6. KSZTAŁCENIE

Profesor Cempel prowadził zajęcia we wszystkich formach z Mechaniki, Wytrzymałości Materiałów, Mechaniki Płynów, Wibroakustyki, Diagnostyki, Teorii i Inżynierii Systemów i Metodologii Badań. Te dwa ostatnie przedmioty na studium doktoranckim w Politechnice Poznańskiej, Warszawskiej i ATR, gdzie jednym z efektów jest wydanie skryptu **Wybrane Zagadnienia Metodologii i Filozofii Badań**, dostępnego obecnie w Internecie i w postaci wydawniczej (Wyd. ITE Radom 2003).

Pierwszy doktorant zagraniczny…

Jest twórcą specjalności Wibroakustyka Maszyn w Politechnice Poznańskiej i opracował dla niej trzy skrypty; Drgania Mechaniczne, Wibroakustyka, Diagnostyka Maszyn, a dwa ostatnie po uzupełnieniach stały się krajowymi monografiami. Był opiekunem ponad 170 prac dyplomowych, promotorem 17 prac doktorskich, konsultantem i opiekunem wielu habilitacji z wibroakustyki i diagnostyki w kraju i w swym zespole. Był opiniodawcą wielu wniosków i awansów profesorskich w całym kraju.

Doktoranci krajowi, też wojskowi…

W czasie kierowania Wydziałem Budowy Maszyn i Zarządzania wykreowano dwa 3 letnie granty europejskie TEMPUS na kształcenie inżynierów w kierunku **Techniczno Handlowym**, oraz w kierunku **Mechatronika**. Zmodernizowano także w tym czasie całkowicie program studiów inżyniersko - magisterskich na kierunku Mechanika i Budowa Maszyn dla całego Wydziału.

Podczas jego kadencji ustanowiono **studia doktoranckie** na Wydziale, ustanawiając dla nich nowatorski program studiów z takimi przedmiotami jak między innymi; Technologie Informatyczne i Symulacyjne w Badaniach i Kształceniu, Inżynieria Systemów, Metodologia Badań. Przedmioty te kończą się nowatorską forma zaliczenia, wybranym i opracowanym samodzielnie przez studenta problemem projektowym wprowadzenia na rynek wyrobu, usługi, lub efektów swego doktoratu.

Profesor Cempel kieruje obecnie Zakładem **Wibroakustyki i Bio-Dynamiki Systemów** Instytutu Mechaniki Stosowanej, w ramach którego uruchomił specjalność Eksploatacja i Diagnostyka, oraz pięć laboratoriów badawczo kształceniowych: Pomiarów Wielkości Mechanicznych, Drgań i Dynamiki Maszyn, Dynamiki Systemów Biomechanicznych, Diagnostyki Systemów, Inżynierii Wibroakustycznej – w budowie. Dążąc zaś do integracji studiów i studiowania, w obliczu niebywałego rozwoju technologii informatyczno symulacyjnych, oraz zagrożenia środowiska, zaproponował obecnie i uruchomił koncepcję zintegrowanego kierunku kształcenia w Politechnice pod nazwą **Ekoinżynieria**, prowadzonym wspólnie przez dwa wydziały Politechniki od 2005r.

Taka niebywała aktywność Profesora jest od zawsze wspierana przez najbliższych: żonę Krystynę, najbliższą Rodzinę i niekiedy przez Przyjaciół.

W trudnych chwilach żmudnej pracy naukowca zawsze można na Nią liczyć…

Sylwetka profesora Cempla opisana jest wielokrotnie w amerykańskich i angielskich wydawnictwach biograficznych. To samo dotyczy polskojęzycznych wydawnictw biograficznych.

Był proszony wielokrotnie o recenzje dorobku w sprawie nadawania honorowego doktoratu przez różne uczelnie: Politechnika Łódzka dla profesora Z. Osińskiego, AGH dla profesora Z Osińskiego i profesora Z Engela, Politechnika Lubelska dla profesora M. Kleibera, Politechnika Szczecińska dla prof. J. Doerfera, dla profesora A. H., Nayfeh z Virginia Polytechnic Institute USA, prof. L. Kobylińskiego z Politechniki Gdańskiej, prof. K. Marchelka z Politechniki Szczecińskiej (*dwukrotnie*), prof. J. Nizioła z Politechniki Krakowskiej.

PODSUMOWANIE

Jakże trudno syntetycznie napisać o dokonaniach wielu lat życia tak wybitnego uczonego i naszego Profesora. Zasługi i odkrycia Profesora, jakich dokonał w swym niezwykle pracowitym życiu są wręcz uderzające, a opisane zostały w oparciu o udostępnione mi i bardzo uporządkowane Jego materiały – bo któż inny lepiej ogarnie zasięg tych dokonań.

Profesor CEMPEL jest wybitną jednostką. Według mojej oceny Jego osiągnięcia dotychczasowe można ocenić także na podstawie działalności Jego uczniów. Cały ich zastęp realizuje idee i oczekiwania swojego Mistrza.

Pod kierownictwem i przy udziale Profesora polska ***DIAGNOSTYKA, WIBROAKUSTYKA I TEORIA SYSTEMÓW*** wysunęły się na czołowe miejsca w świecie.

Życie samo dopisze dalszy scenariusz ...

Pełny tekst referatu wraz ze spisem monografii, książek i skryptów oraz wykaz ważniejszych publikacji Profesora jest dostępny w materiałach IV Międzynarodowego Kongresu Diagnostyki Technicznej.

WKŁAD PROFESORA CZESŁAWA CEMPELA W ROZWÓJ WIBROAKUSTYKI

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1. WSTĘP

Nowa dziedzina wiedzy wibroakustyka, której Współtwórcą jest Profesor Czesław Cempel powstała w naszym Kraju około 40 lat temu. Było to możliwe, gdyż w Polsce rozwijały się różne działy nauki w tym szeroko pojęta mechanika. Powstały znaczące ośrodki zajmujące się problematyką drganiową, powstały silne ośrodki akustyki.

Do powstania wibroakustyki przyczyniła się polska szkoła teorii drgań oraz krakowska szkoła drganiowa tworzona przede wszystkim przez profesorów Stefana Ziembę, Władysława Bogusza, Zbigniewa Osińskiego, Romana Gutowskiego, Janisława Skowrońskiego, Kazimierza Piszczka oraz innych. Drugą dyscypliną naukową, która w znaczący sposób przyczyniła się do powstania wibroakustyki była akustyka. Prace Marka Kwieka, Edmunda Karaśkiewicza, Ignacego Maleckiego, Stefana Czarneckiego i wielu innych doprowadziły do rozwoju tej dziedziny nauki.

Rozwój mechaniki i jej branż, akustyki i innych dziedzin naukowych pozwoliły na wykrystalizowanie się nowej dziedziny wiedzy – wibroakustyki.

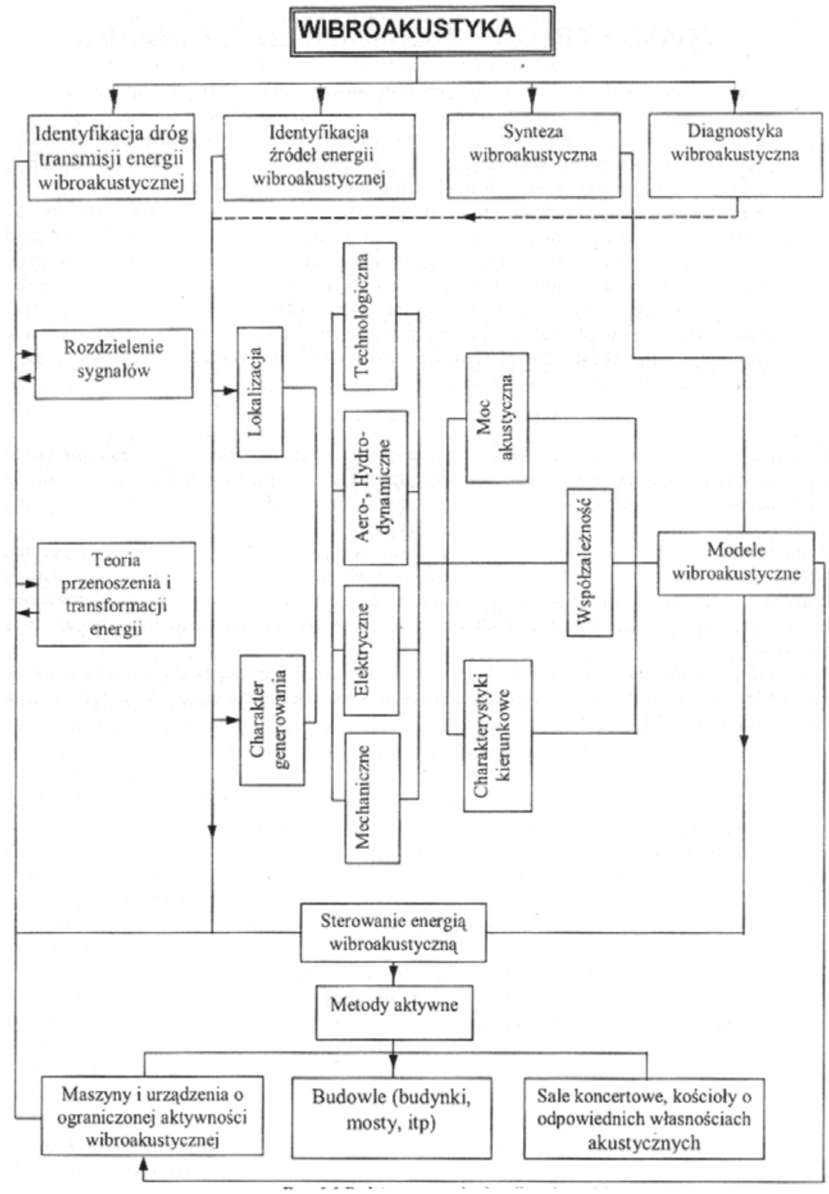
Wibroakustyka jest nową dziedziną nauki zajmującą się wszelkimi problemami drganiowymi i akustycznymi zachodzącymi w przyrodzie, technice, maszynach, urządzeniach, środkach transportu i komunikacji, a więc w środowisku.

2. WSPÓŁCZESNE ZADANIA WIBROAKUSTYKI

Znając definicję wibroakustyki można przedstawić jej cel: „Celem utylitarnym wibroakustyki jest obniżenie zakłóceń wibroakustycznych maszyn, urządzeń, instalacji oraz ich otoczenia do minimum możliwego na danym etapie wiedzy i technologii, a także wykorzystanie informacji zawartych w sygnale wibroakustycznym do oceny jakości maszyn i urządzeń, budowli itp. oraz realizowanych procesów technologicznych. Wykorzystanie sygnału dla celów diagnostyki medycznej".

Dla tak sformułowanego celu można podać podstawowe zadania wibroakustyki. Na rysunku 1 przedstawiono schematycznie te zadania. Są to:

a. Identyfikacja źródeł energii wibroakustycznej, która polega na zlokalizowaniu źródeł w obrębie maszyny, obiektu, urządzenia. Następnie podać należy charakterystyki źródeł, określić współzależność między poszczególnymi źródłami, określić moc akustyczną, a także podać charakter generacji drgań i dźwięków.
b. Identyfikacja dróg transmisji energii wibroakustycznej w określonym środowisku (budowlach, obiektach, maszynach, urządzeniach itp.). Opracowanie teorii transformacji i przenoszenia energii, rozdzielenie sygnałów wibroakustycznych, opracowanie biernych i czynnych metod kontroli zjawisk, opracowanie metod analizy na pograniczu falowego i dyskretnego ujęcia zjawisk.
c. Diagnostyka wibroakustyczna wykorzystująca sygnały emitowane przez maszyny, urządzenia itp. Sygnały wibroakustyczne zawierają informacje o stanie zdrowia, stanie budowli, obiektu, maszyny i urządzenia. Te własności sygnałów są często wykorzystywane zarówno w diagnostyce medycznej jak również w diagnostyce maszyn i urządzeń oraz realizowanych procesów technologicznych, a także w badaniach nieniszczących. Zasady diagnostyki wibroakustycznej stosowane są w każdej fazie istnienia maszyn i urządzeń: w konstruowaniu, wytwarzaniu i eksploatacji oraz przy sterowaniu procesami wibroakustycznymi.
d. Synteza wibroakustyczna maszyn, obiektów oraz sygnałów. Zadania podzielić można na dwie grupy zagadnień:
   -synteza parametrów opisujących pole akustyczne, względnie synteza wielkości stosowanych metodach aktywnych, synteza w akustyce mowy;
   -synteza maszyn i obiektów, przez co rozumiemy syntezę strukturalną, kinematyczną i dynamiczną prowadzącą do uzyskania odpowiedniej aktywności wibroakustycznej.
e. Czynne zastosowanie energii wibroakustycznej. Procesy wibroakustyczne nie zawsze muszą być procesami szkodliwymi. Zastosowane celowo przy użyciu odpowiednich środków zabezpieczających mogą być efektywnym nośnikiem energii, która może być wykorzystana do realizacji różnych procesów technologicznych. Czynne zastosowanie energii wibroakustycznej związane jest z kontrolowanym wykorzystaniem tej energii,



Rys. 1. Zadania wibroakustyki

przy warunku maksymalnej efektywności energetycznej i minimalnych zakłóceniach zewnętrznych.

Energia wibroakustyczna wykorzystana może być również dla celów medycznych przy tzw. „terapii wibroakustycznej".

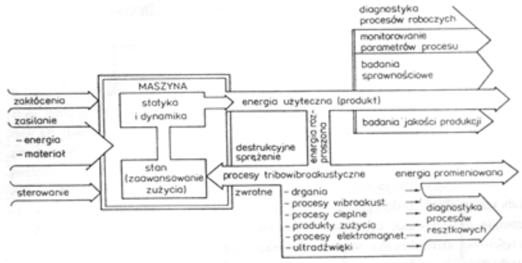
f. Opracowanie metod kontroli emisji, propagacji i eimisji energii wibroakustycznej w środowisku, w tym również w maszynach i urządzeniach, a także opracowanie metod sterowania procesami wibroakustycznymi, co się łączy z tzw. metodami aktywnymi. Podstawową cechą układów aktywnych jest to, że zawierają one zewnętrzne źródło energii. Układy te odpowiednio sterowane mogą dostarczać lub absorbować energię wibroakustyczną w określony sposób z dowolnych miejsc układu. Metody sterowania procesami wibroakustycznymi stanowią nowy dział nauki szybko rozwijający się i mający już szereg praktycznych zastosowań.

Wszystkie maszyny i urządzenia, obiekty znajdujące się w środowisku tworzą złożony układ fizyczny, który pozwala przez zastosowanie odpowiednich uproszczeń przejść do modelu mechanicznego, a następnie do modelu wibroakustycznego. Modelowanie wibroakustyczne należy również do ważnych zadań wibroakustyki.

3. MASZYNY I URZĄDZENIA JAKO PRZETWORNIKI ENERGII

Profesor Czesław Cempel swoich pracach [15, 16] pokazał, że wszelkie maszyny i urządzenia są przetwornikami energii. Na rys. 2 pokazany jest model takiego przetwornika.

Celowo skonstruowane obiekty (maszyny, urządzenia, budowle) dla wykonania określonego zadania traktujemy jako systemy działaniowe. Są to systemy otwarte z przepływem masy (materiału), energii i informacji. Można więc stwierdzić, że są to układy transformujące energię z nieodłączną jej dyssypacją wewnętrzną i zewnętrzną. Wejściowy strumień masy, energii i informacji na energię użyteczną w postaci innej jej formy lub produktu oraz na energię niepożądaną, dyssypowaną, która jest częściowo emitowana do środowiska, a częściowo akumulowana w obiekcie jako efekt różnych procesów zużyciowych zachodzących podczas jego pracy. Zaawansowanie procesów zużyciowych determinuje jakość każdego obiektu technicznego i nosi nazwę stanu technicznego. Stan techniczny może być określony poprzez obserwację przekształconej energii tj. energii użytecznej i energii niepożądanej.



Rys. 2. Maszyna jako system przetwarzania energii

Analizując energię dyssypowaną obserwujemy różnego typu tzw. procesy resztkowe różnego typu np. wibroakustyczne, termiczne, elektromagnetyczne itp. niezamierzone przez projektanta. Obserwacja wyjść daje duże możliwości diagnozowania stanu technicznego z jednej strony, zaś z drugiej minimalizację czynników ujemnie wpływających na środowisko, ale także na sam obiekt.

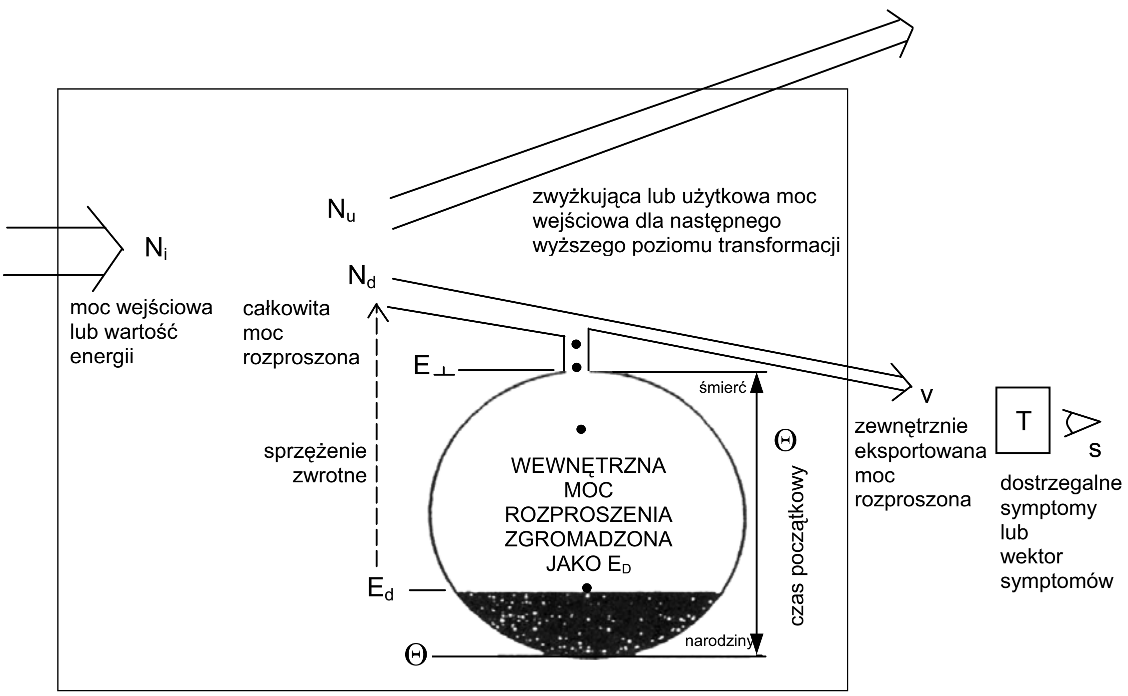
Wewnętrzna dyssypacja energii w każdym systemie działaniowym ma charakter kumulacyjny, determinujący stan tego systemu. Dyssypacja energii wynika z tytułu zachodzących w systemie procesów zużyciowych jak: zmęczenie we wszystkich formach, tarcie, erozja w strumieniu cząstek oraz korozje wszelkiego typu, a także płynięcie materiału, zwłaszcza przy wysokich temperaturach, łącznie z pełzaniem przy wysokich obciążeniach. Te procesy są przyczynkami sumarycznej dyssypacji energii.

Sumaryczną dyssypację energii w systemie E_d można wyrazić następująco [15]:

$$E_d(\theta) = \int_0^{\theta} N_d[V(\theta),\theta]\, d\theta \le E_{db}, V \ll N_d$$

gdzie: N_d - intensywność dyssypacji (moc);
θ - czas działania(życia) obiektu;
$V(\theta)$ – moc dyssypacji zewnętrznej;
E_{db} - pojemność dyssypacji energii przed zniszczeniem systemu;

Wartość intensywności dyssypacji energii zależy od czasu działania (życia) obiektu θ oraz od mocy dyssypacji zewnętrznej. Prof. Czesław Cempel wykazał, że całkowita moc dyssypowana, a także moc dyssypacji zewnętrznej rosną monotonicznie w funkcji czasu życia θ dążąc do nieskończoności dla czasu awarii. Pokazany na rys. 3 model ewolucji stanu układu transformującego energię można stosować do opisu zmian stanu eksploatacyjnego. Ujawnia się w tym fraktalna natura przekształcania energii.



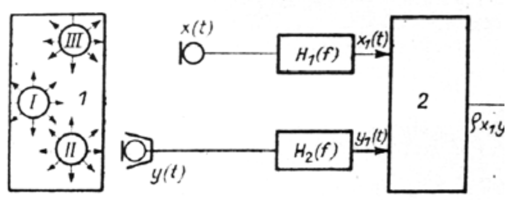
Rys. 3. Model energetyczny systemu działaniowego

Koncepcja procesora energii doprowadziła do sformułowania pojęcia czasu życia i czasu przeżycia, jako miary zdyssypowanej wewnętrznie energii, mierzonej od urodzenia systemu aż do jego śmierci. Umożliwiło to z kolei wprowadzenie czasu życia innych systemów działaniowych, w ramach którego następuje ewolucja własności systemów.

Dało to narzędzie do sformułowania przez Profesora Cempela „Holistycznej Dynamiki Systemów Mechanicznych", dynamiki ujmującej dwa czasy: ewolucję własności systemów w czasie ich działania – makro czas, a także zjawiska dynamiczne i drgania w systemie mikro czas.

4. IDENTYFIKACJA ŹRÓDEŁ ENERGII WIBROAKUSTYCZNEJ

Jednym z podstawowych zadań wibroakustyki jest identyfikacja źródeł generacji energii wibroakustycznej. Identyfikacja ta obejmuje między innymi lokalizację poszczególnych źródeł, określenie charakterystyk i współzależności pomiędzy poszczególnymi źródłami.. W wielu przypadkach przyjmowało się, że maszyna lub urządzenie jest pojedynczym źródłem tej energii. Takie przyjęcia były dużym uproszczeniem, gdyż nawet prosta maszyna czy urządzenie posiada od kilku do kilkuset elementarnych źródeł. Zagadnieniami identyfikacji źródeł energii wibroakustycznej zajmowało się szereg osób w naszym kraju, między innymi Prof. Cz. Cempel, który na drodze teoretycznej i doświadczalnej prowadził tego typu badania. Na podkreślenie zasługuje stosowanie przez niego do identyfikacji metod koherencyjnych. Na rys. 4 przedstawiony jest schemat układu do identyfikacji źródeł przy zastosowaniu metod koherencji, zastosowany przez Profesora Cempela.

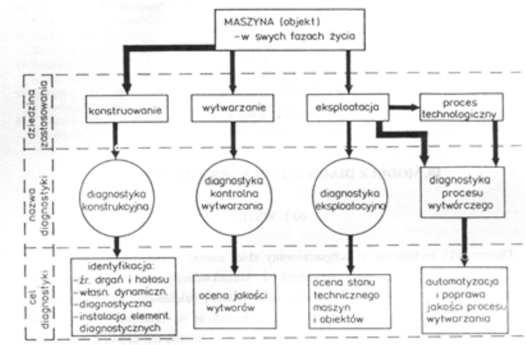


Rys. 4. Schemat zastosowanej procedury

5. DIAGNOSTYKA WIBROAKUSTYCZNA

Na specjalne podkreślenie zasługuje wkład Profesora Cempela w rozwój diagnostyki wibroakustycznej maszyn i urządzeń. Czesław Cempel stworzył podstawy teoretyczne diagnostyki wibroakustycznej, pokazał jej praktyczne zastosowania. Wyniki swoich badań opublikował w kilku monografiach i publikacjach w renomowanych czasopismach naukowych. Monografie te były przetłumaczone na języki obce i opublikowane przez takie wydawnictwa jak Springer stały się one podstawowymi podręcznikami z tego zakresu w świecie naukowym.

C. Cempel stwierdzał, że diagnostyka to zorganizowany zbiór metod i środków do oceny stanu technicznego obiektów, maszyn, urządzeń. W większości przypadków są to systemy działaniowe generujące i przenoszące procesy wibroakustyczne.



Rys. 5. Rodzaje i cele diagnostyki wibroakustycznej.

Procesy te są nośnikami informacji o stanie technicznym. Stan techniczny obiektu podawany jest w kategoriach jakości i bezpieczeństwa jego działania poprzez wektor miar bezpośrednich lub pośrednich. Miary bezpośrednie są np. wymiary, parametry technologiczne itp. Miary pośrednie stanu technicznego noszą nazwę symptomów, czyli wielkości współzmienniczych z miarami stanu technicznego.

W diagnostyce maszyn należy wyróżnić cztery rodzaje zastosowań: diagnostykę konstrukcyjną, diagnostykę kontrolną, diagnostykę eksploatacyjną oraz diagnostykę procesów (rys. 5). Celem diagnostyki konstrukcyjnej dokonywanej na etapie badań prototypu jest identyfikacja źródeł zakłóceń wibroakustycznych jako zjawisk świadczących o niedociągnięciach projektowych i konstrukcyjno – montażowych, a także identyfikacja własności dynamicznych. Celem diagnostyki kontrolnej jest ocena jakości wytworzonych elementów i podzespołów maszyn i urządzeń, natomiast diagnostyka eksploatacyjna ma za zadanie ocenę bieżącego i przyszłego stanu eksploatacyjnego maszyn i urządzeń w trakcie ich eksploatacji. Wreszcie diagnostyka procesów technologicznych ma na celu ocenę jakości i etapu procesu.

Problemy badawcze i aplikacyjne diagnostyki wibroakustycznej są wielorakie i coraz lepiej rozwijane za pomocą współczesnych środków pomiarowych, technologii informatycznych oraz sztucznej inteligencji. Do nich zaliczyć można:

- wybór miejsca pomiaru sygnału wibroakustycznego, co decyduje o zawartości sygnału użytecznego;
- wybór sposobu przetwarzania sygnału dla uzyskania symptomu stanu;
- ekstrakcja całościowej informacji diagnostycznej ze zbioru symptomów stanu i selekcja

rozwijających się niezależnych uszkodzeń w obiekcie;
- ocena zaawansowania uszkodzeń i podjęcie decyzji o stanie obiektu.

Każdy z tych cząstkowych celów diagnostyki wibroakustycznej może być rozwiązywany na wiele sposobów i w różnych zakresach wypełnienia zadania.

Reasumując, należy stwierdzić, że identyfikacja uszkodzeń w diagnostyce wibroakustycznej odbywa się poprzez pomiar specjalnych uszkodzeniowo zorientowanych symptomów. Profesor Cempel jako pierwszy zdefiniował te wielkości oraz dodał kilka łatwo mierzalnych jak np. współczynnik impulsowości, luzu, częstości Rice'a, współczynniki harmoniczności. Zaproponował softwarową procedurę dyskryminacji i klasyfikacji uszkodzeń maszyn poprzez wybór zbioru symptomów o minimalnej redundancji opisujących stan maszyny. Procedura ta oparta była o metody rozpoznawania obrazów, a w szczególności o metodę składowych głównych macierzy uszkodzeń. Prof. C. Cempel wprowadził również do zastosowań w diagnostyce wibroakustycznej pojęcie niezawodności symptomowej.

Omówione problemy diagnostyki były i są przedmiotem prac badawczych Profesora Cempela, a także licznych Jego publikacji w tym monografii.

6. PODSUMOWANIE

Profesor Czesław Cempel jest współtwórcą wibroakustyki – nowej dziedziny wiedzy. Określił nie tylko podstawowe zadania i metody współczesnej wibroakustyki, lecz również pokazał praktyczne zastosowania. Działalność naukowa i publikacyjna Czesława Cempela z zakresu wibroakustyki może być podzielona na kilka grup:
-wibroakustyka maszyn i środowiska;
-wibroakustyka narzędzi ręcznych, głównie pneumatycznych;
-dynamika układów wibrouderzeniowych;
-diagnostyka wibroakustyczna.

W ramach tych grup zagadnień, Prof. Czesław Cempel opublikował dużą ilość prac. Wyniki swoich badań przedstawiał na licznych kongresach, konferencjach i sympozjach naukowych. Był wielokrotnie zapraszany do wygłaszania referatów plenarnych na światowych kongresach.

Szerokie, różnorodne Jego osiągnięcia naukowe i wdrożenia z zakresu wibroakustyki przyczyniły się do rozwoju tej dziedziny wiedzy nie tylko w Polsce, lecz również na całym świecie.

LITERATURA

1. Cempel C.: *Podstawy wibroakustycznej diagnostyki maszyn.* WNT Warszawa,1982.
2. Cempel C. *Wibroakustyka stosowana.* PWN Warszawa 1978.
3. Cempel C.: *Diagnostyka wibroakustyczna maszyn*. Wyd. Politechniki Poznańskiej 1985.
4. Cempel C. *Wibroakustyczna diagnostyka maszyn.* PWN Warszawa,1989.
5. Cempel C.: *Vibroakustische Maschinen-Diagnostik*. Verlag Technik Berlin 1990.
6. Cempel C. *Vibroacoustic Condition Monitoring.* Horwood, Chichester, New York,1991.
7. Cempel C:. *The Tribovibroacoustical Model of Machines*. Wear 105, str. 297-305, 1985.
8. Cempel C.: *The Wear Process and Machinery Vibration – a Tribovibroacoustic Model*. Bull.of the Pol. Acad.of Sc. vol. 35, nr. 7-8, str. 347-363, 1987.
9. Cempel C.: *Theory of Energy Transforming Systems and their Application in Diagnostics of Oprerating Systems*. Applied Mathematics and Computer Science, vol. 3, nr. 3, str. 533-548, 1993.
10. Cempel C.: *Energy Processors in Systems Engineering and their Evolution*. Bull. Of the Pol. Academy of Sc. Vol. 45, nr 4, str. 495-511, 1997.
11. Cempel C.: *Diagnostically Oriented Measures of Vibroacoustical Processes*. Journal of Sound and Vibration 73(4), str. 547 -561, 1980.
12. Cempel C. *Modele ewolucji systemów.* Problemy Eksploatacji nr. 3, 47- 69, 1997.
13. Cempel C., Kosiel U.: *Noise Sources Identification in Machines and Mechanical Devices*. Archives of Acoustics 1,1, str. 5-19, 1976.
14. Cempel C., Engel Z.: *Wibroakustyka maszyn, geneza dziedziny i jej podstawowe problemy*. Zeszyty Naukowe AGH, nr. 728, str. 13-17, 1979.
15. Cempel C., Lotz G.: *Efficiency of Vibrational Energy Dissipation by Moving Shot*. Journal of Structural Engineering, Vol 119, no 9, str. 2642-2652, 1993.
16. Cempel C., Natke H. G.: *The Modeling of Energy Transforming and Energy Recycling Systems*. Journal of Systems Engineering. Vol. 6, str. 79-88, 1996.
17. Engel Z., Cempel C.: *Vibroacoustics and its Place in Science*. Bull. Of the Pol. Acad. of Sc. Vol 49, nr 2, str. 185-198, 2001.
18 Natke H. G., Cempel C.: *Model-Aided Diagnosis of Mechanical Systems*. Springer Verlag, 1997.

Prof. zw. dr hab. inż. **Zbigniew ENGEL** jest wieloletnim profesorem AGH w Krakowie i Centralnego Instytutu Ochrony Pracy w Warszawie. Jest specjalistą zakresu mechaniki i inżynierii środowiska, twórca nowej dziedziny nauki – wibroakustyki. Dorobek publikacyjny prof. Engela obejmuje ponad 550 publikacji, w tym monografie, skrypty, podręczniki, artykuły w znanych czasopismach zagranicznych i krajowych, referaty na konferencjach naukowych. Jest doktorem honoris causa Akademii Górniczo-Hutniczej i Politechniki Krakowskiej.

ROZWÓJ DIAGNOSTYKI I KONGRESY DIAGNOSTYKI TECHNICZNEJ W POLSCE

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Streszczenie
W artykule przedstawiono rozwój diagnostyki i Międzynarodowych Kongresów Diagnostyki Technicznej w Polsce. Przedstawiony rozwój dotyczy okresu od początku kumulowania się wiedzy praktycznej i technologii określania stanu technicznego obiektów technicznych do uzyskania przez diagnostykę poziomu naukowego jako nowej odrębnej dyscypliny.

Słowa kluczowe: diagnostyka techniczna, kongresy, historia.

DEVELOPMENT OF DIAGNOSTICS AND DIAGNOSTIC CONGRESSES IN POLAND

Summary
Development of machinery diagnostics and International Congresses on Machinery Diagnostics in Poland are presented in the paper. Presented development is concerned with a period since beginning of cumulating practical knowledge and technology defining of technical objects condition to obtainment by Machinery Diagnostics of scientific level as a new independent discipline.
Keywords: technical diagnostics, diagnostic congresses, history.

Początek rozwoju diagnostyki technicznej, jako nauki zaliczanej do inżynierii mechanicznej, przypada na lata siedemdziesiąte. Diagnostyka techniczna jest zatem stosunkowo młodą nauką. W pierwszej połowie lat siedemdziesiątych wykształciła się ona w efekcie kumulacji praktycznej wiedzy dotyczącej eksploatacji maszyn oraz metod badawczych pozwalających określić stan techniczny obiektów technicznych w czasie eksploatacji. Nauka ta pojawiła się na początku, jako naturalna potrzeba mierzenia różnych parametrów pracy maszyn, które mogłyby sygnalizować niepoprawną pracę maszyny lub jej awarię. Zaliczyć do nich można pomiar temperatury, ciśnienia oleju w systemach smarowania, drgania i hałas. Dla tych wielkości fizycznych ustalono wartości dopuszczalne i opracowano normy zalecane do stosowania. Wszystkim nam znane są np. normy VDI 2056 i normy IRD Mechananalysis Inc. Pamiętamy również pierwszą znaną amerykańską książkę Bleke'a M. P. i Mitchell W. S.: *Vibration and Acoustic Measurements Handbook* (Spartan Books 1972), która dotyczyła bardzo praktycznych spraw związanych z pomiarami, ale bez ich postaw teoretycznych. Podstawy teoretyczne diagnostyki technicznej nie były wtedy jeszcze znane. Pierwszą książką, która w tytule zawierała słowo diagnostyka, była książka rosyjska zatytułowana: Akustyczna Diagnostyka Maszyn autorstwa Pavlov'a B. V., wydana w Moskwie w 1971 roku. W książęce tej rozpoczęto wyjaśniać co, dlaczego i kiedy należy zrobić w diagnostyce maszyn. Był to początek monitorowania stanu technicznego maszyn w praktyce, który rozpoczął racjonalne i naukowe myślenie, dlaczego jest tak i jakie to pociąga skutki oraz co można udoskonalić.

Aktywność w obszarze diagnostyki w przemyśle i na uczelniach wyższych odnotowano również w Polsce. Pierwsze warsztaty naukowe na temat diagnostyki maszyn odbyły się w 1973 roku i były zorganizowane przez zespól Prof. L. Muellera. Od tego momentu dziedzina diagnostyki maszyn w Polsce zaczęła gwałtownie wzrastać. Wystąpiła potrzeba organizowania więcej kursów, szkoleń i spotkań, a w 1977 roku powołano oficjalnie Zespół Diagnostyki przy Komitecie Budowy Maszyn PAN. W organizowaniu nowej dziedziny nauki – czyli diagnostyki, od początku aktywnie uczestniczył Prof. C. Cempel. Jako młodemu profesorowi, zaproponowano mu prowadzenie Zespołu Diagnostyki. Spotkania odbywały się co kwartał każdego roku, na których wygłaszano kilka referatów i wymieniano różne idee oraz wiedzę. Natomiast, co dwa lata, organizowano tzw. „Szkoły Diagnostyki". Pierwsza Szkoła Diagnostyki zorganizowana była w 1977 r. w Białym Borze, zatytułowana: *Diagnostyka Urządzeń Mechanicznych*. Kolejne cztery Szkoły Diagnostyki – II, III, IV i V odbyły się również w Białym Borze w latach: 1978, 1979, 1980 i w 1981, a ich tematyka była następująca: *Podstawy Diagnostyki Urządzeń Mechanicznych, Metody Cyfrowej Analizy Sygnałów Wibroakustycznych, Diagnostyka Łożysk Tocznych oraz Diagnostyka Pojazdów*.

Kolejne cztery Szkoły Diagnostyki VI, VII, VIII i IX zorganizowane przez zespół z Politechniki Poznańskiej odbyły się w Rydzynie koło Leszna w latach 1983, 1985, 1987 i 1989. Poświęcone one były w kolejnych latach następującej tematyce sygnalizowanej w ich tytułach: *Komputerowe Przetwarzanie Sygnałów* oraz w trzech kolejnych latach – *Wnioskowanie Diagnostyczne*.

Ostatnia X Szkoła Diagnostyki odbyła się w 1992 r. w Zajączkowie koło Poznania.

W międzyczasie, przeprowadzono kilka innych konferencji dedykując je dla poszczególnych branż przemysłu lub wyposażenia, jak np. silników wysokoprężnych czy maszyn roboczych ciężkich.

Cel do osiągnięcia i zakres diagnostyki był już bardzo duży, co doprowadziło do powołania Polskiego Towarzystwa Diagnostyki Technicznej w roku 1990. Liczyło ono wtedy 150 członków krajowych.

W historii rozwoju diagnostyki technicznej w Polsce, *Diagnostyka Wibroakustyczna Maszyn* (DWA) zajmuje swoje początkowe miejsce. Sformułowanie zapisu matematycznego uśredniania synchronicznego sygnałów wibroakustycznych miało miejsce właśnie na początku lat 70-tych. W celu identyfikacji uszkodzeń maszyn w diagnostyce WA wprowadzono pomiary specjalnych uszkodzeniowo zorientowanych symptomów. Do najbardziej znanych zaliczyć można zdefiniowanie takie wielkości jak: np. współczynnik impulsowości, luzu, częstości Rice'a, współczynniki harmoniczności i różnego typu kumulanty [2]. Wielkości te są stosowane do dnia dzisiejszego w diagnostyce wibroakustycznej maszyn.

W roku 1980 opracowano softwarową procedurę dyskryminacji i klasyfikacji uszkodzeń maszyn, poprzez wybór zbioru symptomów o minimalnej redundancji opisujących stan maszyny. Procedura ta oparta była o metody rozpoznawania obrazów, a w szczególności o metodę składowych głównych (PCA) macierzy obserwacji diagnostycznej i ich odpowiednich wektorów, jako nowych niezależnych symptomów uszkodzeń. Po dwudziestu latach, wraz z niebywałym rozwojem systemów obliczeniowych, które same w sobie zawierają podobne procedury; np. **SVD** (*Singular Value Decomposition*), można było powrócić do tej koncepcji proponując nową metodę wielowymiarowej i wielouszkodzeniowej diagnostyki maszyn, formułując nową symptomową macierz obserwacji i uogólnione symptomy niezależnych uszkodzeń. W klasyfikacji stanu maszyny pojawiła się konieczność określenia stanu granicznego w przestrzeni symptomów stanu obiektu. W tym celu zaproponowano kilka metod opartych o rozkłady wartości obserwowanych symptomów; np. typu Pareto, Weibulla, Frecheta. Opis tych metod można znaleźć w materiałach wielu konferencji międzynarodowych oraz w czasopismach naukowych takich jak: Mechanical Systems and Signal Processing, Journal of Sound and Vibration, Bulletin PAN, i inne krajowe czasopisma naukowe.

W klasyfikacji stanu maszyny nieodzowne jest określenie stanu granicznego w przestrzeni symptomów stanu obiektu. W tym celu do zastosowań w diagnostyce WA wprowadzono również pojęcie niezawodności symptomowej. Pozwoliło ono później pokazać jej prosty związek z czasem awarii systemu mechanicznego. Był to moment w badaniach, aby zaproponować ogólną Metodologię Wibroakustycznej Diagnostyki Maszyn, która ukazała się w monografiach: *Podstawy Wibroakustycznej Diagnostyki Maszyn* w 1982 [2] oraz w *Wibroakustycznej Diagnostyce Maszyn* w 1989 roku [3, 4]. Wymienione wyżej koncepcje i rezultaty badań uznano w nauce jako podstawowe dla diagnostyki WA, co dało początek nowej nauce w momencie, w którym ***„sztuka pomiaru i intuicja wnioskowania"*** była już dobrze znana. Fakt ten, przejścia do nauki i technologii diagnozowania jest widoczny szczególnie w pracy zbiorowej zatytułowanej ***Diagnostyka Maszyn – Zasady ogólne i przykłady zastosowań*** wydane drukiem w 1992 [10]. Przez wiele lat była ona jedynym zasobem wiedzy teoretycznej i praktycznej w tej szerokiej dyscyplinie. Taką rolę pełni obecnie książka – poradnik liczący 1111 stron, wspólne dzieło wielu autorów zajmujących się diagnostyką w Polsce pod tytułem: ***Inżynieria Diagnostyki Maszyn** – Poradnik,* wydane w 2005 r. [24].

W rozwoju diagnostyki należy również wymienić prace nad modelem ewolucji stanu maszyny, niezbędnym w diagnostyce, które doprowadziły do koncepcji energetycznej ewolucji maszyn i systemów spowodowanej przez rosnące uszkodzenia materiału, elementów i podzespołów maszyny. Za miarę tych uszkodzeń przyjęto zdyssypowaną i zakumulowaną wewnętrznie energię.

W efekcie ww. prac powstał w roku 1985 model tribo-wibroakustyczny opublikowany pierwotnie w WEAR [6] w Anglii, a następnie w Biuletynie PAN i w Journal of Mechanical Systems and Signal Processing. Model ten uogólniono na inne systemy mechaniczne, a także na inne typy systemów działaniowych. W opracowanej w ten sposób teorii Procesora Energii połączono obserwowany **symptom stanu** (*życia)* procesora z jego wewnętrznym zaawansowaniem (*akumulacją*) uszkodzeń z tytułu działania (życia).

Teorię tę połączono z wcześniej sformułowanym pojęciem **niezawodności symptomowej**. Dla mechanicznych procesorów energii (*materiały, maszyny, konstrukcje*) pokazano, że bezwymiarowy czas życia systemu jest odpowiednikiem prawa Palmgrena – Minera, Odkwista – Kaczanowa i odpowiednich praw dla innych form zużywania się.

Koncepcja procesora energii umożliwiła sformułowanie pojęcia **czasu życia**[1] i czasu **przeżycia** (awarii) procesora. Są to miary zdyssypowanej wewnętrznie energii, mierzonej od zaistnienia systemu aż do jego likwidacji. Koncepcja to pozwoliła na wprowadzenie czasu życia innych systemów działaniowych, w których następuje

[1] Taka energetyczna definicja C Cempla została zamieszczona w **International Encyklopedia of Systems and Cybernetics,** K G Saur, Muenchien, 1997

ewolucja własności systemów (*np. zmiana masy, sztywności, tłumienia*) w czasie pracy systemu. W ten sposób sformułowano Holistyczną Dynamikę Systemów Mechanicznych, która jest przedmiotem książki pt. MODEL - AIDED DIAGNOSIS OF MECHANICAL SYSTEMS, Springer Verlag 1997 [10]. Rozwój tej koncepcji prowadzi do systemów złożonych z procesorów energii różnego przeznaczenia.

Rozwój informatyzacji diagnostyki technicznej, a w niej szczególnie informatycznych technik pomiarowych, umożliwił precyzyjne pomiary różnych wielości fizycznych charakteryzujących stan maszyny. Zaliczyć do nich można moc zasilania, moc obciążenia, temperaturę, drgania – amplitudy przyspieszeń, prędkości i przemieszczeń, hałas, produkty procesów tarciowych w maszynach itp. W efekcie prowadzonego *on-line* nadzoru diagnostycznego uzyskuje się przestrzeń możliwych symptomów służących do scharakteryzowana pracy i ewolucji różnych uszkodzeń nadzorowanej maszyny. Dalsza obróbka uzyskanej w ten sposób bazy danych w nowoczesnych metodach transformacji i dekompozycji prowadzi do wydobycia niezależnych informacji uszkodzeniowych. Uzyskuje się w ten sposób **symptomową macierz obserwacji** badanego obiektu i uogólnionych symptomów uszkodzeń.

Jest to tematyka współczesnych badań, o których można dowiedzieć się z materiałów konferencyjnych *np*. IMEKO World Congress, June, 2003, Dubrovnik [13] i czasopism naukowych takich jak np. Mechanical Systems and Signal Processing. Koncepcja wyodrębniania wielowymiarowej informacji diagnostycznej z symptomowej macierzy obserwacji, w skojarzeniu z układami samouczącymi się może ułatwić zaprojektowanie agenta diagnostycznego, jako elementu samodiagnostyki systemów mechanicznych i mechatronicznych.

W zakresie prognozy stanu przyszłego proponuje się w diagnostyce technicznej metody zaczerpnięte z teorii szeregów czasowych i z ekonometrii. Metody te są obecnie wypierane przez sieci neuronowe.

W diagnostyce technicznej pojawiła się również w ostatnim czasie w Europie chińska metodologia związana z teorią szarych systemów. Dzięki niej uzyskuje się dobrą metodę prognozowania, co wykazano w pracach Cempela.

Polityczne i gospodarcze zmiany w Polsce po roku 1990 nie służyły rozwojowi Diagnostyki. Mimo tego, dalsza edukacja i badania w tej dziedzinie były kontynuowane. Potrzeby zintegrowania środowiska i wymiany wiedzy dotyczącej diagnostyki technicznej spowodowały, że Polskie Towarzystwo Diagnostyki Technicznej zorganizowało w dniach 17-20 września 1996 roku **I Międzynarodowy Kongres Diagnostyki Technicznej w Gdańsku. Organizację Kongresu powierzono zespołowi składającemu się z przedstawicieli Politechniki Śląskiej i Instytutu Maszyn Przemysłowych w Gdańsku. Przewodniczącym KO był Wojciech CHOLEWA, wiceprzewodniczącym Jan KICIŃSKI.** W Kongresie wzięło udział ponad 350 uczestników i 11 wystawców, wygłoszono 8 wykładów zaproszonych i 24 plenarnych. Opublikowano 140 artykułów w 3 tomach materiałów kongresowych i zaprezentowano 108 prac w formie posterów. Podczas trwania Kongresu odbyło się 7 specjalnych kursów diagnostycznych, na których było prezentowane wyposażenie specjalistyczne. Program socjalny Kongresu dla uczestników i osób towarzyszących był bardzo dobrze zorganizowany w kilku interesujących miejscach wybrzeża bałtyckiego i w Gdańsku.

Duży rozgłos dotyczący I Kongresu Diagnostyki Technicznej spowodował, że kolejny **II Międzynarodowy Kongres Diagnostyki Technicznej został zorganizowany wspólnie przez zespół składający się z przedstawicieli Politechniki Warszawskiej i Instytutu Energetyki w Warszawie w dniach 19-22 września 2000 roku. Przewodniczącym KO był Stanisław RADKOWSKI, a wice-przewodniczącym Zenon ORŁOWSKI.** W Kongresie wzięło udział ponad 110 uczestników, w tym kilku z zagranicy. Obrady odbywały się w 7 sesjach plenarnych z 36 proszonymi wykładami, w 4 sesjach posterowych z 87 prezentacjami. Wydrukowano dwa tomy materiałów kongresowych i załączono do nich dyski CD. Program socjalny kongresu był również interesujący, w którym uwzględniono kilka najpiękniejszych miejsc w Warszawie, jako stolicy Polski.

Kolejny, **III Międzynarodowy Kongres Diagnostyki Technicznej odbył się w dniach 6-9 września 2004 roku w Poznaniu. Organizatorem Kongresu był zespół składający się z przedstawicieli Politechniki Poznańskiej i Akademii Techniczno – Rolniczej w Bydgoszczy. Przewodniczącym KO był Marian W. DOBRY, a wiceprzewodniczącym Bogdan ŻÓŁTOWSKI.** Uczestniczyło w nim ponad 110 uczestników również kilku z zagranicy, wygłoszono 108 referatów oraz 6 prezentacji dotyczących aparatury diagnostycznej wystawianej przez wystawców. Na III Kongresie wygłoszono 16 referatów plenarnych, 92 referaty sesyjne oraz odbyły się dwie sesje panelowe na temat ważnych zagadnień diagnostyki. Program socjalny związany był z prezentacją lokalnego folkloru oraz zwiedzaniem ciekawych dla uczestników miejsc regionu Wielkopolski.

Organizowane co cztery lata Międzynarodowe Kongresy Diagnostyki Technicznej stają się dobrą tradycją. Pozwalają one dokonać podsumowania dotychczasowych badań, przeglądu aktualnych trendów i nowości w diagnostyce technicznej. Zadaniem Kongresu jest również wytyczać nowe kierunki dalszych badań w zakresie diagnostyki technicznej. Mam nadzieję, że obecny, organizowany przez **zespół z Uniwersytetu Warmińsko-Mazurskiego w Olsztynie oraz**

z Akademii Marynarki Wojennej w Gdyni, IV Międzynarodowy Kongres Diagnostyki Technicznej w Olsztynie w dniach 9-12 września 2008 roku, spełni oczekiwania wszystkich uczestników. **Przewodniczącym KO jest Stanisław NIZIŃSKI, a wiceprzewodniczącym Zbigniew KORCZEWSKI.**

Kierując do Wszystkich życzenia owocnych obrad i miłych spotkań w czasie IV Kongresu – pozostając z wyrazami poważania

– Marian W. DOBRY

LITERATURA

1. Bartelmus W.: *Diagnostyka Maszyn*, Górnictwo Odkrywkowe, Wyd. Śląsk, Katowice 1998
2. Cempel C.: *Podstawy wibroakustycznej diagnostyki maszyn*, WNT, Warszawa 1982
3. Cempel C.: *Wibroakustyka Stosowana*. PWN Warszawa-Poznań 1978, wyd. II-gie 1985
4. Cempel C.: *Wibroakustyka Stosowana*, wyd. II zmienione, PWN, Warszawa, 1989
5. Cempel C.: *Diagnostyka Wibroakustyczna Maszyn*. Wyd. Pol. Poznańskiej 1985
6. Cempel C., *The Tribovibroacoustical Model of Machines*. Wear 105, 1985, s. 297-305.
7. Cempel C.: *Wibroakustyczna Diagnostyka Maszyn*, PWN Warszawa 1989,
8. Cempel C.: *Vibroakustische Maschinen-Diagnostik*. Verlag Technik, Berlin, 1990,
9. Cempel C.: Vibroacoustic Condition Monitoring, E. Horwood, Chichester - New York, 1991
10. Cempel C., Tomaszewski F.: *Diagnostyka Maszyn; Zasady Ogólne - Przykłady Zastosowań - Poradnik*, Wyd. MCNEMT - Radom, 1992
11. Natke H. G., Cempel C.: *Model - Aided Diagnosis of Mechanical Systems*, Springer Verlag, 1997
12. Cempel C.: *Fundamentals of Vibroacoustical Condition Monitoring*, chapter 13, (pp. 324 – 253) in: Handbook of Condition Monitoring, edited by A. Davies, Chapman and Hall, London, 1998
13. Cempel C.: *Multi fault condition monitoring of mechanical systems in operation*, XVII IMEKO World Congress, Dubrovnik June 2003, pp.1422-1425.
14. Cholewa W., Kiciński J.: *Diagnostyka techniczna. Metody odwracania nieliniowych modeli obiektów*. Zeszyt KPKM nr 120, Pol. Śląska, Gliwice 2001
15. Chudzikiewicz A.: *Elementy diagnostyki pojazdów szynowych*, Wyd. ITE, Politechnika Warszawska, Radom 2002
16. Dybała J., Mączak J., Radkowski S.: *Wykorzystanie sygnału wibroakustycznego w analizie ryzyka technicznego*, Wyd. ITE, Warszawa-Radom 2006
17. Engel Z., Plechowicz J., Stryczniewicz L.: *Podstawy wibroakustyki przemysłowej*. Wyd. Wydz. Inż. Mech. i Rob., AGH, Kraków 2003
18. IRD Mechanalysis Inc.: *Special treatments of vibration sources to reduce plant noise*. Technical Pap. No. 110, 1976
19. Kiciński J.: *Modelowanie i diagnostyka oddziaływań mechanicznych, aerodynamicznych i magnetycznych w turbozespołach energetycznych*. Wyd. Instyt. Maszyn Przepływowych PAN, Gdańsk 2005.
20. Michalski R.: *Diagnostyka maszyn roboczych*. ITE. Radom 2004
21. Moczulski W.: *Diagnostyka Techniczna. Metody pozyskiwania wiedzy*. Wyd. Politechniki Śląskiej, Gliwice 2002
22. Niziński S., Michalski R.: *Diagnostyka obiektów technicznych*, Wyd. ITE, Radom 2002
23. Orłowski Z.: *Diagnostyka w życiu turbin parowych*, WNT, Warszawa 2001
24. Żółtowski B., Cempel C.: *Inżynieria Diagnostyki Maszyn - Poradnik*, Wyd. ITE Radom 2004
25. Żółtowski B.: *Podstawy diagnostyki maszyn*, Wydawnictwo Uczelniane Akademii Techniczno-Rolniczej w Bydgoszczy, Bydgoszcz 1996
26. Żółtowski B., Jankowski M., Ćwik Z.: *Diagnostyka techniczna pojazdów*, Wyd. ATR, Bydgoszcz 1994

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GENERALIZED SINGULAR VALUE DECOPOSITION IN MULTIDEIMENSIONAL CONDITION MONITORING OF SYSTEMS

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Summary

With the modern metrology, we can measure almost all variables in the phenomenon field of a working machine, and much of measuring quantities can be symptoms of machine condition. On this basis, we can form the symptom observation matrix (**SOM**) for condition monitoring. From the other side we know that contemporary complex machines may have many modes of failure, so called **faults**, which form the fault space. This multidimensional problem is not a simple one, even if we apply some modern tool like **SVD** for the fault extraction purpose. So the question remains if one can learn considering similar problem when having SOM of similar machine observed just before. In this way, we can consider the application of generalized GSVD to the machine condition monitoring problems, and uncover some new possibilities.

Keywords: machine condition, multidimensional, generalized SVD, observation space, fault space, condition similarity.

UOGÓLNIONY ROZKŁAD WARTOŚCI SZCZEGÓLNYCH W WIELOWYMIAROWEJ DIAGNOSTYCE STANU SYSTEMÓW

Streszczenie

Obecnie potrafimy mierzyć większość procesów pola zjawiskowego pracującej maszyny, a wiele z tych procesów może dostarczyć symptomów jej stanu technicznego. Wychodząc stąd możemy tworzyć symptomową macierz obserwacji (SOM) do celów diagnostyki maszyn, czyli oceny ewolucji jej stanu technicznego w czasie życia θ. Ale współczesne maszyny mają wiele uszkodzeń rozwijających się współbieżnie, stąd tez propozycja diagnostyki wielowymiarowej i zastosowania rozkładu (SVD), co pokazano już w wielu pracach. Powstaje pytanie czy potrafimy uzyskana wiedzę wykorzystać i nauczyć się diagnozować lepiej maszyny, które już są rozpoznane diagnostycznie za pomocą SVD. Taki właśni problem postawiono stosując uogólniony rozkład SVD, umożliwiający porównanie dwu macierzy obserwacji, znanej uprzednio i właśnie rozwijającej się. Tak możliwość istnieje, a stawia przed nami nowe wymogi nauczenia się nowej semantyki wspólnego języka GSVD.

Słowa kluczowe: stan techniczny, wielowymiarowość, uogólnione SVD, przestrzeń uszkodzeń, przestrzeń obserwacji, podobieństwo stanu.

1. INTRODUCTION

The multidemsionality of fault space in machine condition monitoring is nowadays well formulated and explored, for example by the application of neural nets [4], singular value decomposition [6], or principal component analysis [2]. Much worse it looks when considering the decision making process in multidimensional case, where we have some method of data fusion and the concept of symptom reliability applied to generalized fault symptom obtained from the application of SVD [10]. So, there is a room for looking to other promising methods of condition symptoms processing and decision making in a multidimensional case. This paper looks for the possible application of generalization of SVD method, which takes into account the other SOM of the similar object, with the same number of symptoms (*columns*), but the number of rows (*observation*) may differ. This may be the situation of learning from the previous usage of the same object or even similar one. The accessible list of references to **GSVD** application is not big one. One can see a few in connection with engineering, but there are some papers of **GSVD** application in physics and biology, as we will see later on. In such situation the paper introduce the GSVD concept on the basis of previous SVD application, and from these introductory results one can notice the possible application of GSVD in machine condition monitoring, particularly when looking for the similarity of machine wear symptoms and indices.

[1] GeneralSVD06 - Intended to Diagnostic Congress 08.

2. SINGULAR VALUE DECOMPOSITION AND EXTRACTION OF FAULT SYMPTOMS

Having in mind the above, let us take into consideration a critical machine in operation, where we have the possibility to observe several '*would be*' symptoms[1] of condition. During its working life $\boldsymbol{0 < \theta < \theta_b}$, ($\theta_b$ *–anticipated breakdown time*), several independent faults (*usually a few*); $\boldsymbol{F_t(\theta)}$, $t = 1,2,..u,$ are evolving and growing. Hence, we would like to **identify** and **assess** the advancement of these faults by forming and measuring the symptom observation vector; $\boldsymbol{[S_m] = [S_1,...,S_r]}$, which may have components different physically, like vibration amplitudes (*displacement, velocity, acceleration*), the temperature, machine load, life time $\boldsymbol{\theta}$, etc.

In order to track machine condition (*faults evolution*) by these observations, we are making equidistant reading of the above symptom vector in the lifetime moments; $\boldsymbol{\theta_n,\ n = 1, \ldots p,\ \theta_p \le \theta_b}$, forming in this way the rows of a rectangular symptom observation matrix (**SOM**). From the previous research and papers [6], we know, that the best way of **SOM** preprocessing is to center it (*subtract*), and normalize (*divide it*) to the symptom initial value; $\mathbf{S_m(0) = S_{0m}}$, of each given symptom (*column of **SOM***).

It is also known from this research, that amount of diagnostic information in **SOM** increases if we append the lifetime $\boldsymbol{\theta}$ column, as the first approximation of system logistic vector **L** and the load [7]. Finally, in order to minimize stochastic disturbances in readings we will apply also the three points moving average procedure to the successful symptom readings, as it was shown and validated in the last paper [14].

So, after such preprocessing we will obtain the dimensionless symptom observation matrix (**SOM**) in the form:

$$\boldsymbol{SOM} \equiv \boldsymbol{O_{pr} = [S_{nm}],\ S_{nm}} = \frac{\mathbf{S}_{nm}}{\mathbf{S}_{0m}} - 1, \qquad (1)$$

where bold non italic letters indicate primary measured and averaged dimensional symptoms.

As it was already said in the introduction, we apply now to the dimensionless **SOM** (1), the Singular Value Decomposition (**SVD**) [9, 15], to obtain singular components and singular values in the form of matrix formulae;

$$\boldsymbol{O_{pr} = U_{pp} * \Sigma_{pr} * V_{rr}^T}, \qquad (2)$$

(***T***- *matrix transposition*),
where $\boldsymbol{U_{pp}}$ is $\boldsymbol{p}$ dimensional orthonormal matrix of left hand side singular vectors, $\boldsymbol{V_{rr}}$ is $\boldsymbol{r}$ dimensional orthonormal matrix of right hand side singular vectors, and the diagonal matrix of singular values $\boldsymbol{\Sigma_{pr}}$ is as below

$$\boldsymbol{\Sigma_{pr} = diag\ (\ \sigma_1,\ \ldots,\ \sigma_l\ ),\ and\ \ \sigma_1 > \sigma_2 > \ldots > \sigma_u > 0,} \qquad (3)$$

$$\boldsymbol{\sigma_{u+1} = \ldots\ \sigma_l = 0,\quad l = max\ (p,\ r),\quad u \le min\ (p,\ r),\quad u < r < p.}$$

Mathematically it can be shown also, that every perpendicular matrix has such decomposition (2), and it may be interpreted also as the product of the three matrices [15], namely

***O**pr* **= (Hanger) X (Stretcher) X (Aligner).** (2a)

This is very metaphorical description of **SVD** transformation, but it seems to be useful analogy for statistical reasoning and diagnostic decision making in our case.

In terms of machine condition monitoring the above decomposition means, that from the $\boldsymbol{r}$ primarily measured symptoms (*dimension of **observation space***) we can extract only $\boldsymbol{z \le r}$ independent sources of diagnostic information describing evolving generalized faults $\boldsymbol{F_t}$, creating in this way **fault space** (*see Fig. 1)*. As it is seen from Fig. 1 upper right picture, only a few developing faults are making essential contribution to total fault information, the rest of generalized faults are below the standard 10% level of noise. What is important here, that such **SVD** decomposition can be made currently, after each new observation (*reading)* of the symptom vector $[S_m]$*;* $\boldsymbol{n = 1,\ \ldots\ p}$, and in this way we can trace the fault life evolution in any operating mechanical system.

Diagnostic interpretation of SVD results

From the current research and implementation of this idea [11], we can say, that the most important fault oriented indices obtained from **SVD** is the first pair: ($\boldsymbol{SD_t}$, $\boldsymbol{\sigma_t}$), $t=1,2$. This pair presents the lifetime evolution of all independent sources of information contained in our SOM. We interpret them as the fault development life curves $\boldsymbol{F_t\ (\theta)}$. From the other side we need also some measure of total damage advancement in diagnosed object in a form $\boldsymbol{\sigma_t(\theta)}$.

The first fault indices $\boldsymbol{SD_t}$ can be named as discriminant or the generalized symptom of the fault $\boldsymbol{t}$, and one can get it as the **SOM** product and the first singular vector of the matrix $\boldsymbol{V}$, as below

$$\boldsymbol{SD = O_{pr} * V_{rr} = U_{pp} * \Sigma_{pr}}, \qquad (4)$$

and for the one column component of this matrix we will have simply

$$\boldsymbol{SD_t = O_{pr} * v_t = \sigma_t \cdot u_t\ .\ t=1,...z.} \qquad (5)$$

We know from **SVD** theory [9, 15], that all singular vectors $\boldsymbol{v_t}$, $\boldsymbol{u_t}$ are normalized to one, so the energy norm of this new discriminant (*vector*) is simply

$$\boldsymbol{Norm\ (SD_t) \equiv //SD_t// = \sigma_t\ ,\ t = 1,\ ...,z.} \qquad (6)$$

If the number of observation is growing in the life time, so the above discriminant $\boldsymbol{SD_t(\theta)}$ can be also named as lifetime **fault profile**, and in turn singular value $\boldsymbol{\sigma_t(\theta)}$ as a function of the lifetime seems to be its damage advancement (*energy norm*).

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[1] **Symptom** is a measurable quantity taken from the phenomenal field of the machine, which sees to be correlated to machine condition, we are looking for.

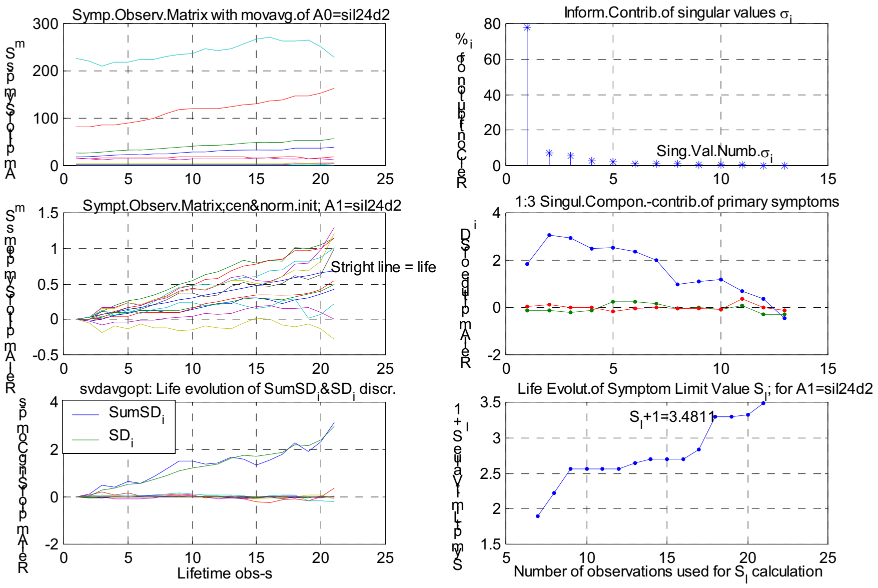

Fig. 1. Illustration of inference possibilities in multidimensional observation by the application of SVD

The similar fault inference can be postulated to the meaning, and the evolution, of summation quantities, what can mean the total damage profile ***SumSD$_i$(θ)***, and total damage advancement ***Sumσ$_i$(θ)***, as follows;

$$SumSD_i(\theta) = \sum_{i=1}^{z} SD_i(\theta) = \sum_{i=1}^{z} \sigma_i(\theta)\cdot u_i(\theta) = P(\theta),$$

$$Norm\ (SumSD_i(\theta)) \equiv //\Sigma\ SD_i\ (\theta)// \leq //\Sigma\ \sigma_i(\theta)\cdot u_i(\theta)// = \Sigma\ \sigma_i(\theta),$$

hence;

$$Sum\sigma_i(\theta) = \sum_{i=1}^{z} \sigma_i(\theta) \sim \sum_{i=1}^{z} F(\theta)_i = F(\theta)\cdot \qquad (7)$$

But it is worthwhile to add, that the meaning of the last relation with *σ$_i$(θ)*eems to be not fully validated experimentally, as yet. It seems to be also, that the condition inference based on the first summation measure; *Sum(SD$_i$)* may stand for the first approach to multidimensional condition inference, as it was clearly shown in the previous papers (*see for example* [17]), and shortly illustrated on Fig. 1 below.

3. GENERALIZED SINGULAR VALUE DECOMPOSITION GSVD

The diagnostic application of generalized **SVD** [9], as far as for today, is not known at all. However, it seems to be different from the ordinary SVD. This is because we have not one but **two** symptom observation matrices **A** and **B**. Let us assume we have primary SOM_p = ***A*** and auxiliary SOM_a = ***B***, and we will try to align SVD decomposition to both matrices, treating the first as primary **SOM** and the second as auxiliary. Even so, the matrices may differ, having different number of rows (*observations*), but they must have the same number of columns (*symptoms*).

Going to the definition of **GSVD** we have following relationships [16].

If we define; gsvd(A,B) ≡ [U,V,X,C,S], than it gives the following decompositions of:

$$\boldsymbol{A = U*C*X^T}, \qquad (8)$$

$$\boldsymbol{and\ ;\ B = V*S*X^T}, \qquad (9)$$

with singular values diagonal matrix:

$$\boldsymbol{\Sigma = C * S^{-1}},\ \textit{\textbf{ascending ordered,}} \qquad (10)$$

and additional identity relation:

$$\boldsymbol{C^T * C + S^T * S = I.} \qquad (11)$$

It maybe important to show, when the **GSVD** becomes **SVD,** because we know already diagnostic interpretation of the second decomposition.

We have from (9);

$$S^{-1} * V^T * B = X^T. \qquad (12)$$

Using it with the decomposition of ***A*** as in the relations (8) one can get;

$$\boldsymbol{A = U*C*X^T = U*C*S^{-1}\ V^T*B = U*\Sigma*V^T*B}\ .(13)$$

So, if the auxiliary matrix is the identity matrix, i. e. ***B = I***,

we have the already known **SVD**, with the properties shown in the paragraph of 2.1 above.

But using ***A*** as a self reference matrix, when ***B=A,*** we obtain from (8) and (9) immediately,

$$\boldsymbol{A = U*C*X^T = V*S*X^T}. \qquad (14)$$

And it can be possible only if : **C=S** and **U=V.** Finally, with this assumption we have:

$$\boldsymbol{\Sigma = C * S^{-1} = I}. \qquad (14a)$$

Hence, if both matrices primary and auxiliary are identical they singular vales obtained from **GSVD** are all equal one! This means that using this property we can investigate the similarity between two **SOM**s, so between respective diagnosed objects. From the other side we can investigate if there is some possibility to learn, using already known knowledge from one object to diagnose the other, not known already.

But before deep penetration of this possibility, let us create the similar condition related (*life*) quantities for both matrices SOM_A and SOM_B .We may try to obtain fault related discriminants from **GSVD** in the same manner as in case of one **SOM** used with usual **SVD** (*see (4) and (5)*.
Several approaches to accomplish this task was made, and one of the best which gives similar results to the case of single **SOM**, (i.e $B=I$) is proposed here as below:

$$SD_A = A * X * S^{-1} = U * C * X^T * X * S^{-1} ,$$

$$SD_B = B X * S^{-1} = V * S * X^T * X * S^{-1} , \qquad (15)$$

and of course matrices have ascending column norms, in contrary to ordinary SVD.

The above-proposed relations give sometimes a little greater numeric results than for one **SOM** case, but the qualitative life course of singular vectors and symptom limit value S_l is much similar. Also this is in some agreement with information contribution (σ_t) of the singular vectors v_t , u_t .

From the relation (13) it is seen that in a case $B \neq I$ all matrices of **GSVD**, that means U, Σ, V , must be aligned to the properties of A and B symptom observation matrices. Hence, we can infer that application of **GSVD** in diagnostic may be interpreted also as some kind of learning process. That mean for example that, based on previous observation (auxiliary $SOM = B$) we are trying to compare the current wear process observed by primary $SOM = A$. That is we should look now for some measures of similarity between matrices A and B.

Having now the possibility of real application of GSVD in condition monitoring let us look for the help at the other branches of science, namely bioinformatics, where one can find already the application of **GSVD** [18]. Following this paper and relation (10) with the additional condition of (14) we can find, that for identical observation matrices **A=B** all singular values of **GSVD** are equal unity; $\Sigma = C * S^{-1} = I$. If we interpret this as the tangent of the angle α between two **SOM**s (A,B). So in the case of their identity we have $\alpha_o = \pi/4 = 45^o$, and in all other cases we will have some angular measure of similarity differing from the angle 45^o . Centering it to zero, for the general case of similarity, we can write in a matrix notation,

$$\Sigma_\alpha = C * S^{-1} - I = tg\ \alpha ; \text{ and } \alpha = arc\ tg\ (\Sigma_\alpha) . \qquad (16)$$

Once more, we may suppose from the above, that if the defined measure is equal zero for a some singular value σ_i of primary **SOM** it may mean that, that the wear process associated with the given singular value is similar as it was previously, for the known already case of auxiliary **SOM = B** .

We can invent the other similarity measures. Moreover, for the **SOM** identity case as in (14) we have **U = V**, and the correlation coefficient calculated between columns or rows is equal one. So, for the general case of **A, B** matrices we can define correlation coefficient between columns (**U, V**) for the matrices defined by GSVD. Using the commonly shared numbers of rows of both matrices (*observations*) $l=min(n,p)$ for a current life time moment θ one can write it in a **Matlab®** notation, with some weighting matrix Σ;

$$C_{uv} = corcoef(U(1:l,:),V(1:l,:)) * \Sigma \qquad (17)$$

In general, this means, that as for now we have two independent measures of similarity between primary and auxiliary **SOM**. The first measure (16), shows the angles α_i in the observation spaces (**A**, **B**), between axes defined by matrices **C** and **S** of **GSVD.**

The second measure (17) shows the same similarity but seen here as the column by column correlation coefficients of (**U**, **V**) matrices defined by **GSVD,** and weighted by multiplication of singular value matrix Σ.. Such weighting gives much better differentiation of values of similarity measures for different objects.

There is another possibility of similarity measure calculation, using the vector of singular values taken from diagonal matrix Σ as in (10). Extracting its diagonal, and treating it as the vector we will have it in the form $Sig=diag(\Sigma)$. We know that in the case of identity all singular vales are equal **1**. So, it will be good if we subtract this identity value from the previous vector. Calculating now the norm of such new vector and normalizing it to the not subtracted value we can define the index of similarity of SOM matrices in GSVD, as below

$$SI = 1 - (Sig -1)^T * (Sig-1)/(Sig^T * Sig) \qquad (18)$$

One can see from the above, that such similarity index ranges from zero to unity, being one if both matrices in GSVD are identical

We will see these possibilities of inferring from the previous observations (*auxiliary SOM*) on the examples below. This will indicate how these measures of similarity of matrices **A** and **B** behaves, and how sensitive they are to the abbreviated data in a SOM, and to the data taken from the another object.

4. COMPARATIVE PROPERTIES OF GSVD IN CONDITION MONITORING, AND POSSIBLE DIAGNOSTIC APPLICATION AND MEANING OF GSVD

As we have mentioned earlier, generalized **SVD** can use auxiliary diagnostic observation. So it is possible to use another SOM obtained previously from the same object, or from the similar diagnosed object. This statement is by analogy to other applications in computational biology [18], as for the author knowledge, no condition monitoring (**CM**) application is known to this date. Starting at beginning let us take the simplest possible case of the same object treated by specially elaborated program written in Matlab® called **gsvdavg.m.** In addition, we have shown earlier, that for the real **CM** industrial data with some instability of

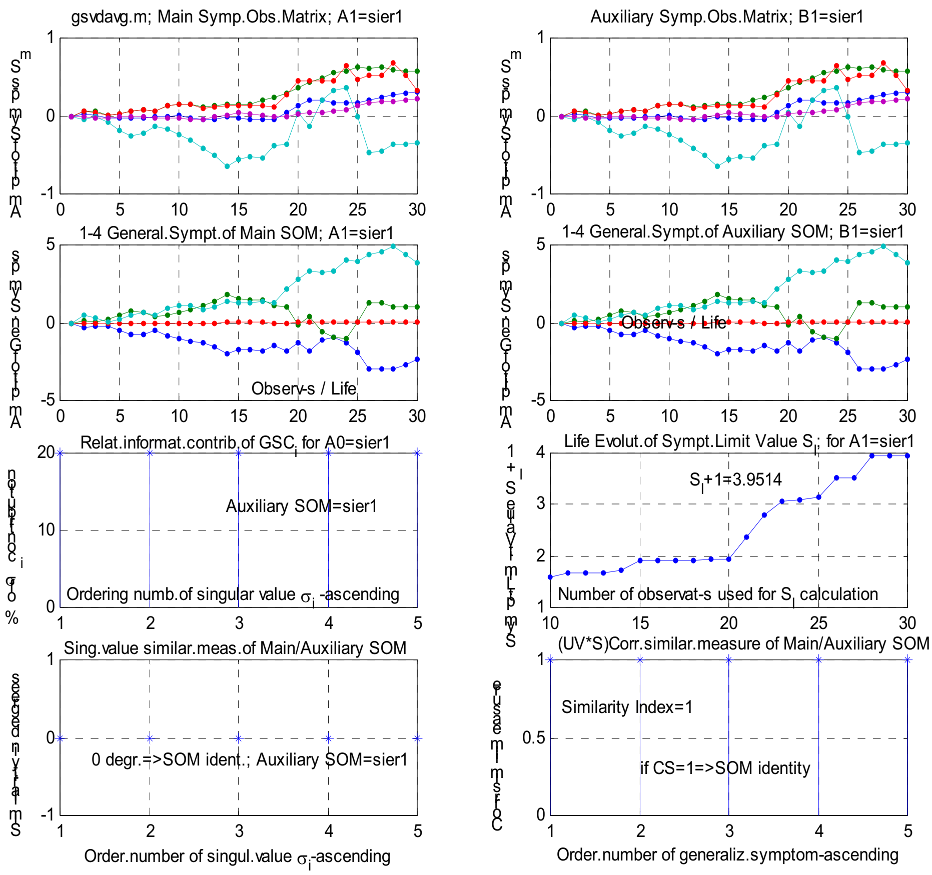

Fig. 2. Industrial fan as an example of application of GSVD applied to the same symptom observation matrix

symptom readings it is good to apply the moving average operation (**avg**) for the primary **SOM** [14]. In the presented example here, we have taken the huge industrial fan, which pumps the air to shaft of the copper mine, and has been working 32 weeks with one reading per week of the vibration symptom vector (*5 components*). Fig. 2 present this example elaborated by special GSVD program and subdivided into the 8 pictures described below.

The first left top picture presents averaged centered and normalized primary symptom observation matrix. As it can be seen, the variability of observed symptoms is not a great one, ranging from zero up to ± 1, although some of the symptom life curve changes the sign of values, their oscillations is not a big one, as a result of an introductory performed averaging operation (***avg***). The same is shown on the top right picture for the auxiliary **B** matrix, and as both were assumed identical, it is the same picture as at the top left. The next two pictures, the second row from the top, present us the results of **GSVD** calculation, and here we show only the biggest four generalized fault symptoms $F_t(\theta)$, t=(1,4), calculated according to formula (15). They are of course the same, due to our identity assumption. The next row of pictures is quite different, from the left one can see singular values, and they are equal each other due to assumed matrix identity. Further on the right picture presents calculated symptom limit value S_l , and one can notice it seems to be quite good evolution of this diagnostically important quantity.

The last row of pictures, at the left, shows the same singular values as above but treated as the tangent of the angle of similarity between the two spaces of symptom observation matrices (16), primary **A** and auxiliary **B**. And of course for the identical matrices the **α** angle is equal zero. The bottom right picture gives another measure of similarity (17), the transformed correlation coefficient between generalized fault symptom of primary and auxiliary matrices, multiplied additionally by the respective part of singular value (**S** matrix). This is in order to make the measure more sensitive. Of course, for the case of identical matrix this measure is also equal one for every singular vale. Therefore, it seems to that in this way as above, we can investigate the similarity between two SOM, and to decide if the fault development during the machine operation is the same as previously or only slightly similar to the previous case.

Knowing this let us take not identical **SOM**s but similar one, like for example auxiliary SOM the same as primary but with smallest number of rows. For the good illustrative purposes it can be the same **SOM** sier1, but with the smaller number of observations. Fig. 3 illustrates this case, and the organization and the meaning of the individual pictures are the same as previously.

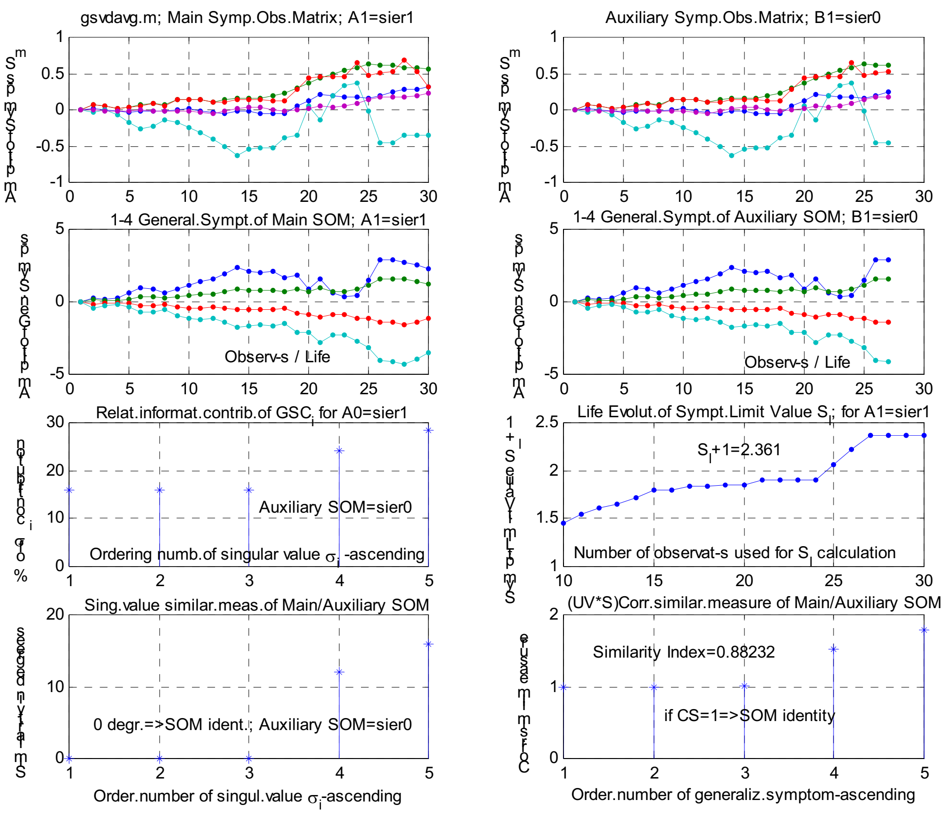

Fig. 3. GSVD comparison of the same SOM's but with the different number of observations (the last sixth cancelled)

Comparing now Fig. 2 and 3 one can notice the essential difference at the last two rows of pictures only. That means, that GSVD singular values are not identical, the value and the course of symptom limit values $\boldsymbol{S_l}$ is also not the same. What is more, the similarity measures at the last row of pictures are not as previously, because the last two singular values are not identical. We can infer that shorter SOM produce such differentiation, although there is no other difference, only in the number of the rows (*observations*). Almost the same situation is noticeable when we exchange the calculation sequence of primary and auxiliary matrix. Above, the first three singular values give the measures of identity 0 (*left picture*) and 1 (*right picture*), and in case of the matrix exchange the last three singular values gives the sign of matrix identity.

Let us now pass to the diagnostic objects of the same type but different copies of it. Fig. 4 present the comparison of two different exemplars of railroad diesel engines with the different primary and auxiliary SOM. This gives of course the difference in generalized symptoms (*second row of pictures*), with the last two singular values essentially different from zero. The angular measure of similarity (*picture bottom left*) is spread here from -50^o to +50^o degrees, giving no essential message to us, but the correlation measure of similarity indicates also one singular value close to unity (*picture bottom right*). Finally, the course of symptom limit value (*picture second right*) is evolving gradually, and growing rapidly at the end of the life of both systems.

Let as now compare another class of diagnosed objects namely rolling bearings at durability-test stand. Fig. 5 gives here the results of comparison in the same way of pictures organization as before for the diesel engines.

As one can notice from the first row of pictures the durability (*expected lifetime*) of bearings is different here, but the measured life curves are similar, and the same can be said with respect of generalized symptoms at the second row of pictures. Again one can notice, that there is one singular value essentially different in quantity from the others (*third row-left picture*), and the symptom limit value $\boldsymbol{S_l}$ evolving gradually. The last row of pictures is similar, like for the diesel engines, namely the angular measure of similarity is spread from -50 to +50 degrees, and correlation measure of similarity indicates one singular value greater than 1. It may mean that there is only **one way of degradation,** common to both tested bearings. But if we reverse the matrix order (*primary-auxiliary*) the last indication on similarity changes a little giving one singular values close to 1, and the second close to -1.

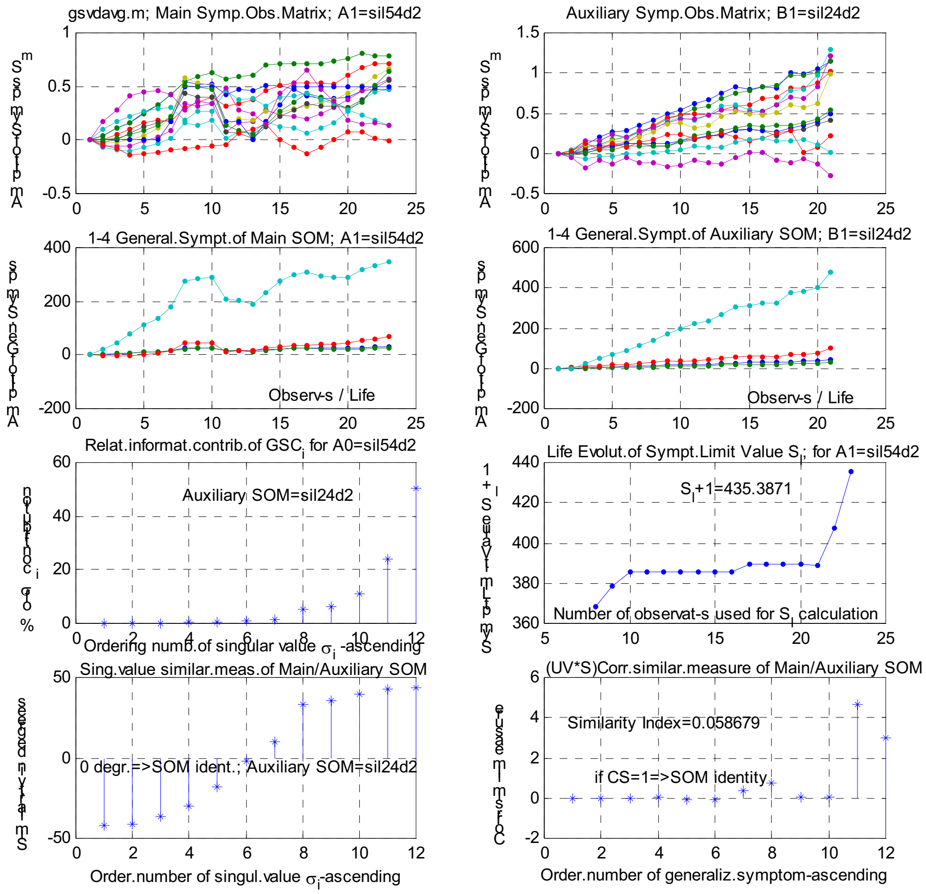

Fig. 4. GSVD comparison of two different exemplars of the same diesel engines

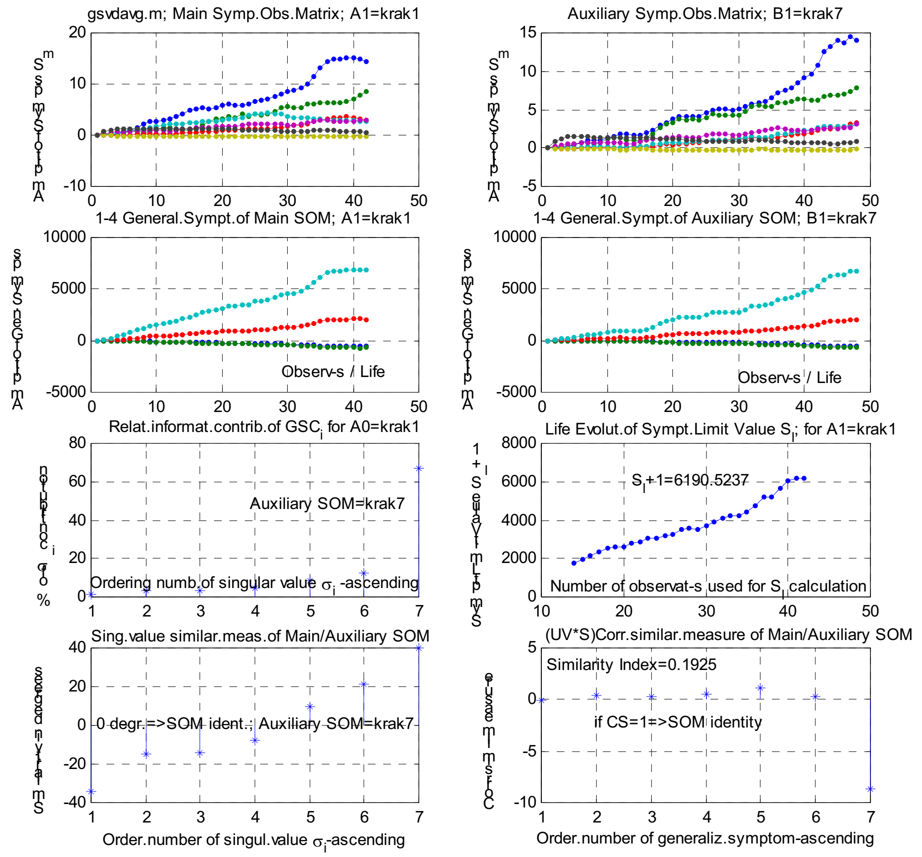

Fig. 5. GSVD similarity of rolling bearings at the durability test stand

Altogether 10 ball bearings were tested at the durability stand, and they damage advancement were described by the same symptom observation vector and SOM with different numbers of rows only. In addition, in every case the measures of similarity between bearings behave like on the last row of the fig. 5. In particular, the angular measure of similarity is spread −50 to + 50 degrees, and correlation measure indicates all singular values close to zero with the exception of the last one being close to unity or much bigger.

Well, these are some introductory diagnostic meaning and possible application of Generalized SVD, and the question now remains, is that all what can be done in condition monitoring? I am sure not, we should investigate the other possible application not only in condition monitoring but also in quality monitoring and comparison, for example.

5. CONCLUSIONS AND FURTHER PROBLEMS

As one can infer from the above consideration and examples of application, there is some possibility of **GSVD** application in machine condition monitoring. This is based mainly on looking at similarities in a machine wear processes and symptoms of its condition. For this purpose, several measure of similarity were defined and calculated for the cases of examples taken from the real monitored objects. There are some promising results. However, it seems to be too early to formulate some solid conclusions concerning GSVD use in machine condition monitoring. Some more approaches and trials seem to be needed to formulate such conclusions.

6. REFERENCES

[1]. Korbicz J., et all, (*eds*.): *Fault Diagnosis – Models, Artificial Intelligence, Applications*, Springer Verlag, Berlin - Heidelberg, 2004, p. 828.

[2]. Tumer I. Y., Huff E. M.: *Principal component analysis of tri-axial vibration data from helicopter transmission*, 56th Meeting of the Society of Machine Failure Prevention Technology, 2002.

[3]. Bartelmus W., Zimroz Z., Batra H.: *The gearbox vibration signal preprocessing and input values choice for neural network training*, AI Methods Conference, Gliwice, Poland, 2003.

[4]. Pantopian N. H., Larsen J.: *Unsupervised condition detection in large diesel engines*, Proceedings of the IEEE Workshop on Neural Networks,1999

[5]. Cempel C.: *Vibroacoustic Condition Monitoring*, Ellis Horwood, London, 1991, p 212.

[6]. Cempel C.: *Innovative developments in systems condition monitoring*, Keynote Lecture DAMAS'99, Key Engineering Materials, Vols. 167-168, 1999, pp. 172-189.

[7]. Natke H. G., Cempel C.: *The symptom observation matrix for monitoring and diagnosis*, Journal of Sound and Vibration, 248, 597 – 620, 2002.

[8]. Natke H. G., Cempel C.: *Model Aided Diagnosis of Mechanical Systems,* Springer Verlag, Berlin,1997, p. 248.

[9]. Golub G. H., VanLoan C. F.: *Matrix Computation***,** Oxford, North Oxford Academic, 1996.

[10]. Cempel C., Natke H. G., Yao J. P. T.: *Symptom Reliability and Hazard for Systems Condition Monitoring*, Mechanical Systems and Signal Processing, Vol. 14, No 3, 2000, pp 495-505.

[11]. Cempel C.: *Multidimensional Condition Monitoring of Mechanical Systems in Operation*, Mechanical Systems and Signal Processing, 17(6), 2003, p. 1291 – 1303.

[12]. Żółtowski B. Cempel C. (*eds.*): *Engineering of Machine Diagnostics***,** (*in Polish*), ITE Press, Radom, 2004, p 1308.

[13]. Cempel C., Tabaszewski M.: *Multidimensional vibration condition monitoring of nonstati-onary systems in operation*, Mechanical Systems and Signal Processing, Vol. 21, 2007, pp 1233-1247.

[14]. Cempel C., Tabaszewski M.: *Averaging the Symptoms in Multidimensional Condition Monitoring for Machines in Nonstationary Operation*, (*paper No519 on CD*) 13 Interna-tional Congress on Sound and Vibration, Vienna, July 2006.

[15]. Will T.: *Hanger matrix, two-thirds theorem,* Internet, (2005); http://www.uwlax.edu/faculty/will/svd/svd/index.html .

[16]. *Matlab, GSVD Function Reference,* MathWorks, 2006.

[17]. Cempel C.: *Multi fault vibrational diagnostics of critical machines*, Zagadnienia Eksploatacji Maszyn, 2005, pp135-142, (*in Polish*)

[18]. Alter O., at all: *Generalized singular value decomposition for comparative analysis of genome-scale expression data sets of two different organisms*, PNAS, March 18, 2003, vol.100, no. 6, pp 3351-3356.

[19]. Gui L., Wu X.: *KPCA based multisensor data fusion for the machine fault diagnosis*, Proceeding of ICME06, Chengdu, China October 2006, pp 342-352.

THE ISSUE OF SYMPTOMS ARISING DELAYS DURING DIAGNOSTIC REASONING

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Summary

The paper shows the influence of the dynamics of the symptoms forming on the correctness of generated diagnoses. There are given a few approaches that allow to take into account the symptoms delays in the algorithms of diagnostic reasoning. Finally, there is presented the algorithm of proper reasoning while the information about symptoms delays is omitted. Key issues are illustrated with simple examples.

Keywords: fault isolation, diagnostics, dynamic systems.

PROBLEM UWZGLĘDNIENIA DYNAMIKI POWSTAWANIA SYMPTOMÓW WE WNIOSKOWANIU DIAGNOSTYCZNYM

Streszczenie

W artykule rozważany jest wpływ dynamiki powstawania symptomów na poprawność formułowanej diagnozy. Zaprezentowanych jest kilka algorytmów pozwalających na uwzględnienie opóźnień symptomów w procesie wnioskowania. Zaprezentowane są także mechanizmy prawidłowego wnioskowania (pod względem formułowanych diagnoz) pomijające bezpośrednio informację o opóźnieniach symptomów. Kluczowe zagadnienia zilustrowane są na prostym przykładzie.

Słowa kluczowe: lokalizacja uszkodzeń, diagnostyka, systemy dynamiczne.

1. PROBLEM FORMULATION

In most of the diagnostic strategies, to be able to proceed with diagnosis, the mapping of the diagnostic signal space (residual values) onto the fault space is necessary. Different forms of this representation are known [3, 4, 8]. Most of them have static nature. However, the diagnosed processes are dynamical systems. Therefore, from the moment of fault occurrence to the moment when one can obtain measurable symptoms the particular time period elapses. In general, this time period is different for each fault and each diagnostic signal which detects that fault. Only after some period of time all symptoms are observed. Just a few approaches reference this problem [2].

The wrong diagnosis could be generated if one didn't take the dynamic of symptoms into consideration. This is illustrated by the following example.

Example 1. Let us consider the diagnostic binary matrix presented in Fig. 1. Let us assume, that fault f_3. occurred. It is detectable by diagnostic signals s_2, s_3 and s_4. Assume that symptoms arising times are different for each diagnostics signal and equal respectively: θ_1=1, θ_2=2, θ_3=4, θ_4=6 [s]. Parallel diagnostic reasoning runs as follows:

- *Time 0-2 [s]: the fault is not detected.*

S/F	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8
s_1	1				1			
s_2	1	1	1		1	1		
s_3		1	1	1			1	
s_4			1	1			1	1

Fig. 1. Example of diagnostic binary matrix

- *Time 2-4 [s]: achieved diagnostic signals - S={0,1,0,0}; diagnosis - DGN_{2-4}={f_6}.*
- *Time 4-6 [s]: achieved diagnostic signals - S={0,1,1,0}; diagnosis - DGN_{4-6}={f_2}.*
- *Time ≥6 [s]: achieved diagnostic signals - S={0,1,1,1}; diagnosis - DGN_6={f_3}.*

Only diagnosis DGN_6 is proper and has final nature. The earlier ones were false.

The following problems appears: How to take into account the symptoms delays in the fault isolation algorithms in order to eliminate possibility of formulating false diagnosis? Is it possible to develop faults isolation algorithm insensitive to symptoms delays? The problems presented above are the subject of this paper. Firstly, the formal description of symptoms delays is introduced together with the theoretical way of its calculation. Then, several diagnostic reasoning strategies that take these delays into account are presented. There are shown complex as well as simplified approaches.

2. SYMPTOMS DELAYS

The delays of symptoms forming depend on the dynamic characteristic of the process, fault type (abrupt, incipient), its time development characteristic, the applied method and detection algorithm parameters. It's possible to calculate analytically these times basing on the dynamic description (e.g. transmittance) of the controlled part of the process (where the fault is an input and the process value is an output) and the transient response of fault appearance. We make an assumption that the limitation function parameters are known and there is no influence of the diagnostic test methods on the process operation.

The mathematical process description can be achieved based on the equations describing the physical effects taking place in the process. In this case, it is necessary to treat all the possible faults as separate inputs in the system of equations. After the linearization at the operating point and applying Laplace transformation one achieves linear model in the form [3, 4, 8]:

$$y(s) = G(s)u(s) + G^F(s)f(s) \ . \tag{1}$$

Each constituent equation has the following form:

$$y_j(s) = G_j(s)u(s) + G_j^F(s)f(s) \ , \tag{2}$$

while $G_j(s)$ (j=1,…,J – number of diagnostic signals) denotes input-output transmittance:

$$G_{p,j}(s) = y_j(s)/u_p(s); \ p = 1,...,P \ , \tag{3}$$

and $G^F_j(s)$ denotes the transmittance for each fault-output couple:

$$G^F_{k,j}(s) = y_j(s)/f_k(s); \quad k = 1,...,K \ . \tag{4}$$

If there are no existing faults in the process, then the following dependence is satisfied:

$$y_j(s) - G_j(s)u(s) = G_j^F(s)f(s) = 0 \ . \tag{5}$$

The residuals are calculated based on the following equation called calculation form:

$$r_j(s) = y_j(s) - G_j(s)u(s) \ . \tag{6}$$

Equation (7) (internal form) reflects general relation between particular residual and faults:

$$\begin{aligned} r_j(s) &= G_j^F(s)f(s) = \\ &= G^F_{j,1}(s)f_1(s)... + G^F_{j,k}(s)f_k(s)... + G^F_{j,K}(s)f_K(s). \end{aligned} \tag{7}$$

If r_j is sensitive for fault f_k and no other faults are present (f_m=0) then one achieves:

$$r_j(s)\big|_{f_k} = G^F_{k,j}(s)f_k(s), f_m = 0 : m = 1,2,...,K, \ m \neq k \ . \tag{8}$$

For so defined residual its time development function is defined by the following relation:

$$r_j(t) = L^{-1}\left(G^F_{k,j}(s)f_k(s)\right). \tag{9}$$

The analytical calculation of the symptom forming times is difficult in practice because it requires the modeling of fault influence on measurable outputs. The fault development function as well as residual threshold value must be assumed arbitrary. Because of modeling errors the precision of analytical estimation of symptom times is poor.

In practice, based on the knowledge about the process and detection algorithms, it is possible to estimate symptom times by giving their minimum and maximum values [4, 6]. Let us use the following notation:

- $\theta^1_{k,j}$ – minimal time period from k^{th} fault occurrence to j^{th} symptom appearance,
- $\theta^2_{k,j}$ - maximal time period from k^{th} fault occurrence to j^{th} symptom appearance.

These parameter can be expressed in seconds or dimensionless units equal multiple of the smallest process value sampling time. They are assigned to each ordered pair (fault, diagnostic signal) $<f_k,s_j>$ satisfying the relation S⇒F. The actual symptom time belongs to interval $< \theta^1_{k,j}, \theta^2_{k,j} >$.

During process state monitoring the diagnose should be formulated after all of the symptoms are time invariant. The approach that takes into account only the maximum symptom times $\theta^2_{k,j}$ allows to avoid generating false diagnosis.

The problem can be additionally simplified, by assigning the cumulative symptom time θ_j to each diagnostic signal [5, 7]. The cumulative symptom time is defined as the maximum interval from the appearing of any of the faults controlled by this test to the moment when the symptom is detected:

$$\theta_j = \max\{\theta^2_{k,j}\}, k : f_k \in F(s_j) \ . \tag{10}$$

The use of cumulative symptom times simplifies the way of describing the process dynamic properties and, especially, the reasoning algorithm. It is easier to define these parameters, however, it is still not an easy task.

The use of cumulative symptoms times was implemented in DTS and F-DTS methods presented by Kościelny (1995). The full description of the dynamic properties was applied in method i-DTS [7].

3. DIAGNOSTIC REASONING TAKING INTO ACCOUNT CUMULATIVE SYMPTOMS TIMES

Presented below diagnostic reasoning is based on the analysis of successive diagnostic signals and its cumulative symptoms times θ_j introduced in section 2. The diagnosis is formulated in several steps, in which the set of possible faults is gradually constrained [4]. In the case of such reasoning (serial approach), the diagnostic relation R_{FS} is defined by attributing to each diagnostic signal the subset of faults detectable by this signal:

$$F(s_j) = \{f_k \in F : f_k R_{FS} s_j\}. \tag{11}$$

The isolation procedure is started after the first symptom is observed. Its occurrence indicates that one of the fault from the set $F(s_x)$ of the faults detectable by that diagnostic signal had arisen. Such a subset of possible faults is indicated in the primary diagnosis:

$$(t = t^1) \wedge (s_x = 1) \Rightarrow DGN_1 \equiv F^1 = F(s_x = 1) . \quad (12)$$

The subset of diagnostic signals S^1 useful for isolation of faults from the set F^1 is created:

$$S^1 = \left\{ s_j \in S \colon F^1 \cap F(s_j) \neq \varnothing \right\} . \quad (13)$$

The values of the diagnostic signals from the set S^1 are interpreted, step-by-step, according to the sequence determined by the attributed symptoms times. The j^{th} diagnostic signal is used under the following condition that protects against formulating false diagnosis:

$$(t - t^1) > \theta_j . \quad (14)$$

The time instants of consecutive diagnostic signals interpretations are determined. They create the following series:

$$\theta^1 \le \theta^2 \le ... \le \theta^r \le ... \le \theta^p , \quad (15)$$

where $\theta^r \in \{\theta_j : s_j \in S^1\}$, while r defines the sequence of analysis of the diagnostic signals from the set S^1.

Successively, in the time instant $t = t^1 + \theta^r$ for r=1,...p, the values of particular diagnostic signals are analyzed and the reduction of the set of possible faults takes place. The process state $z(f_k)$ is attributed to each of the faults f_k from the set F. It is defined in the following way:

$$z(f_k) = \begin{cases} 0 - \text{the state without fault } f_k \\ 1 - \text{the state with fault } f_k \end{cases} \quad (16)$$

The "0" value of the diagnostic signal testifies, that none of the faults controlled by that diagnostic signal had occurred:

$$s_j = 0 \Leftrightarrow \underset{k:f_k \in F(s_j)}{\forall} z(f_k) = 0 . \quad (17)$$

The "1" value testifies, that at least one of the faults from the set $F(s_j)$ had occurred:

$$s_j = 1 \Leftrightarrow \underset{k:f_k \in F(s_j)}{\exists} z(f_k) = 1 . \quad (18)$$

When single fault occurrence is assumed, the following rules of reducing the set of possible faults indicated in the consecutive steps of diagnosis formulation are used:

- The value of „0" of the diagnostic signal causes the reduction of the set of possible faults by the faults detectable by that signal:

$$s_j = 0 \Rightarrow DGN_r = DGN_{r-1} - DGN_{r-1} \cap F(s_j) . \quad (19)$$

- The value of „1" of the diagnostic signal causes the reduction of the set of possible faults by the faults undetectable by that signal. The new set of possible faults is a product of past possible faults and the set of faults detectable by that signal $F(s_j)$:

$$s_j = 1 \Rightarrow DGN_r = DGN_{r-1} \cap F(s_j) . \quad (20)$$

During the diagnostic reasoning the preliminary diagnosis is formulated after the first symptom is observed and then constrained when further, consecutive diagnostic signal values are taken into account. Usually, there is no need to analyze all the signals to be able to formulate the final diagnosis. Such situation takes place when the diagnosis consists of only one fault or the set of indistinguishable faults.

Example 2. *The serial reasoning in the case of fault f_6 appearance (example form Fig. 1) is show below. The first observed symptom is s_2=1. As a result, the following sets are created: the subset of possible faults $F^1=\{f_1,f_2,f_3,f_5,f_6\}$ and the subset of useful diagnostic signals: $S^1=\{s_1,s_2,s_3,s_4\}$.*

The time instants when the successive diagnostic signals should be analyzed are determined:

$$\theta^2 = \theta_1 = 1;\ \theta^3 = \theta_3 = 4;\ \theta^4 = \theta_4 = 6 .$$

Then, in the following steps, the diagnosis is constrained:

- $t = t^1 + 1; s_1 = 0 \Rightarrow DGN_2 = \{f_2, f_3, f_6\}$
- $t = t^1 + 4; s_3 = 0 \Rightarrow DGN_3 = f_6$.

After the second step the process of diagnosing is stopped. Finally, the same diagnosis as in the case of parallel reasoning is assumed but it is concluded basing on only three diagnostic signal values after 4 seconds when the first symptom was observed. The value of diagnostic signal s_4 was not needed for final diagnosis formulation.

4. SYMPTOMS BASED REASONING

In the above described diagnostic reasoning methods the information about the symptoms delays was used to avoid formulating false diagnosis before all the symptoms occur. However, achieving the data concerning the times of symptoms arising is not easy. The following question appears: Is it possible to formulate proper diagnosis without taking into account the symptom arise times? It is shown below, that is it possible.

In the described reasoning rules the information about the appearance of the particular symptoms, in the predefined interval, as well as the lack of other ones was used during diagnosis formulation. While the symptom appearing is easy to observe, one must wait for proper time period, when the symptom should appear, to be able to take into account its lack. It is possible to simplify the reasoning procedure by taking into account only the observed symptoms and rejecting the information carried out by the lack of symptoms. It means the use of the rule (18) and rejecting the rule (17). The set of possible faults is reduced only according to the rule (20). The diagnosis, in each reasoning step, is proper and points out such faults, for which the observed symptoms are consistent with those ones defined in the signatures. However, the fault isolability can be lower.

<u>Example 3.</u> Let us assume, that the fault f_2 appears (example form Fig.1). It is detected by the symptom s_2=1, so: $t^1 = 0$;

$$DGN_1 = F^1 = \{f_1, f_2, f_3, f_5, f_6\},\ S^1 = \{s_1, s_2, s_3, s_4\}.$$

The diagnosis is modified after each new symptom appears. In this case, only one symptom appears: s_3=1. According to (20) one achieves: $s_3=1 \Rightarrow DGN_2=\{f_2, f_3\}$. It is a final diagnosis, because none other symptoms will appear. In comparison, the serial reasoning which takes into account symptom times was finished after taking into account the diagnostic signal s_4=0, in time moment $t=t^1+6$. It leads to more precise diagnosis: $DGN_2=f_2$.

One must also notice, that in the case of fault f_6 considered in Example 2, the serial reasoning based on symptoms is finalized in the first step: $s_2=1 \Rightarrow DGN_1=\{f_1, f_2, f_3, f_6\}$ with the diagnosis that pointing out four faults that are unisolable in respect to only one observed symptom (so far).

5. DIAGNOSIS BASED ON THE SYMPTOMS SEQUENCE

The sequence of symptoms arising is an important information which is worth of using in the diagnostic process. The different sequence of symptoms arising can allow to isolate undistinguishable faults with identical fault signatures.

The symptoms sequence for particular fault does not depend on the fault time development characteristic $f_k(t)$. Based on (9), assuming particular form of a function $f_k(t)$ (e.g. step function) and the threshold residual value it is possible to calculate the time, after which the symptom of a k^{th} fault will appear. Such calculations must be done for all the residuals sensitive for k^{th} fault.

The sequence of symptoms forming can be done by arranging the values of symptoms delays for a particular fault in ascending order. Finally, the signature of the symptoms forming sequence for particular set of residuals for each fault is achieved:

$$SK(f_k) = < s_i, s_m, s_p, ... > . \qquad (21)$$

The signature consists of the series of symptoms s_j for particular faults f_k written down in the order of appearing.

The different symptoms sequence can characterize faults that are unisolable based on binary diagnostics matrix (fault with the same signatures). The symptoms are not isolable (in respect to the relation R_N) based on symptoms sequence if their sequence signatures (21) are identical:

$$f_k R_N f_n \Leftrightarrow SK(f_k) = SK(f_n) . \qquad (22)$$

In this case, the reasoning consists of comparing registered symptom sequence with pattern ones describing particular faults:

$$DGN = \{f_k : SK(f_k) = SK\} , \qquad (23)$$

where SK denotes currently registered symptoms sequence.

It is sufficient to be able to isolate any pair of faults for which the sequence of any pair of fault symptoms is different:

$$SK(f_k) = < s_j, s_p >,\ SK(f_n) = < s_j, s_p > . \qquad (24)$$

6. DIAGNOSTICS BASED ON THE KNOWLEDGE ABOUT SYMPTOM INTERVAL DELAYS

This section presents the fault isolation algorithm that utilizes the knowledge about the diagnostic relation and the values of the minimal and maximal symptoms forming delays. It assumes single fault scenarios, however, the multiple faults issue is also addressed. The algorithm implements serial diagnostic reasoning. The following notation is used: DGN_r – final diagnosis elaborated in r^{th} step of reasoning; DGN^*_r, DGN^{**}_r – intermediate diagnosis.

Three main stages of reasoning algorithm can be distinguished: initialization, diagnosis specifying, and final diagnosis formulation.

Initialisation of isolation procedure. The isolation algorithm starts in the time t^1=0 when the first symptom s^1_x=1 is observed (fault detection). The following steps are conducted:

- *Determining the set of possible faults*. The primary set of possible faults is determined based on diagnostic relation. It consists of all the faults, for which the diagnostic signal with the observed symptom is sensitive for:

  $$(s^1_x = 1) \Rightarrow DGN^*_1 = \{f_k : [q(f_k, s^1_x) = 1]\} \qquad (25)$$

  where: DGN^*_1 denotes temporary diagnosis, elaborated under the condition of use of the first diagnostic signal s^1_x but without taking into account the intervals of symptoms delays; $q(f_k, s^1_x)=1$ denotes that diagnostic signal s^1_x detects the fault f_k according to the diagnostic relation.
- *Reduction of primary set of possible faults*. Let us introduce the notations $\theta^1_{k,x}$ and $\theta^2_{k,x}$ for minimal and maximal periods from k^{th} fault occurring to the first, detected symptoms $s^1_x = 1$ formulation, respectively. The faults, which occurrence should cause another symptoms to be

observed before the symptom s_x^1, in respect to known intervals of symptoms delays, are eliminated from the set $DGN(s_x^1)$:

$$DGN_1 = \{f_k \in DGN_1^* : \forall_{s_j \neq s_x^1} \theta_{k,j}^2 < \theta_{k,x}^1\}, \quad (26)$$

while DGN_1 denotes first, temporary diagnosis elaborated while taking into account the intervals of the symptoms delays.

- *Determining the set of diagnostic signals useful for further fault* isolation in the following form:

$$S^* = \{s_j : F(s_j) \cap DGN_1 \neq \varnothing\} - s_x^1 . \quad (27)$$

- *Defining the intervals of symptoms possible consecutive forming*. Due to the fact that the real time of fault occurring is unknown (only the time of the first symptom detection is registered) the time intervals of the appearing of the consecutive symptoms of the diagnostic signals from the set S* must be recalculated in respect to the moment of the first symptom detection. Such calculations must be conducted for the faults pointed out in the diagnosis in the following way:

$$\beta_{k,j}^1 = \begin{cases} 0 & \text{if } \theta_{k,j}^1 - \theta_{k,x}^2 \leq 0 \\ \theta_{k,j}^1 - \theta_{k,x}^2 & \text{if } \theta_{k,j}^1 - \theta_{k,x}^2 \geq 0 \end{cases} \quad (28)$$

$$\beta_{k,j}^2 = \theta_{k,j}^2 - \theta_{k,x}^1 . \quad (29)$$

The parameters $\beta^2_{k,j}$ for the faults $f_k \in DGN_1$ and the diagnostic signals $s_j \in S^*$ are arranged in ascending order.

Iterative diagnosis specifying. The second part of the reasoning has iterative nature. The elaboration of the following diagnosis takes place:

- after the detection of each, successive faults symptom,
- each time when the maximal period of the symptom delay $\beta^2_{k,j}$ from the ordered series of these parameters passes.

During this stage, the following steps are conducted iteratively:

- *The reduction of the set of possible faults based o on diagnostics relation.* If the symptom $s_j=1$ ($s_j \in S^*$) was detected in the proper period of delays than the set of possible faults is reduced according to formula:

$$(s_j^r = 1) \wedge (s_j \in S^*) \Rightarrow DGN_r^* = \\ = \{f_k \in DGN_{r-1} : q(f_k, s_j) = 1 \wedge (t \in [\beta_{k,j}^1, \beta_{k,j}^2]\} \quad (30)$$

Such an operation is realised for all the faults from the set $f_k \in F(s_j)$.

- *The reduction of the set of possible faults based on the analysis of delays interval.* The faults, which occurrence should cause another symptoms $s_p = 1$ to be observed before the currently observed symptom, in respect to the known intervals of symptoms delays, can be eliminated from the diagnosis elaborated in previous step:

$$DGN_r^{**} = \{f_k \in DGN_r^* : \beta_{k,p}^2 < \beta_{k,j}^1\} \quad (31)$$

- *The reduction of the set of possible faults after the analysis of the maximal times of the symptoms delays*. The lack of symptom after predefined time period, $t > \beta_{jk}^2$, allows for the reduction of the set of possible faults due to the formula:

$$(s_j = 0) \wedge (s_j \in S^*) \wedge (t > \beta_{k,j}^2) \Rightarrow \\ DGN_r = \{f_k \in DGN_r^{**}\} - f_k \quad (32)$$

The end of fault isolation. The algorithm stops when all the diagnostic signals from the set S^* are taken into account.

Taking into account the symptoms forming delays can increase faults distinguishability comparing with the diagnosis elaborated basing only on binary diagnostic matrix. In some cases it reduces the diagnosing time.

<u>Example 4.</u> *On the base of binary diagnostic matrix from Fig.1 faults f_1 and f_5 as f_4 and f_7 are undistinguishable. Let assume the symptoms delay intervals for the first pair of undistinguishable faults as follows:*

$[\theta_{1,1}^1, \theta_{1,1}^2] = [1,3]$, $[\theta_{1,2}^1, \theta_{1,2}^2] = [4,5]$,

$[\theta_{5,1}^1, \theta_{5,1}^2] = [6,8]$, $[\theta_{5,2}^1, \theta_{5,2}^2] = [2,5]$.

This implicates that in case of f_1 fault the symptom $s_1=1$ always appears before the symptom $s_2=1$, whereas f_5 fault occurrence will cause reverse sequence of the symptoms. It makes their unique recognition possible.

Let us assume that delays intervals for undistinguishable faults f_4 i f_7 are as follows:

$[\theta_{4,3}^1, \theta_{4,3}^2] = [2,3]$, $[\theta_{4,4}^1, \theta_{4,4}^2] = [4,5]$,

$[\theta_{7,3}^1, \theta_{7,3}^2] = [1,3]$, $[\theta_{7,4}^1, \theta_{7,4}^2] = [7,9]$.

Both faults results with the same symptoms sequence but in spite of this they are distinguishable. Maximal $s_4=1$ symptom delay after $s_3=1$ symptom for f_4 fault equals 5-2=3, whereas minimum time interval between these symptoms for f_7 fault equals 7-3=4. Therefore if $s_4=1$ symptom is delayed relatively to $s_3=1$ symptom less than 3 seconds that this indicates f_4, fault, if delay is bigger we are inferring about f7 fault occurrence.

The algorithm has also limited ability to isolate multiple faults. In general, if the new symptom $s_j = 1$ is observed, and if it does not appeared in the predefined period of symptoms delays in respect to the first observed symptom, than the *new fault isolation thread* is started. In that case it is assumed that this symptom is caused by another fault than the faults pointed out in the previous steps. In this case it is sometimes possible to formulate final diagnosis about multiple faults if the proper sets of diagnostic signals used in each isolation thread fulfill some necessary conditions. The detailed description of that problem is not in the scope of this paper. Some information about creating fault isolation threads can be found in [7].

7. FINAL REMARKS

The Section 3 presents the reasoning algorithm that takes into account the simplified information about symptoms delays and enables to elaborated proper diagnosis for dynamic systems.

It was also shown, in Section 4, that one can achieve proper diagnosis without taking directly into account the information about symptom forming times, however, it leads to lower fault isolability.

The knowledge about symptoms interval delays enables, in many cases, to isolate the fault that are unisolable based on binary diagnostic matrix. However, to be able to determine the symptoms intervals we need the residual equations in the inner form or very precise expert knowledge. This is very difficult to obtain in practice. Such algorithm with detailed description was presented in Section 6.

The alternative approach was shown in Section 5. The knowledge about the sequence of symptoms generation also enables, in many cases, to isolate the fault that are unisolable based on binary diagnostic matrix. It is easier to define such a sequence than precise symptoms interval delays.

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REFERENCES

[1] Blanke M., Kinnaert M., Lunze J., Staroswiecki M.: *Diagnosis and Fault-Tolerant Control*. Springer 2003.
[2] Combastel C., Gentil S., Rognon J. P.: *Toward a better integration of residual generation and diagnostic decision*, Preprints of: 5th IFAC Symposium SAFEPROCESS`2003, Washington D. C., USA, 9-11.VI
[3] Gertler J.: *Fault Detection and Diagnosis in Engineering Systems*. Marcel Dekker, Inc. New York - Basel – Hong Kong 1998.
[4] Korbicz, J., Kościelny J. M., Kowalczuk Z., Cholewa W.: *Fault Diagnosis: Models, artificial intelligence methods, applications*. Springer, 2004.
[5] Kościelny J. M.: *Fault Isolation in Industrial Processes by Dynamic Table of States Method*. Automatica, 1995, Vol. 31, No.5, 747-753.
[6] Kościelny J. M. and K. Zakroczymski.: *Fault Isolation Algorithm that Takes Dynamics of Symptoms Appearances Into Account*. Bulletin of the Polish Academy of Sciences. Technical Sciences. 2001, Vol. 49, No 2, 323-336.
[7] Kościelny, J. M. and M. Syfert: *On-line fault isolation algorithm for industrial processes*. Preprints of: 5th IFAC Symposium SAFEPROCESS`2003, Washington D. C., USA, 9-11.VI, 777-782.
[8] Patton R., P. Frank, R. Clark (Eds.): *Issues of fault diagnosis for dynamic systems*. Springer, 2000.

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AUTOMATIC METROLOGICAL DIAGNOSTICS OF SENSORS

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Summary

As the number of sophisticated technical complexes with automatic control systems grows, the number of embedded sensors increases. The specific scientific problems that emerge while developing the sensors characterized by fault tolerance and long-term lifetime without metrological maintenance are considered. The possible ways of solution of these problems are outlined. The features of metrological diagnostics are demonstrated.

Keywords: automatic metrological diagnostics, sensor, fault tolerance.

AUTOMATYCZNA DIAGNOSTYKA METROLOGICZNA CZUJNIKÓW

Streszczenie

W miarę wzrostu liczby skomplikowanych technicznych kompleksów z automatycznymi systemami sterowania zwiększa się liczba wbudowanych czujników. Rozpatrywane są problemy naukowo-techniczne związane z konstrukcją czujników charakteryzujących się długim czasem pracy bez obsługi metrologicznej i odpornością na uszkodzenia. Zostały zarysowane drogi rozwiązania tych problemów i mozliwosci diagnostyki metrologicznej.

Słowa kluczowe: automatyczna diagnostyka metrologiczna, czujnik, odporność na błędy.

1. INTRODUCTION

Development of industrial equipment and increasing number of sophisticated technical complexes goes with complication of automatic control systems (ACS) and with increase in the number of in-built sensors. At the same time:

- participation of personnel in the equipment control decreases;
- expenditures on metrological assurance of ACS grows;
- intervals between scheduled outages become longer;
- probability that invalid information can pass to ACS increases;
- risk of accident or failure grows.

More and more, trouble-free operation and production quality depend on sensor condition.

In many cases in order to carry out metrological assurance procedures such as calibration or verification (hereinafter referred to as calibration), it is necessary to interfere in a technological process. Meanwhile, the experience shows that calibration does not ensure the sufficient credibility of measurements over calibration period.

In current situation, modern technological processes require industrial sensors which are expected to provide many years of operation without metrological maintenance while ensuring a high level of confidence in their measurement data [1].

First of all, such sensors are necessary for technical systems with long-term technological cycle. However, in the near future, the other high duty objects including transport equipment, power units, etc., will need the sensors with enhanced metrological reliability. Moreover, the development of diagnostic systems depends, to a great extent, on the possibilities of their application.

The distinctive features of such sensors are:

- specified lifetime of many years without metrological maintenance (the lifetime should be proved experimentally);
- ability to self-diagnosing and revealing the growing uncertainty;
- the ability of a sensor to keep the measurement uncertainty for the most of single sensor defects within an enlarged, but permissible, range as defined by the user (fault tolerance), as well as to correct the uncertainty automatically (in a number of cases).

The set of these features affords ground for considering the corresponding sensors as "intelligent" [2].

2. ABOUT ASSESSMENT OF QUALITY OF SENSORS INTENDED FOR LONG-TERM OPERATION

The first problem the solution of which predetermines the possibility of intelligent sensors development is elaboration of the methods for sensors quality control with respect to their design and technology, taking into account the long-term lifetime. There is no point in complicating sensors by introduction of the diagnostic features if the sensors fail in a short period. Customers need to know the estimate of the sensor lifetime T during which the sensor uncertainty is kept within the specified limits. This value is equal to the sensor calibration interval. We could not find any special requirements for quality check of the sensors with a specified long-term lifetime neither in current standards, nor in any guides, including ISO documents.

Fridman in [3] proved that it is inexpedient to apply fundamental assumptions of the classical reliability theory (independence of failure rates and failure rate stability) to measuring instruments. Therefore, the lifetime estimation should be based on certification tests.

Taking economical reasons into account, sensor lifetime tests should be chosen at least 50 – 150 times shorter than the planned sensor lifetime without maintenance, while the number of tested sensors should be minimal. Test influencing factor values are limited: they are to be within the limits which provide that the sensor degradation mechanisms under test conditions and during actual operation are adequate. The plan of the certification tests should take the sensor design, technology and operation conditions into consideration.

Taking into account [4], in order to evaluate T, it is possible to recommend a technique which includes: determination of influencing factors that characterize sensor operating conditions; study of degradation processes; detection of probable reasons for the uncertainty increase; ranging of the uncertainty components according to their contribution; after that, certification tests themselves.

For the certification tests plan, one should choose only those influencing factors that give rise to the most "dangerous" (significant) uncertainty components of the sensor, i.e. predominant components or those tending to rise quickly.

Estimate of T can be obtained by processing the results of complex tests consisted of a simulation test and accelerated test.

In simulation test, harsh operation conditions that may take place during operation are simulated. At the stage of the accelerated test, it is expedient to expose the sensors to influencing factors by equal cycles. One cycle may include exposure to one or several factors, e.g. vibration and temperature of a maximum permissible level [5].

Stability of sensor manufacturing technology should be proved by periodic and extraordinary (in case of modification of the sensor design or technology) tests. For these tests, the cycles like those that were chosen for the accelerated test can be applied [6].

At present, approaches for the plan of the tests to evaluate T are different in different companies. Therefore, the results of T evaluation can be different. In order to obtain comparable results, it is necessary to work out international guides that will include corresponding test procedures. Before the necessary documents become operational, it is expedient to specify the test procedure on the basis of which the lifetime of sensors would be assigned.

3. METHODS OF AUTOMATIC DIAGNOSTICS OF SENSORS

In general, there are the following differences between metrological diagnostics and conventional procedures of metrological assurance of sensors:

- the value estimated in diagnostic procedure is the parameter defined by a set of uncertainty components (not the overall instrumental uncertainty);
- diagnostics conditions are identical with the technological process conditions (not the reference conditions);
- the sensor diagnosed remains in-situ (not in a calibration laboratory);
- metrological diagnostics envisage on-line method which does not require interruption of technological parameter measurements, while the conventional procedures are out-of-process methods.

The first way of organizing the metrological diagnostics is integration of sensors in a system with common diagnostic means. This system can be organized by several methods.

The most wide-spread method is application of a number of identical sensors and comparison of their output signals [7].

However, for mass-produced sensors of the same type, a drift of metrological parameters in the same direction and with a close speed is the most probable [2, 8]. If integration of such sensors is used, this drift cannot be revealed. The drawback is also in the necessity to place several (e.g., three) sensors in the equipment, which, in many cases, is impermissible by an argument of engineering limitations.

The second method implies integration of sensors that measure various quantities characterizing physical field parameters that correlate between each other.

The drawbacks of this method are:

- presence of the uncertainty components due to the diagnostic method, which depends on the accuracy of relationship between the measurements,
- necessity to apply more accurate sensors.

The third method involves application of a more accurate sensor in addition to other sensors.

However, in order to organize the effective diagnostics using this method, it is necessary to set a stationary state of technological equipment, on one hand, and on the other hand, to keep a comparatively short calibration interval for the most accurate sensor of the system.

Nevertheless, in a number of cases, metrological diagnostics of mass-produced sensors by their integration in a system ensures a higher confidence in measurements.

The other way is development of sensors with the in- built capability of self-checking [2].

There are two different ways of realization of this function. The first consists in embedding a reference standard (a reference measure or additional sensor, which is more accurate than the sensor under check) in the equipment and comparing output signals of the reference standard and checked sensor. The second way is associated with sensor intellectualization. It consists in comparison of several signals or parameters, which are close in accuracy, i.e. metrologically equivalent. We call the latter method metrological diagnostic check (MDC) [1, 2, 5].

If the metrological self-check is accompanied by a quantitative evaluation of measurement quality, it is usually called self-validation [9].

Development of the intelligent sensor requires a deep metrological investigation to be carried out. This investigation should result in determination of the limited number of the most dangerous uncertainty components and formation of the required dependence of diagnostic parameters on influencing factors. The distinguishing features of sensors capable of performing the metrological diagnostic checking are presence of:

- structural and/or information redundancy which afford ground for obtaining an additional signal regarding ambient conditions and/or sensor "health",
- microprocessor that provides processing of measurement and diagnostic data.

Metrological diagnostics allows to determine whether the sensor uncertainty is being kept within the specified limits. If the uncertainty exceeds the specified limits, it is possible to diagnose the uncertainty variation specifics and to localize a defect.

As a rule, on the basis of metrological self-diagnostics, the specified calibration interval can be considerably increased in comparison with its value which can be set on the basis of conventional method of metrological assurance.

The method requires the sensor sensitivity to be higher than it is required for usual measurements in the technological process. However, fulfilling this requirement, as a rule, does not cause serious difficulties.

The efficiency of the method is proved by the measuring and diagnostic system with an eddy current sensor of the DPL-KV type (MS). The MS was developed at the VNIIM [10] in order to apply it in the linear stepping drive that move a control rod in the WWER-1000 nuclear reactor. The sensor of the MS realizes a combinatory code chain. Besides measuring the control rod position, the MS performs metrological and technical diagnostics of the sensor and microprocessor unit. The MDC generally consists in comparison between:

- the code combinations identified and the code combinations specified;
- the code combinations related to consequent control rod positions and the specified code combinations;
- the control rod position and the number of steps made by the rod.

In various countries, new self-diagnosing, self-checking, or self-validating devices have been developed, for example [11-20]. Since recently, along with conventional devices, a number of companies have started mass-production of measuring instruments which can perform metrological self-diagnostics. Such instruments are double thermocouples or resistance thermometers in the same housing, a temperature transmitter which can accept 2 independent temperature sensor inputs (either Pt100 or thermocouples), as well as self-diagnosing electromagnetic and ultrasonic flow meters.

Some metrological self-check modes (under various names) have been used in industry for many years. The first national regulations [21, 22] were published in Russia (1989) and the UK (2001). Their main statements were developed in new documents [23-25]. Attempts to systematize such methods were made, for instance, in [9, 26-28].

4. SELF-CORRECTION AND FAULT TOLERANCE

The capability of self-diagnostics which is the inherent feature of the intelligent sensor allows to increase metrological reliability significantly by the application of measures of active character. These measures are aimed at self-correction of the external influences and ageing of components as well as at the support of fault tolerance.

Structural and Information redundancy of sensor as well as computer technology afford ground for these measures.

The simplest example for self-correction in the presence of transient errors is frequency filtration or time filtration. In order to apply such a correction, it is sufficient to use a priori information on the parameters of a signal coming from the sensor and on the specified limits of the signal.

If a fault occurs, the intelligent sensor shell:

- register the fact of fault,
- inform the human operator that the measurement reliability decreased,
- correct the measurement result and continue operating.

An example of how the sensor fault tolerance is assured is the MS [10] mentioned above. The sensor of the MS contains a set of inductance coils. If a fault occurs, e.g. any signal wire breaks or any coil fails, the sensor is keeping operation.

In the most part of the position range, due to incorporating a redundant number of coils into the sensor (in comparison with minimally needed), the code combination is distorted, but it keeps information regarding the control rod position. In addition, the position of the rod can be corrected on the basis of the known number of steps made by the rod from the nearest position that was reliably measured.

In many cases, it is not possible to obtain a quantitative estimation of the uncertainty. For a considerable part of applications, it is expedient to estimate the quality of measurement results using measurement value status (MVS) [9]. In [9] the following status values were recommended: secure, clear, blurred, dazzled, and blind.

In the joint paper of Oxford and St.Petersburg scientists [29] a comprehensive justification of the necessity to introduce the measurement value status was given and some details were proposed. It was noted that the number of status states should depend on the number of human operator's actions required in response to information about the measurement value status. The number of MVS states is comparatively small:

A) Firm confidence, that a measurement value is reliable, corroborated by an additional information source, i.e. it is based on redundant information. The sensors are fault-free.
B) Assumption that a measurement value is reliable, but there is no corroboration from any additional information sources.
C) Understanding that measurement confidence has been decreased due to some fault. Measurement value was corrected for this fault condition, but the uncertainty is not too great. The measurement confidence is sufficient to get operator's bearings in the technological process and technological equipment condition.
D) Conception that measurements are not reliable for a short period of time. This relates to carrying out a special test, technological operation, or data filtration. In such a situation the measurement values are projected from the past history.
E) Confidence that measurement values are not reliable. This situation obliges, if necessary, to stop the technological process. If the substituted data concerning the measurements are available, step must be taken to move the process away from any critical technological constraints.

5. CONCLUSION

In order to provide reliable functioning of sophisticated technical complexes with automatic control systems, besides technical diagnostics of the equipment, it is necessary to apply high-reliability sensors. They must provide long-term operation and realization of automatic metrological diagnostics.

Development of such sensors should go with development of specific methods for assessment of quality of sensors in respect of their design and technology. Automatic diagnostics should be provided on the basis of structural and/or information redundancy and computer technologies.

Success in developing such sensors depends, to a great extent, on elaboration of international regulatory documents which can establish the requirements for sensors characterized by long- term lifetime.

REFERENCES

[1] Tarbeyev Yu., Kuzin A., Taymanov R., Lukashev A.: *New Stage of Development of Sensors Metrological Assurance*, Measurement Technique, 3, 2007. p. 69-72.

[2] Taymanov R., Sapozhnikova K.: *Problems of Developing a New Generation of Intelligent Sensors*, Proc. of the 10th IMEKO TC7 Symposium, St.Petersburg, 2004, p. 442-447.

[3] Fridman A. E.: *Theory of Metrological Reliability, Measurement Technique*, 1991, 11, p. 3-10.

[4] Efremov L., Sapozhnikova R.: *Assessment of the Sensors Lifetime on the Basis of Test Results*, Proc. of the 10th IMEKO TC7 Symp., St. Petersburg, 2004, p. 448-453.

[5] Sapozhnikova K., Taymanov R.: *Development of Sensors Distinguished by Enhanced Reliability*, Proc. of Conf. "Nuclear Power Instrumentation, Controls, and Human Machine Interface Technology", Albuquerque, New Mexico, USA, 2006.

[6] Taymanov R., Moiseeva N.: *Application of the Metrological Investigation to the Development of the Manufacturing Technology of High-reliable Sensors*, Proc. of the 10th IMEKO TC7 Symp., St. Petersburg, 2004, p. 433 - 436.

[7] Hashemian H. M.: *Maintenance of Process Instrumentation in Nuclear Power Plants*, Springer - Verlag, Berlin Heidelberg, 2006.

[8] Reed R. P.: *Possibilities and Limitations of Self-validation of Thermoelectric Thermometry, Proc. of the Conf.* "Temperature: Its Measurement and Control in Science and Industry", 7, D. C. Ripple et al. eds., AIP Conference Proceedings, Melville, New York, 2003, p. 507-512.

[9] Henry M. P., Clarke D. W.: *The Self-validating Sensor. Rationale, Definitions, and Examples*, Control Eng. Practice, v. 1, 1993, 4, p. 585-610.

[10] Taymanov R., Sapozhnikova K., Druzhinin I.: *Measuring Control Rod Position*, Nuclear Plant Journal, 2007, 2, USA, p. 45-47.
[11] Henry, M.P., Clarke, D. W., et al.: *A Self-validating Digital Coriolis Mass-flow Meter: an Overview*, Control Engineering Practice, 8, 2000, 5, p. 487-506.
[12] Yang J. C.-Y., Clarke D. W.: A Self-validating Thermocouple, IEEE Transactions on Control Systems Technology, v. 5, 1997, 2.
[13] Bernhard F., Boguhn D., et al.: *Application of Self-calibrating Thermocouples with Miniature Fixed-point Cells in a Temperature Range from 500 ^{o}C to 650 ^{o}C in Steam Generators*, Proc. of the XVII IMEKO World Congress, 2003, Dubrovnik, Croatia, p. 1604-1608.
[14] Feng Z.-G., Wang Q., Shida K.: *Structure Design and Finite Element Analysis of Self-Validating Pressure Sensor*, Chinese Journal of Sensors and Actuators, 20, 2007, 2, p. 279-282.
[15] Belevtczev A. B., Karzhavin A. V., et al.: *In-built Method for Estimation of Confidence in Thermocouple Measurements*, Mir Izmerenii, 2005, 3, p. 12-15.
[16] Hans V., Ricken O.: *Self-monitoring and Self-Calibrating Gas Flow Meter*, Proc. of 8th International Symposium on Measurement Technology and Intelligent Instruments, Sept 24-27, 2007, p. 285-288.
[17] Barberree D.: *Dynamically Self-validating Contact Temperature Sensors, Proc. of the Conf. "Temperature: Its Measurement and Control in Science and Industry*", 7, D. C. Ripple et al. eds, AIP Conference Proceedings, Melville, New York, 2003, p.1097-1102.
[18] WO2007097688, *Redundant Level Measurement in Radar Level Gauging System*, G01F23/284; G01F23/14; G01F25/00, Haegg L., Larsson L.O., et al, Rosemount Tank Radar AB, 2007.08.30.
[19] Kao I., Zhang K.: *Miniaturized Sensors for Intelligent System Fault Detection and Diagnosis (FDD)*, Proceedings of SPIE, 2007, part 1, art. No. 65290U.
[20] Frolik J., Abdelrahman M.: *A confidence – based Approach to the Self-validation, Fusion and Reconstruction of Quasi-redundant Sensor Data*, IEEE Transactions on Instrument and Measurement, v.50, 2001, 6, p. 1761-1769.
[21] MI Recommendation 2021-89, *Metrological Assurance of Flexible Manufacturing Systems. Fundamentals*, Committee on Standard. and Metrology, Moscow, 1991.
[22] BS 7986:2001, *Data Quality Specification for Industrial Measuring and Control Systems*, British Standards Institute, London, 2001.
[23] MI Recommendation 2233-00. *Assurance of Measurement Efficiency in the Control of Technological Processes*. Fundamentals, VNIIMS, Moscow, 2000.
[24] BS 7986:2005. *Specification for Data Quality Metrics of Industrial Measurement and Control Systems*, British Standards Institute, London, 2005.
[25] NAMUR Recommendation NE 107, *Self-monitoring and Diagnosis of Field Devices*, 2005.
[26] Sapozhnikova K. V.: *Metrological diagnostic check*, Metrological Service in the USSR, 1991, 2, p.18-24.
[27] Werthschutzky R., Muller R.: *Sensor Self-Monitoring and Fault-Tolerance, Technisches Messen*, v.74, 2007, 4, p. 176-184.
[28] Feng Z., Wang Q., Shida K.: *A review of self-validating sensor technology*, Sensor Review, 27, 2007, 1, p. 48-56.
[29] Sapozhnikova K., Henry M., Taymanov R.: *Proc. of the Joint IMEKO TC1+ TC7 Symp.*, Ilmenau, Germany, 2005, p. 71-72.

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PORTABLE MULTI-CHANNEL DEVICE FOR ACOUSTIC EMISSION MONITORING OF STRUCTURES AND PRODUCTS

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Summary

In the paper eight channel acoustic emission (AE) device for selection, recording and processing signals of AE intended for use in the sphere of non-destructive testing of materials, products and structures of various forms and functional applications is described. The device is designed using a wide range of SMD elements and is adapted to work with Windows family operating systems. Specially developed software realizes functions of input data processing and its visualization, determination of defect position and storing the obtained results into computer memory.

The above-listed characteristics as well as high rate of data exchange between the device and PC (12 Mbit/s), enables to work in real-time mode, and efficient software allow to compete with developments of such world leading manufacturers as PAC, Vallen Systeme, Interunis etc.

Keywords: acoustic emission, destruction, non-destructive testing, technical diagnostics.

1. TOPICALITY OF PROBLEM

Presently in most production spheres new materials and technologies are launched, experience of using which under conditions of intensive strain and activity of aggressive working environment is insufficient. Therefore the objects using new materials or technologies need to be monitored to provide their reliable maintenance. With this purpose new progressive methods and means of diagnosing firmness and durability of the mentioned items, constructions and buildings are used.

Analysis of reasons for construction materials fail, which are widely used in mechanical and power engineering, pipeline transport, aircraft building, chemical and oil industry etc. showed that in the majority of cases it is the result of initiation and development of crack-like defects [1, 2]. Therefore the research of these processes has become a topical task.

Experience of the last decades proved great potential possibilities of the acoustic emission (AE) method. Its application is especially relevant under conditions when visual control is impossible or access to the object under control is complicated [3]. Distance control, high sensitivity, possibility of remote defect detection, which considerably exceed their sizes, possibility to obtain information regardless of form and sizes of the object under control, recording real time destruction development etc. are the advantages that have put the method of AE in a leading place among the known perspective methods of non-destructive testing (NT) [4].

For its successful implementation new effective portable devices based on modern achievements of electronics have to be developed.

2. STATE OF PROBLEM

If all the developments of AE devices known in literature are generalized, they can be classified into the following groups: for complex researches, specific purpose, for control over the state of large-sized objects and portable one- and multichannel ones.

Facilities for complex researches are intended for the reception of AE signals during defect development, which initiate in materials, wares and constructions. Equipped, as a rule, by devices are able to distinguish the signals from background noises and hindrances, they allow to estimate various parameters of AE signals and determine the state of the object under control.

Facilities for the specific purpose are developed mostly to solve particular NT tasks: to reject as defective wares during their mechanical testing; to record by AE signals the moment of initiation in construction machine-building materials the tensions which correspond to the physical limit of fluidity; to estimate plastic volume of material; to research the phenomenon of corrosion under tension; to record and analyze AE signals during the friction of solids etc.

Facilities of large-sized objects AE control allow determining the location of developing defects. Knowledge of coordinates of AE sources allows estimating distribution of defects within control area and taking into account power parameters of the radiation to estimate the level of damage risk. Such AE systems serve to reveal danger of initiation and accumulation of defects, location of AE sources and as preventive control systems for emergency situations of responsible buildings.

When testing the state of overall objects of complicated configuration, the determination of coordinates or areas of emission sources location is performed using various methods. The most widespread is the method of calculating coordinates by means of triangulate calculations and area method of locating AE sources. Both are based on registering the difference in arrival times of AE signals perceived by the group of primary transformers.

Purpose of work – to develop and do experimental approbation of the portable eight-channel acoustic emission device.

3. DESCRIPTIONS AND BASIC ADVANTAGES

Eight channel acoustic emission (AE) device for selection, recording and processing signals of AE is intended for use in the sphere of non-destructive testing of materials, products and structures of various forms and functional applications. The device is designed using a wide range of SMD elements and is adapted to work with Windows family operating systems. Specially developed software realizes functions of input data processing and its visualization, defect location and storing the obtained results into computer memory.

The above-listed characteristics as well as high rate of data exchange between the device and PC (12 Mbit/s), enabling to work in real-time mode, and efficient software allow to compete with developments of such world leading manufacturers as PAC, Vallen Systeme, Interunis etc.

In comparison with developments of world-famous manufacturers the designed device has a number of advantages:

- portability allows the device to be used not only in field conditions of inspected objects diagnosing but also in hard-to-reach, high-altitude and other difficult conditions;
- self-contained power supply enables to use the device under conditions of limited or unavailable network power supply;
- supply current 120 mA;
- sensitivity to tested surface displacement $10^{-14}...10^{-12}$ m;
- USB interface connection provides high rate of data exchange between the device and a PC;
- programmed control capabilities: choice of number of working channels, variability of sampling duration etc.
- inaccuracy in determination of AE source location depending on inspected object testing conditions does not exceed 10 %;
- user-friendly software interface together with convenient help system allow users to quickly acquire skills of working with the device;
- overall dimensions: 370×256×30 mm, weight – 2,1 kg;
- compactness and good constructional solution of the device conduce to easy and convenient transportation;
- the price of the device is significantly lower in comparison with similar AE equipment of this class of other well-known manufacturers.

4. CONDUCTING EXPERIMENTAL RESEARCHES

An approbation of the device when monitoring the state of several bridges, overpasses, tunnel transitions etc. was conducted, that is represented in proper publications and acts of NT applied methods implementation (fig. 1).

(a)

(b)

Fig. 1. Application of the developed AE system when diagnosing heat-and-power engineering equipment (a) and bridge transition (b)

5. AREA OF APPLICATION

The device can be used for monitoring and technical diagnostics of long-term operation objects:

- bridges;
- tanks, pressure vessels;
- pipelines;
- elements of bridge, frame and tower cranes;
- port lift-and-carry mechanisms;
- other components and mechanisms,

as well as in laboratories for fundamental and applied researches of structural materials:

- static and cyclic crack growth resistance;
- creeping, plastic deformation;

- nucleation and propagation of cold - and autocracks while welding;
- threshold value of stress intensity factor for hydrogen-induced and stress corrosion cracking of materials;
- composites research etc.

LITERATURE

[1] Skalsky V. R., Sergienko O. M., Oliyarnyk B. O., Plakhtiy R. M., Sulym R. I.: *Development of methods and means for detecting initiation and development of cracks in large-sized objects under the influence of loading and working environment.* Sc. Art. Col "Problem of resource and safety of constructions, buildings and machines maintenance", Kyiv, 2007, P. 48.

[2] Skalsky V. R., Koval P. M.: *Some of methodological aspects of acoustic emission application.* Lviv, Spolom, 2007.

[3] Skalsky V. R., Koval P. M., Stashuk P. M., Plakhtiy R. M., Sulym R. I.: *Operative acoustic emission control of oil tank defectiveness.* Methods and devices of quality control. №15, 2005, P. 3.

[4] Skalsky V. R., Andreykiv O. E., Sulym G. T.: *Theoretical bases of acoustic emission method in mechanics of destruction.* Lviv, Spolom, 2007.

[5] Skalsky V. R., Oliyarnik B. O., Plakhtiy R. M., Sulym R.I.: *The portable eight-channel acoustic emission device.* Lviv Polytechnic National University Radio electronics and telecommunications Bulletin. №534, 2005, P. 55.

[6] Sulym R. I.: *Software of acoustic emission device SKOP-8.* Proceedings of *XIX* conference of KMN–2005. Lviv, 2005, P. 427.

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STEERING INSPECTION BY MEANS OF TYRE FORCE MEASURE

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Summary

A few systems, such as steering, brakes or suspension, critically affect the vehicle's safety. In light of this, it is necessary to check these elements up to a certain age in order to maintain the vehicle in optimal safety conditions. This study is part of a project about effectiveness of Periodic Motor Vehicle Inspections (PMVI), in order to suggest metodologies, instruments and criterions to inspect the vehicle´s safety. It´s well known the relationship between steering geometries and the force in contact patch. The measurement of these geometries is important to evaluate the vehicle dynamic performance.

The main objective is to evaluate the steering inspection method at low speed, current rejection criteria in order to analyze the effect of these results in vehicle´s safety behaviour in real dynamic conditions. The angle that has more influence on the PMVI inspection is the toe angle, being this one the principal parameter of analysis. Experimental force in contact patch with dynamometer plate and simulation results with CarSimTM have been carried out in order to validate the methodology of steering inspection and to check the information obtained in these tests.

Keywords: Vehicle's safety, steering inspection, dynamometer plate, lateral tyre force, PMVI.

1. INTRODUCTION

The recent need to increase vehicle safety leads to study every one of the parameters that influence traffic accidents. Different authors such as Van Schoor, 2001 [17], or G. Rechnitzer, 2000 [13], have investigated PMVI influence on traffic safety, concluding that vehicle defects are a contributing factor over 6% of crashes.

Nowadays, PMVI analyses the vehicles steering system. Several studies show that steering disalignment could be an important factor in traffic accidents. However, very little statistics are available. It is very complicated to check that an accident has been produced by steering disalignment and generally other factors influence the accident.

International Motor Vehicle Inspection Committee (CITA) does not establish a reject value for the steering inspection by means of standard alignment plate. Moreover, spanish PMVI program establishes steering disalignment, measured by standard alignment plate, as a minor defect and no vehicle is rejected by this measure. In this article the need of measuring effectively the steering condition is presented, therefore, in order to solve this problem the dynamometer plate is proposed [1, 5].

A dynamometer plate has been used to carry out this investigation, because it allows measuring in the contact patch the force in the three spatial directions. Therefore, not only the lateral deviation will be obtained by means of the lateral force, as carried out in PMVI, but also the longitudinal and vertical force. In addition, to characterise the vehicle steering system in different dynamic situations, simulations have been carried out by means of CarSim™, a well known simulation tool [2].

The main objective of this study is to evaluate the steering inspection method at low speed, current rejection criteria in order to analyze the effect of these results in vehicle´s safety behaviour in real dynamic conditions. The angle which has more influence on the PMVI inspection is the *toe angle (toe* describes the angle between the tire's centerline and the vehicle's longitudinal plane*)*, being this one the principal parameter of analysis in this study. Therefore, not only the available adherence in the contact tyre-road for different toe angles will be investigated [3], but also the consequences over the final steering characteristics of the vehicle [18].

2. THEORETICAL ANALYSIS

Driving dynamics deal with the mechanical laws that govern a vehicle's motion with respect to the vehicle's properties and the ones of the road. The description of the vehicle performance is very complex and mathematical models are required for the design and construction of the vehicles themselves [2, 3, 4, 11, 12].

For instance, the forces acting in the contact area between the tyre and the road are the longitudinal or tangential force and the lateral or side force. The longitudinal force in a straight path causes a driving tractive or braking movement. During cornering, the front wheels are at an angle to the longitudinal axis of the vehicle, thereby causing the development of a lateral force F_R that is responsible of lateral or side friction f_R, defined as:

$$f_R = \frac{F_R}{Q} \quad (1)$$

where Q is the weight vertical force on the wheel.

When both the radial and longitudinal forces are present, the resultant force should not exceed an upper limit that could lead to the vehicle sliding off the road.

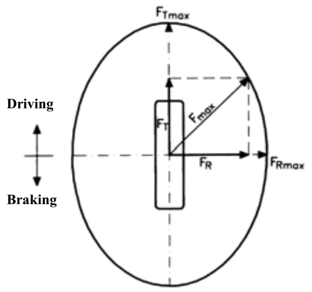

Fig. 1. Ellipse of adhesion limits, Kiencke U. and Nielsen L., 2000 [9]

In order to provide a safe and accurate directional control, the steering and suspension design on the front axle of the vehicle has lead to sophisticated steering geometries where the wheel alignment is governed by the following inclination angles which play an important role in the vehicle dynamic performance: camber, toe, caster and steering axis angle or kingpin [8, 14].

2.1. Cornering performance

When a vehicle supports a certain lateral load (wind, centrifugal force, etc.) a force is generated in the tyre contact to counteract that effect. The tyre ability to generate the needed forces so as to follow the correct path is very important, as it allows evaluating the safety vehicle condition. Therefore, the forces generated in the contact patch depend on the steering angles, and this relationship is the one analysed in this investigation. It has been considered as a reference case that, in which the vehicle follows a circular path and it is subjected to a centrifugal force [8,16].

For low values of the steering angles (the bend radius is much bigger than the vehicle wheelbase) and if the centrifugal force is applied in a perpendicular direction to the vehicle longitudinal plane the lateral forces on the front tyres F_{yd} and on the rear tyres F_{yt} are:

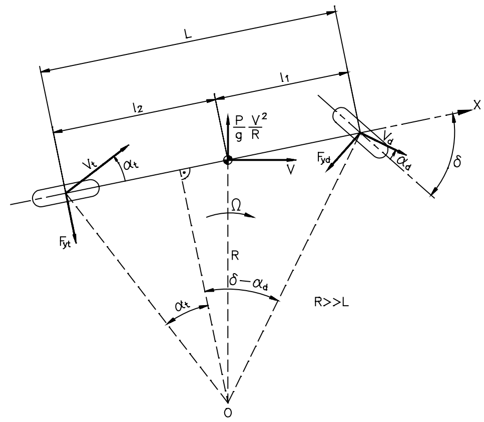

Fig. 2. Two axles vehicle model

$$F_{yd} = 2P_d \frac{V^2}{gR} \quad (2)$$

$$F_{yt} = 2P_t \frac{v^2}{gR} \quad (3)$$

Taking into account that $\alpha = F_y/K_\alpha$, where K_α is the cornering stiffness of one wheel, substituting in Eq. (2) and Eq. (3), and considering that both wheels of the same axle have two times the stiffness of one of them:

$$\alpha_d = \frac{F_{yd}}{2K_{\alpha d}} = \frac{V^2}{gR}\frac{P_d}{K_{\alpha d}} \quad (4)$$

$$\alpha_t = \frac{F_{yt}}{2K_{\alpha t}} = \frac{V^2}{gR}\frac{P_t}{K_{\alpha t}} \quad (5)$$

These equations for the slip angles for the front and rear axle can be introduced in Eq. (6), obtaining Eq. (7):

$$\delta - \alpha_d + \alpha_t = \frac{L}{R} \quad (6)$$

$$\delta = \frac{L}{R} + \left(\frac{P_d}{K_{\alpha d}} - \frac{P_t}{K_{\alpha t}}\right)\frac{V^2}{gR} \quad (7)$$

or:

$$\delta = \frac{L}{R} + K_V \frac{V^2}{gR} \quad (8)$$

$$K_V = \frac{P_d}{K_{\alpha d}} - \frac{P_t}{K_{\alpha t}} \quad (9)$$

K_V, is the **understeer increment** and its value is of great importance to analyse the vehicle steering performance. The vehicle cornering performance is measured by the understeer increment sign. From Eq. (8) it is obtained the the steering angle required for a constant radius turn varies with the speed, or it will be independent, depending on the sign of K_V. Thus, a vehicle can be **neutral steer**, **understeer** or **oversteer**. Considering R = cte:

Neutral steer:	**Understeer:**	**Oversteer:**
$K_V = 0$	$K_V > 0$	$K_V < 0$
(independant of V)	(δ decreases when V decreases)	(δ decreases when V increases)
$\delta = \dfrac{L}{R}$	$\delta = \dfrac{L}{R} + K_V \dfrac{V^2}{gR}$	$\delta = \dfrac{L}{R} - \lvert K_V \rvert \dfrac{V^2}{gR}$

Calculating K_v allows knowing the vehicle cornering performance. It is important to highlight that usually vehicles are designed neutral or understeer, due to the fact that in an oversteer vehicle the guidance angle will become negative for a certain value of V, called the **critical speed** (view Eq. (10)). From this point on, the steering wheel will have to be rotated in the opposite direction to the vehicle turning and the vehicle will become **unstable.**

$$V_{cri} = \sqrt{\frac{gL}{|K_V|}} \qquad (10)$$

3. EXPERIMENTAL ANALYSIS

In this study a dynamometer plate has been used to obtain the instantaneous force and momentums values in the contact patch.

The experimental data obtained by means of dynamometer plate has been registered in PMVI test conditions: a vehicle cross over the dynamometer plate at low speed (1-5 Km/h). It's important to emphasize that the forces measured in this speed range have a very little variations (less than 2 %), therefore the dynamometer plate shows a great robustness for speed variations in the considered speed range.

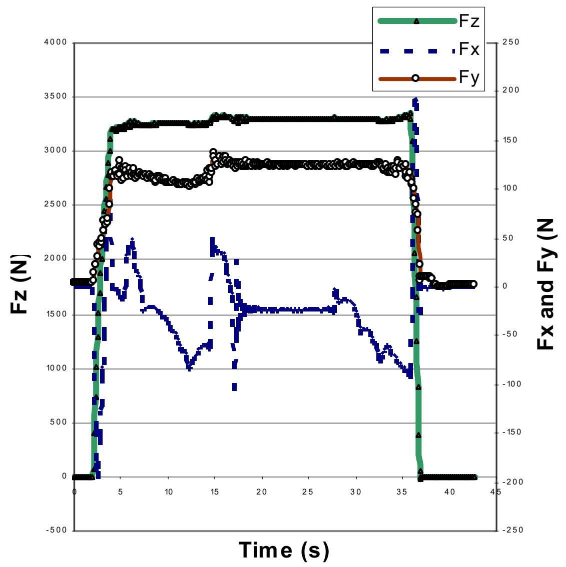

Fig. 3. Force measurement in contact patch (PMVI conditions).

A dynamometer plate consists of a metallic plate supported by eight load cells that measure the forces in the vertical direction and in the contact patch (longitudinal and lateral forces). The dynamometer plate allows a complete force and momentum measurement which is essential to obtain an objective reject value, whereas the standard plate, by itself, does not provide it. The standard plate does not register the vertical force which is a fundamental parameter to be taken into account.

The fig. 3 shows the force mesurement in this test, when the vehicle cross over the dynamometer plate. The results of the same test for different toe angles are depicted in fig. 4.

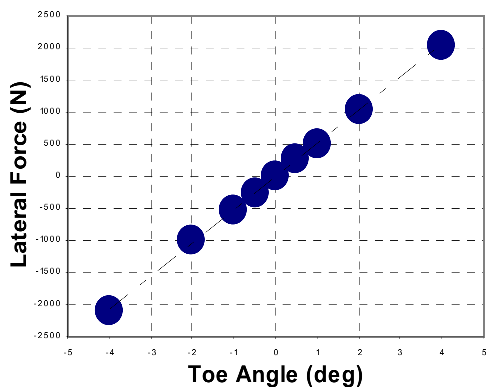

Fig. 4. Lateral forces variation obtained in diferents test for nine different toes angles (PMVI conditions).

The data obtained by means of dynamometer plate has been completed with other experimental results for diferent vertical loads and slips [18]. These measures have been obtained by means of dynamometer drum and trailer.

The input parameters of the simulation application are the measurements obtained by mean of the dinamometer plate, dynamometer drum and trailer.

Fig. 5 shows the experimental data of the lateral tire force in contact patch that was introduced in simulation tool *CarSim*^{TM}. Similar data about longitudinal tire force and aligning moment have been introduced.

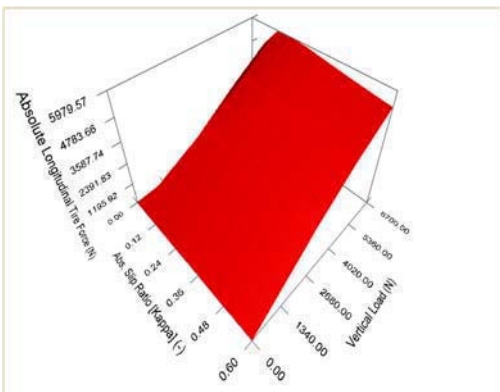

Fig. 5. Experimental three-dimensional graphics of the relationship between longitudinal tire force and slip ratio for diferent vertical loads.

4. SIMULATION PROGRAM

An existing simulation program *CarSim™* [10], [15] was used for this particular study. The program is a vehicle industry standard, specifically developed for simulating the dynamics of vehicles with tires. It shows how vehicles respond dynamically to inputs from the driver and the immediate environment (road and wind).

It produces the same kind of outputs that might be measured with physical tests involving instrumented vehicles. The program is based in part on technologies developed by the University of Michigan Transportation Research Institute.

The model of a vehicle is built up by using different components that are mathematically described by mass and inertias. The movements of the different components are restricted relative to each other by connection elements (ball joints, links and swing axels) which are also described mathematically. Force elements as coil springs, anti-roll bar, and dampers are placed between the components. The force characteristics of these elements may be nonlinear. A tire model based on Pacejka 5.2 [12] version of the Magic Formula is usually used by the program to simulate the behaviour of the tire. In this study the experimental measurements have been used in order to achieve the desired accuracy, so that safety conditions due to steering geometry are correctly evaluated.

The input to the system consists of a path that the vehicle has to cross at a certain speed. Other inputs are external forces acting on the vehicle (wind forces), the steering angle of the wheel, torque on the driver wheel and road excitation. For the simulation of the transition closed loop handling test (double lane change), it is necessary to use a driver model that steers the vehicle along the prescribed path.

Outputs of the simulation program, which can be extracted against time or other variable, include over 500 parameters as:

- Displacement, velocity and acceleration in any of the six degrees of freedom of the sprung mass.
- Tire force and moments.
- Spring and damping forces and displacements.

5. VEHICLE CHARACTERISTICS

A typical model for a small class European vehicle has been used for the purpose of this study. The main vehicle parameters which have been used are listed in Table 1. The rest of parameters that are not listed in Table 1 have less influence on side behaviour and medium values obtained from CarSim™ database have been used.

The steer due to the steering system is obtained by combining the steering wheel control with nominal gear ratio, while nonlinear tables combines the geared-down steering wheel angle to the road steer angle, with Ackerman and others effects.

An important item to take into account is the performance of the tire. Parameters from a 175/65 R14 tire have also been used.

Table 1. Vehicle characteristics summary.

Item	Unit	Value
Wheelbase	m	2.49
Front Track	m	1.47
Rear Track	m	1.445
Total Weight	N	11368
Front Weight	N	6595.4
Rear Weight	N	4772.6
Height of centre gravity	m	0.54
Front Sprung mass	kg	603
Rear Sprung mass	kg	387
Front Unsprung mass	kg	70
Rear Unsprung mass	kg	100
Roll inertia (Ixx)	$kg{\cdot}m^2$	288.0
Pitch inertia (Iyy)	$kg{\cdot}m^2$	1152.0
Yaw inertia (Izz)	$kg{\cdot}m^2$	1152.0
Total length	m	3.925
Width	m	1.68
Height	m	1.545
Tires		195/60 R15

6. TEST CONDITIONS

In order to evaluate the influence of wheel alignement (front axel) on handling characteristics of the vehicle, a double lane change manoeuvre has been tested. Three vehicle conditions have been compared:

Vehicle Condition A → (Toe angle = 0º) Usual design specification.

Vehicle Condition B → (Toe angle = 2º) Bad condition.

Vehicle Condition C → (Toe angle = 4º) Very bad condition.

The double lane change (DLC) is a well-known and commonly used test that has been prescribed in a concept standard ISO TR-3888-1 [7]. This test allows for the evaluation and comparison of the handling characteristics of vehicles through some objective parameters such as roll angle, roll rate, yaw rate, lateral acceleration (a_y) and the Dynamic Stability Index (DSI) [6].

Double lane change tests are implemented with a transition length of 35 m and a width of 3.5 m, following the path illustrated in fig. 5. Tests have been done following the suggestion of the standard ISO TR-3888-1 [7], which involves beginning at 40, 60, 80 km/h and increasing the speed until the vehicle fails the test.

The article simulations have been carried out at 60 km/h.

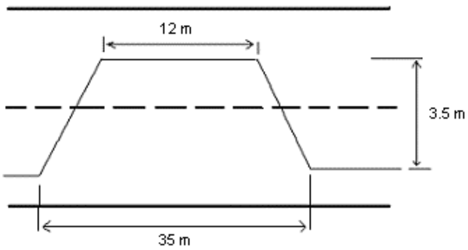

Fig. 6. Asymptotic driving course for a DLC test.

Stationary tests have also been considered to study the vehicle steering characteristics [16]. These tests allow obtaining the cornering stiffness, K_v, and how it changes when dynamic conditions are also altered, as well as its relationship with the toe angle. The proposed tests are detailed below:

- **Constant radius tests**: During this test the vehicle travels along a constant radius turn, at different speeds, measuring either the speed or the lateral acceleration $a_y = V^2/R$, and controlling the steering angle by means of the steering wheel angle δ_V, which allows knowing the wheel steering, allowing us to characterise the cornering stiffness as a function of the centrifugal force.
- **Constant speed tests**: Now the vehicle travels at a constant speed for different steering angles, the path will be of different radius and the vehicle will also be subjected to different lateral accelerations (V^2/gR), obtaining the cornering stiffness as a function of the centrifugal force.
- **Constant steering angle test:** In this case, the steering wheel angle δ_V is constant, and when the vehicle travels at different speed different paths and lateral accelerations will be obtained. Thus, the relationship between the cornering stiffness and the centrifugal force is obtained.

7. TEST RESULTS

Preliminary simulations show the lateral forces in a test for PMVI conditions (straight movement at 3 km/h) as fig. 7, 8 and 9 show. This information is important to compare the simulations with experimental test in the same conditions (fig. 4).

The results indicate the enourmous resemblance between both kinds of data. It is a normal conclusion because in these conditions, at low speed, there is no load transference neither other dynamic effects, and the results are a direct consequence of tire data introduced.

It can be seen that the introduced toe angle in each of the vehicles results in different lateral forces linear proportional for the studied range (0º - 4º). This implies, that the lateral force for vehicle A that travels in a straight path is lower than vehicle B and this one lower than vehicle C. It can be checked that the relationship between the toe angle and the lateral force is approximately equal when comparing the simulation results (Fig. 7, 8 and 9) and the experimental tests (Fig. 4).

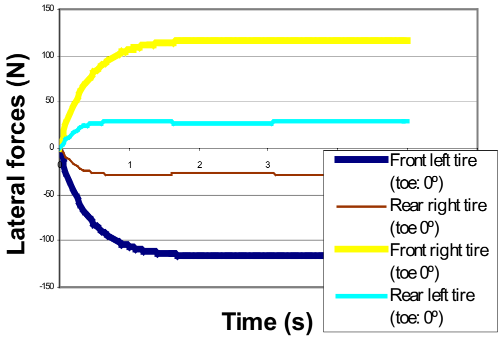

Fig. 7. Vehicle" A" lateral tire forces evolution in a simulation (PMVI conditions).

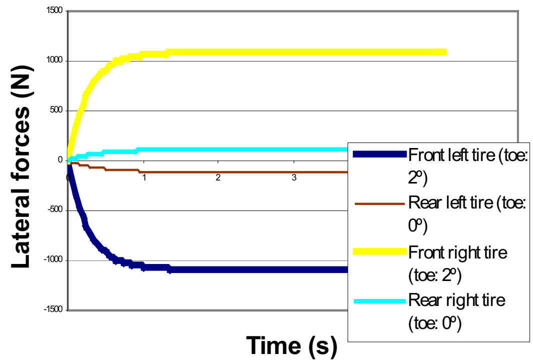

Fig. 8. Vehicle "B" lateral tire forces evolution.

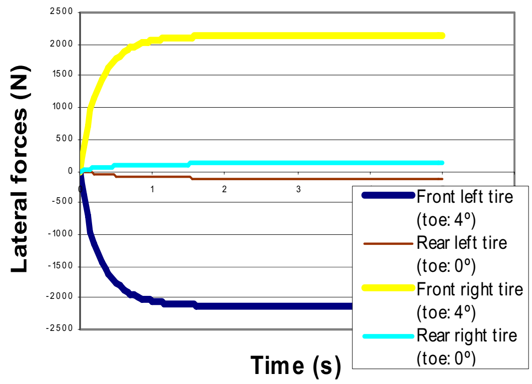

Fig. 9. Vehicle "C" lateral tire forces evolution.

If it is taken into account that the maximum forces that can be transmitted to the ground are those limited by adherence in the longitudinal and lateral direction, as shown by the adherence ellipse shown in Figure 1, it can be observed that the margin for case A is bigger than for case B, and for this one bigger than case C. Thus, a vehicle travelling along a straight line uses more lateral adherence when the toe angle is bigger, reducing its lateral adherence margin for dynamic conditions.

Without taking into account the load transfer and the slip angle, and considering a good pavement condition with lateral adherence value of μ_y = 0.64

the 3500 N that each wheel of the front axle support leads to a maximum transmitted lateral force of 2240 N. This value is very near to that achieved for a toe angle of 4 degrees (2100 N), that is, vehicle C will therefore have less adherence capacity than vehicles A or B before beginning to slip in the lateral direction and less capacity to transmit longitudinal forces. Therefore, the proposed assumptions, although severs, allow carrying out a first order approximation to how the system is conditioned and to justify the need to have a good steering system inspection.

To complete this argument a simulation was done in a demanding dynamic situation, double lane change ISO TR-3888-1 [7], to compare the differences introduced for three differents toe angles.

Initially there were obtained qualitative outputs to compare the different behaviours for these vehicle configurations.

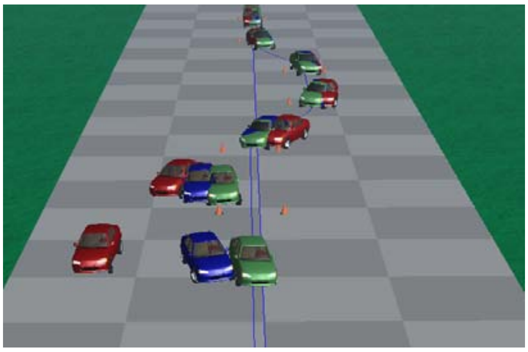

Fig. 10. Three different trajectory described for the vehicles: A (green), B (blue) and C (red).

The fixed trajectory is correctly described by vehicle A, however, vehicles B and C could not describe it correctly, as depicted in fig. 10, 11.

Vehicles that are not able to follow the trajectory describe the most nearer trajectory to the reference one under limit adherence conditions. It is defined a performance measure to evaluate the ability of the vehicle to follow a predetermined path as the maximum lateral deviation with respect to the reference one. For vehicle condition A, the maximum lateral deviation is 1.5 m, for vehicle B, 2.5 m and 7 m for vehicle C.

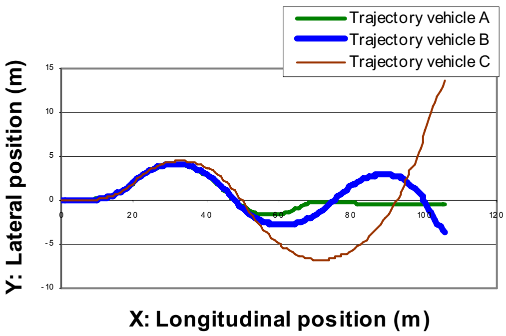

Fig. 11. Trajectory for the three different toe angles. Simulation time: 5s.

The double lane change ISO TR-3888-1 [7] is a very hard dynamic situation, and is difficult even for the vehicle A. The vehicle B keeps the trajectory until the last corner, and the vehicle C loses the trajectory on the third corner. As it has been described previously, the vehicle with a toe angle included between ±0.25º has more adherence available than vehicles with upper toe angles.

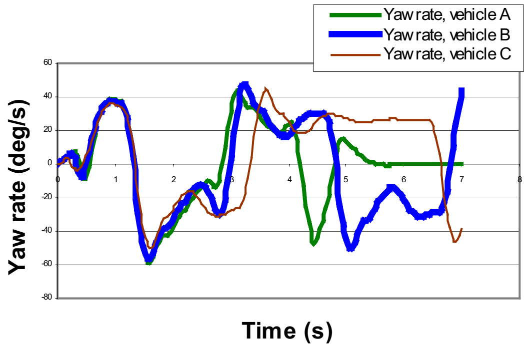

Fig. 12. Yaw rate (sprung masses). Simulation time: 7s

From Figure 12 it can be observed the progressive vehicle B held up concern the vehicle A, and the vehicle C concern vehicle B. The maximum values for yaw rate are similar for three vehicles. This maximum values for the vehicle A fit in with the corner positions for the double lane change test fixed.

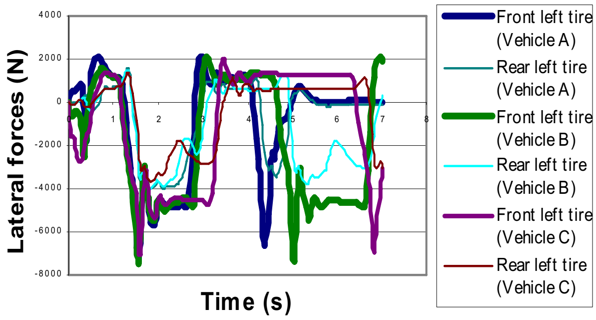

Fig. 13. Tire lateral forces (Fy), left side. Simulation time: 7s

It is very interesting to observe how at the beginning of the test the lateral forces are very different, before the first corner, as shows fig. 13. Before the first corner, vehicle C already consumes almost all force necessary to describe the corner and therefore, it does not trace the correct trajectory. From that moment on the vehicles with the three configurations cannot describe the same trajectory; their initial conditions do it impossible.

From above, it arise the need to characterise in an objective and precise procedure the steering characteristics of a vehicle. Therefore, simulations of the stationary tests were carried out in order to compare the values of the cornering stiffness for different vehicle configurations.

Next, different figures show the proposed tests (Fig. 14, 15, 16 and 17), and the influence of the cornering stiffness is analysed for each of them.

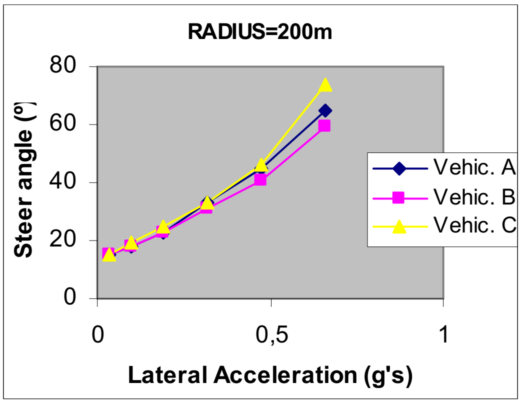

Fig. 14. Stationary test: constant radius turns of 200m.

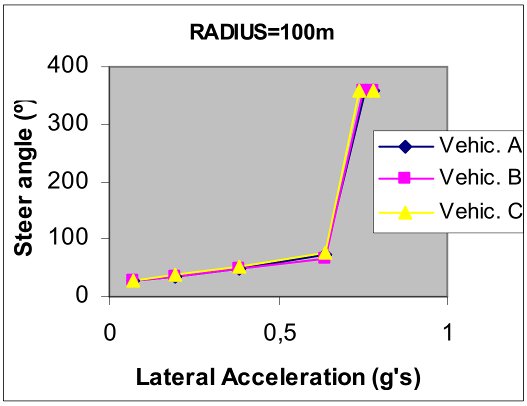

Fig. 15. Constant radius turns of 100m.

In Fig. 14, 15, 16 and 17 the most representative results for the stationary tests are depicted. Therefore, although other simulations with constant steering angle and many others for turns with different radius, different speeds, etc. because the four figures show the most important information about steering behaviour.

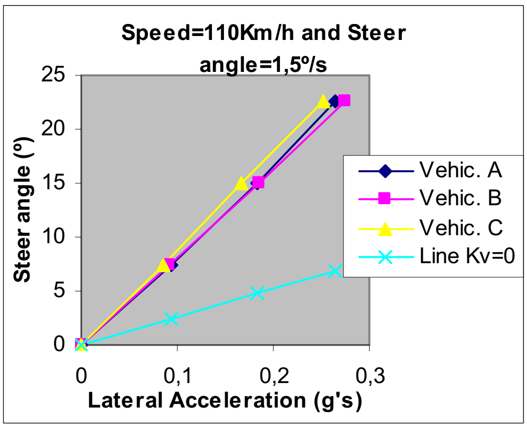

Fig. 16. Stationary test: constant speed of 110km/h constant steer angle variation 1.5º/s.

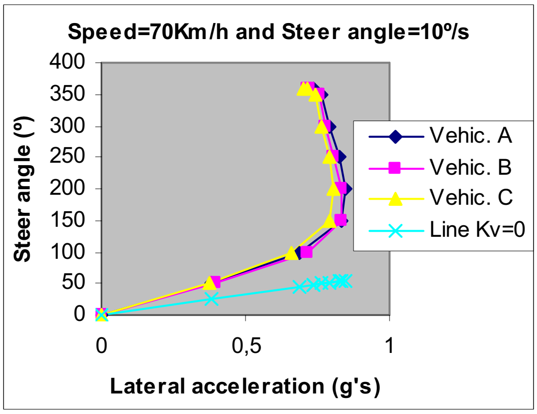

Fig. 17. Constant speed of 70km/h constant steer angle variation 10º/s.

In Fig. 14, 15, 16 and 17 it can be seen that the vehicle with bigger understeering behaviour is the vehicle with bigger toe angle. Specifically, in Fig. 14 and 15 it can be seen that for different radius turns the graphic slope is more positive for bigger values of the toe angle. If it is taken into account that the slope of the graphic has a direct proportion with K_V, which will be negative when the slope is negative (oversteer), equal to zero when the slope is zero (neutral) and positive when the slope is positive (understeer), it is clearly observed that there is an increase of the understeer behaviour for bigger values of the toe angle. On the other hand, Figures 16 and 17, also show that there a relationship between the graphic slope and K_v, but in this case the slope of 45º corresponds to K_v =0, slopes bigger than 45º will be for understeer vehicles and for lower slopes the vehicle will be oversteer. For the case of constant speed the vehicle will have an unstable steering behaviour for negative slopes, which is first arrived for bigger values of the toe angle, as shown in Fig. 17. All of these results indicate the due to the fact that the available adherence capacity is decreased due to the increase of the toe angle, the vehicle suffers a slip of the front axle leading to an increase of the understeer behaviour. However, this analysis has been carried out for vehicles with different types of suspension configurations and it has been seen that understeer behaviour strongly depends on the type of suspension employed.

Nowadays, and taking into account the tests and simulations shown in this investigation, a possible reject limit for the dynamometer plate of μ_y = Fy/Fz = 0.15 is proposed. However, no experimental tests have been carried out to validate that value. The possible range to establish a reject value of μ_y is between 0.12 and 0.2. For the case of the analysed vehicles: A, B and C, μ_y would be very near to 0.065, 0.57 to 1.14 respectively. However, it has to be taken into account that extreme cases have been considered; a value of 0.15 for this vehicle implies a toe angle of 0.5º in each test, which is bigger than the conventional values fixed during steering design.

8. CONCLUSION

- Measurements with dynamometer plate in periodic inspection conditions, double lane change simulations and stationary conditions simulations have been carried out. The results obtained show the need to carry out some kind of steering inspection to guarantee the safety vehicle conditions.
- Simulations show the toe angle influence, and the important behaviour dynamic variations. Also it has been analyzed the camber angle, but its influence is notably fewer than the toe angle influence, and for this reason it has not been included in this paper.
- Other steering angles have not been studied, because they should not change in the vehicle life, except if the vehicle suffers an accident or an important reform. These situations are out of the objectives of a periodic inspection and out of this study.
- For the cornering vehicle behaviour, it has been shown that the vehicle becomes understeer for bigger values of the toe angle. This is due to the increase of the slip of the front axle because the available adherence is diminished for bigger values of the toe angle.
- Dynamometer plate measurements have shown to be representative of vehicle safety.
- In future studies other kind of dynamic tests will be carried out, and dump conditions, toe angle influence in emergency brake, etc. will be included. Furtheremore the dynamometer plate system will be analyzed as an instrument used to carry out periodic motor vehicle inspections.

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REFERENCES

[1] Blab R:. *Introducing Improved Loading Assumptions into Analytical Pavement Models Based on Measured Contact Stresses of Tires*, International Conference on Accelerated Pavement Testing, Reno, NV, Paper Number: CS5-3, (1999).

[2] Díaz V., Ramírez M. Muñoz B.: *A wheel model for the study of the wheel angle measurement in the periodic motor vehicle inspection*. International Journal of Vehicle Design, vol.34, Nº3. pp.297-308 (2004).

[3] Dugoff H., Fancher P. S. and Segel L.: *An Analysis of Tire Traction Properties and Their Influence on Vehicle Dynamic Performance*, SAE Paper No. 700377, (1970).

[4] Gim G. and Nikravesh P E.: *An Analytical Model of Pneumatic Tires for Vehicle Dynamic Simulations. Part 1. Pure Slips*, International Journal of Vehicle Design, 11(2):589-618, (1990).

[5] Gobbi M., Mastinu G., Giorgetta F.: "*Sensors for measuring forces and moments with applications to ground vehicle design and engineering*", 2005 ASME IMECE, November 5-11, 2005, Orlando, Florida USA (2005).

[6] Heydinger G. J., Howe J. G.: "*Analysis of vehicle response data measured during severe manoeuvres*", SAE Paper 2000-01-1644, 2000.

[7] ISO TR-3888-1 Passenger Cars. "*Test track for a severe lane-change manoeuvre*", International Organization for Standardization, 1999.

[8] Dixon J. C.: *Tires, Suspension and Handling*, Society of Automotive Engineers, (1996).

[9] Kiencke U. and Nielsen L.: *Automotive Control System for Engine, Driveline and Vehicle*, Springer-Verlag, Berlin, 412 p., 2000.

[10] Mechanical Simulation Corporation, "CarSimTM Reference Manual", 2005.

[11] Muñoz B.: *Modelo de comportamiento de placa alineadora*. ThD Thesis, EPS Universidad Carlos III de Madrid (2001).

[12] Pacejka H. B., Sharp R. S.: "*Shear force development by pneumatic tyres in steady state conditions: A review of modelling aspects*", Vehicle System Dynamic, Vol. 20, pp. 121-176, 1991.

[13] Rechnitzer G., Haworth N., Kowadlo N. 2000. *The effect of vehicle roadworthiness on crash incidence and severity*. Monash University Accident Research Centre. Report nº 164, 2000.

[14] Sakai H.: *Theoretical and Experimental Studies on the Dynamic Properties of Tyres III. Calculations of the Six Components of Force and Moment of a Tyre*, International Journal of Vehicle Design, 2(3):182-226, (1981).

[15] Sayers M. W., Mousseau C. W., Gillespie T. D.: "*Using simulation to learn about vehicle dynamics*", International Journal of Vehicle Design, Vol. 29, Nos. 1 / 2, pp. 112-127,2002.

[16] Gillespie T. D.: *Fundamentals of vehicle dynamics,* Society of Automotive Engineers.Inc, (1992).

[17] Van Schoor O., van Niekerk J. L., Grobbelaar B., 2001. *Mechanical failures as a contributing cause to motor vehicle accidents*- South Africa. Accident Analysis and Prevention 33, 713-721, 2001.

[18] Woltson B. R.: *Wheel Slip Phenomena*, International Journal of Vehicle Design, 8(2):177-191, (1987).

PROBLEMS AND SOLUTIONS IN CONDITION MONITORING AND DIAGNOSTIC OF OPEN CAST MONSTER MACHINERY DRIVING SYSTEMS

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Summary

In the paper is given discussion on demands connected with vibration signal analysis for condition monitoring of driving systems of monster machinery used in open cast mines. Because of external load variation which cause that the vibration signal generated by driving systems is no-stationary there is a need to use special techniques for signal analysis. The description of proper signal analysis techniques is given together with machinery description and external load characteristic. The description leads to design, production technology, operation, change of condition factors analysis [1].

Keywords: condition monitoring, mining machines, open cast mines, external load variation.

PROBLEMY I ROZWIĄZANIA W DIAGNOSTYCE UKŁADÓW NAPĘDOWYCH MASZYNOWYCH GIGANTÓW PODSTAWOWYCH GÓRNICTWA ODKRYWKOWEGO

Streszczenie

W pracy przedstawiona jest dyskusja o wymaganiach związanych z analizą drganiowego sygnału dla monitorowania układów napędowych maszynowych gigantów używanych w górnictwie odkrywkowym. Ponieważ drganiowe sygnały generowane przez układy napędowe na skutek zmienności obciążenia generują niestacjonarny sygnał istnieje potrzeba wykorzystania specjalnych technik do analizy sygnału. Przedstawiono opis niektórych maszynowych gigantów wraz z technikami analizy sygnałów i charakterystyki zmienności obciążenia. Opis prowadzi do analizy czynników konstrukcyjnych, technologicznych, eksploatacyjnych i zmiany stanu [1].

Słowa kluczowe: monitorowanie stanu, maszyny górnicze, górnictwo odkrywkowe, zmienne obciążenia.

1. INTRODUCTION

For driving of open cast machinery there are used systems which consists of electric motor, hydraulic coupling or damping mechanic coupling (in some cases both) and different type of gearboxes. Taking into consideration type of the external load, which may be classified as: varying slowly with random cycles of many minutes or a few minutes, varying quickly with cycle from less than a second to a few seconds. For driving systems of belt conveyors the length of cycle depends mainly of the length of a conveyor and from the current output of bucket wheel or chain excavators. Taking into consideration driving systems a bucket wheel load period variation depends on a bucket frequency. Another period for bucket wheel excavators is connected with the slewing of a bucket wheel. The external load of driving systems causes non-stationary vibration which is the signal for the driving system condition. This situation demands special treatment used for vibration signal analysis.

2. SOME MONSTER MACHINERY DRIVING SYSTEMS

Fig. 1 shows a driving station for belt conveyor systems with the scheme of a driving subsystem. The driving station incorporates three or four subsystems. Fig. 2 shows a bucket wheel during the operation and the scheme of bucket wheel drive with three subsystem positions. The discussed bucket wheel drive has three independent driving systems driven by three electric motors. The subsystem consists of planetary gearbox with a fixed rim z3 and three cylindrical stages of gearboxes z4 – z9. One of alternative solutions for a compact drive used for driving bucket wheels is given in Fig. 3. The system consists of a bevel gear stage and a special solution gearbox which gives possibility of driving power distribution into two ways. This possibility is given by planetary gearbox in which the sun z3 and rim z5 are rotated.

a)

b)

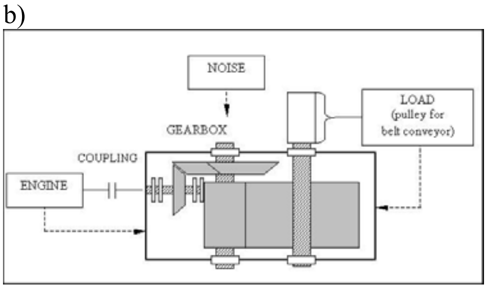
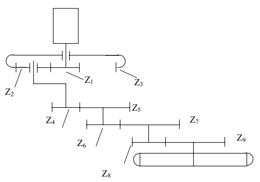


Fig. 1. a) General view of belt conveyor driving system, b) scheme of one subsystem

a)

b) c)



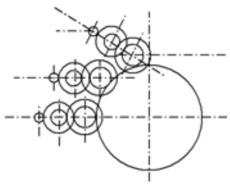


Fig. 2. a) Bucket wheel during operation
b) scheme of subsystem bucket wheel drive
c) subsystem positions

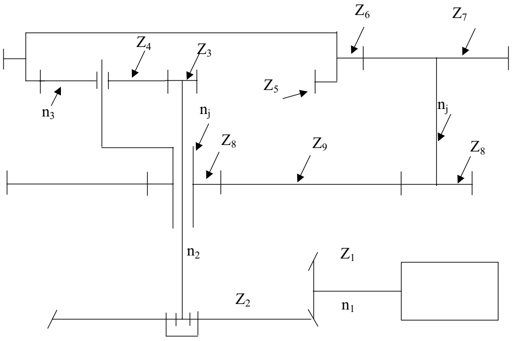
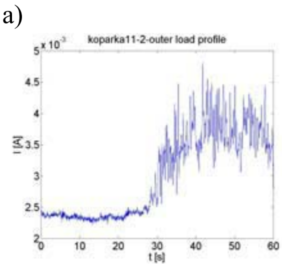


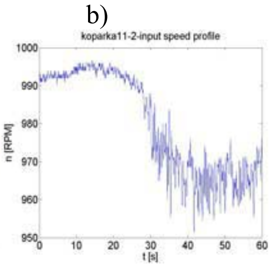
Fig. 3. Bucket wheel alternative driving system

2. EXTERNAL LOAD DESCRIPTION

The bucket wheel design which comes from digging principle is the reason of periodic variation of external load. Much longer period of load variation is connected with the boom slewing. The other operation factors influencing the load variability are connected with digging ground properties. These design and operation factors leads to external load variations and closely connected with generated vibration represented by time courses given in Fig. 4. In Fig. 4a) is given electric current consumption variation which represents directly load variation. The vibration signal variation is given in Fig. 4c). Fig. 4a) and c) show positive correlation between load and vibration. Fig. 4b) and c) shows negative correlation between load and rotation speed or between vibration and rotation speed. Detailed signal analysis can show load variations connected with bucket frequency. The vibration signal showing the value proportional to load variation is given in Fig. 10. The vibration signal procedures for load variation extraction is given in [2-4].

a) b)





c)

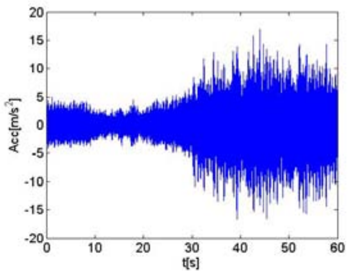


Fig. 4. a) Electric current consumption variation
b) input shaft rotation speed RPM variation
c) vibration signal variation

4. FACTORS INFLUENCING DIAGNOSTIC SIGNALS

Fig. 5 and 6 show general and detailed division of factors having influence the vibration signal. Fig. 5 shows that primary and secondary factors having influence generated vibration signal can be divided into four groups of factors. More details for further division of factors is given in Fig. 6. The detailed description of factors having influence to vibration signals is given in [1] it also well to look into publications [5 – 7] where many examples are given where different factors influencing vibration signals are considered.

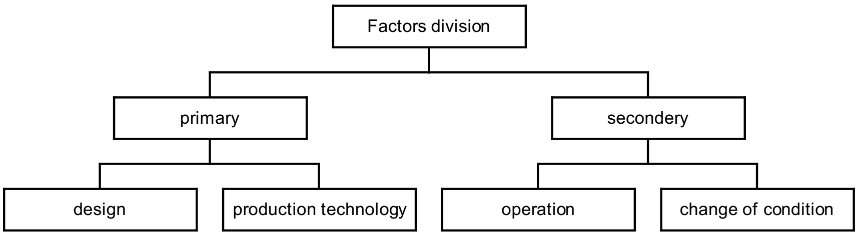


Fig. 5. General division of the factors influencing diagnostic signals

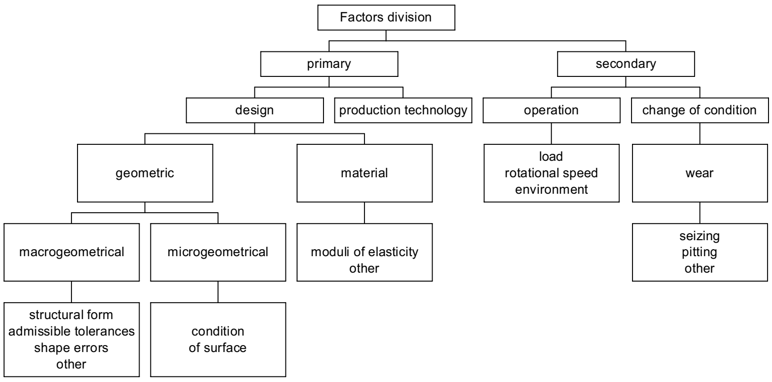


Fig. 6. More detailed division of factors influencing diagnostic signals

5. VIBRATION SIGNALS ANALYSIS

The choice of a vibration signal analysis depends of an external load variation. If the signal is constant or with the slow variation the first step for signal analysis is a spectrum analysis [6–9]. It is used for the object presented in Fig. 1. For deeper analysis are used also other techniques for signal analysis like cepstrum given in Fig. 7 and time-frequency spectrograms given in Fig. 8.

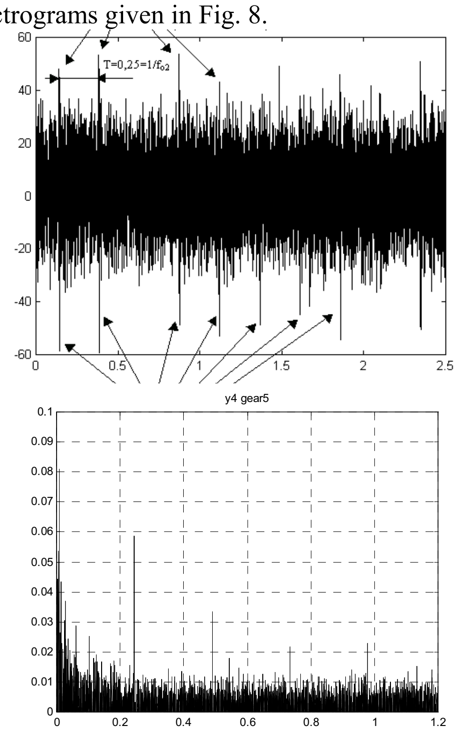


Fig. 7. Acceleration [m/s2] signal time [s] trace with series of peaks (peaks marked with arrows) and cepstrum for signal

a)

b)

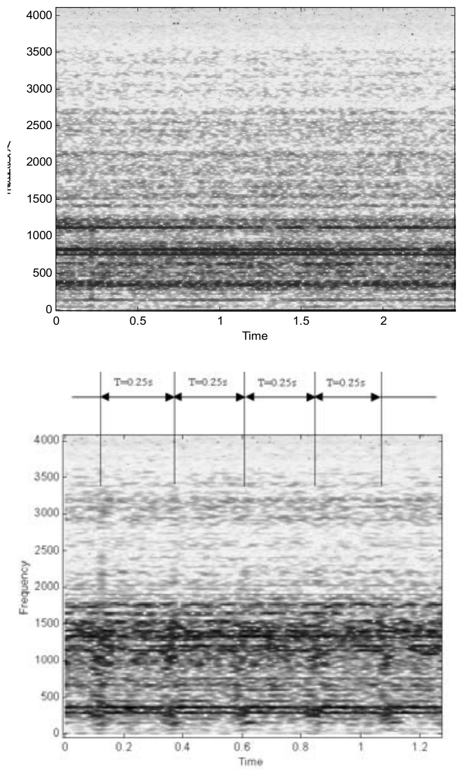


Fig. 8. Time-frequency [s]-[Hz] spectrograms
a) spectrogram of signal without regular peaks
b) spectrogram of signal with marks equivalent regular peaks

Details for these techniques of signal analysis are given in publications [6, 9].

Further analysis is connected with Fig. 9 where classification of gearing condition is given it is based on publications [7, 8]. It should be noticed that the inclination of the line separated the gear condition classes are also the measures of a gear condition.

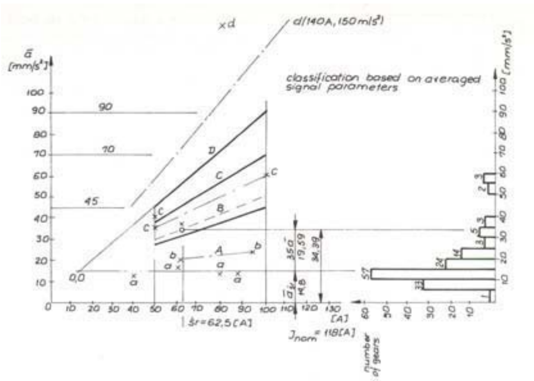


Fig. 9. Effect of load on gear transmission condition symptom value, accelerations in band 100-3500 Hz: A÷D – gear transmission classes; a÷d – gear transmission points, number of gear transmissions [7, 8]

The obtained results of signal analysis lead to identification of distributed and local faults and it is also the measure of the increase of a backlash in rolling elements bearings. More details about increase of the backlash are given for considering the case when the cycle varying load occurs.

Non-stationary vibration signal generated by some monster machinery needs special techniques for signal analysis. The signal analysis should give the background for condition evaluation and maintenance decisions. As the result of signal analysis one can expect detection of local and distributed faults and increase of elements play caused by the increased bearing backlash as result of harsh mine environment. For identification of the external load variation can be used signal demodulation techniques to obtain results as it is given in Fig. 10, [2–4] which envelopes are proportional to load variation; a) signal from gearbox before replacement b) signal from replaced gearbox. It can be seen that if the system is in bad condition it more yields under varying cyclic load as is given in Fig. 10a).

Variability of some parameter, which characterized the digging process are given in Fig. 10 to 12. In Fig. 10 and 11 are compared results of signal analysis of two gearboxes in bad and good condition. Fig.10 gives envelopes proportional to load variation: a) signal from a bad gearbox before replacement b) signal from a new replaced gearbox. Fig. 11 gives time [s] – frequency [Hz] spectrograms a) signal from a gearbox before replacement b) signal from a replaced gearbox. Fig. 10 shows the periodic variation of the signal with the bucket digging period Tb. this period is also depicted in the time-frequency spectrogram given in Fig. 11. Additionally one can noticed weak a period connected with a planetary gearbox arm/carrier rotation Ta. Fig. 12 gives more clear evaluation of the period by Wigner-Ville distribution with change in condition of the arm of the planetary gearbox: a) occurrence of distinct perturbations at the period equivalent the second harmonic of the arm rotation frequency, the gear condition before replacement of the gearbox b) occurrence of distinct perturbations at the period of the arm rotation frequency Ta for an other gearbox in a bad condition.

a)

b)

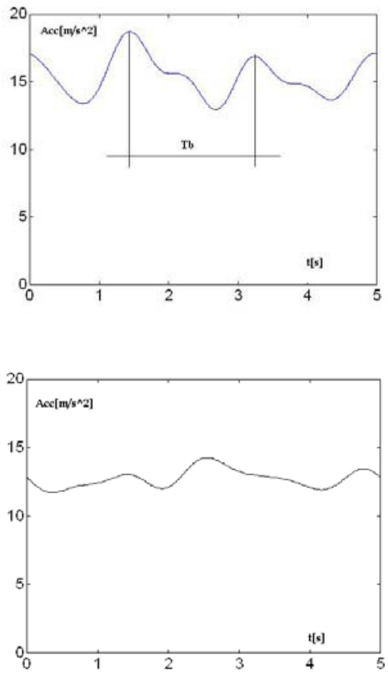


Fig. 10. Envelopes proportional to load variation: a) signal from bad gearbox before replacement – bad condition, b) signal from new replaced gearbox – good condition

a)

b)

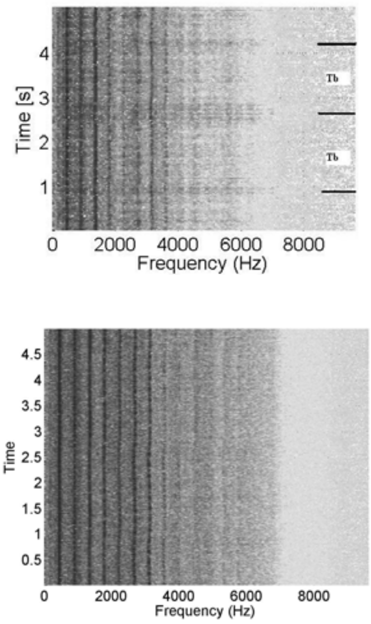
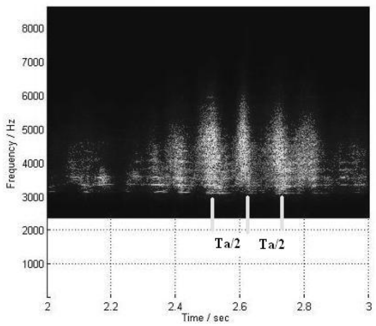


Fig. 11. Time [s] – frequency [Hz] spectrograms: a) signal from gearbox before replacement (bad condition) b) signal from replaced gearbox (good condition)

a)



b)

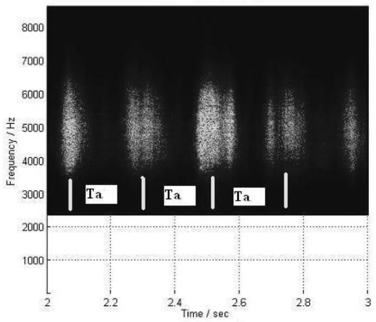


Fig. 12. Evaluation of Wigner-Ville distribution with change in condition of the arm of the planetary gearbox a) occurrence of distinct perturbations at second harmonic of the arm rotation frequency, condition before replacement of the gearbox b) occurrence of distinct perturbations at the arm rotation frequency for an other gearbox in a bad condition

Fig. 3 shows the scheme of a driving system which condition will be evaluated. It is a compact system which consists of an electric motor, one stage bevel gear (gears z1, z2), planetary gearbox with rotating sun z3 and rotating rim z5 and a planet z4. The power in the compact system is transmitted to the main gear z9 through two pinions z8 to accomplish it two gear are added z6 and z7. The variation of different parameters characterizing phenomenon of bucket wheel operation are given in Fig. 4. Fig. 4 shows in c) an input shaft rotation speed variation in RPM a) electric current consumption variation b) vibration signal variation.

Fig. 9 shows positive correlation between investigated values; Fig. 15 shows negative correlation for investigated values. The linear characteristics can be expected only for some range of an increased backlash in rolling elements bearings.

To obtain vibration parameters the signals were processed to get vibration spectrums as is given in Fig. 13. It should be stressed that the spectrums should be done for short time intervals to obtain no smeared spectrums. The intervals are equivalent to a bucket digging period Tb. The examples for the smeared and non smeared frequency component are given in Fig. 14.

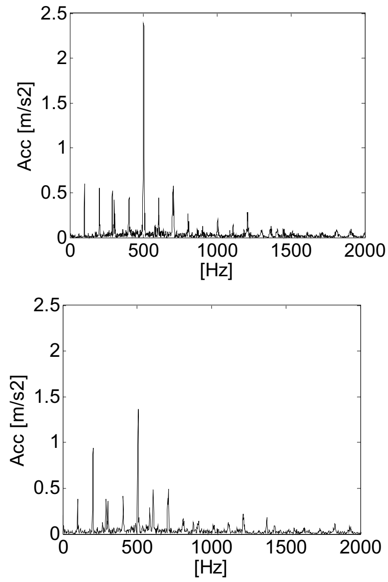
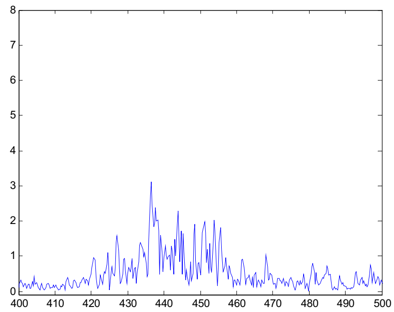


Fig. 13. Examples of short time segment frequency analysis

a)



b)

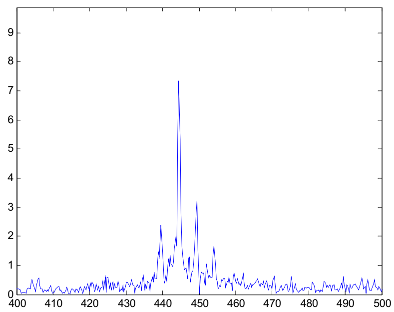


Fig.14. a) Smeared spectrum caused by frequency modulation b) non smeared spectrum

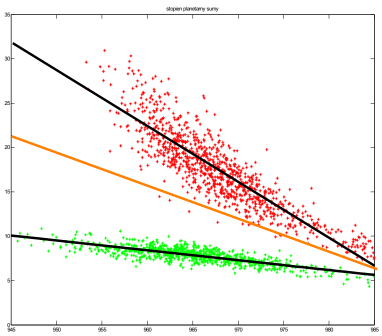


Fig. 15. Vibration signal RMS component sum versus rotational speed for planetary stage

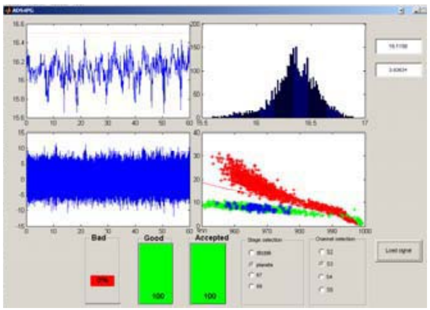


Fig. 16. Graphic interface for data analysis system

Fig. 16 shows a graphic interface for a data analysis system. In Fig. 16 one can see the course of rotation frequency variation in [Hz] as a function of time [s] (at the gearbox side of hydraulic coupling), distribution of the rotation frequency [Hz], variation of acceleration signal [m/s2] as a function of time, the plot of vibration parameters as a function of [RPM]. The plot has been obtained as the results of several vibration signals as are given in Fig. 4b) The values of parameters equivalent 60[s] period for a gearbox in good condition is given by green dots. From the vibration signal given in Fig. 4 part of the results has been automatically rejected. Into consideration are taken only spectrums, which have been obtained for a proper loaded gearbox for the distribution of the rotation frequency similar to distribution given in Fig. 16. For the data presented in the plot given in Fig. 15, which is also given in Fig. 16 the linear regression analysis has been done and obtained the equation of the external load yielding statistical characteristics in the form $y = ax + b$ for good and bad planetary gearbox.

6. CONCLUSIONS

The Paper shows the different ways of signal analysis, which have been used for condition monitoring and diagnostic for monster machines used in open cast mines. Some of the ways are connected with traditional ways of the signal analysis; these ways can be used when external load is constant or almost constant. There have been also shown new ways of signal analysis and its interpretations. These ways are suitable for the varying external load.

LITERATURE

[1] Bartelmus W.: *Root cause analysis of vibration signals for gearbox condition monitoring*. BINDT Inside Journal Vol 50 No 4 April 2008.

[2] Bartelmus W., Zimroz R.: *Influence of random varying load to vibration generated by planetary gearbox driving bucked wheel in excavators*. International Conference on COMADEM Lulea Sweden June 2006.

[3] Bartelmus W., Zimroz R.: *Bucket wheel variability identification on vibration analysis*. Proceeding of the International Symposium Mine Planning and equipment selection Torino Italy, 20-22 September 2006 pp.71-76.

[4] Bartelmus W. Zimroz R.: *Vibration condition monitoring of planetary gearbox under varying external load, Mechanical Systems and Signal Processing* (accepted for publication).

[5] Bartelmus W. *Mathematical Modelling and Computer Simulations as an Aid to Gearbox Diagnostics*. Mechanical Systems and Signal Processing 2001 Vol.15, no. 5, pp. 855-871.

[6] Bartelmus W.: *Computer-aided multistage gearbox diagnostic inference by computer simulation*. Scientific Papers of the Institute of Mining of Wroclaw University of Technology. No.100, 2002 (available on Internet at Dolnoslaska Digital Library).

[7] Bartelmus W.: *Condition monitoring of open cast mining machinery*. Oficyna Wydawnicza Politechniki Wrocławskiej Wrocław 2006 (available on the Internet at Dolnoslaska Digital Library).

[8] Bartelmus W.: *Vibration condition monitoring of gearboxes*. Machine Vibration 1992 nr1 s.178-189.

[9] Bartelmus W.: *Diagnostic information on gearbox condition for mechatronic systems*. Transaction of the Institute of Measurement and Control 25,5 (2003), pp. 450-464.

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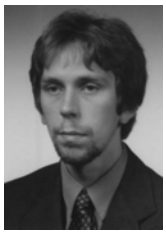

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MARINE GAS TURBINE PERFORMANCE DIAGNOSTICS: A CASE STUDY

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Summary

The paper discusses how performance models can be used for marine gas turbines. A particular performance model, built for on board training purposes is employed to demonstrate the different aspects of this process. The model allows the presentation of basic rules of gas turbine engine behavior and helps understanding different aspects of its operation. A smart designed graphics user interface is used to present engine operation in different ways: operating line, operating points of the components, interrelation between performance variables and parameters etc. The perception of fault signatures on monitoring parameters is clearly demonstrated. Diagnostics capabilities of the existing performance model installed at the Hellenic Naval Academy Gas Turbines Virtual Lab are examined and tested using the measurement data from real marine gas turbines. A case study is discussed in this paper where the model results and the real engine conditions are compared for diagnostic purposes.

Keywords: gas turbines, performance, diagnostics.

1. INTRODUCTION

The propulsion system of a specific type of frigates consists of a conventional two shaft CODOG configuration with two MTU 956 20V TB 82 cruise diesel engines; two boost GE LM 2500 gas turbines, Renk Tacke reduction gearboxes and two Escher Wyss controllable pitch propellers.

Gas turbines are complex engineering systems and performance monitoring and fault diagnosis is a subject that has to be addressed in gas turbine related –onboard and off board- training courses for all level of personnel involved with gas turbine operation and maintenance. Time and means for education and training are limited and therefore they must be used in an optimized manner. Computer assisted training comes to provide tools to increase training efficiency and fulfil such requirements [1]. The present paper discusses how marine gas turbines condition monitoring and fault diagnosis software is used for practical purposes.

Data from a GE LM 2500 marine gas turbine is used for the examination and testing of the existing performance model installed at the Hellenic Naval Academy Gas Turbines Virtual Lab [2]. A case study is discussed where the report from the practice and the software generated malfunctions are compared. The compressor efficiency is the independent variable affecting a series of operating parameters. The error between the calculated and the actual values is finally obtained.

2. PROPULSION PLANT PERFORMANCE

LM 2500 is an aero-derivative robust engine of increased power output and high efficiency developed and manufactured by General Electric. Overall engine design includes an annular combustor with mechanically independent high pressure and low pressure rotating systems. Vessel's propeller shaft can be driven by either one or both gas turbines at any given time [3].

A computer model produces very easily a lot of information that would be difficult, expensive and some times even impossible to obtain on an actual engine. Engine behavior can be studied at all possible permissible operating conditions, while even physically non-permissible conditions can be examined, if sufficiently deep modeling is involved. Any physical quantity can be observed, without the need of expensive instrumentation, which must be used on an actual engine. Even quantities that would be impossible to obtain due to geometrical or operating restrictions can be obtained (for example, turbine entry temperature, interstage pressure for a multistage compressor or turbine etc). In addition, for given ambient conditions and turbine inlet temperature, the change in the operating parameters (mass flow rate, compressor discharge pressure, compressor discharge temperature, fuel mass flow rate, which is directly related to specific fuel consumption and thermal efficiency, and exhaust gas temperature), when the compressor is fouled, can be directly and accurately evaluated.

3. UNDERSTANDING THE EFFECTS OF MALFUNCTIONS

The advantages of computer models implementation become even more pronounced when operation under abnormal conditions, namely deteriorated engines or engines with faults, are considered. If experience is to be gained by observing actual engines this will have to happen either by (a) studying cases where faults have occurred on an operating gas turbine or (b) by setting up tests in which faults have been artificially introduced.

The understanding of the effects of malfunctions can be achieved through the simulation of component faults. Such faults are simulated by modification of the performance characteristics of the components. The modified characteristics are then introduced into the model and the deviations of cycle or performance parameters are observed. In this way one can, for example, demonstrate very easily the performance drop due to compressor fouling or exhaust gas temperature variations due to turbine nozzle erosion [1].

Map modifications are effected by using scalars, multiplying the component performance parameters. Such scalars have been, for example, introduced in the past under the term ‘‘modification factors’’ MF defined as MF=X/X_{ref}, where X is the current value of a parameter and X_{ref} its value for a component in intact condition [4].

Introduction of malfunctions gives several possibilities for demonstrating their effect on engine parameters. First of all, by performing simulations for healthy and faulty engines the impact of faults can be directly assessed. The important notion of "fault signature" can be very easily introduced, when the above-mentioned possibility exists. Values of measured quantities can be calculated for both healthy and faulty operation and their differences are calculated to provide the signatures. The model used is the one installed in the Hellenic Naval Academy Gas Turbines Virtual Lab and it is equipped with the capability of directly evaluating such a signature, whenever a fault is simulated. This particular application was developed by the National Technical University of Athens/ Laboratory of Thermal Turbomachines in cooperation with the Hellenic Naval Academy/Naval Engines Laboratory and features a powerful, user friendly, functional, training tool which comes up with fast and safe conclusions about engine healthy behaviour and operating trend both in moderate and extreme conditions. The detailed description of the specific capabilities of the Gas Turbines Virtual Lab and its characteristics (performance simulation and monitoring) has already been demonstrated [1, 2].

In this paper special attention is paid on the software diagnostic capabilities.

A layout of the screen related to the GE LM 2500 performance is given in the following Fig. 1.

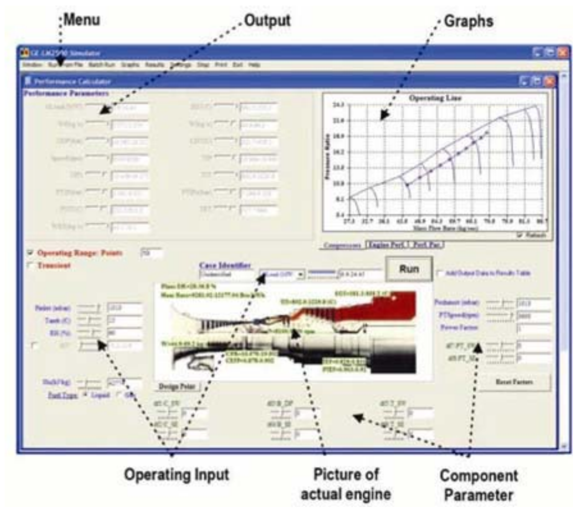

Fig. 1. GE LM 2500 performance layout

4. GAS TURBINE PERFORMANCE AND ASSUMPTIONS

The information provided for the GE LM 2500 is based on engines having clocked 2500 working hours and on PLA actuator (torque motor located on the GT main fuel pump) value of 72. PLA value corresponds to 72 % propulsion plant control levers – engine loading conditions, 2500 RPM power turbine rotating speed and 22 knots vessel's speed. Controlled pitch propeller variations were negligible and the ratio P/D attained a constant value of 1.45 [5, 6].

The following assumptions were made regarding the real gas turbine operation and the software simulation:

4.1. No inlet or exhaust losses

The pressure drop through the inlet air barrier screen is estimated to be about 4 in H20 at maximum flow rate. The maximum total pressure loss is estimated not to exceed 12 in H20 measured at the inlet bell mouth, while the back pressure is estimated to be about 6 in H20 and not to exceed 20 in H20, static pressure, measured at the exhaust extension outlet [5, 6].

4.2. Constant atmospheric pressure

Atmospheric pressure at sea level is considered to be constant getting a default value of 1013 mbars.

4.3. Fuel heating value

The fuel used has a lower heating value (LHV) of 42800 KJ/Kg which refers to F-76 fuel properties, regularly feeding marine gas turbines.

5. RESULTS AND DISCUSSION

A series of runs was performed and the results are compared to the actual values (measurements) available from the practice. To simulate the existence of a malfunction, modification factors with values different from unity are introduced.

In the case study examined in this paper the compressor has ''experienced'' a change in efficiency as a percentage of the reference value, namely -3%, -1%, +1%, +3%.

The influence of the four different efficiency levels on five different parameters is examined, i.e. mass flow rate (W), compressor discharge pressure (CDP), compressor discharge temperature (CDT), fuel mass flow rate (W_f), which is directly related to specific fuel consumption (SFC) and thermal efficiency (η_{th}), and exhaust gas temperature (EGT). Load is the sixth parameter demonstrated in the fault signature, although load assumed to remain constant throughout the entire case study.

In the following fig. 2 the effect of a 3% reduction in the compressor efficiency on the gas turbine performance is presented.

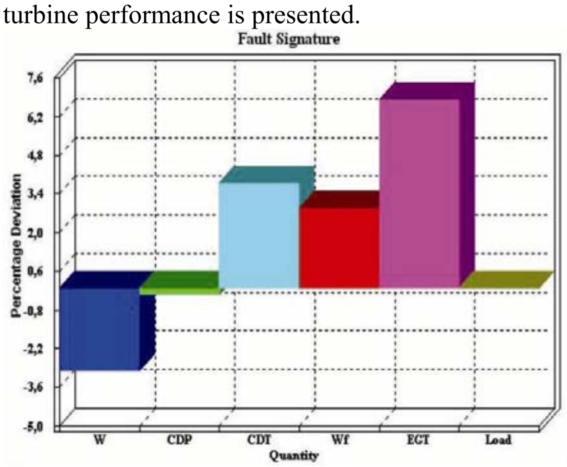

Fig. 2. 97% of the reference compressor efficiency

In the following fig. 3 the effect of a 1% reduction in the compressor efficiency on the gas turbine performance is presented.

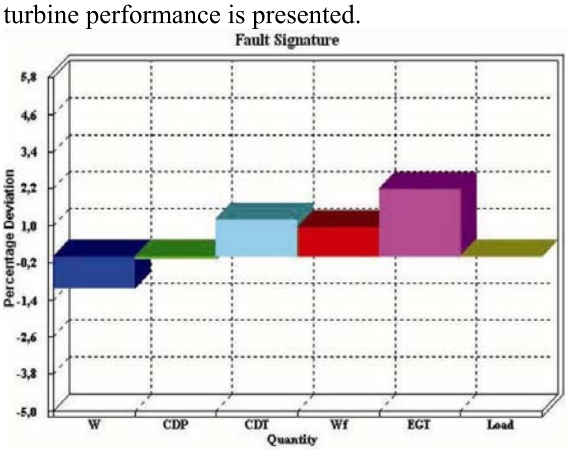

Fig. 3. 99% of the reference compressor efficiency

In the following fig. 4 the effect of a 1% improvement in the compressor efficiency on the gas turbine performance is presented.

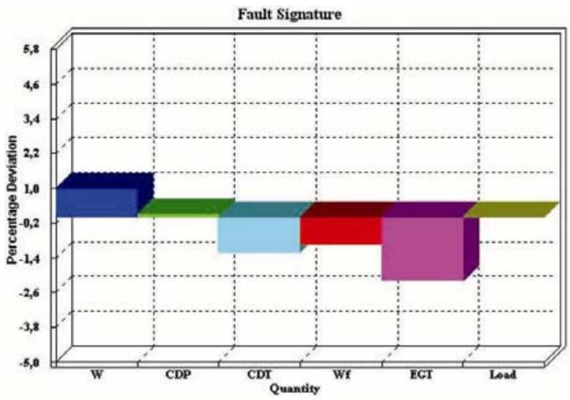

Fig. 4. 101% of the reference compressor efficiency

In the following fig. 5 the effect of a 3% improvement in the compressor efficiency on the gas turbine performance is presented.

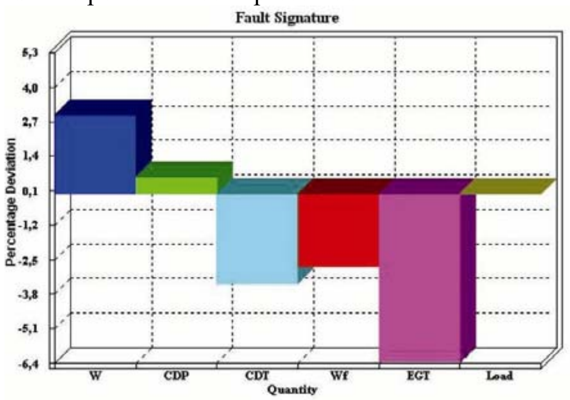

Fig. 5. 103% of the reference compressor efficiency

According to the previous figures when the compressor efficiency changes from 97% to 103% of the reference value, the following results are obtained. Mass flow rate (W) changes from 97% to 103% of the reference value. There is a very slight deviation on the compressor discharge pressure (CDP) related to the reference value. Compressor discharge temperature (CDT) changes from 104% to 96% of the reference value. Fuel mass flow rate (W_f) changes from 103.5% to 96.5% of the reference value. Finally, exhaust gas temperature (EGT) changes from 106.5% to 93.5% of the reference value.

In the following table data from the practice (real gas turbine behavior) and simulation program results (prediction of the virtual gas turbine behavior) are being presented and compared. The error is derived through the following equation:

$$\%error = \frac{calculated\ value - actual\ value}{actual\ value} \times 100$$

The calculated and actual values used for the estimation of the error are related to the specific case when a reduction of 3% on the compressor efficiency is observed.

Table 1. Error between calculated and actual values

OPERATING PARAMETER	ERROR %
Mass flow rate (W)	-1.8
Compressor discharge pressure (CDP)	-2.5
Compressor discharge temperature (CDT)	+3.9
Fuel mass flow rate (W_f)	+2.7
Exhaust gas temperature (EGT)	+4.2

The error obtained shows that the simulation software underestimates W and CDP and overestimates CDT, W_f and EGT.

6. CONCLUSIONS

The Hellenic Naval Academy Gas Turbines Virtual Lab is used in order to act as a malfunction generator and a diagnostic tool. Data from the practice is used in order to evaluate the accuracy of the simulation software calculated values. As a case study the change in the compressor efficiency is considered.

Particular aspects, which can benefit from the use of computer models, have been discussed. Specific simulation software designed and developed for training and – potentially- diagnostic purposes has been used, examined and evaluated. The evaluation results presented a significant accuracy when the software is used as a malfunction generator and diagnostic tool, since the error obtained is less than 4.5% for the parameters chosen to be under observation.

REFERENCES

[1] Mathioudakis, K., Aretakis, N., Kotsiopoulos, P. N., and Yfantis E. A. *A Virtual Laboratory for Education on Gas Turbines Principles and Operation*. ASME Turbo Expo 2006: Power for Land, Sea and Air, GT2006-90357, 8-11 May 2006, Barcelona, Spain.

[2] Mathioudakis, K., Aretakis, N., and Yfantis E. A. *A Possibility for On-Board Training for Marine Gas Turbine Performance, Monitoring and Diagnostics*. *MECON 2006,* 29 August –1 September 2006, Hamburg, Germany. Proc. pp. 128-132.

[3] Technical Manual, *Propulsion Gas Turbine System* 7LM2500-SA-MLG22 (MEKO-G), Operating Instructions, GEK 50500-12.

[4] Stamatis A., Mathioudakis K., Papailiou K. D., 1990a, *Adaptive Simulation of Gas Turbine Performance*. ASME Paper 89-GT-205, 34th ASME TURBO EXPO 1989, June 4-8, Toronto, Canada, also, Journal of Engineering for Gas Turbine and Power, ASME, vol.112, No 2, April 1990, pp.168-175.

[5] *LM 2500-30 Marine Gas Turbine Performance Data*, MID-TD-2500-8, Revised July 1981.

[6] *Training Manual, LM 2500 Marine Gas Turbine*, System Description (29/1/1993).

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ENDOSCOPIC DIAGNOSTICS OF MARINE ENGINES

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Summary

There have been presented within the paper optic (qualitative) and digital (quantitative) methods of endoscoping internal spaces with industrial endoscopes and videoscopes presented within the paper which are applied willingly during a technical shape evaluation of the complex technical objects. They stand for a very effective diagnostic tool and they are very often reached by marine engines operators of both the fleets: naval and merchant. There have been also demonstrated selected metrological techniques that could be applied during diagnostic examination of the working spaces within marine diesel and gas turbine engines. An evolution of contemporary endoscopies as well as theoretical bases of optic and digital endoscopy has been brought forward. There have been also shown the methods enabling measurements of surface defects on the chosen inner parts of marine engines' construction structure. The are based on digital recording of endoscopy imagines: "Stereo Probe", "Shadow probe", laser method as well as RGB method.

Keywords: marine diesel and gas turbine engines, technical diagnostics, industrial endoscopy, measurements methods.

DIAGNOSTYKA ENDOSKOPOWA SILNIKÓW OKRĘTOWYCH

Streszczenie

W artykule przedstawiono optyczne (jakościowe) i cyfrowe (ilościowe) metody wziernikowania przestrzeni wewnętrznych z wykorzystaniem endoskopów i videoskopów przemysłowych, które stanowią bardzo efektywne narzędzie diagnostyczne, po które również coraz częściej sięgają eksploatatorzy silników okrętowych zarówno flot wojennych jak i wielu armatorów cywilnych jednostek pływających. Zaprezentowane zostały wybrane techniki metrologiczne, które mogą znaleźć zastosowanie w diagnostycznych badaniach przestrzeni roboczych okrętowych tłokowych i turbinowych silników spalinowych. Przybliżono ewolucję współczesnych endoskopów oraz podstawy teoretyczne endoskopii optycznej i cyfrowej. Zaprezentowano metody pomiaru defektów powierzchniowych wybranych elementów struktury konstrukcyjnej silników okrętowych, które bazują na cyfrowym zapisie obrazu endoskopowego: metodę „Stereo" („Stereo Probe"), metodę „Cienia" („Shadow Probe"), metodę laserową, metodę RGB.

Słowa kluczowe: okrętowe tłokowe i turbinowe silniki spalinowe, diagnostyka techniczna, endoskopia przemysłowa, metody pomiarowe.

1. INTRODUCTION

The visual investigation of surfaces creating internal spaces of the high - and medium-speed marine engines with use of specialist view-finders so called endoscopes is at present a basic method of technical diagnostics. The superficial structure of constructional material is visible during investigations like through magnifies glass, usually from sure increase, which makes possible the detection, recognition and the possible quantitative opinion of stepping out failures and the material defects, and in result - the opinion of degree of waste and the dirt of studied constructional elements.

In dependence on applied method of observation and the processing of visional painting of studied surface it distinguishes oneself the classic optical endoscopy, from utilization to this aim stiff (lenticular) borescopes and elastic (optical) fiberoscopes as well as the dynamically developing digital endoscopy, with use the more and more perfect videoscopes, equipped with miniature digital cameras at high resolution [6, 10].

2. MEASUREMENT METHODS APPLIED WITHIN DIGITAL ENDOSCOPY

During visual inspection through an optical endoscope of surface restricting internal spaces of engine it often lacks the reference patterns, which can be used for qualification of dimensions of detected defects. The observed dimension is the function of not only the real dimension of the defect, but also a distance between the speculum lens and studied surface. Because the manufacturers of engines pass the admissible values of superficial defects of the most vulnerable constructional elements, the evaluation of real dimensions of defect represents the key diagnostic question. In traditional, optical approach to this question there is applied the comparative method, using with this aim the calibrated measuring profiles put on the ending of fiberoscope's speculum lens - [10]. Additionally, a suitable objective head should be chosen, which will assure, in direction of observation, the optimum angular limitation of field of sight straight on, alternatively - in direction of observation side. In dependence on a distance between the lens and studied surface there is matched such a width of sight field which will make possible maximum increasing the studied surface at being kept on the required depth of sharpness (the expressiveness of painting). Digital endoscopy brings in this regard completely new possibilities. The digital analyzers of painting, co-operating with measuring heads of "Stereo", "Shadow" or "Laser" type, basing on theory of triangulation[1], are able to qualify exactly a distance from the speculum lens to observed surface, and consequently to mark the dimensions of the detected surface defects. The measuring heads give the possibility of digital processing the stereoscopic effects, which enables measuring the seen paintings in such way, to give the quasi three - dimensionality impression - with its depth, the massiveness and the mutual distribution.

2.1. „Stereo" method

The basis of method "Stereo" is the suitable utilization of the prism proprieties splitting the painting, what makes possible for digital camera its registration from two points limited with span of parallactical lenses, similarly to human brain receiving information about the surrounding world from the pair of eyes placed each other in a distance of several centimeters (it is so called an eye optical base making about 65 mm) [3]. Paintings transmitted from parallactical lenses differ each other, and assignment of the high resolution, resultant, digital painting on monitor LCD represents the effect of realization of a computational algorithm. A distance from the lens to the observed surface is marked by counting pixels in horizontal plane of computer's monitor between analogous points of the left and right view of the observed element. The larger distance to the surface is observed the larger distance is between cursors of the left and right view on monitor screen. In the next stage of measurement technology the appropriate measuring technique should be chosen. The following metrological options are well-known for the realization of digital measurement within the "STEREO" method offered by significant manufacturers of endoscopy equipment i.e. OLYMPUS and EVEREST [7, 12, 14]:

- length,
- multisegment length, length broken (circuit),
- distance from point to base straight line
- depth (salience),
- area of surface (the area).

In every metrological option the measurement exactness is defined. When the operator possesses high skillfulness it reaches even 95-98% [12, 14].

2.2. „Shadow" method

Different area for the application of the triangulation theory, in order to mark the dimensions of surface defects takes the "Shadow" method being applied in digital endoscopy. The ending of videoscope's speculum head is equipped with the special optics generating the shadow about characteristic shape (the most often the line of straight line).inside the light stream (like the projector) on surface of the studied element. The projection of the shadow holds at known angle of the speculum head position, in relation to the observed surface and known angle of the observation sector. The shadow generated in the vicinity of detected defect is then located and recorded by camera CCD placed inside an assembly head. The nearer to the observed surface is the speculum head the nearer form the left side of monitor screen is the line of shadow. Because there is well-known the position of shadow generating the painting on the matrix of LCD monitor screen, a magnification of the painting can be simply enumerated. Moreover, the linear dimension of distance among individual pixels, and then the real dimensions of detected surface defects can be evaluated.

Within the "Shadow" method the same measurement options like in "Stereo" method are accessible.

The possibility of taking the immediate decision in case of doubts regarding proper interpretation (unambiguous distinction) of detected surface defects being effective with decrease or accumulation of material is the very essential advantage of the "Shadow" method. Such diagnostic problems step out during the evaluation process of technical state in the working space of combustion engines: piston or turbine.

Often, because of optical and light effects the usual dirt on surfaces of the air and exhaust passages, in figure of mineral settlings or the products of burning the fuel (the carbon deposit), is interpreted as the corrosive or erosive decrement of the constructional material. The depression of surface (its larger distance from the speculum head) is associated with the shadow line breaking and shifting towards the right side of the screen, and its salience (its larger approaching to speculum head) - the shadow line breaking and shifting towards the left side of the screen.

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[1] W. Snellius was the creator of triangulation theory (1615). The measurement method consists in division of the measuring area into adjacent rectangular triangles and marks on the plane the co-ordinates of points by means of utilization of the trigonometrical functions.

The confirmed in investigations of diagnostic shipping engines utilitarian values characterize the method of "Shadow", and also high exactness which, at keeping on required conditions of the measurement, might achieve even 95% [14]. The maximum approach to studied surface of the speculum head represents the most essential factor of high measurement exactness (the line of shadow moves towards the left side as the speculum head gets closer to the surface) as well as maintaining perpendicular to this surface the position of speculum head (the line of shadow runs perpendicularly to the basis of a monitor screen).

2.3. Laser method

Laser method is the youngest measuring technology applied in digital endoscopy. In technical diagnostics two ways of laser rays utilization for the measuring surface defects are well-known. The first one is so called marker (multipoint) laser method, patented by German concern KARL STORZ Gmbh & Co. KG - [13]. The creature of the multipoint measurement is the estimation of distance from the videoscope's speculum head to studied surface (the increase of the real painting) on the basis of a base plane created by at least 3 the best well-fitting (from among 49) laser points of the marker matrix, throwed on the observed element by means of distracting optical arrangement of the measuring probe [10]. The smaller distance is to studied surface the larger is the shift of laser gauges towards left side of the monitor screen. The painting of surface, in the next stage of measurement realization, is recorded (stop-frame), and then by the utilization of triangulation theory of triangulation dimensions of detected defect are marked, in the following options (similarly to measuring systems of OLYMPUS and EVEREST company): the length, depth (the salience), the area, distance from the point to the base straight line.

A scanning method is the second way of application of laser rays to measure surface defects. The method has been patented by Australian company REMOTE VISION SOLUTIONS Pty Ltd [8]. The method is applied by the service groups of Boeing to search surface defects on a airplane hulk.

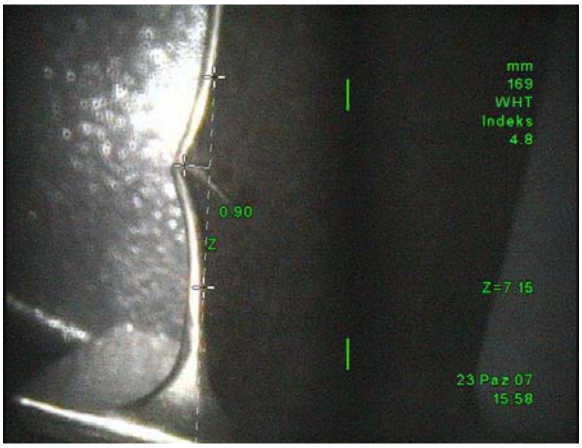
The optical arrangement of laser scanner makes the transformation (the dispersion) of the laser ray in the system of whirling mirrors. Dispersed laser bundle raining on studied surface undergoes reflection, which is directed on assembling lens and measuring detector. The quantity of reflected laser light is dependent on the state of studied surface. If the scanning laser ray shifts over the surface defect an absorption will occur, resulting from the smaller quantity of reflected light. As a consequence, the intensity of reflected light (density of light stream on assembling lens) is smaller than in the case surface being free from defects. The dimension evaluation of detected surface defects is then made on the basis of spectral analysis of distracted laser bundle in computer analyzing programme of the scanner. The usage of cylindrical optics in a laser bundle of the scanner enlarges superbly its application values (the laser ray is distracted into continuous circuit line) giving the possibility of technical state opinion about smaller surfaces e.g. internal spaces of combustion engines, especially intracylindrical spaces of piston engines.

2.4. RGB method

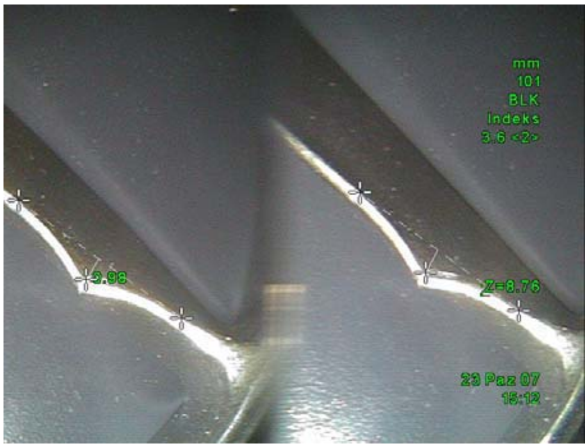
A digital painting recorded in videoscope's computer consists of separate elements, so called pixels. Each of them is specified as a group of value of colours: red, green and blue of the painting component in this point - RGB format. With them suitable confusion can get all different colours. Each of the colour in RGB format characterizes the tint, degree of clearness (or the brightness), the degree of saturation and the cleanness. It worth pointing out in this place that the colour, as a special feature of material objects, optically favoured, is dependent on the objects' physical-chemical structure, the way of absorbing and reflecting the light rays by the observed surface, the character of only light, properties of the air and peculiarity of surroundings (the light reflexes). Taking into consideration characteristic colours a simple spectral analysis of the colour composition reflecting the registered surface of construction element's painting can be carried out and this way its structure might be estimated. Because certain surface defects, as the alterations of physical properties of constructional material, characterize themselves with a definite pattern of colours spectrum it is possible to recognise closely was can for mediation of comparative analysis of ghostly paintings recognize early development stages of the unfavorable structure. The additional diagnostic information can be gathered by the analysis of digital record features on the borders of individual colours: their sharpness, brightness, surface density etc.

Within the range of conducted research works on diagnosing marine diesel engines worked out by the paper author's scientific team, there has been also undertaken trials to implement RGB method for the estimation of carbon deposits (degree of dirt) on the surfaces restricted the combustion chamber of cylindrical sets.

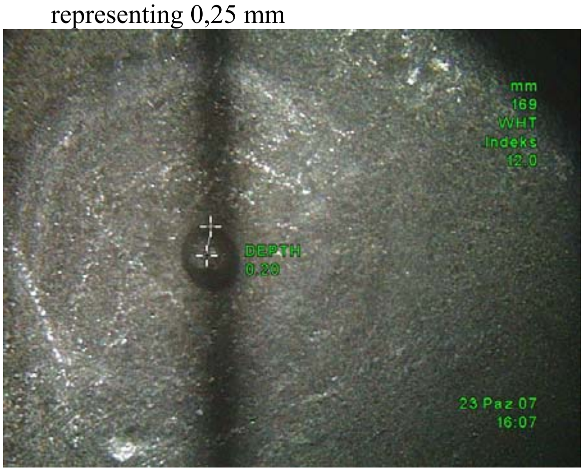
The registered results of routine endoscopic investigations of an engine being in current operation were used in this aim. IPEG format was applied in order to record the pictures. In spite of pilotage character (only) of undertaken investigations, during acquisition there has been paid special attention on keeping constant comparable intensity of lighting incidencing onto observed surfaces of the piston bottom, by making records in the same piston position in relation to Inner Dead Centre (IDC). Because of the character of making estimation (only intensity of the surface dirt) there has been given up full analysis of the colours distribution's intensity, but intensity of



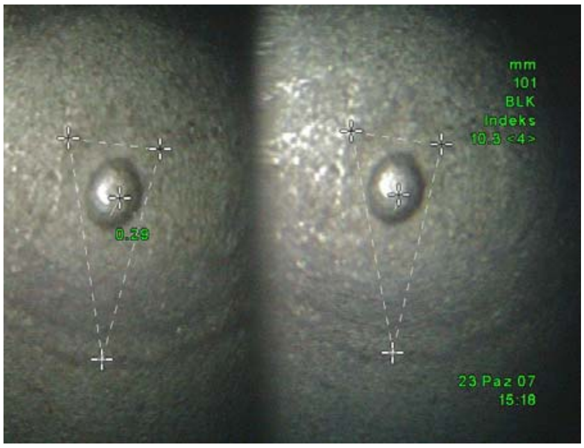
a) Depth measurement of dent on the blade's trailing edge by means of „Shadow" method in the option of "distance from point to base straight line" - 0,90 mm, at measurement accuracy index 4,8, representing 0,25 mm



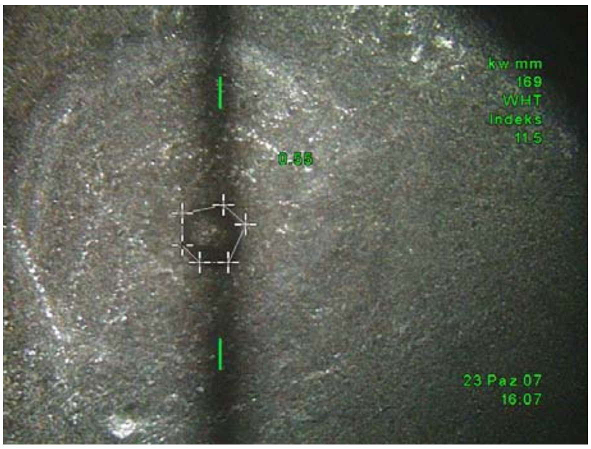
b) Depth measurement of dent on the blade's trailing edge by means of „Stereo" method in the option of distance from point to base straight line - 0,98 mm, at measurement accuracy index 3,6, representing 0,5 mm



c) Convexity measurement of surface „bulge" on the blade-bed by means of „Shadow" method - 0,20 mm, at measurement accuracy index 12,0, representing 0,15 mm



d) Convexity measurement of surface „bulge" on the blade-bed by means of „Stereo" method - 0,29 mm, at measurement accuracy index 10,3, representing 0,1 mm



e) Surface „bulge" area measurement (closed broken line) on the blade-bed by means of „Shadow" method - 0,55 mm^2, at measurement accuracy index 11,5, representing 0,1 mm^2

f) Surface „bulge" area measurement (closed broken line) on the blade-bed by means of „Stereo" method - 0,45 mm^2, at measurement accuracy index 10,8, representing 0,1 mm^2

Fig. 1. The results of measurement of surface defects on blades of naval gas turbine engines with the utilization of "Stereo" and "Shadow" method

greyness tints schedule of monochromatic paintings has been taken into consideration. The introduced method which bases on usable Able of Image the Analyser v3.6 programme analysing the paintings in relation to intensity of pixels occurrence of given colour or the pixels of greyness tints was described in publication in detail [10].

The registered results of performed by the author endoscopic investigations of the naval gas turbine engine's rotor blades are presented in fig. 1. It order to estimate dimensions of detected surface defects "Stereo" and "Shadow" method have been applied as well as "EVEREST" videoscope XL PROTM type has been put into use (thanks to politeness of company representatives in Poland).

3. CONCLUSION

The detecting the material defects in the internal spaces of machines and industrial devices by means of endoscopes utilization represents one of the youngest methods of technical diagnostics, in contrary to medical diagnostics, where it has been acknowledged as the key method of searching pathological states inside human body since ancient times.

Introduced in the article optical (qualitative) and digital (quantitative) method of examining visually internal spaces with the utilization of optical endoscopes and industrial videoscopes are more and more willingly applied method in the evaluation process of technical state of the complex technical objects. They constitute the very effective diagnostic tool and the operators of marine engines (diesel and gas turbine) apply them very willingly in both the fleets: war and merchant. Especially merchant shipowners are very interested in endoscopy application during engines servicing.

LITERATURE

[1] Błachno J., Bogdan M.: *A non-destructive method to assess a degree of overheating of gas turbine blades.* Journal of Polish CIMAC. Diagnosis, Reliability and Safety. Vol. 2 No. 2. 2007.

[2] Breen J., Stellingwerff M.: *Application of optical and digital endoscopy.* Proceedings 2nd EAEA-Conference, Vienna 1995.

[3] Brześcińska W.: *Fotogrametria.* Wydawnictwo Szkolne i Pedagogiczne. Kraków 1998.

[4] Doglietto F., Prevedello D. M., Jane J. A., Han. J., Laws E. R.: *A brief history of endoscopic transsphenoidal surgery - from Philipp Bozzini of the first World Congress of Endoscopic Skull Base Surgery.* Neurosurgery Focus. Vol. 19/2005.

[5] Gardner A. P.: *How to excel in endoscopic photography.* British Journal of Urology. No. 81/1998.

[6] Hlebowicz J.: *Endoskopia przemysłowa.* Biuro Gamma. Warszawa 2000.

[7] *Industrial endoscopy system guide.* Version 2. Oferta OLYMPUS Industrial.

[8] *InspectCam SDMS laser measurement system. Fast and Accurate.* Oferta REMOTE VISION SOLUTIONS Pty Ltd.

[9] Korczewski Z.: *Endoscopic examination of naval gas turbines.* Polish Maritime Research, No. 4/1998, p. 18-21.

[10] Korczewski Z.: *Endoskopia silników okrętowych.* AMW. Gdynia 2008.

[11] Rainer M. E.: *Philipp Bozzini - the father of endoscopy.* Journal of Endourology. No.17/2003.

[12] *Remote visual inspection.* Product guide. Oferta OLYMPUS Industrial.

[13] *Techno pack with multipoint measuring system.* Oferta KARL STORZ - Endoscope. Industrial Group.

[14] *XL PRO videoprobe measurement system.* Oferta EVEREST VIT.

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DECISION MAKING ABOUT AIRCRAFT ENGINE BLADES CONDITION BY USING NEURAL NETWORK AT THE STEADY-STATE AND NON-STEADY-STATE MODES

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Summary

The work is devoted to problem solution of the gas-turbine engines (GTE) blades condition monitoring and diagnosis of the crack-like damages at the steady-state and non-steady-state modes of GTE. It is based on the development of theoretical basis of the vibroacoustical diagnosis methods, the application of the modern signal processing methods and new information technique for decision making. The application of the following signal processing methods: Wavelet-transformation and dimensionless characteristics of the vibroacoustical signals is proved. Neural networks are used for decision making about blades condition by the above mentioned features application. Classification of turbine blade condition was carried out using a two-layer Probability Neural Network (PNN).

Keywords: blade, crack-like damages, vibroacoustical condition monitoring, neural networks.

INTRODUCTION

The problem of prolongation of aircraft turbine engine working life and increasing their reliability is the issue of the day. This problem may be solved using improved existing and new methods and diagnostic instruments. Despite the fact that the progress in development of existing methods and instruments is considerable, the problem of functional diagnostics of fatigue defects in compressor and turbines blades of an aircraft engine is not solved yet. We propose to solve this problem by using the vibration and vibroacoustical diagnostic methods [1]. Since the most fatigue defects of the GTE rotor components directly connect with vibration processes which take place in operating engine. On the other hand, vibration and vibroacoustical methods provide the possibility to diagnose and non-destructively evaluate defects without disassembling the engine. It may be done using advances in computer-based technology and information handling methods for recognition of the rotor component condition in the operating engine. Creation of the monitoring system is based on application and further development of low-frequency vibroacoustical diagnostic methods which use vibrating and acoustical noise as diagnostic information.

1. PROBLEM STATEMENT

Generally monitoring is a continuous process of information gaining about the object vibrating condition, transformation and analysis of it, and making decision about object technical condition. The stages of the mentioned informative process depend on the engine operation modes. These modes define specific character of vibrating and acoustical excitation of the compressor and turbine blades, and consequently, they define the methods and algorithms of signal processing which must be chosen or developed.

Initiation and increase of a fatigue crack in the blade lead the instantaneous change of its stiffness. Usually the change of stiffness is modeled by the piecewise-linear characteristic of the restoring force [1, 2]. Non-linearity leads to variation of oscillation parameters and to occurrence of local non-stationary component in the measured signal.

The dynamic model of gas-turbine engine as an object for fatigue cracks diagnostics in turbine blades and compressors was created. This model is used for simulation and analysis of vibroacoustical processes which occur at the steady-state and non-steady-state modes of GTE at absence and presence of small fatigue cracks in one blade of the turbine stage (the relative rigidity changing at the crack presence is considered ϑ=0,03;0,05). The three modes of GTE are simulated and investigated: m1 - steady-state (constant value of the rotor rotation frequency); m2 - non-steady-state (the fast increase of the rotor rotation frequency); m3 - non-steady-state (the decrease of the rotor rotation frequency).

Simulated signals were processed using Wavelet-transformation and amplitude dimensionless characteristics of the vibroacoustical signals. The preliminary Wavelet decomposition of signals is used for the sensitivity increasing of the amplitude dimensionless characteristics of the vibroacoustical signals as fault features [3]. The following amplitude dimensionless characteristics are used: J_3 - peak factor and J_4 - factor of background. Thus, the fault features are detected and the following feature vectors are formed: $\vec{X}_{mi} = (J_3^{(mi)}; J_4^{(mi)})$, $i = \overline{1,3}$.

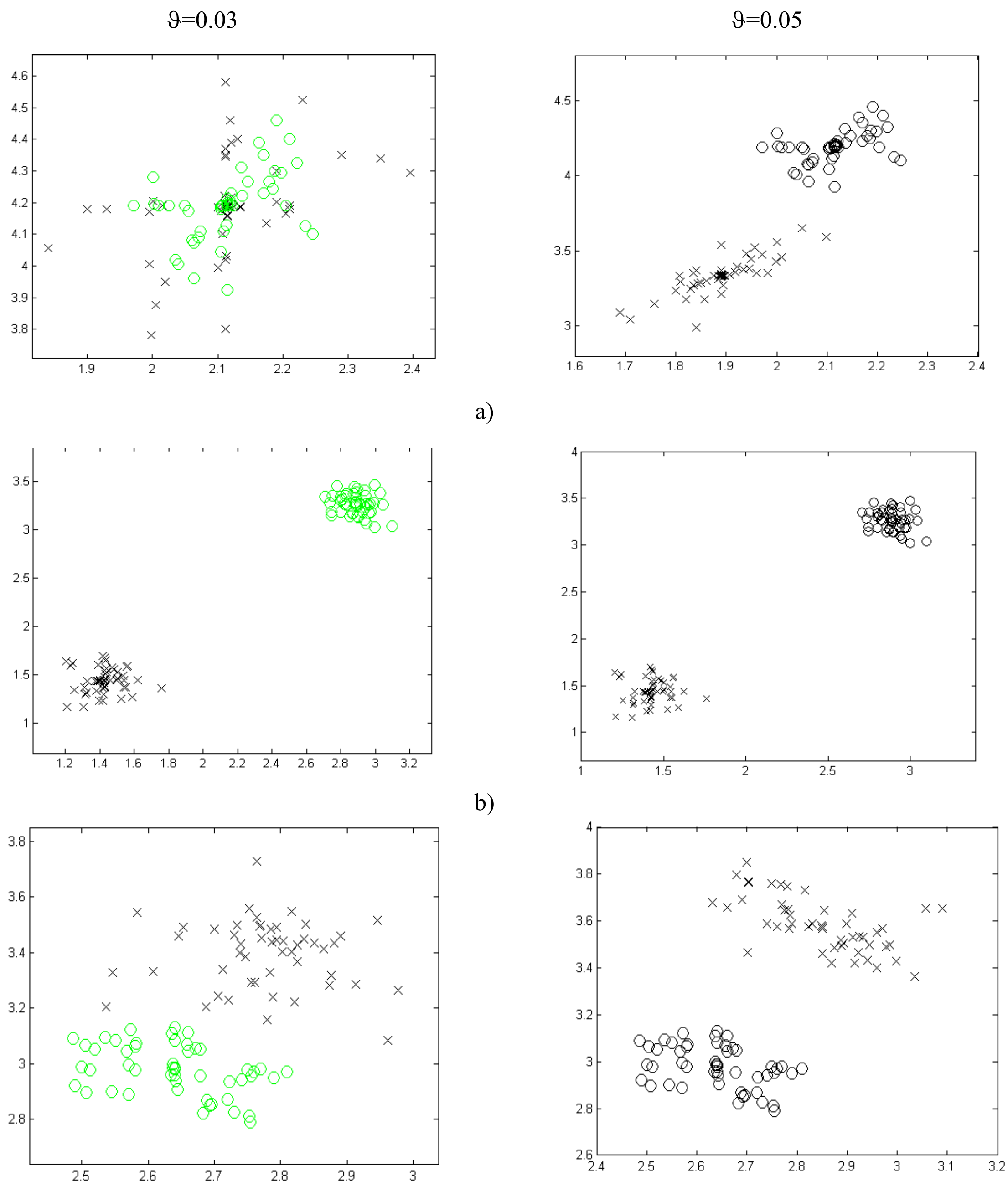


Fig. 1. The learning sets of the feature vectors for the three modes of GTE: a) m1, b) m2 and c) m3 (o – without damage S_0, x – with damage S_1).

The mentioned vectors are used for the decision making about blades condition: the absence (S_0) or the presence (S_1) crack-like damage.

By using the feature vectors the learning and test sets are received for the above mentioned three modes of GTE: m1, m2 and m3. The learning sets are shown in Fig. 1 for the relative rigidity changing at the crack presence ϑ=0.03 and ϑ=0.05. Axes indicate the peak factor and factor of background.

As it can be seen from a given plot, the linear division into blades conditions S_0 and S_1 occurs for the learning sets only at the m2 mode for both cases ϑ=0.03 and ϑ=0.05, but at the m1and m3 – only for ϑ=0.05.

The aim of this work is efficiency analysis recognition of aircraft engine blades condition at the steady-state and non-steady-state modes of GTE by using neural networks.

2. RECOGNITION OF BLADES CONDITION

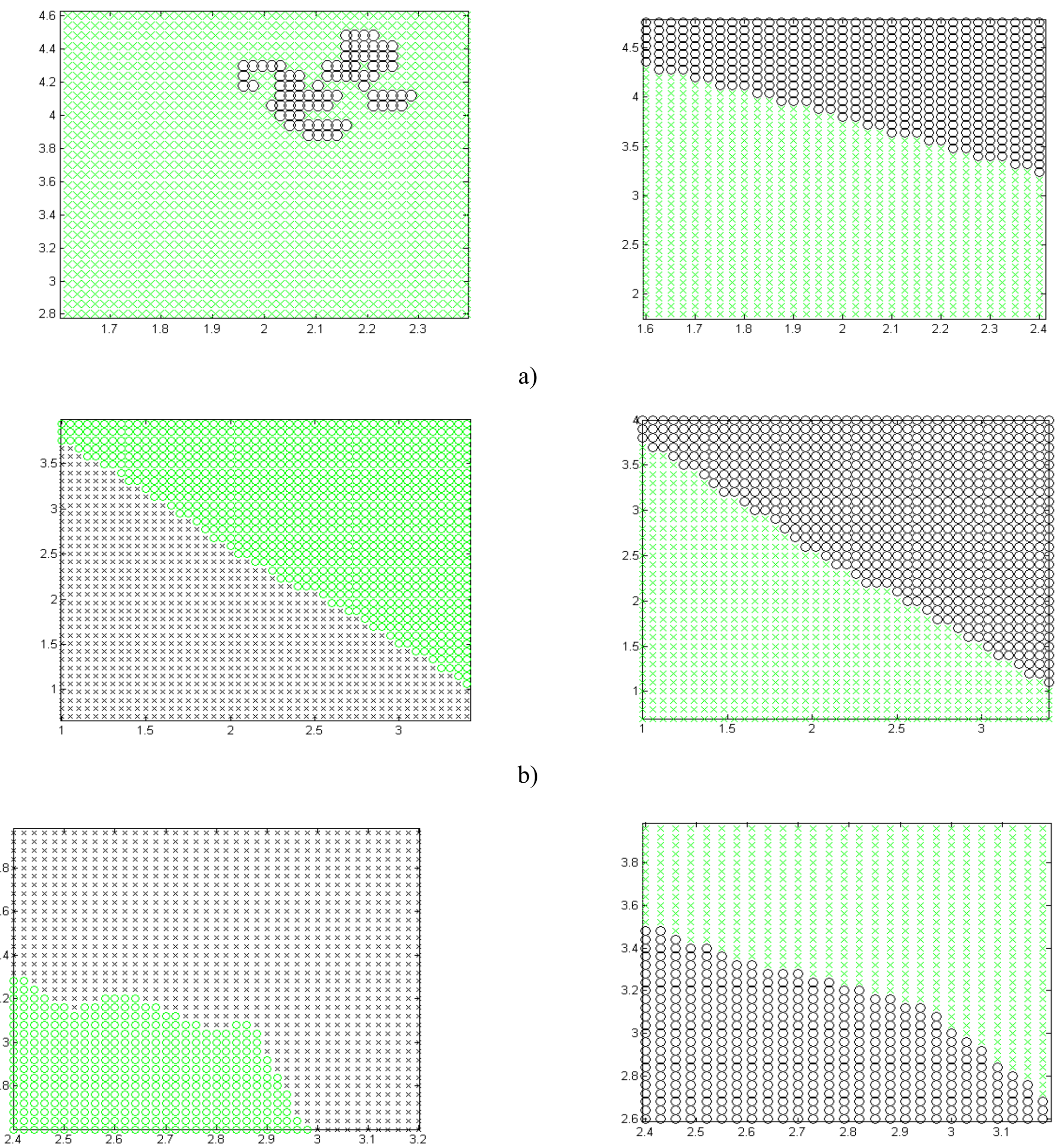
Classification of turbine blade condition was carried out using a two-layer Probability Neural Network (PNN) [4]. The first layer consists of 100 neurons. As a second layer it is used the so called competitive layer from 2 neurons. These neurons determine correct solution probability - the input vector belongs to a faulty type or not. Such classification is based on Bayes methods and needs probability density estimate for a condition type. For that, set of learning vectors are used. Every vector is described by Gauss function with a center in the point corresponding to this vector. The sum of named functions according to the whole available set of learning vectors is equal to probability density of input vectors for each condition types. The value of the Gauss function mean-square deviation σ specifies the width of the neurons activation function and defines their influence on a probability density estimate sum. This implies that the parameter σ influences on the classification result, therefore its value is determined mostly experimentally.

The results of classification are shown in Fig. 2 for the relative rigidity changing at the crack presence ϑ=0,03 and ϑ=0,05.

The effectiveness of turbine blades condition classification by PNN was judged by the coefficient K (this coefficient is a value of correct classification probability). Relationships between the coefficient K and the influence parameter σ for test sets of the feature vectors is shown in Fig. 3. As it can be seen from a given plots, PNN recognizes the blades condition with the following minimum values of the correct classification probability:

- m1 (steady-state mode) – K=0.93 for ϑ=0.05 at the σ=0.1 (recognition for ϑ=0.03 is not correct – K=0.3);

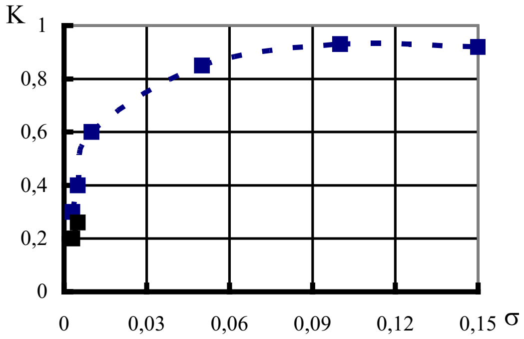
ϑ=0.03 ϑ=0.05



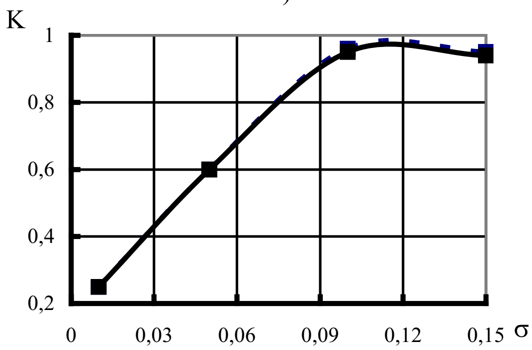
c)

Fig. 2. The results of classification for three modes of GTE: a) m1, b) m2 and c) m3 (o – without damage S_0, x – with damage S_1).

- m2 (non-steady-state mode) – K=0.96 for both cases ϑ=0.03 and ϑ=0.05 at the σ=0.1,…0.12;
- m3 (non-steady-state mode) – K=0.94 for both cases ϑ=0.03 and ϑ=0.05 at the σ=0.1.



a)



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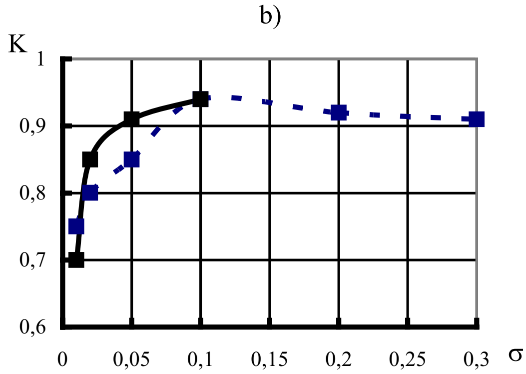

c)

Fig. 3. Dependencies of correct recognition probability on the influence parameter σ of a neural network for three modes of GTE: a) m1, b) m2 and c) m3 (continuous lines – ϑ=0.05, dotted lines – ϑ=0.03).

So, in spite of diagnostic features irregularity and little changes at turbine blade condition changing from defectless to faulty one, PNN provides classification of diagnostic object condition with the high values of the correct classification probability at the steady-state and non-steady-state modes of GTE.

CONCLUSION

1. Simulation and analysis of vibroacoustical signals radiated at steady-state and non-steady-state modes by an engine rotor with defectless and cracked blades allow to form the learning and test sets of the feature vectors.
2. Application of a Probability Neural Network provides turbine blades condition classification using the peak factor and factor of background of the results of Wavelet Decomposition of vibroacoustical signals with the high values of the correct classification probability at the steady-state and non-steady-state modes of GTE.
3. Received results are new and justify efficiency of turbine blades condition recognition at the presence of small crack-like damages. These results can be used to create a vibroacoustical monitoring system for aircraft engine rotor components.

REFERENCES

1 Bouraou N. I., Marchuk P. I., Tyapchenko A. N.: *Condition Monitoring Diagnosis Method of Aircraft Engine Rotating Details*, in Proceedings of the 15th World Conference on Non-Destructive Testing, 11pp.
2 Wong C. W., Zhang W. S., Lau S. L.: *Periodic forced vibration of unsymmetrical piecewise-linear systems by incremental harmonic balance method*. J. of Sound and Vibration, p.91-105.
3 Bouraou N., Sopilka Yu., Protasov A.: *The features Detection of the small rigidity faults of rotary machine elements*. In Review of Progress in QNDE, p.152.
4 Sankar K. Pal. and Sushmita M.: *IEEE Transaction on Neural Networks*, 3, #5, 683-696 (1992).

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DIGITAL CINEMA DIAGNOSTIC SYSTEM BASED ON SPECTRAL ANALYSIS AND ARTIFICIAL INTELLIGENCE METHODS

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Summary

In this paper digital cinema diagnostic complex is described. Its working algorithms are based on wavelet preprocessing, statistic analysis and neural network classification. Considered methods were practically incarnated using modern systems of computer modeling.

Keywords: diagnostics, digital cinema, wavelets, artificial intelligence.

Modern system of digital screening and film production demands modern approach not only from the point of view of equipment developing and designing, but also from diagnostic one. Being a complicated, self-optimizing system, digital cinema complex should be observed as a segment of informational networks, in case of diagnostic view, and imply an estimation of big amount of various parameters.

Such systems consist of number of simple parts, connected to each other. This condition makes difficulties for usage of ordinary automated systems of diagnostic and quality control. The most complicated are description of allowable working rate for hardware parts.

Diagnostic signals are complex-structured and generally transient:

$$s(n) = S(n) + \sigma_1 e_1(n) + \sigma_2 e_2(n) \qquad (1)$$

where *s(n)* – measured signal, *S(n)* – normal functioning signal, $e_1(n)$ - noise, $e_2(n)$ - distortions due to systems defects, σ_1 and σ_2 - distortion levels, *n* – discrete or continuous variable.

Wavelet analysis possesses an ability of time-frequency localization of signals distortion. That is why it is most preferable basis for diagnostic problems solution. For our purposes, the most informative components of signal are the noise ones - $e_1(n)$ and $e_2(n)$, since they carry an original imprint of system, which makes diagnostics possible (figure 1).

The solution of diagnostic task for noise characteristics is rather complicated, because of number of problems supposed to be solved. One of the most important problem is noise separation. It should be divided to local components and background. For each of these two components special analysis and thresholding methods are used. Statistic and spectral analyses of noise components should be performed, including threshold function type, wavelet basis and decomposition level selection.

Wavelet analysis is based on representation

$$s(n) = \sum_k A_k \psi_k(n) \qquad (2)$$

where $\psi_k(n)$ - basis functions, A_k - decomposition coefficients.

Due to its time-frequency localization, wavelets allow to analyze the non-regular signal structure. Time localization implies that wavelet's energy is concentrated in some finite time interval. Frequency localization means compactness of wavelet's Fourier-form, in other words it means its energy localized inside of finite frequency interval. Wavelets could be constructed from mother wavelet function $\psi_k(n)$ by translation $\psi_k(n) \to \psi_k(n-b)$ and dilatation $\psi_k(n) \to \psi_k(\frac{n-b}{a})$, where parameter *b* called transition and *a* – scale. Wavelet transform in its discrete version uses *a* and *b* with steps divisible by 2:

$a = 2^m, b = k2^m$, $k, m \in Z$.

Thus, wavelet function could be represented like

$$\psi_{m,k}(n) = a_0^{\frac{m}{2}} \psi(a_0^m n - k) \qquad (3)$$

where $a_0 > 1$ (here we take $a_0 = 2$).

Spectral transform coefficients $A(m,k)$ are defined as convolution of signal $s(n)$ and wavelet $\psi_{m,k}$. Farther, in the course of getting diagnostic information from object, there comes a necessity of incoming data clustering to classes depending on object's characteristics.

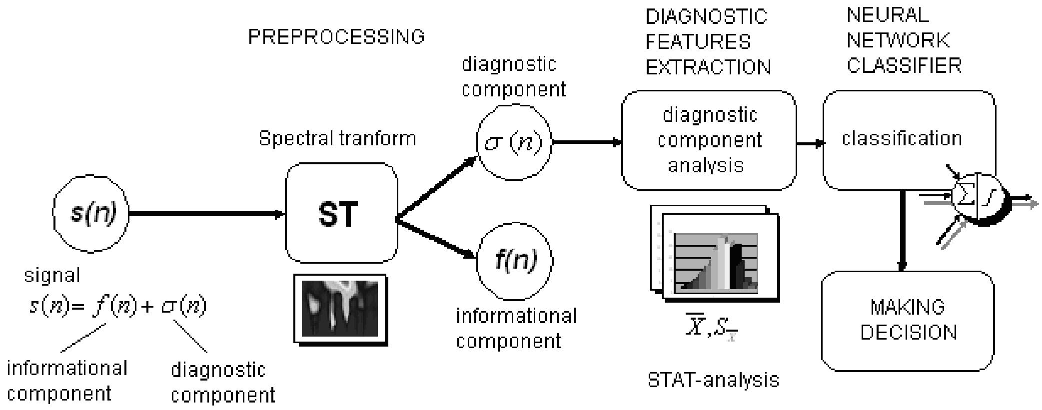

Fig. 1. Diagnostic algorithm

Clustering is performed using neural network algorithms. The present state of neuron is calculated like

$$g(A)=G_i^T A \qquad (4)$$

where $G^T=(G_1,G_2,...,G_n)$ - weight array, T-transposition.

Array A is formed from coefficients $A(m,k)$ for fixed frequency ranges $\omega_1,\omega_2,...,\omega_n$. For components $e_1(n)$ and $e_2(n)$ to be extracted according to [1], the present state of neuron is calculated like

$$g(A)=G_i^T f(A) \qquad (5)$$

where $G^T=(G_1,G_2,...,G_n)$ - weight array, $f(A)$ - array function.

Let us observe an example of $f(A)$ calculation. Informational signal's spectrum could be presented by array $A_m^T=(A_{m1},A_{m2},...,A_{mn})$. Now, we have to transform array's components [2, 3]:

$$f_{mi}(A_{mi})=\frac{A_{mi}}{2}[\ \mathrm{sgn}(A_{mi}-\Delta_{ki})+1\ ] \qquad (6)$$

i=1,2,...,n;

$$\mathrm{sgn}\,x=\begin{cases}1, x>0;\\ -1, x\le 0,\end{cases}$$

where Δ_{ki} - threshold value for i frequency;,

$\Delta_{ki}=k\Delta_i$, $k=1,2,...$

Diagnosed parameters $\boldsymbol{r}$ define the values of spectral coefficients (4). Among them, received during statistic or fuzzy analysis of coefficients (4), let us select such frequency ranges $\omega_1,\omega_2,...,\omega_n$ which coefficients A_{mi} are monotonous functions of $\boldsymbol{r}$. Threshold value Δ_i should be considered as function of i, that is $\Delta_i=\varphi(\Delta,i)$, where Δ - modified parameter.

Frequency-dependent threshold Δ leading is necessarily for excluding of resonance influence to informational signal's analysis while mechanics diagnostic. In case of sound and video processing it allows to exclude non-informational components.

Function $g(A)$ depends on threshold value Δ and diagnosed parameter $\boldsymbol{r}$:

$$g(A)=\sum_i G_i\left\{\frac{A_{mi}}{2}\mathrm{sgn}\left(A_{mi}(r)-\varphi\left(\Delta,i\right)\right)+1\right\}. \qquad (3)$$

For classification of diagnostic data Probabilistic Neural Network (PNN) is used. It has a structure based on radial base network architecture. PNN structure [1] for MATLAB modeling is shown on figure 2.

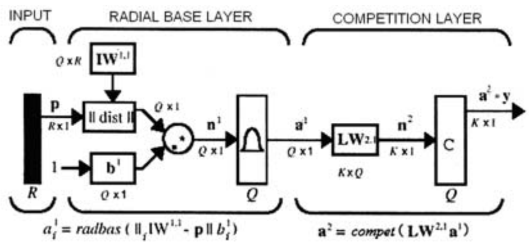

Fig. 2. PNN structure [1].

Let us observe the PNN working algorithm [1]. Let the learning multitude is defined and consists of Q pairs of input arrays. Each array consists of K elements, which are related to some class. Thus, we get matrix T with dimension K x Q, its rows correspond to classes and columns do to input arrays. First layer weight matrix $IW^{1,1}$ is formed from input arrays, taken from learning multitude (matrix P'). If new array multitude is entered, the ‖dist‖ block calculates proximity of new array to existed ones. Then, proximities are multiplied by deviations and got to activation function input (*radbas*). The nearest learning multitude array to input one will be presented in output array a^1 by number close to 1.

Matrix $LW^{2,1}$ (second layer weight matrix) corresponds to matrix T (current learning multitude tie-up matrix). By multiplication T and a^1, correspond elements of array a^1 will be defined. Thus, function *compet* (competition activation function of second layer) forms 1 if largest value of array n^2 and 0 otherwise. So, reviewed network solves problem of input arrays classification by K classes.

Considered model could be incarnated as *LabView* virtual instrument (VI for short). For this purpose *Advanced Signal Processing Toolkit* is used. It has wide collection of different means of wavelet transform. For example, let us observe the part of diagnostic complex, responsible for noise estimation. On fig. 3 and 4 front panel and block diagram of program are shown.

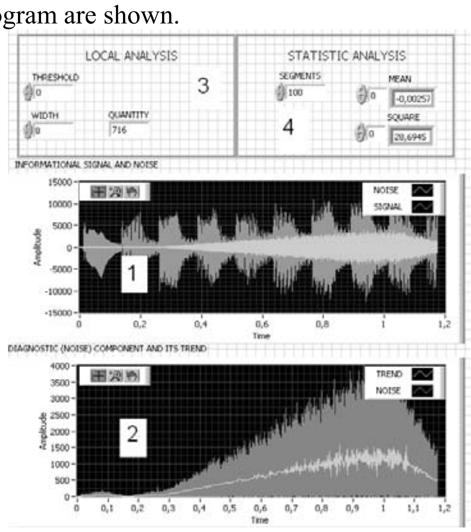

Fig. 3. Front panel of virtual instrument

Assignment of front panel elements:

1. Oscillogram of informational signal and noise component, extracted during wavelet preprocessing
2. Oscillogram of noise (diagnostic) component and noise trend detected
3. Local analysis results (quantity of peaks of certain width in signal)
4. Statistic analysis results (quantity of segments, mean, square values)

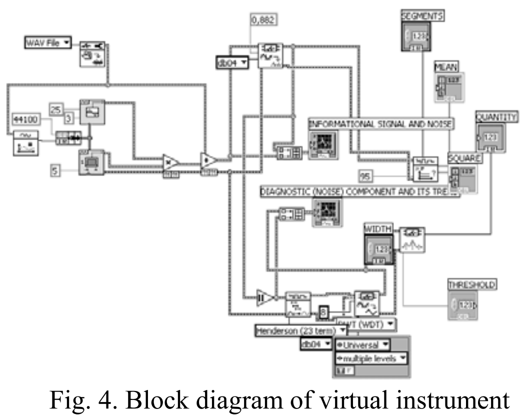

Fig. 4. Block diagram of virtual instrument

Program is based on following VIs - *WA Read From File.vi, WA Detrend.vi, WA Denoise.vi, TSA Stationarity Test.vi.*

In present version, data should be contained in wav file, although *LabView* supports other formats like AIFF, TXT, BMP, JPEG. It should be clear that analysis of 1D signals (vibration, sound) would be performed separately from 2D signal one (pictures) because of wavelet analysis algorithm differences, but in some cases it is useful to estimate distortion correlation between vibrations, sound and picture in the same moments of time. So, on the technologic point, to perform a diagnostic procedure, one just have to start *LabView* and choose some options. If to work with recorded data only, considered version of diagnostic instrument is enough, without supplementary hardware needed to gather information.

REFERENCES

[1] Medvedev V. S., Potemkin V. G.: *Neironnie seti. MATLAB 6*. – M.: DIALOG-MIFI, 2002. 496 p.

[2] Yavlensky K. N., Yavlensky A. K.: *Vibrodiagnostika i prognozirovanie katschestva mekhanitscheskih sistem*. – L.: Mashinostroenie, 1983. – 239 p.

[3] Yavlensky A. K. (with others): *Mekhanitsheskie sistemi vakuumno-kosmitscheskih robotov i manipulyatorov*: T.2 – Tomsk: MGP "RASKO", 1998. – 378 p.

FEATURES OF ALGORITHMS OF DIAGNOSING AND MAINTENANCE OF RELIABILITY OF HYDRAULIC DRIVES OF MACHINES

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Summary

The paper discusses the possibilities of applying some algorithms of diagnosing and maintenance of reliability of hydraulic drives of machines. Some typical algorithms of diagnosing are considered. The conceptual positions of structural maintenance of reliability of hydraulic drives have been proposed.

Keywords: technical diagnosing, reliability, hydraulic drive.

1. INTRODUCTION

One of the basic functions of the test system of a hydraulic drive is the establishment of conformity of its technical condition to normative requirements. The properties of hydraulic systems, defining their technical condition, are subject to the certain changes while in service machines.
Experience is confirmed, that with a significant part of technogenic failures are tie up with the mistakes admitted at designing and operation of machines, and that the price of such mistakes is exclusively great [1]. Therefore it is necessary to pay the big attention to working off of algorithms of technical diagnosing of hydraulic systems, increase of their efficiency and reliability.

2. FEATURES OF TECHNICAL DIAGNOSING OF HYDRAULIC DRIVES

For machines that are complex, power-intensive and potentially dangerous to the person, environment and economy of technical devices especially important requirement is maintenance of trouble-free operation. Admissible values of parameters and attributes, preemergency and emergency conditions of system are defined with the obligatory account of features inherent in actually hydraulic systems. First of all is a centralization of functions and the mass distribution of influences which are carried out by a uniform working body (liquid).

Depth of troubleshooting and reliability of results of diagnosing define a degree of safe operation of the machine, and also reliability of the forecast of the technical condition of the system during the future moments of time.

While in service hydraulic drives of machines the complex of methods of diagnosing (fig. 1) is applied.

At functional diagnosing of the condition of a hydraulic drive is defined by results of the current control of parameters (constructive, regime, operational, etc.)

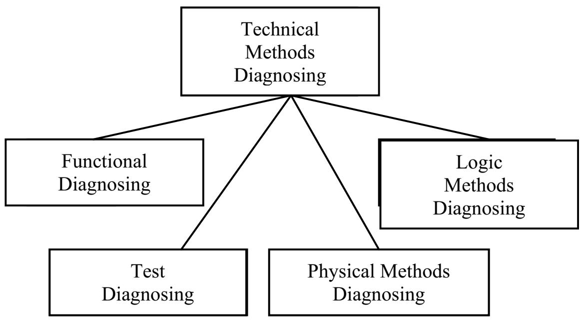

Fig. 1. Methods of technical diagnosing

The basic lacks of the specified methods are increased requirements to a memory size of the monitoring system of parameters and low efficiency of such systems. Especially it concerns to cases of the control of realization of signals or their statistical characteristics for all conditions of functioning.

3. REQUIREMENTS TO ALGORITHMS OF DETECTION OF MALFUNCTIONS

Maintenance service of hydraulic systems of machines demands participation of highly skilled experts on which arms there are the modern precision diagnostic devices having an output on a computer, allowing to define methods of elimination of malfunctions and maintenance of reliability of diagnosed devices. Such method of diagnostics is modern, but, unfortunately, yet has not received enough wide circulation basically for the reason that in operation often there are machines manufactured long time ago and not equipped by such complex diagnostic systems. However even in this case at presence of the skilled expert it is possible to define quickly enough and authentically the reasons of malfunction of hydraulic system, using a so-called logic method [2].

All malfunctions of the hydraulic system can be divided into two greater groups:

- The malfunctions which at present are not influencing functioning of the machine (the outflow, the raised noise, the raised temperature, etc.);
- Functional malfunctions (jamming, decline of productivity, ignitions, etc.);

Searching of malfunctions is carried out by different algorithms. Experience of the experts and their practical skills, as well as common sense, thus have crucial importance. The operational documentation, as a rule, contains a lot of the valuable information on background of the arisen problem (whether there were earlier the similar malfunctions, what works were spent on maintenance service and adjustment of those or other units and systems). The logical analysis of such information allows to save a lot of time at diagnosing and prevents failures in due time.

Revealing the elementary malfunctions of type of outflow, foaming or overheat of the working liquid, insufficient speed of the agencies, the raised noise in separate devices, etc. by means of sense organs and on the basis of experience allows to avoid excessive complications of test systems. It promotes increase of their own reliability and certain concentration of functionalities on search and the analysis of more complex malfunctions.

Experience of diagnosing and good knowledge of the device of hydraulic system allow to define the priority procedure for test of units. If at once at preliminary check the faulty unit is not found, spend deeper check of each unit by means of special control devices and stands.

After finding of the faulty unit the reasons and possible consequences of malfunction (clearing or replacement of a working liquid, adjustment of safety and conditioning devices, etc.) are defined and eliminated.

Algorithms of preliminary logic diagnosing of hydraulic systems usually include a number of consecutive checks of conformity of marks and installations of units, correctness of their adjustments and signals of management [2].

With the purpose of increasing of efficiency of built-in diagnosing systems of mobile machines base diagnostic models and schemes (base algorithms) automatically in search of possible malfunctions of hydraulic drives [3] are developed. Thus in schemes of recognition transients in hydraulic system are considered.

Adequate work of system of diagnosing is possible only under condition of the coordination of character and parameters of transients in a hydraulic drive with parameters of the measuring equipment.

For formation of a diagnostic model of the hydraulic drive the special technique in which basis the analysis of the basic scheme of a hydraulic drive and an establishment of communications between elements is put is offered. Synthesis of the general algorithm of search of malfunctions is carried out by means of connection of base algorithms according to graphic model. If necessary the algorithm can be supplemented with heuristic algorithms of search of the possible defects caused by features of connection of elements in a uniform system (structure of the system).

The mathematical model is developed for the formalized modeling hydraulic drives of any structure in an automatic mode

$$\begin{cases} \dfrac{d^2x_i}{dt^2} = \dfrac{1}{A1_i}[p_{i-1} - p_i - (A2_i + B2_i)\left(\dfrac{dx_i}{dt}\right)^2 \operatorname{sgn}\dfrac{dx_i}{dt} - \\ \qquad\qquad - A3_i\dfrac{dx_i}{dt}], \ i = 1...NU, \ i \neq i_c; \\ \dfrac{d^2x_i}{dt^2} = \dfrac{1}{A1_i}[p_{i-1} - \chi p_i - \dfrac{P_z + P_0 + P_T}{f_i} - \\ \qquad -(A2_i + B2_i)\left(\dfrac{dx_i}{dt}\right)^2 \operatorname{sgn}\dfrac{dx_i}{dt} - A3_i\dfrac{dx_i}{dt}], \ i = i_c; \\ \dfrac{dp_i}{dt} = \dfrac{E_{a0} + a_p p_i}{V_i}\left(f_i\dfrac{dx_i}{dt} - f_{i+1}\dfrac{dx_{i+1}}{dt}\right), \ i = 1...NU, \ i \neq i_p; \\ \dfrac{dp_i}{dt} = \dfrac{E_{a0} + a_p p_i}{V_i}\left(f_i\dfrac{dx_i}{dt} - f_{i+1}\dfrac{dx_{i+1}}{dt} - f_{i+k}\dfrac{dx_{i+k}}{dt}\right), \ i = i_p. \end{cases}$$

Here: NU – quantity of sites; i – number of a site; p_i – pressure; x_i – moving; V_i – volume of a liquid on *i-th* site; E_a – the module of elasticity of a liquid; a_{PA} – the factor considering influence of pressure on E_a; f_i – the area of section *i-th* site; P_T – force of friction; P_0, P_Z – constant and item loadings; i_c – a site with the hydraulic cylinder; $i_{p.}$ – unit of a branching; $A1_i$, $A2_i$, $A3_i$, $B2_i$ – the factors considering various kinds of losses of pressure.

Adequacy of the mathematical model and algorithm is confirmed by computer experiment. In fig. 2 results of dynamic calculation of a brake drive and a drive of the elevating mechanism of the car-dumper are presented.

Transients at functioning hydraulic drives are speedy and are accompanied by high-frequency pulsations of pressure and significant control over, and instant value of pressure exceeds a threshold of adjustment of a safety valve. If not to consider dynamics of internal processes in a hydraulic drive it can lead to the false conclusion about a technical condition of a hydraulic drive. Not to admit possible wrong of diagnoses, transfer of characteristics of quality of transient to the system of automatic search of defects for updating of actions in case of discrepancy of entrance and target signals is stipulated.

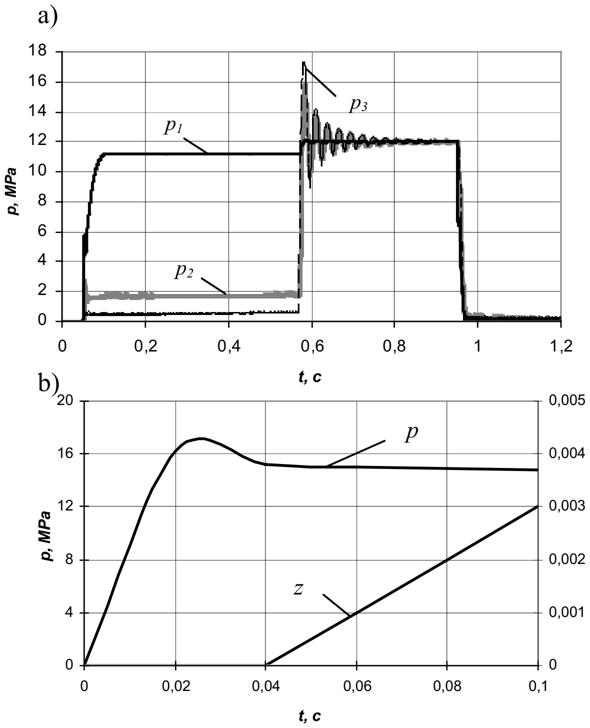

Fig. 2. Results of dynamic calculation:
a – a brake drive (p_1,p_2,p_3 – pressure accordingly on input of a contour, in a branching and in the actuating cylinders),b – the elevating mechanism (p – pressure ,z–moving platforms, t– time).

4. DIAGNOSING AND MAINTENANCE OF RELIABILITY OF HYDRAULIC DRIVES

Diagnosing of a hydraulic drive assumes obligatory check of conformity of pressure and of liquid consumption to demanded values for corresponding modes. Thus adjusting installations of units of system, streams of a working liquid through a safety valve and drainage system, and also vacuum an input of the pump are supervised.

Well-known, that results of diagnosing, the information received at this stage, should be used in the further for maintenance of working capacity and reliability of the system of the hydraulic drive. Experience has shown, that traditional use of progressive technological processes and high-quality materials by manufacturing the hydraulic devices, already given a new push to development in this area, has allowed at the same time to reveal the certain restrictions which cannot be overcome by only one improvement of technology and material resources. Prospects of overcoming of difficulties and the further development of hydraulic drives of machines are connected with the application of new approaches of structural maintenance of their reliability.

Structural maintenance of reliability of hydraulic drives of machines is carried out due to purposeful development or change of the block diagram of a hydraulic drive at a stage of its designing [4]. Its basic essence says that, so-called subsystems of maintenance of reliability, entered into structure of a hydraulic drive, carry out active influence on the parameters defining reliability.

The protection devices warning of possible failures are known. More often they switch off the system before elimination of the reasons of possible refusals. Such a way is the most comprehensive at operation concerning simple systems.

Generally management of the processes defining reliability of a hydraulic drive of machines and their elements can be realized on principles of indemnification of indignations or deviations of the parameters defining reliability. For such management it is necessary to have an opportunity of registration of deviations, the nobility of the characteristic of indignations and to compensate them (fig. 3).

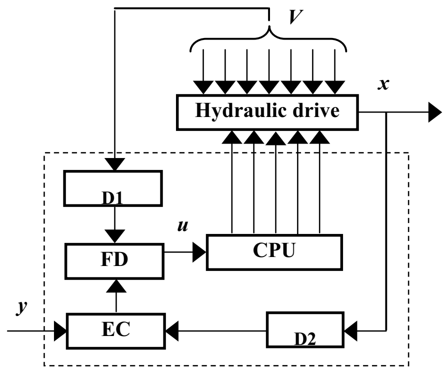

Fig. 3. The scheme of management of the processes defining reliability of a hydraulic drive

Indignations *V* influencing on a hydraulic drive are registered by sensitive element D_1 and act in formation device *FD.* The signal of a mismatch from an element of comparison *EC,* formed as a result of comparison of a deviation of adjustable size *x* (it is registered by sensitive element D_2) and the set coordinate *y* also come in FD. In *FD* operating influence *u*, getting in a power drive of control system *CPU* is developed. According to the acted signals the drive of a control system influences the certain element of a hydraulic drive, providing its normal functioning. Thus, in the given general scheme the complex of devices D_1, D_2, *EC, FD, CPU* represents providing subsystem which changes character of influence of indignations in the necessary direction and influences a course of processes in a hydraulic drive as a result of change of cycling of loadings, a mode of greasing, air-conditioning, inclusion of correcting parts, etc.

Antifriction functions of subsystems of maintenance of reliability are characteristic for all types of hydraulic drives. The cores from them – exception of hit of aggressive impurity in system of a hydraulic drive, creation of a greasing layer between cooperating elements, indemnification of deterioration and deformation, maintenance of demanded properties of a greasing liquid, reduction of specific pressure and speeds of influence.

For severe loading hydraulic drives the most typical functions of subsystems of maintenance of reliability are unloading (indemnification of deformations, decrease in specific pressure, reduction of vibrations, etc.), and also maintenance of tightness of systems.

THE CONCLUSION

Technique and the algorithms of simulation of a hydraulic drive are applied as the software product for engineering calculations on mechanical engineering firms.

The offered conceptual positions and schemes of structural maintenance of reliability of hydraulic drives of machines are based on characteristic properties of hydraulic systems, results of diagnosing of their conditions and introduction of subsystems of active maintenance of reliability. Distinctive property of the specified subsystems is their ability automatically to support and if necessary to restore working functions of hydraulic drives during their long operation.

THE LITERATURE

[1] *Reliability of technical systems and technogenic risk*. The electronic manual http://www.obzh.ru/nad/10-4.html.

[2] Kornjushenko S. I. *Diagnos and treatment*. "Building technics and technologies" 2006. №1 (41). P. 32 – 37.

[3] Thilevich M. I.: *Substantiation of parameters of the built in system of diagnosing of the incorporated hydraulic drive for increase of safety and efficiency of career dumpers.* The Dissertation on competition of a scientific degree., Minsk, 2006. 249c.

[4] Bogdan N. V., Kishkevich P. N., Shevchenko V. S.: *Hydraulic and pneumatic automatics and a hydraulic drive of mobile machine*s. Operation and reliability гидро-and pneumatic systems: the Manual. – Minsk: Uradzai, 2001.396 p.

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EVALUATION OF QUALITY OF HETEROGENEOUS MECHANICAL SYSTEMS USING IMPEDANCE METHOD

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Summary

The paper analyzes methodology for investigation of dynamic characteristics of heterogeneous systems: honeycomb optical tables and pipelines with sediments, applying mechanical impedance. The developed methodology may be used to assess the quality of plate or cylindrical heterogeneous structures, according to the dynamic characteristics and parameters established in the methodology. It was shown that impedance characteristics are informative to determine some parameters of the quality of honeycomb optical tables and are correlated with the thickness of the pipe's inner sediment layer. Therefore it is possible to choose typical resonance frequencies and according to their changes, the decision about inner layer presence and its value can be made.

Keywords: heterogeneous mechanical systems, quality, impedance, diagnostics.

1. INTRODUCTION

The composite structures are not just used for creation of various constructions in the technology, but they also could be formed as the by-product while implementing some technological processes.

For example, for precise measurements various light honeycomb constructions, which are characterized by optimal ratios of mass, compression strength and bending strength are often used. In this case the quality of composite structure (e.g. the honeycomb optical tables' tabletops (Fig. 1) have been more and more widely applied in laser technologies and nanotechnologies) is related with good dynamic characteristics and properties of vibration damping in vertical and other directions.

The characteristic features of the tables of honeycomb construction are the following: resistance to impact of static and dynamic forces and optimal ratio of mass and rigidity.

The features of honeycomb are determined by core density, size of cells, material, the way of joining (pasting, clinching, welding), thickness and form of walls, fillings, etc. When the core density increases (i.e. the size of cell diminishes), the rigidity, shear module and mechanical connection with upper and lower layers get bigger, and in such a way they improve the characteristics of table. These layers are made from steel, aluminium, plastic and other materials.

The main features of tabletop are the following: local flatness, general flatness, static/dynamic rigidity and maximum relative tabletop motion.

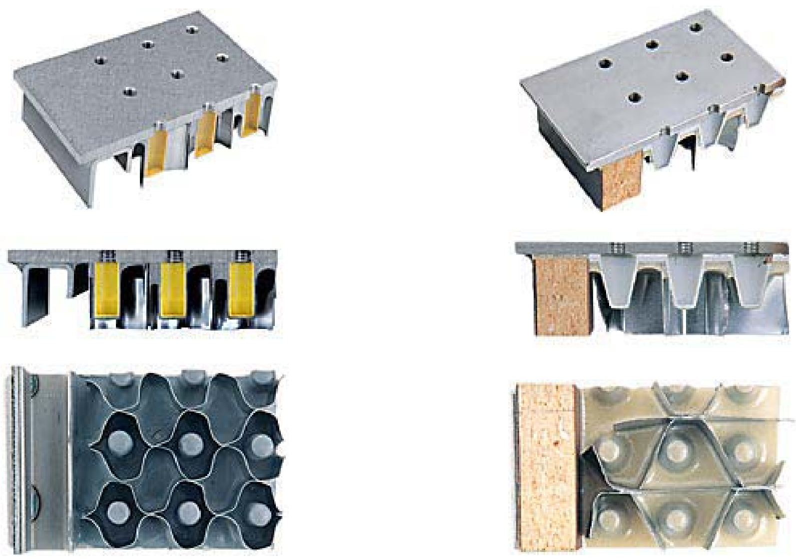

Fig. 1. Examples of Honeycomb Plates' Constructions

All these items describe the main values of concrete quality parameters of table. They are introduced in the producers' catalogues and the consumers may perform the comparative analysis and choose the product suitable for the needs.

The by-product may be the formation of the heterogeneous sediment inside the pipes while implementing the technological processes in the industrial companies, for example while processing the oil inside the pipe the layer of sediments (such as combustion char and like it) is formed. In this case the quality of pipes is related to the thickness of sediment's layers, which affect the dynamic characteristics and efficiency of pipes. The control of the sediment layer is characterized by the fact that the measured dimension is integral in certain distance, which is much bigger than the wall's thickness, e.g., in pipe's section or area, while the volume of measurements, i.e. lengths of pipes, are very big.

In both cases we deal with heterogeneous mechanical systems with special features. In such a way the technology encounters plate and cylinder composite constructions, while it is important for the technological development and safe maintenance to control simply and reliably the quality characteristics and parameters of such constructions.

2. DETERMINATION OF DYNAMIC CHARACTERISTICS OF OPTICAL PLATE OF HONEYCOMB CONSTRUCTION

While assessing the quality of optical tables, it is necessary to prepare and approbate the methodology for determination of dynamic characteristics of honeycomb optical tables.

The features of optical table are characterized by static and dynamic rigidity. The maximum deflection under the impact of static load is considered to be the measure of tabletop's rigidity. Dynamic rigidity describes the resistance of table plate to the impact of vibrations. The dynamic characteristics of the table can be measured the best by dynamic compliance – the dimension that is inverse to the dimension of dynamic rigidity. The dynamic compliance experimental curve may be determined by impedance method. Then the following things may be calculated using experimental data [1]:

1. Dynamic Deflection Coefficient – *DDC* that assesses the relative dynamic characteristics of tabletop. It is determined in compliance curve.
2. Transmissibility of Isolator - *T* – frequentative function of ratio of tabletop's motion and reaction of floor (base) that is expressed in decibels (dB).
3. Relative Tabletop Motion, i.e. relative movement between two points of tabletop. The quicker the motion is, the less possible justiration of the components mounted on the table surface becomes. The relative motion depends not only on the dynamic characteristics of tabletop, but on the characteristics of isolation system and environmental vibrations, as well.
4. Maximum Relative Tabletop Motion is determined after the transmissibility of isolator, factor of compliance strengthening *Q* and power's spectral density are evaluated.

There were experimental tests made for optical plates of honeycomb construction 1HT 12-24-20 [4]. The transmission characteristics were determined by applying mode analysis. The reaction of the object to the strike was fixed by stimulating vibrations in certain points with the help of special strike gauge MODALHAMMER mod. 2302-10, and accelerometer that was fastened near the strike place and connected to analyzer PULSE 3560 (Fig. 2).

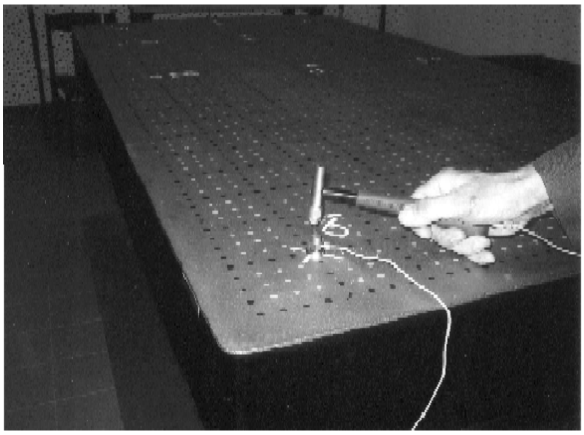

Fig. 2. Determination of Dynamic Characteristics of Optical Plate of Honeycomb Construction 1HT 12-24-20

Due to the created methodology the following items were determined:

- Dynamic compliance (10…1000) Hz in frequency range;
- First resonant frequencies;
- Dynamic deflection coefficient – *DDC*;
- Maximum relative tabletop motion – *MRTM.*

For this purpose the received dynamic compliance curve (Fig. 3) of analyzed plate was used, where two quite high resonant peaks of 199 Hz and 220 Hz may be observed.

The table until 80 Hz is presumed to be a perfectly solid body, where compliance diminishes inversely to square of frequency ($\omega = 2\pi f$). The compliance curve helps the frequencies that are higher than 80 Hz to diverge from the straight line of perfectly solid body. The table cannot be considered to be a perfectly solid body, it starts deforming because of the vibration's impact.

Dynamic Deflection Coefficient (*DDC*) and Maximum Relative Tabletop Motion (*MRTM*) were calculated according to the methodologies of Newport and Melles Griot [2, 3].

The factor of compliance strengthening *Q* of table's point 1 in the resonant frequency f_n is calculated by drawing the characteristics of perfectly

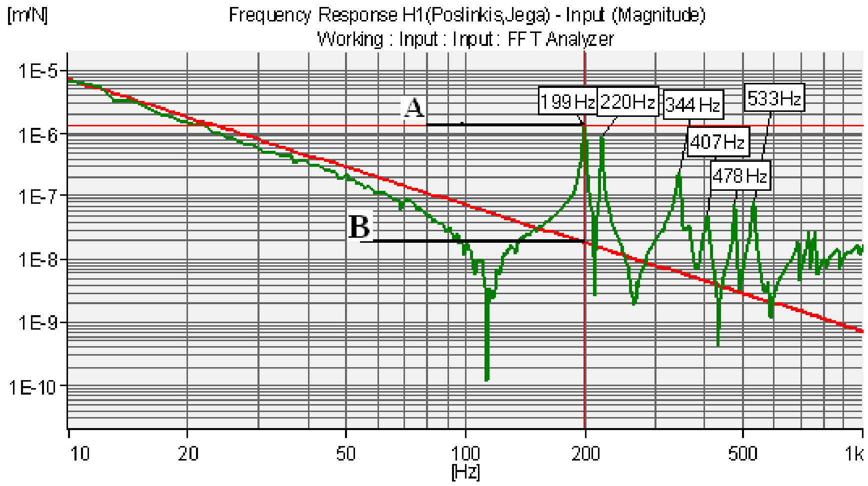

Fig. 3. Dynamic Compliance Curve and Resonant Frequencies (in point 1) of Optical Plate 1HT 12-24-20.

solid body, i.e. the straight line, by the compliance curve (Fig. 3). Starting from the lowest frequency, the compliance curve slopes down without discontinuities until the optical table is rigid and no relative motion is observed on the surface.

The ratio calculated according to the curve of Fig. 3 in the zone of the first resonance (f_n = 199 Hz) is the following:

$$Q = A/B = 71.7$$

Dynamic Deflection Coefficient (DDC) is calculated according to the formula:

$$DDC = \sqrt{Q/f_n^3} = 0{,}00302 = 3{,}02 \cdot 10^{-3}$$

Inverse dimension of dynamic deflection coefficient is $DDC^{-1} = 331$.

Maximum relative tabletop motion is calculated according to the formula:

$$MRTM = CT\sqrt{(Q/f_3^n \bullet PSD)}\,,$$

where: T- transmissibility of isolator, PSD – power's spectral density, C – constant that determines the acceleration units and assesses the worst case between any two points. In the case being analysed C = 0,623 m/s^2; PSD = 10^{-9} g^2/Hz (in the environment close to busy roads); T = 0,01 (accepted according to [3] Melles Griot Super Damp ™ qualitative isolators).

$$MRTM = 0{,}623 \cdot 0{,}01 \cdot \sqrt{\frac{71{,}68}{199^3} \cdot 10^{-9}} = = 0{,}59 \cdot 10^{-9}$$

[mm/s^2].

Such a dimension may be explained by the fact that relative motion of tabletop's point is measured under the impact of 1 m/s^2 acceleration, therefore the value of the maximum relative motion in the point 1 of probative table 1HT 12-24-20 is 0,59 nm.

The calculated maximum relative plate motion is the following:

$MRTM = 0{,}00176 \cdot 10^{-7}$ m m/s^2 = $0.176 \cdot 10^{-9}$ m.

Relative Tabletop Motion (max) in the catalogue of MELLES GRIOT [3] is the following: < 0,18 nm ($7 \cdot 10^{-9}$ in.)

Consequently, the performed calculations are correct and corresponding to the dynamic characteristics presented in the catalogues [2-4].

3. EXPERIMENTAL TEST OF INNER SEDIMENT LAYER IN PIPES

The known measurement methods of thickness [4, 5] are not effective while measuring the thickness of heterogeneous sediment. Firstly it is explained by a very large number of measurements done in the measurement point in order to receive an integral value in certain range. The sediment layer is honeycomb and it is quite difficult to receive a better reflection from the inner sediment layer that is necessary for resonant or impulse measurement of thickness. According to the tests, the wave interference method [6] that is now used for the control of sediment layer has a number of advantages, but it also has several disadvantages. These could be the fact that the measurements are done when the acoustic transformers are in good contact with the exterior surface of the pipes. This surface is often corrosive, mechanically damaged or difficult to access. In order to overcome these difficulties, the possibility to use the impedance method was analyzed experimentally by determining the existence and thickness of the inner layer of multilayered cylinder system.

The experimental test was done with the steel fragments of the pipes (~1 m length), which have the calibrated thickness of inner sediment layer of 0 mm, 10 mm and 20 mm, the real (formed while exploiting) inner sediment layer from 10 mm to 25 mm, or which do not have any inner sediment layer at all. The external diameter of the fragments of analyzed pipes is 150 mm, inner – 134 mm, their layer of sediment – slash – is formed while using the pipes in oil processing (process of petrol making).

The tests used the method of mechanical impedance in order to compare its possibilities and results with the already approved and analyzed method of interference [6, 7]. The methodology of the mechanical impedance was implemented with the help of the specialized equipment of the company Brüel & Kjær GmbH, Pulse™ 360, with the stroke hammer of the 8202 type and software BZ 7760. Such a set of equipment allowed recording a number of impedance curves, getting their average and analyzing them. The characteristic shock's frequency range is presented in Fig. 4. The registration of the impedance characteristics was done in various points of pipes' fragments in the radial direction and along the pipe.

While analyzing the impedance characteristics, the attention was paid to the changes of their parameters (resonant frequencies, forms, etc.) and their correlation with the condition of pipe's inner layer in the measurement place.

In order to eliminate the pipe's parry conditions, which affect the experiment, we chose the range of frequencies from 500 Hz to 5000 Hz for the test.

The results of the experimental test are shown in Figs. 6–7.

Fig. 4. Mechanical shock's range

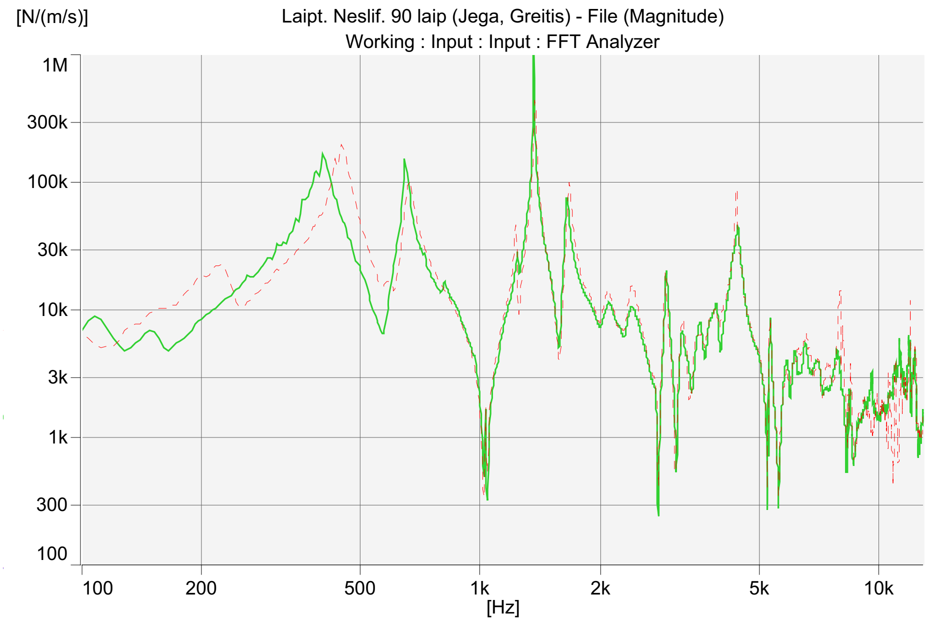

Fig. 5. Impedance of the calibrated pipe with the thickness of slash layer of 0 mm: continuous curve – excitation (stroke by hammer) in the pipe's polished place; spot curve – in the unpolished pipe's place

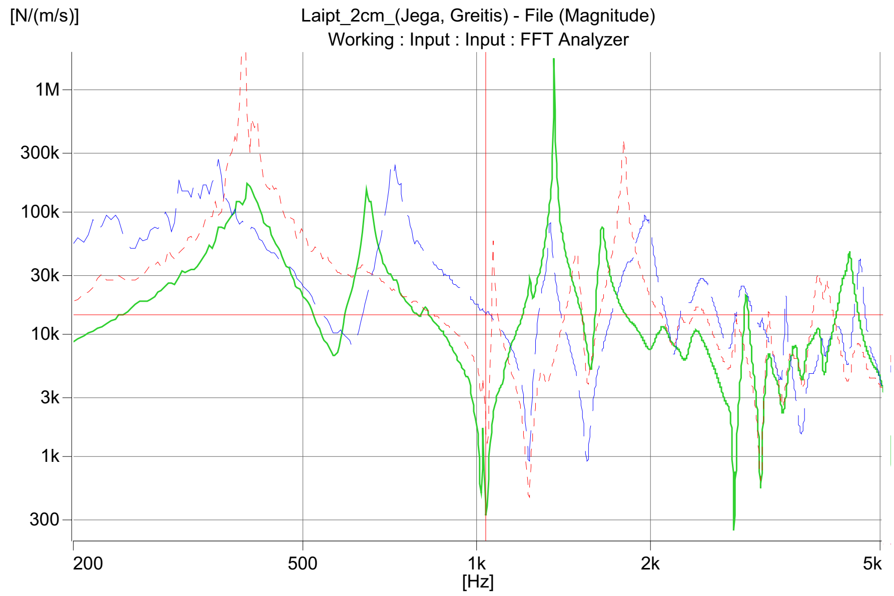

Fig. 6. Impedances of the calibrated pipe: continuous curve – 0 cm of slash (cursor's frequency 1036 Hz); spot curve – 1 cm of slash (cursor's frequency 1040 Hz); stroked curve – 2 cm of slash (resonance frequency 1224 Hz)

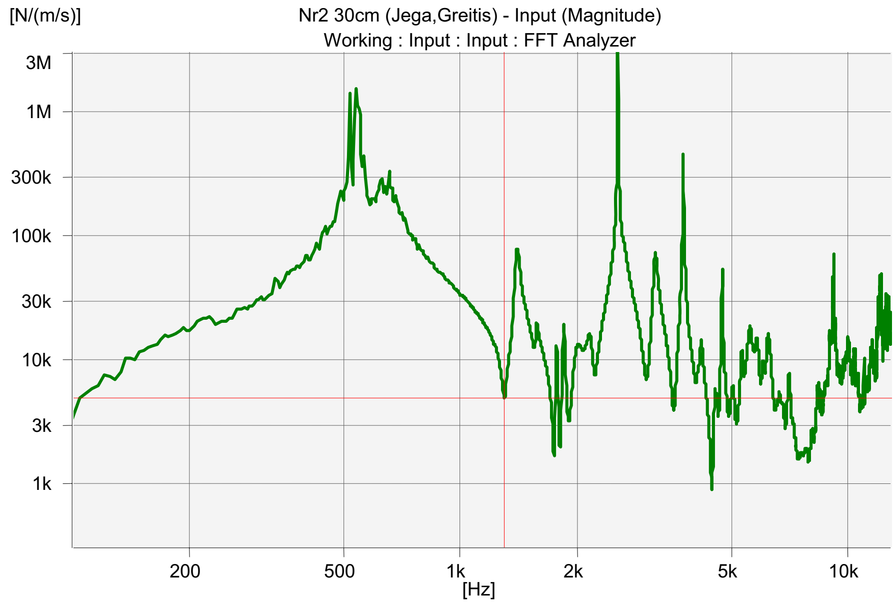

Fig. 7. Impedance of the control pipe with real layer of slash (ca. 25 mm) (cursor's frequency 1296 Hz).

According to the results averaged on the basis of identical measurements, the method of impedance is indifferent to the condition of surface affected by the impulse power in the contact area (see Fig. 5). The impedance characteristics essentially do not differ from 1000 Hz, independently whether the excitation is done in the polished or unpolished part of the pipe. Besides, it has been noticed that the characteristic of the impedance in the pipe with real slash does not depend on the excitation place in terms of average in the analyzed ranges of frequencies.

The results presented in Fig. 6 show the general changing tendency of resonance in pipes without slash and in real pipes with the 10÷20 mm layer of slash. It can be explained by the fact that the casing's resonance in case of n=3 and m=2 (parameters of frequency equation) is about 1020 Hz without slash, while the layer of slash affects more the characteristics of system's rigidity than mass, that is why the resonance (see Fig. 6) has shifted. The impedance of the control pipe (the other pipe that has a 20-25 mm slash layer) in the frequency range of 1000÷1300 Hz showed a similar change. This result is correlated with the impedance characteristics of the stepped (calibrated) pipe. According to the presented results, the resonance frequency changes the most in case of thicker slash layer. This shows that thinner layers change the dynamic characteristics of the mechanical system a little. However after the complete modal analysis is done, it is possible to expect other n, m combinations and relevant frequencies, in case of which this shift may get clearer.

4. CONCLUSIONS

The done tests showed that the measurements of mechanical impedance are informative enough to identify the dynamic characteristics of heterogeneous mechanical systems. In general meaning, the quality of these systems can be defined by certain quantitative parameters, determined from the impedance curves.

The following parameters are determined in case of plane heterogeneous mechanical systems: dynamic compliance, first resonant frequency, dynamic deflection coefficient, maximum relative top motion.

With regard to the cylinder non-homogeneous mechanical systems it was determined that:

- the impedance characteristics are correlated with the thickness of heterogeneous layers of inner cylinder systems;
- the information on the dynamic behavior of cylinder system is received from the impedance characteristics and it allows selecting the frequencies, which are informative for the evaluation of inner sediment layer's thickness;
- the shift of pipe's resonance frequency may be used to create the simple indicator of critical thickness of sediment layer;
- contrary to the Lamb Wave Inference method [6], the impedance method does not need special conditions of acoustic contact.

The developed methodology may be used to assess the manufacturing quality of optical tables, according to the dynamic characteristics and parameters established in the methodology, and to solve the identification task of the technical condition of heterogeneous systems.

REFERENCES

[1] Gulbinas R., Slavickas E. S., Volkovas V., Stankus R.: *Investigation of Dynamics of Optical Tables*. Proc. of the 5-th Int. Conf. "Vibroengineering 2004", Kaunas Technological University, p.p. 137-139.

[2] *Data about Optical Tables and Vibro-Isolators of Firm Newport* www.newport.com.

[3] *Data about Optical Tables and Vibro-Isolators of Firm Melles Griot* www.mellesgriot.com.

[4] Alleyne D., Cawley P. A *Two-Dimensional Fourier Transform Method for the Measurement of Propagating Multimode Signals'*. J. Acoust. Soc. Am. 89/3/, 1991, p. p. 1159-1198.

[5] *Devices and Equipment for NDT of Materials*. A Review of Production Program of Krantkramer Firm. www.krantkramer.com.

[6] Patent of Lithuanian Republic (V. Volkovas and V. Sukackas), Nr. 3304, 1996.

[7] Sukackas V., Volkovas V.: *Investigation of the Lamb Wave Inference in a Pipeline with Sediments on the Inner Surface* // Russian Journal of Nondestructive Testing. ISSN 1061-8309. Kluwer Academic/Plenum Publishers, Vol. 39, No 6, 2003, p.p. 445-452.

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DIAGNOSTICS OF CONTROL ROD DRIVE. POSSIBILITIES TO EXTEND ITS LIFETIME AT NPP'S

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Summary

According to specifications, lifetime of a linear stepping electromagnetic drive in WWER-1000 nuclear reactors is limited by the pre-assigned lifetimes of the drive components such as electromagnets, a latch assembly, drive rack, and control rod position sensor. The lifetime of the drive components is from 7 to 20 years. On the basis of diagnostics of these components under real conditions, actual lifetimes of the components at nuclear power plant (NPP) were forecasted. It is shown that in order to extend the lifetime of the drive components up to the reactor lifetime (60 years), it is necessary to replace the sensor of the DPL-type by the new one (of the DPL-KV type) and to decrease the electromagnet temperature. The Measuring and Diagnostic System with the DPL-KV sensor enables diagnosing the sensor, electronic processing unit and drive. Economic effect due to the cumulative technical decisions is estimated to be 7 mln.euro per NPP unit.

Keywords: linear stepping electromagnetic drive, control rod position sensor, lifetime, nuclear reactor.

DIAGNOSTYKA NAPĘDU PRĘTA STERUJĄCEGO. MOŻLIWOŚCI ZWIĘKSZENIA CZASU EKSPLOATACJI NAPĘDÓW W ELEKTROWNIACH ATOMOWYCH

Streszczenie

Zgodnie z dokumentacją czas eksploatacji elektromagnetycznych silników krokowych prętów sterujących w reaktorach jądrowych WWER-1000 jest ograniczony ustalonymi czasami eksploatacji ich składników (blok przesunięcia, pręt, elektromagnesy, czujnik) – od 7 do 20 lat. Na podstawie wyników diagnostyki tych składników w warunkach realnych została zrobiona prognoza ich rzeczywistej żywotności w elektrowniach atomowych. Wykazano, że w celu wydłużenia czasu eksploatacji składników do czasu życia reaktora (60 lat) trzeba wymienić czujnik DPL na inny, bardziej niezawodny – DPL-KV i znacznie obniżyć temperaturę elektromagnesów. Układ pomiarowo-diagnostyczny wyposażony w czujnik DPL-KV pozwala przeprowadzać diagnostykę czujnika, osprzętu elektronicznego i silnika. Całkowity efekt ekonomiczny wprowadzenia zaproponowanych rozwiązań technicznych jest szacowany na 7 milionów Euro na blok energetyczny.

Słowa kluczowe: elektromagnetyczny liniowy silnik krokowy, czujnik położenia pręta sterującego, czas eksploatacji, reaktor jądrowy.

1. INTRODUCTION

At present, more than twenty power units with nuclear reactors of the WWER-1000 type are in operation in Russia, Ukraine, Bulgaria, and Czechia. The expected lifetime of such reactors will be about 60 years (the lifetime of 30 years, which was specified initially, will be prolonged).

In most WWER-1000 power units, the control and protection system applies linear stepping drives which move control rods (CR's).

Each drive comes in the form of a high cylinder and comprises mechanical unit (a housing, motion unit, and rack) and electrical unit (an electromagnet assembly and sensor).

An internal drive part (the motion unit, rack, and a lower part of the sensor) is in the primary coolant (the temperature is up to 350 °C and pressure is up to 18 MPa), whereas an external part (the electromagnet assembly and a higher part of the sensor) is outside the coolant.

The housing provides hermeticity of the internal part. Under a reactor control mode, the electromagnet assembly is moving the rack with the control rod by interaction with the motion unit through the housing. The sensor function is measuring the control rod position. Under the emergency shutdown mode, the electromagnet assembly is de-energized. The rack drops together with the control rod on an arresting device.

The specified lifetime of these drives is not longer than 20-30 years. Accordingly, during the expected reactor lifetime, all the drives should be replaced at least once, that is not economic.

This problem is particularly important for the drives of the SHEM-2 type, which are in operation at the most WWER-1000 Nuclear Power Plants (NPP's). The specified lifetime of mechanical unit of this drive is 20 years. The lifetime of electrical unit of the drive is 10 years or less. In the specification, the value of rated life is 6000 double strokes and the number of rated drops from any height in response to scram signal (the function of emergency shutdown) is 200.

Operation experience of the SHEM-2 drives as well as theoretical and experimental investigations show that at the operating NPP the lifetime of such a drive can be enhanced up to the reactor lifetime. The prolongation can be achieved by drive modernization at a reasonable cost.

2. LIFETIME OF MECHANICAL UNIT

In the first place, the validity of correlation between the specified drive lifetime and specified resource as well as that of the specified resource should be analyzed taking into account operation experience.

The main components of the drive mechanical unit are the motion unit and rack. Dynamic mechanical loads (vibration and shocks) and friction influence the durability of these components significantly. Correspondingly, the lifetime of the motion unit and rack must depend on the time of using of the resource.

The estimate of the average lifetime of the drives can be got on the basis of information about operation of the SHEM-2 drives during a fuel cycle. Such information was obtained in the Measuring and Diagnostic Systems with the DPL-KV sensor (MS's) [1, 2], which were in operation at the 2nd power unit of the Kalinin NPP in Russia. According to the information obtained in 9 fuel campaigns, in the control group, each drive made not more than 217 double strokes, while in the emergency shutdown group the drives made only 100 double strokes.

If the operation intensity is the same, the resource of the motion unit for the control group drives will be equal to approximately 250 years. The drives are usually operating in the control group only during several years. After that, they are moved to the emergency shutdown group. So, during 60 years of operation, the SHEM-2 motion unit will use only
a small part of its resource.

The lifetime of the rack depends on both the intensity of control mode (step movement) and the number of drops. The interaction of rack teeth with latches of the motion unit leads to rack teeth deterioration. Falling loads cause distortion of the rack and wear of a rack damper.

The most period of time during the fuel cycle, the drives of the emergency shutdown groups are at the top end switch and do not move. Meanwhile, the drives in the control group move only in the higher part of the displacement range. Correspondingly, only a part of the drive teeth is wearing in interaction with the rack latches. Therefore, according to the criterion of rack wear, the rack resource depends on the maximum load per rack tooth.

The MS's were recording all the steps of the drives during each fuel campaign.

Fig. 1 shows a typical diagram of distribution of the number of steps during the campaign. In order to identify the position of the control rod, a two- digit decimal scale is applied. After matching the control rod positions with the number of the teeth, it follows from this diagram that the maximum load per tooth during a campaign is 300 times.

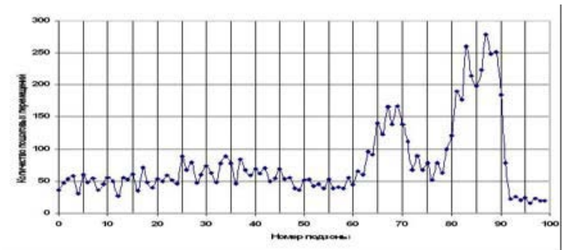

Fig. 1. Typical diagram of distribution of the number of steps during the campaign

The average duration of the fuel cycle was 10 months or so. Therefore, the resource of the rack teeth defined on the basis of maximum load per rack tooth is approximately 80 campaigns. Taking into account maintenance works (2 months), that is equal to 80 years. If the duration of the campaign increases up to 18 months, the above estimate does not change significantly and exceeds 60 year if we use any method of assessment. In reality, the resource will be much higher because of transposition of the drives from the control group to the emergency shutdown group.

According to the information obtained in the MS's, if the equipment is faultless (there is no unscheduled outage) the average number of the drops is not less than 4 times a year. Consequently, the estimate of the forecasted drop rack resource is 50 years. In case of 18-months fuel cycle and the same number of drops during the campaign, the forecasted drop rack resource is more than 80 years.

Taking into account that after the life test including 200 drops, the condition of the rack is satisfactory, we can consider the real rack resource to be significantly higher than the specified one.

The diagnostic information obtained in the 9 campaigns of the MS's operation leaves no doubt that the drop time will not exceed the maximum permissible value of 4 c during 60 years.

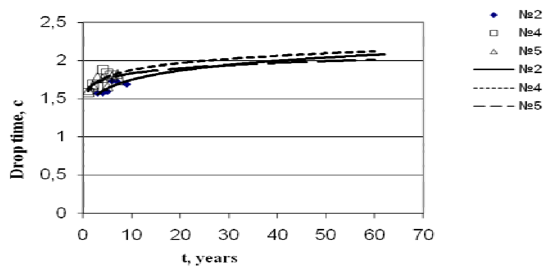

Fig. 2. Dependence of drop time of the rack on time for three MS's (extrapolation to 60 years)

An additional argument that the lifetime of the racks is longer than 60 years is the positive result of tests of similar racks used for SHEM-I and SHEM-3 drives. These tests included 400 and 470 drops, correspondingly.

Thus, the forecasted lifetime of the main components of the SHEM-2 mechanical unit exceeds the lifetime of the reactor.

3. LIFETIME OF ELECTRICAL UNIT

Estimate of a forecasted lifetime of the electrical unit of the SHEM-2 (electromagnet assembly and DPL sensor) is of great importance, because these components are very expensive whereas their specified lifetime is too short.

The drive of the SHEM-2 type comprises three electromagnets identical in design. Depending on their designation, they perform functions of pulling, locking, and fixing electromagnet. According to [3], life time of these electromagnets depends on the coil temperature when the drive is not moving. The lifetime of the fixing electromagnet is 25-30 years, for pulling and locking electromagnets it is much longer than the lifetime of the reactor.

Possible methods for decreasing the electromagnet temperature were analyzed. They are:

- increasing the heat transfer from the electromagnet to air;
- decreasing the power of inner heat generation in the electromagnet coil by reducing the value of current;
- decreasing the radiant heat exchange between the housing and electromagnet.

Decreasing the radiant heat exchange can be achieved by application of a thin heat-reflective screen with a high reflectivity that does not change significantly during long term operation. The screen should be inserted at the inner surface of the fixing electromagnet [3, 4].

Simulation of the electromagnet operation has shown that application of the screen is the most effective method for electromagnet temperature decreasing. Insertion of the screen can be carried out at the operating NPP during maintenance works. The simulation results made it possible to determine the optimum parameters of the screen, which can provide decrease in temperature not less than 10 °C. Such decrease corresponds to the forecasted lifetime of 60 years. Tests of the electromagnet with the screen under actual environment conditions confirmed the correctness of calculations.

The least durable component of the electrical unit is the DPL sensor. Its specified lifetime is 5-10 years. The reason for rejection of the DPL sensors during operation is mainly concerned with oxidation of a wire and increasing the sensor coil resistance. As a result, actually, the sensor lifetime is 3-7 years.

In order to avoid the multiple replacing of the DPL sensor during the power unit operation, the new sensor of the DPL-KV type that is much more longevous should be applied. At the same time, an opportunity appears to eliminate the other defects which are inherent for the SHEM-2 drive and electronic unit operating with the DPL sensor. They are: significant error of position measurement, unreliability, very small capability to organize diagnostics, etc. The electrical components of the DPL-KV sensor are characterized by the lifetime longer than 60-80 years. The validity of these values is confirmed by diagnostic information obtained in 9 operation campaigns. The sensor signals (at the same positions and under the same conditions) has changed insignificantly. Resistance of the inductance coils tended to stabilization (Fig. 3).

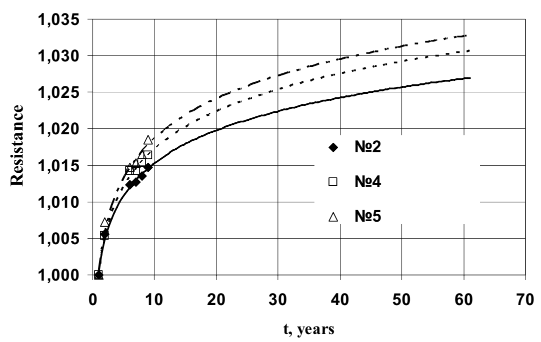

Fig. 3. Dependence of sensor resistance (relative value) on time (extrapolation up to 60 years)

The forecasted variations of the average value of the DPL-KV coils resistance are not more than 3.5%. In practice, such variations do not influence the MS operation. All the more, its algorithm includes adaptive procedures which correct the signals under changing environment.

The specified lifetime of a sensor housing is not less than 30 years. It can be prolonged up to 40-60 years on the basis of diagnostics results.

It follows from the above-said that the stability of the DPL-KV parameters is sufficient to provide its reliable functioning during the expected reactor lifetime. In order to apply the DPL-KV sensor, it is necessary to replace the standard rack by the similar rack that includes a multi-component shunt. Since the racks which have partly used their drop resource (that is the most critical parameter) will be also replaced, such a replacement will provide the sufficient resource of the new racks which will be capable to operate up to the end of the reactor lifetime.

Thus, the replacement of the DPL sensor and standard rack with the DPL-KV sensor and the new rack, as well as insertion of the heat-reflective screen inside the fixing electromagnet enable prolonging the drive lifetime up to the lifetime of the reactor.

4. DIAGNOSTIC CAPABILITIES OF MS

It should be noticed that the lifetime of each drive component set in the documentation was calculated and confirmed by the life test of several samples. The actual resource of each component depends, to a great extent, on the quality of manufacturing, which is checked ineffectively in many cases [5]. Removal of a failue arisen in the drive during the reactor operation leads to significant expenses. In order to minimize the probability of such a failure, it is necessary to diagnose the drive directly during the fuel cycle. Such diagnostic possibilities are realized in the MS, which provide:

- CR position measurement (accuracy is within 0.3% under all possible conditions);
- metrological diagnostic check of the reliability of CR position measurements (it is not necessary to calibrate the sensor during operation);
- fault tolerance (maintenance of operating integrity if any signal wire breaks or any coil fails);
- automatic correction of a sensor, shunt and processing unit parameters (this eliminates the influence of temperature variations, defects of joints, material and component aging);
- filtration of various noises;
- self-diagnostics of whole MS with failure localization;
- generation of textual recommendations for malfunction elimination;
- assessment of the condition of main drive components (rack teeth, latches of the motion unit and, partly, electromagnets);
- drive condition diagnostics (step missing or delay, as well as teeth slippage);
- checking of the CR and rack coupling;
- sensor to processing unit connection diagnostics;
- control connection diagnostics;
- measurement and recording of CR drop time diagram (this allows to diagnose the condition of a guide sheath and rack curvature in case of CR emergency shutdown or spontaneous drop);
- determination of the top and bottom oscillation points during the CR damping process (this allows to diagnose the condition of a rack damper);
- checking whether the CR has fallen down on the arresting device.

The high diagnostic sensitivity allows to reveal incipient defects (even before appearance of a significant failure). Diagnostic capabilities can be further enhanced in the future.

Information about all CR moves, control commands, operation modes, malfunctions or failures as well as operator's actions are logged in a "black box" recorder. At the same time, the MS estimates the drive operational conditions by accumulating parameters like the number of drops, steps made, input control signals, etc.

The real time CR position is displayed on a front panel. Complete set of information can be transferred to a special palm computer and shown on its display. If necessary, data can be transferred to a PC for archiving and analyzing. Each MS can be connected to a local network. In this case, the MS can perform cross system diagnostics. This improves the MS fault-tolerance. For instance, the local network gives an opportunity to inform operators about the wrong positions of CR, including the case of CR position mismatch in the control group as well as of any CR slipping down from the end switch.

Based on diagnostic information obtained during system operation, an individual "registration certificate" is automatically issued for each drive. This certificate contains an assessment of drive condition as well as recommendations for operators how to carry out preventive maintenance.

Fig. 4 illustrates the diagnostic capabilities of the MS. The diagnostics applies the diagrams of displacement. The diagram enables:

- defining the actuation time of the motion unit latches,
- checking the correctness of response to a cyclogram of the electromagnet current,
- checking the control rod and rack coupling.

The ability to obtain such diagrams is determined by both the high displacement sensitivity of the sensor and the fact that the time interval between two consecutive control rod position measurements is very short. In case of the drive fault, the form of the diagram is changing. This makes possible to find out the origin of the fault or to reveal the incipient fault (even before appearance of a significant failure).

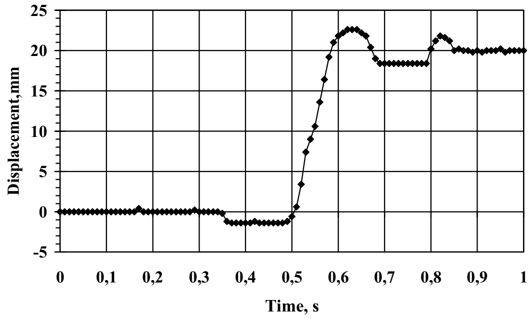

Fig. 4. Diagram of drive rack move: a step up

5. CONCLUSION

In order to increase the lifetime of the control rod drive up to the expected lifetime of the nuclear reactor (60 years), it is necessary to replace the standard sensor and standard rack with the DPL-KV sensor and the new rack, as well as to decrease noticeably the electromagnet temperature, using the screen.

The MS with the DPL-KV sensor excels the analogues at reliability, diagnostic capabilities, fault-tolerance, and accuracy significantly. Diagnostic capabilities of the MS make it possible to switch from pre-assigned terms to forecasting equipment condition during the future campaign and to repairing the drives depending on their technical condition.

The economical effect of the totality of the suggested technical decisions is about 7 million euro per power unit. These decisions can be also applied to the other types of the stepping drives, for example SHEM-3, used at the WWER-1000 nuclear reactor.

REFERENCES

[1] Sapozhnikova K., Taymanov R., Druzhinin I.: *About the Effective Approach to the Modernization of the NPP Control and Emergency Shutdown System*, IAEA Technical Meeting 13-16 September 2005, Chatou, France, http://entrac.iaea.org/I-and-C/TM_EDF_2005_09/Session%24%20Wedn%20PM/Sapozhnikova%20paper%20updated.pdf.

[2] Taymanov R., Sapozhnikova K., Druzhinin I.: *Measuring Control Rod Position, Nuclear Plant* Journal, 2007, 2 (March-April), USA, p. 45-47.

[3] Druzhinin I. I., Gerasimov N. P., Taymanov R. Ye.: *Possibility for Enhancing the Lifetime of Electromagnets of the Drives in the Control and Protection System in a Nuclear Reactor*, Energoma-shinostroenie, 2006, 2-3, p. 18 - 24.

[4] Patent RU 44867 U1, МПК7 H01F7/16, G21C7/12. *Electromagnet of the Drive moving a Control Rod in a Nuclear Reactor, Gerasimov*, N. P., Druzhinin, I.I., Taymanov, R. Ye., 27.03.2005, Bulletin, 2005, 9.

[5] Taymanov R. Ye., Sapozhnikova K. V., Lukashev A. P, Pronin A. N.: *About Estimation of the Quality of Manufacturing of Sensors with the Long-term Calibration Interval*, Datchiki I Systemi, 2006, 9, p. 67 - 80.

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DIAGNOSTICS IN CAR MAINTENANCE

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Summary

The paper proposes an extension of the currently applied vehicle inspection, based on the OBD II system, and periodical inspection, by vehicle dynamic load testing. The method involves generating faults based on an analytic model of traffic. The method takes into account the static and dynamic properties of a vehicle within the whole range of its operation, taking into account the variable traffic intensity, and enables early detection of defects which accumulate at variable random loads. The highest precision of computation is ensured by traffic models with elastic and damping constraints, with variable rigidity and damping.

Keywords: diagnostics, vehicle maintenance, dynamic load.

DIAGNOSTYKA W UTRZYMANIU POJAZDÓW SAMOCHODOWYCH

Streszczenie

W pracy zaproponowano rozszerzone podejście do obecnie stosowanej kontroli stanu pojazdów, opartej na OBD II i kontroli okresowej, o pomiary obciążeń dynamicznych pojazdu. Zaproponowano metodę generacji niezdatności pojazdu na podstawie modelu analitycznego ruchu drogowego. Metoda ta uwzględnia własności statyczne i dynamiczne pojazdu w całym zakresie jego pracy z uwzględnieniem zmiennej intensywności ruchu i pozwala na wczesne wykrycie rozwoju uszkodzeń kumulujących się przy zmiennych obciążeniach losowych. Największą dokładność obliczeniową mogą zapewnić modele ruchu z więzami sprężystymi i tłumiącymi o zmiennej sztywności i tłumieniu.

Słowa kluczowe: diagnostyka, utrzymanie pojazdu, obciążenie dynamiczne.

1. INTRODUCTION

The basic tasks of technical diagnostics include detection and identification of failures and faults in cars, which – directly or indirectly – result in their unreliability. The elements of faults in which various factors result in disturbing the balance of forces, moments or balance in the continuity of energy and information flow, which may result not only in a vehicle fault, but also in its failure or even a car accident. Another task is the choice and implementation of a strategy of car maintenance, whose aim is to slow down the process of its degradation and to restore its fitness for use [6].

The theoretical foundations for developing various diagnostic methods are algorithms of car inspection on various levels of its complexity (decomposition). The knowledge of the dynamics of a vehicle steering provides more in-depth and comprehensive information about the vehicle condition and static characteristics. The degrading effect of dynamic load on kinematic nodes is greater than that of static load or natural wear. The causes of failures and faults in the system of vehicle operation system are the following [6]:

- dynamic input function in the course of vehicle operation,
- a driver's errors made in the "man – car – road – service" system,
- construction errors made in the process of designing the system of a vehicle operation,
- manufacturing errors, made in the production process,
- maintenance errors, made in the condition inspection and during the process of maintenance.

The problem of diagnosing the condition of a vehicle during its operation can be reduced to checking the correctness of parameter changes in relation to the operation time t and determination of status control cycles as well as locating the faults in a vehicles.

Diagnosing a vehicle may be reduced to comparing actual characteristics u with assumed ones u_o, according to the following relationship:

$$\int_{t_0}^{t_k} \rho(\bar{e})\left[u_0(\bar{e}_0,t)-u(\bar{e},t)\right]^k dt = \min$$

where:

$\rho(\bar{e})$ - function of weight, $\rho \in [0,1]$;

$\bar{e}_0$ and $\bar{e}$ - a set of assumed and actual diagnostic parameters;

t - variable time of vehicle condition inspection;

$k = 1{,}2$ - exponent of integrand.

The essence of the currently applied diagnostic systems can be reduced to the action of a summing node

$$\sum_i \overline{e}_i - e_{0i} = \Delta\overline{e}_i$$

where the programmed values e_0 are compared with the set $\overline{e}$ which describes the current status, taking into account the defects and faults of a vehicle.

2. STANDARDS OF ON-BOARD DIAGNOSTICS (OBD)

The current standards adopted for the assessment of the technical condition of cars as OBD I in the last decade of the 20th century have a number of restrictions. Since 1996, the OBD II standard has been applied for cars. Technical diagnostics in this approach consists in identification and location of a failure where it originated, usually defects in the power transmission system, assemblies and the vehicle functional systems from the point of view of road safety and environment protection [4].

The principles of on-board diagnostics were determined by SAE (Society of Automobile Engineers) in its standard SAE J 1830, while the requirements of on-board diagnostics by European car manufacturers in the standard ISO 9141-2. These standards constitute a set of technical and legal requirements which define the on-board diagnostic system as diagnostic procedures, installing diagnostic sockets, processing the diagnostic signal, monitoring the basic parameters of the power transmission system, including exhaust emission parameters.

The criterion of assessment of whether an assembly and its functional elements work properly is the exceeding of the adopted threshold of 50% of the diagnostic parameter, which is signalled and recorded with relevant error codes [5]. The OBD II system is able to detect faults which are the main elements of a power transmission system, i.e. increased waste emission above the accepted threshold. They are mainly related to signalling of faulty operation of electronic systems, sensors in the engine power supply system, leaks in the fuel system, etc. Ultimately, the existing OBD II will provide a basis for developing a comprehensive diagnostic system for an entire vehicle, with the possibility of connecting to a remote service for locating any defects and failures of the vehicle with the use of the GPS system.

The adopted system has a number of restrictions which are a consequence of reducing the status control only to selected test points and the location of errors at the assembly and test element level. The difficulties encountered here include diagnostic inference, identification of diagnostic relations and locating the types of failures. Therefore, this paper proposes to extend the scope of a vehicle diagnostics by new diagnostic signals, taking into account the intensity of the vehicle work and the dynamic load in the process of its use.

3. IDENTIFICATION OF DYNAMIC LOAD AND VIBRATIONS IN VEHICLE MOTION

A vehicle and its elements are adapted for transferring specific static and dynamic load. The load taken into account in the process of a vehicle design, in terms of the course as well as the values and time, correspond to the average operating conditions. Such conditions can be referred to as the average vehicle load with cargo, good road surface condition, moderate utilisation of engine power and driving speed [2].

The level and nature of the dynamic load originating in a vehicle depends on its structure and technical condition and on the traffic conditions. Dynamic load is a result of vibrations produced by a vehicle motion. The vibration intensity and, consequently, the level of dynamic load increases with:

- increase in the driving speed and vehicle weight;
- increase in the power transmitted by the power transmission system;
- deterioration of the road surface condition;
- driving style, including frequent changes in the engine rotational speed, engaging the clutch and gears;
- increasing clearance in connections, which cause parts to hit one another.

The most dangerous values of high dynamic load and the resulting extreme tensions in the vehicle parts may be caused by:

- driving at high speed on a bumpy road;
- vehicle overloading;
- construction changes which are at variance with the documentation provided by the vehicle manufacturer, e.g. increasing the engine power, wheel track;
- resonance in the power transmission system or suspension.

Additionally, all the rotational elements with clearance in connections, imperfect shape or balance, may result in periodical dynamic interactions. They increase with increasing rotational speed, and the coincidence of the rotational speed with the natural frequency of an element or assembly results in resonance and rapidly increasing dynamic load.

The actual load changes are random. Despite the complex character of load which corresponds to particular stages of a vehicle drive, they can be approximately substituted with blocks of repeatable cycles with predetermined amplitude and frequency. The results of such tests can be shown, e.g. as a Wöhler's diagram. The diagram was used to present the relationship between the variable load σ_A and the number of load cycles N before the vehicle damage (destruction). If, while driving, a vehicle element is subjected to load with an amplitude of σ_{Ai}, it can withstand without defect the number N_i of load change cycle, which may correspond to the number of kilometres of driving (Fig. 1).

Further considerations involved Palmgren-Miner's hypothesis of fatigue life, which describes the process of linear accumulation of fatigue failures of machine elements. The greater the load changes amplitude, the more intensive the microdamage development. If the load cycles are repeated, microdamages accumulate (add up) in the element and the element becomes damaged (e.g. cracks) after a certain number of load cycles.

In order to describe the process of damage accumulation, the coefficient (*D*) is introduced:

$$D_i = \frac{n_i}{N_i}$$

where:

n_i - number of load cycles with the amplitude σ_{Ai};

N_i - the number of load cycles σ_{Ai}, after which the element becomes damaged.

The number n_i is determined from the load change course in the analysed element, and N_i is determined from the Wöhler's diagram. An element damage, i.e. exceeding its durability, takes place after the sum of load cycles is equal to:

$$D = \sum_i D_i = 1$$

These considerations will be used in a computational example. An example changes course of a bearing load is shown in Fig. 2.

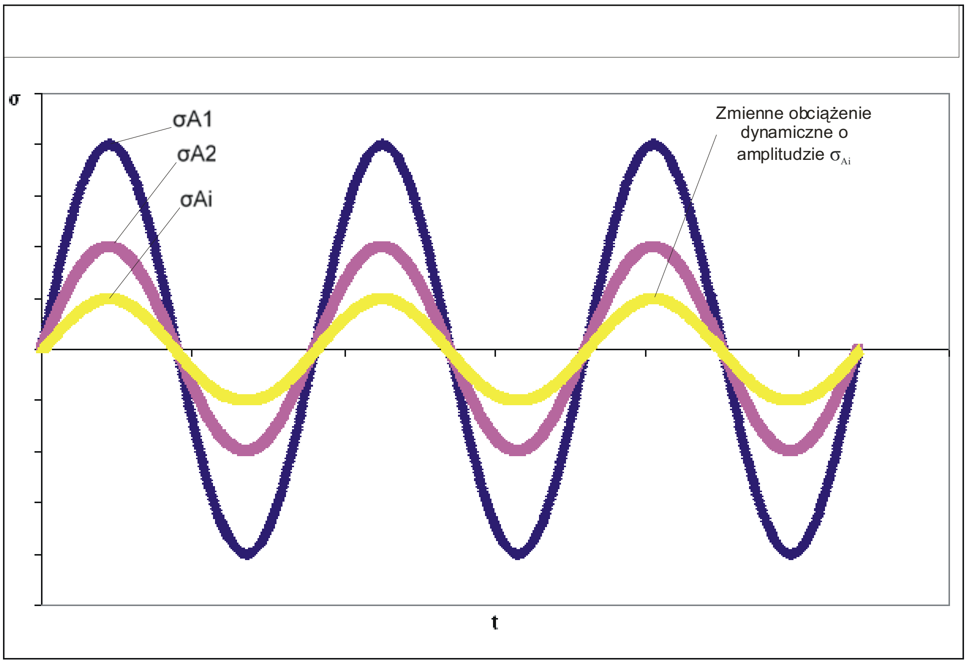

Fig. 1. Idealised load changes during the tests of the elements durability

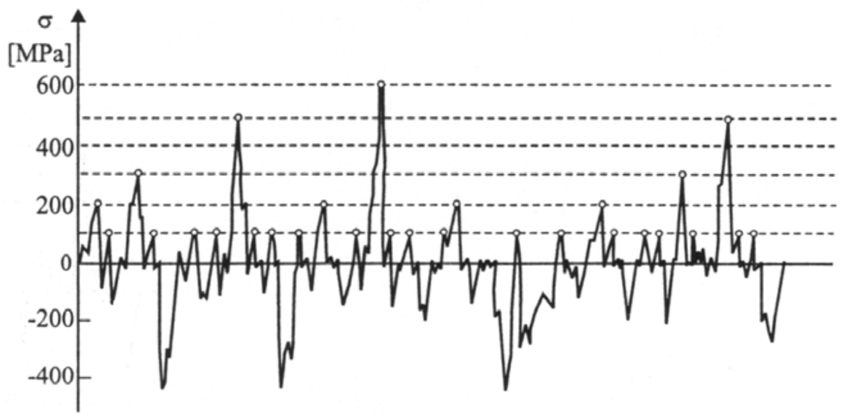

Fig. 2. An example change course of a drive wheel bearing dynamic load

It has been chosen to show the effect of the manner of a vehicle use and the dynamic load which results from it on the vehicle condition. Table 1 shows example results of a bearing fatigue test, performed by the manufacturer. These are the numbers N_i of load cycles with the amplitude of σ_{Ai} until the bearing is destroyed. They were juxtaposed with the results of bearing load test results during the drive over the distance of 10 km. Static load have been omitted in Fig. 2.

The random changes of the operational load was the basis of determination of the load spectrum. To do this, the distribution of peak loads, i.e. local extremes, were found. After the extreme values were counted on particular levels of load, the numbers of cycles n_i of load with amplitude of σ_{Ai} were determined and shown in Table 1.

Adding up the drive wheel bearing load cycles over a distance of 10 km:

$$D = \sum \frac{n_i}{N_i} = \frac{1}{1000} + \frac{2}{10000} + 0 + \frac{2}{200000} + \frac{4}{500000} + \frac{19}{1000000}$$

$$D = 0{,}001237$$

Using the linear hypothesis of damage accumulation, the bearing forecast has been calculated, expressed by the mileage done before a failure (L) for D=1.

$$L_L = \frac{1 \cdot 10}{0{,}001237} \cong 8084 km$$

Mileage 10 km - failure coefficient D = 0.002476
X km -failure coefficient D = 1.

Therefore, the mileage before the damage calculated for the second case is equal to:

$$L = \frac{1 \cdot 10}{0{,}002476} = 4039 km$$

The computational example clearly confirms that the higher the values of dynamic load during the drive, the shorter the time of the bearing work before a failure. Similar physical phenomena occur with other structural elements of a vehicle. Therefore, assuming a 20% surplus of an element durability, the technical condition of a bearing should be checked in the first case after the mileage of 6,500 km and in the second case – after that of 3,400 km. In the adopted standards of on-board diagnostics, the issues of vehicle dynamics have been practically omitted.

Vibrations during the vehicle work not only create dynamic load of elements and assemblies, contributing to their lower durability, but they also significantly affect the effectiveness and efficiency of the driver's actions and those of people travelling in the vehicle.

4. A FAILURE – DIAGNOSTIC - ORIENTED MODEL OF DYNAMIC LOAD IN A POWER TRANSMISSION SYSTEM

Considerable dynamic load may appear in the power transmission system, due to:

- variable nature of the action of resistance forces while driving;
- uneven work of a combustion engine;
- improper action of the driver on the clutch, brake system and when changing gears;
- lack of balance and kinematic compatibility of the drive shaft and axle-shafts;
- imprecise workmanship, wear and clearance in assemblies of the drive transmission system.

These factors produce primarily torsional vibrations as well as vibrations and noise in the power transmission system.

A vehicle model is a set of interconnected partial models:

- a driver model;
- a steering system model;
- a power transmission system model;
- a model of wheel cooperation with the ground (a wheel model in combination with the ground model);
- a chassis model;
- a work environment model.

The driver model describes the forcing actions performed by the driver (the force on the steering wheel, the position of the clutch and brake levers, batching fuel, etc.). It is related closely to the function of senses, mental processes in the brain, reflexes, the level of manual skills. The steering system model describes the geometrical and dynamic relationships in the steering mechanism. It helps to examine clearances and friction. It helps determine the position of turning wheels and moments on the stub axles depending on the steering wheel position and the force applied to it, as well as the shift of the suspension elements.

The basic tool applied in the process of the vehicle model construction, are automatic system of generating the equations of motion, used to analyse multi body systems (MBS - **M**ulti **B**ody **S**ystem Formalizm), which include: [8]:

* - Failure – loss of a vehicle's ability to perform the required functions.
Critical failure – one which poses a threat to humans, results in considerable material damage or other unacceptable outcome [PN-93/N-50191].

**- Fault – a condition of a vehicle in which it is unable to perform the required functions [PN-93/N-50191].

Table 1. Number of load cycles n_i, isolated from dynamic load changes of a drive wheel bearing, assumed during the drive over the distance of 10 km

Number of load cycles	Amplitudes of load cycles					
	σ_{A1}	σ_{A2}	σ_{A3}	σ_{A4}	σ_{A5}	σ_{A6}
	600MPa	500 MPa	400 MPa	300 MPa	200 MPa	100 MPa
N_i	1000	10 000	50 000	200 000	500 000	1 000 000
Number of load cycles n_i, recorded during the drive in nominal conditions	1	2	0	2	4	19
Number of load cycles during extreme driving	2	3	6	5	10	11

- ADAMS (**A**utomated **D**ynamic **A**nalysis of **M**echanical **S**ystems);
- SIMPACK (**SIM**ulation **PACK**age for multibody systems);
- MEDYNA (**ME**hrkörper DYNAmik);
- DADS (**D**ynamic **A**nalysis and **D**esign **S**ystem);
- SD/FAST (**S**ymbolic **D**ynamics/**FAST**);
- MADYMO (**MA**thematical **DY**namical **MO**del);

According to Schiehlena W., the most common and advanced MBS systems include: ADAMS and DADS.

DADS helps analyse dynamics in the time domain of rigid body systems (the latest version of the program enables analysing pliable bodies). Such bodies may be interconnected by kinematic and pliable nodes.

The model notation and analysis employing it are made possible by the following program blocks:

- DADS Pre-processor – makes it possible to enter model data;
- DADS Analysis – generates motion and node equations which are used to determine: position, speeds, accelerations and reactions.
- DADS Postprocessor – generates computation results in the form of time series;
- DADS Graphic Environment – generates graphic interpretation of computation results (animation).

The DADS environment has been used to generate the equations of motion of a vehicle. A system of difference equations is generated automatically based on Lagrange's equation of the second type in it input form [8]:

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{q}_i}\right) - \frac{\partial E_k}{\partial q_i} + \frac{\partial E_p}{\partial q_i} = Q_{qi} \ ,$$
$$i = 1,2,...,s \ ;$$

where:
E_k – the system kinetic energy;
E_p – the system potential energy;
q_i – i-th generalised coordinate;
Q_{qi} – generalised force corresponding to the i-th generalised coordinate;
s – the number of the system's degrees of freedom.

Assuming the forces of gravity, elasticity and attenuation as external forces, the equation has the following form:

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{q}_i}\right) - \frac{\partial E_k}{\partial q_i} = Q_{qi} \ , \ i = 1,2,...,s \ .$$

An attempt to link dynamic stresses (σ_d) (load) of any vibrating element in a vehicle with the speed of its vibration can be presented as:

$$\sigma_d = V_p \cdot \rho \cdot c \cdot k_d \quad \text{for } \sigma_m=0$$

where:
σ_d – dynamic stress;
V_p – peak amplitude of vibration speed, measured at the site of maximal dynamic deformations;
ρ – density of the material mass;
c – velocity of speed propagation in the material;
k_d – the dynamic coefficient depending on the energy concentration;
σ_m – working stress.

These equations can be used to identify failures in specific functional circuits of a vehicle. Diagnostic inference employs models of R relationship definite on the cartesian product of the sets of a vehicle failures and faults

$$F = \left\{ f_i ; i = \overline{1, I} \right\}$$

and diagnostic signals (vibrations, power, moment, efficiency, clearances, etc.)

$$S = \left\{ s_j ; j = \overline{1, I} \right\}: \ R_{F/S} \subset F \times S$$

The expression $f_i R_{sj}$ means that the diagnostic signal s_j identifies the fault f_i. For example, the occurrence of the failure f_i (clutch clearance) results in power drop and is a diagnostic signal with the value of *1*. Then the matrix of relationships $R_{F/S}$ can be shown as a binary diagnostic matrix, defined as follows:

$$r\left(f_i, S_j\right) = \begin{cases} 0 \Leftrightarrow \left\langle f_i, S_j \right\rangle \notin R_{F/S} \\ 1 \Leftrightarrow \left\langle f_i, S_j \right\rangle \in R_{F/S} \end{cases}$$

The relationships $R_{F/S}$ may be defined by assigning to each diagnostic signal a subset of failures $F(s_j)$, detected by such a signal:

$$F\left(s_j\right) = \left\{ f_i \in F : f_i R s_j \right\}$$

Binary diagnostic matrices can be determined by conducting simulation tests on a physical model of
a vehicle or station tests with programmed dynamic loads, and based on expert knowledge.

5. SUMMARY

With the development of car constructions, the dynamics of their work increase, which creates the demand for new diagnostic models based on failure-oriented physical models of vehicle motion. Such diagnostic models help improve the effectiveness of vehicle maintenance by adapting the vehicle inspections to operational input functions. Thanks to early detection of a fault in a vehicle it is possible to prevent a failure and to improve traffic safety.

This paper proposes an extended approach to the currently applied vehicle condition inspection, based on OBD II, and periodical inspection, by a vehicle dynamic load measurement. It proposes a method of generating a vehicle fault based on an analytic model of traffic. The method takes into account the static and dynamic properties of a vehicle throughout the period of its operation, with variable motion intensity, and enables early detection of failures which accumulate at variable random loads. The highest precision of computation is ensured by traffic models with elastic and damping constraints, with variable rigidity and damping.

However, there are some obstacles in this approach which are related to the structure of the diagnostic matrix, the absence of clear diagnostic relations, the effect of non-linearity of models which determine the failure development. As a consequence, it may result in missing the failures to which the adopted diagnostic signals are sensitive.

REFERENCE

1. PN-93/N-50191 *Niezawodność, jakość usługi*.
2. Prochowski L.: *Mechanika ruchu, pojazdy samochodowe*. WKiŁ. Warszawa 2005.
3. Michalski R, Wierzbicki S.: *Diagnostyka pojazdów samochodowych. Wybrane zagadnienia transportu samochodowego.* PNTTE. Warszawa 2005.
4. Bocheński C.: *Badania kontrolne samochodów.* WKiŁ. Warszawa 2005.
5. Merkisz J., Mazurek St.: *Pokładowe systemy diagnostyczne pojazdów samochodowych.* WKiŁ. Warszawa 2002.
6. Niziński S., Michalski R.: *Utrzymanie pojazdów i maszyn*. Wydawnictwo Technologii Eksploatacji-PIB. Radom-Olsztyn 2007.
7. Korbicz J., Kościelny J., Kowalczuk Zdz., Cholewa W.: *Diagnostyka procesów, Modele, Metody sztucznej inteligencji, zastosowania*. WNT 2002.
8. Szczyglak P.: *Wpływ własności dynamicznych agregatu maszynowego na jego stateczność*. Rozprawa doktorska. Politechnika Warszawska 2005.

Prof. dr hab. inż. **Ryszard MICHALSKI** jest kierownikiem Katedry Budowy, Eksploatacji Pojazdów i Maszyn na Wydziale Nauk Technicznych UWM w Olsztynie.

W działalności naukowej zajmuje się diagnostyką techniczną, niezawodnością, technologią napraw i analizą systemową eksploatacji pojazdów i maszyn roboczych. Posiada w swoim dorobku naukowym ponad 260 publikacji naukowych i naukowo-technicznych oraz 6 patentów. Jest autorem lub współautorem opracowań zwartych w tym: Pokładowe systemy nadzoru maszyn ze sztuczną inteligencją (1997), Metody oceny stanu technicznego, wyceny pojazdów i maszyn (1999), Diagnostyka obiektów technicznych (2002), Diagnostyka maszyn roboczych (2004), Utrzymanie pojazdów i maszyn (2007). Jest członkiem Zarządu Głównego Polskiego Towarzystwa Diagnostyki Technicznej, Redaktorem Naczelnym czasopisma „Diagnostyka”, członkiem zarządu Polskiego Naukowo-Technicznego Towarzystwa Eksploatacyjnego, członkiem zespołu środowiskowego Podstaw Eksploatacji Komitetu Budowy Maszyn Polskiej Akademii Nauk, Komitetu Motoryzacji i Energetyki Rolnictwa PAN Oddział w Lublinie.

TECHNICAL DIAGNOSTICS OF FOLDED OBJECTS. DIRECTIONS OF DEVELOPMENT

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Summary

The destruction processes of technical systems extort need the changes of supervising their technical state. Modern technical diagnostics methods are the tool of diagnosing their technical state what is the basis undertaken the decision. The technical diagnostics, he is one from basic sciences about the rational exploitation of objects next to tribology, reliability, safety and exploitation theory. The acquaintance of physical phenomena drawing ahead while functioning machine engine makes possible the qualification of qualitative relationships between destructive processes and the machine engine condition. The great dispersion of the initial properties of machine, how and undeterminancy and the continuity of aging and the cells processes and the tasks of the diagnostics machine which has to work out the specific gathering of diagnosing clearly use up outline methods.

The important problems of the article enclose: modelling the machine engines dynamics in the aspect of diagnostics, multidimentions and her the various ways of solving SVD, PCA, Date Fusion, diagnostics integrated with the object, artificial intelligence, diagnostic agent and system solutions of folded objects diagnostics.

Keywords: technical state, dynamics, destruction, symptoms, fault diagnostic system, development.

DIAGNOSTYKA ZŁOŻONYCH OBIEKTÓW TECHNICZNYCH. KIERUNKI ROZWOJU

Streszczenie

Procesy destrukcji systemów technicznych wymuszają potrzebę nadzorowania zmian ich stanu technicznego. Metody diagnostyki technicznej są narzędziem diagnozowania ich stanu technicznego, co jest podstawą podejmowanych decyzji. Diagnostyka techniczna, obok tribologii, niezawodności, teorii bezpieczeństwa i teorii eksploatacji jest jedną z podstawowych nauk o racjonalnej eksploatacji obiektów. Poznanie zjawisk fizycznych zachodzących w czasie funkcjonowania maszyny umożliwia określenie związków jakościowych między zachodzącymi procesami destrukcyjnymi a stanem maszyny. Duży rozrzut własności początkowych maszyny, jak i nieoznaczoność i ciągłość procesów starzenia i zużyć wyraźnie zakreślają cele i zadania diagnostyki maszyn, która musi wypracować sobie specyficzny zbiór metod i środków diagnozowania.

Ważne problemy tego referatu obejmują: modelowanie dynamiki maszyn w aspekcie diagnostyki, wielowymiarowość i jej różne sposoby rozwiązywania, SVD, PCA, Data Fusion, diagnostyka zintegrowana z obiektem, sztuczna inteligencja, agent diagnostyczny oraz systemowe rozwiązania diagnostyki obiektów złożonych.

Słowa kluczowe: stan techniczny, dynamika, destrukcja, symptomy, system diagnostyczny, rozwój.

1. INTRODUCTION

The presented considerations concern modern approach towards the dynamic state modeling objects with the use of descriptions and researches within the scope of identification, distinguishing the possibilities modern IT technologies and issues directly supporting different methods of machine dynamics evaluation and forming. Emerging evolutionary dynamic models improve the methodology and inference in dynamic state evaluation which is increasingly often used for the optimization of constructions and which supports exploitation decisions.

The search of ways and manners to describe the energetic wear and tear of machines and their elements already has some methodological premises and first applications. However, these are still theoretical considerations, here and there supported by practical researches approximate to the sought-after energetic mappings, not always, however, with a simple physical interpretation. The modeling of dynamic state changes and object functioning capability, taking into consideration variable load as well as individual approach towards the state changes of each element, is merely the beginning within the scope of evolutionary models application. Such models require an analytic base while at the same time appropriately reflect construction and exploitation changes taking place during the time of machine's life.

The knowledge of dynamic state and system structure allows to describe its behavior, as well as allows to create forecast models of system behavior in the function of dynamic evolution time, based on the model of technical state symptoms increase. Most frequently, however, equations describing system behavior in the function of dynamic evolution time are not known, which justifies the need of implementing new tools for dynamic state research. There is, therefore, the requirement of experimental verification for analytic models of technical objects, for a proper model is one which verifies itself in practice. Therefore, an experiment is only an inspiration for further research leading to construction optimization.

In the procedure of dynamic state experimental identification, we have distinguished: the methodology of information acquisition; the methodology of vibration estimators making; the methodology of information processing; the methodology of cause-and-effect concluding as well as the methodology of results static preparation. Within these ranges, many new programs have been offered within the framework of specified state identification procedures, verifying their usefulness in partial researches of the critical machines dynamic state.

Connection of the identification of the dynamic condition of machine with the technical diagnostics gives many new problems and shows on roads developmental fields.

2. DYNAMIC STATE IDENTIFI-CATION METHODS

Researches of dynamic characteristics and loads of machines are performed directly on objects and with the use their physical and mathematical models. Direct object examinations are very costly and time-consuming: they require a technically apt object and they often lead to its damage or destruction. In order to avoid many of these difficulties, in the process of creating new constructions or modernizing existing ones, more commonly and widely simulation methods and model examining techniques are implemented in place of researches on objects.

Dynamic is a science on how things change in time, and forces which are the cause of these changes [14, 15, 18]. The aim of the system dynamic study is understanding the rules of functioning, the changes of dynamic loads state, and foreseeing the proper behavior of the system. The necessity to know the system's dynamics stems from growing requirements set for machines. Along with the increase of their motion velocity and load values, the increase of requirements concerning their durability and reliability, as well as the necessity of automatic steering, the importance of the construction dynamics analysis increases.

Dynamics analysis of a system consists of the following stages [15, 18]:

- **stage I** – accurate determination of the system, its crucial characteristics and building a physical model whose dynamic characteristics will be, to an adequate degree, correspondent to characteristics of the real object;
- **stage II** – analytical description of dynamic phenomena reflected by a physical model, i.e. finding a mathematical model, differentia equations describing the motion of the physical model;
- **stage III** – studying dynamic characteristics of a mathematical model on the basis of solving differentia equations of the motion, determining the predicted motion of the system;
- **stage IV** – making design decisions, i.e. accepting physical parameters of the system, with modernization adjusted to expectations. The synthesis and optimization leading to obtaining required dynamic characteristics of the construction.

The presented procedure is based on the knowledge of the system's model, and conclusions drawn form actions on models depend on their quality.

3. TECHNICAL SYSTEM STATE ANALYSIS

The technical systems state analysis is compound for a set of mathematical procedures that they can be related to each other to develop analysis of superior order and to find relationships between procedures and states in different systems. The procedures can be classified according to the analysis stage in that they are executed: pre-processing, processing, post-processing.

There are many relationships that can be possible with the procedures, in this work is proposed only a few relations (see fig. 1), it is possible to formulate other relations of procedures to do another kind of methodologies or analysis.

PRE-PROCESSING

Import *.UNV format

The Universal file format (.UNV) is a set of ASCII file formats widely used to exchange analysis and test data. These files are text plane archives of data set from experimental tests and they are available to the public domain. The data set can come from data acquisition systems with different sources as acceleration, displacements, temperature, noise, etc. the data are in the dynamic time domain, t. Starting from .UNV files, the Measures Matrix, Mmtx, could

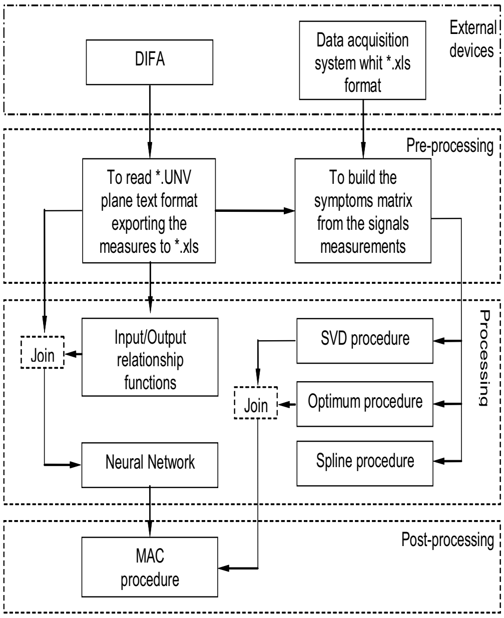


Fig. 1. Flow diagram of the technical systems state analysis

be made with the q observation vectors; the observation vectors have p observations, that means:

$$Mmtx = \overbrace{\begin{bmatrix} m_{11} & m_{12} & \cdots & m_{1q} \\ m_{21} & m_{22} & \cdots & m_{2q} \\ \vdots & \vdots & \ddots & \vdots \\ m_{p1} & m_{p2} & \cdots & m_{pq} \end{bmatrix}}^{Measures} \begin{array}{l} \to Observation_1 \\ \to Observation_2 \\ \quad\vdots \\ \to Observation_p \end{array}$$

To build symptom matrix

The symptoms result from a Measures Matrix, *Mmtx*, and are separated in two classes according to the related between the signals: single signals analysis, related signal analysis.

These distinctions are due to the mathematical differences procedures, and generate a classification of symptoms (see Table 1).

Table 1. Classification of symptoms

Indicators	Single symptoms	Indicators	Related symptoms
Amplitude	Average	Cross-correlation	Time in highest correlation
	RMS time domain		
	RMS frequency domain		
	RMS power		
	Pick		Frequency in highest correlation
	Kurtosis		
	Skewnees		
	Standard deviation		
	Shape factor		Amplitude in highest correlation
	Crest factor		
	Impulse factor		
	Looseness factor		
Frequency	Velocity of rice frequency		Covariance in highest correlation
	Displacement of Rice frequency		
	Harmonic index		
Auto-correlation	Correlation time	Coherence	Frequency
	Correlation frequency		
	Correlation Amplitude		
	Correlation covariance		
	Noise level [%]		
Probability	Distribution < 2(std)		Frequency of maximum coherence
	Density [0,2std]		
High order	Spectrum (Fast Fourier Transformation)		
	Frequency of Power spectrum		
	Bi-coherence		Amplitude of maximum coherence
	Tri-spectrum		
	Wigner Ville		
	Wavelet		

The symptom matrix is develop starting from the choose symptoms $Smtx = \{S_1, S_2, ..., S_j, ..., S_n\}$, where S_j represents the *j-th* symptom vector in the life time of the system θ, that means:

$$
\begin{array}{cc}
 & \begin{array}{c} S_j \\ \downarrow \end{array} \\
Smtx = & \begin{bmatrix} s_{11} & \cdots & s_{1j} & \cdots & s_{1n} \\ \vdots & \ddots & \vdots & & \vdots \\ s_{i1} & \cdots & s_{ij} & \cdots & s_{in} \\ \vdots & & \vdots & \ddots & \vdots \\ s_{m1} & \cdots & s_{mj} & \cdots & s_{mn} \end{bmatrix} \begin{array}{l} \rightarrow State\ \theta_1 \\ \vdots \\ \rightarrow State\ \theta_i \\ \vdots \\ \rightarrow State\ \theta_m \end{array}
\end{array}
$$

PROCESSING

SVD procedure

Given a set of *n* data, $Smtx = \{S_1, S_2, ..., S_j, ..., S_{n-1}, S_n\}$, where symptom vector $S_j \in \mathbb{R}^n$ a multidimensional space, and contain *m* stages in the time domain θ. The approach is focused to realize a linear analysis of the symptomatic space. A singular value and corresponding *singular vectors* of the matrix *Smtx* are a scalar σ and a pair of vectors *u* and *v* that satisfy

$$Smtx \cdot v = \sigma \cdot u,$$
$$Smtx^T \cdot u = \sigma \cdot v. \qquad (1)$$

With the *singular values* on the diagonal of the matrix Λ and the corresponding *singular vectors* forming the columns of two orthogonal matrices *U* and *V*, it is obtain:

$$Smtx \cdot V = U \cdot \Lambda \text{, and}$$
$$Smtx^T \cdot U = V \cdot \Lambda, \qquad (2)$$

Since *U* and *V* are orthogonal, this becomes the singular value decomposition.

The SVD of an *m*-by-*n* Smtx matrix involves an *m*-by-*m U*, and an *n*-by-*n V*. In other words, *U* and *V* are both square. If *Smtx* is square, symmetric, and positive definite, then its eigenvalues and singular value decompositions are the same. But, as *Smtx* departs from symmetry and positive definiteness, the difference between the two decompositions increases.

The singular value decomposition is the appropriate tool for analyzing a mapping from one vector space into another vector space, possibly with a different dimension. The procedure calculates the First Generalized Damage, GS1, and Evolution of Damage (see Fig. 2).

OPTIMUM method

Given a set of n data, $Smtx = \{S_1, S_2, ..., S_j, ..., S_{n-1}, S_n\}$, where symptom vector $S_j \in \mathbb{R}^n$, a multidimensional space, and contain m stages in the time domain θ, time of system life. The approach is focused to realize an analysis of the symptomatic space with statistical criteria.

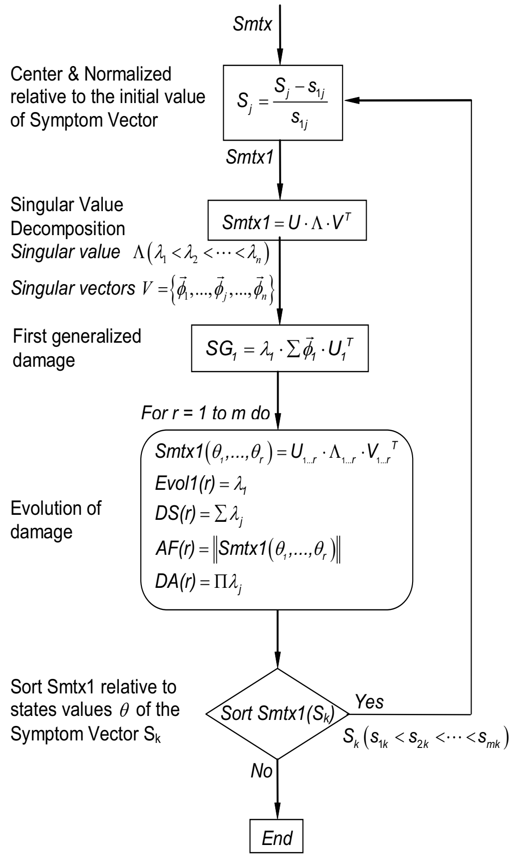


Fig. 2. Flow diagram of SVD

OPTIMUM establish the variation coefficient as the parameter $f1_j$,

$$f1_j = \frac{\sigma_j}{\bar{S}_j}, \qquad (3)$$

where σ_j is the standard deviation and $\bar{S}_j$ is the average, of the *j-th* symptomatic vector.

The parameter $f2_j$ can be calculate to three different ways:

- correlation coefficient,
- sensibility of symptoms,
- the Modal Assurance Criterion (MAC).

A time vector is created to computer the $f2_j$ in the correlation coefficient. The time frame Θ represents the existent connectivity between the states θ. Θ is a linearly spaced and increase vector, it is mean a degradation linearly progressive between the states $\{\theta_1, ..., \theta_j, ..., \theta_m\}$ is assumed; when θ_1 is the first stage of fault, θ_2 is the second stage of fault and consecutively.

Then the correlation coefficient is defined as:

$$f2_j^1 = \frac{C(\Theta, S_j)}{\sqrt{C(\Theta, \Theta) \cdot C(S_j, S_j)}}, \qquad (4)$$

C is the variance of the vector elements and its expression is:

$$C\left(\Theta,S_j\right)=E\left[\left(\Theta-\mu_\Theta\right)\left(S_j-\mu_{S_j}\right)\right], \tag{5}$$

where E is the mathematical expectation and $\mu_{S_j}=ES_j$.

The calculation of the sensibility of symptoms has similar expression to the variation coefficient in the parameter $f1_j$, therefore exist a relationship strongly linear. The expression of sensibility of symptoms is

$$f2_j=\left|\frac{S_{j\max}-S_{j\min}}{\bar{S}_j}\right|. \tag{6}$$

MAC procedure uses the time frame Θ defined at correlation coefficient to realize the calculus, then MAC assumes equal considerations in the stages characteristics θ. MAC expression has the form

$$f2_j=\frac{\left|\Theta^T\cdot S_j\right|^2}{\left|\Theta^T\cdot\Theta\right|\cdot\left|S_j^T\cdot S_j\right|}. \tag{7}$$

To carry out the maximization of the parameters f_i, a normalization of each element of them relative to the maximum value is executed:

$$fi_j^*=\frac{fi_j}{\max\left(fi_j\right)};\text{ where i = 1, 2.} \tag{8}$$

fi^* represents the statistical behavior of the each symptom performance, which later on will permit to mark the coordinates of ideal point.

It is possible to get an index to quantify the relationship between each symptom performance fi^* and the ideal performance. This relationship is established through trigonometric focus, the calculus of the existing norm L_j between the statistical symptoms performance points $\left(x=f1_j^*, y=f2_j^*\right)$ to the ideal point $(x=1, y=1)$

$$L_j=\sqrt{\left(1-f1_j^*\right)^2+\left(1-f2_j^*\right)^2}. \tag{9}$$

Then, L_i are converted weight expressions w_j (coefficients) to have better interpretation of results:

$$w_j=\frac{1/L_j}{\sum_{j=1}^{n}\left(1/L_j\right)}; \tag{10}$$

it is requisite $\sum w_j=1$.

The global algorithm OPTIMUM is described in the Fig. 3.

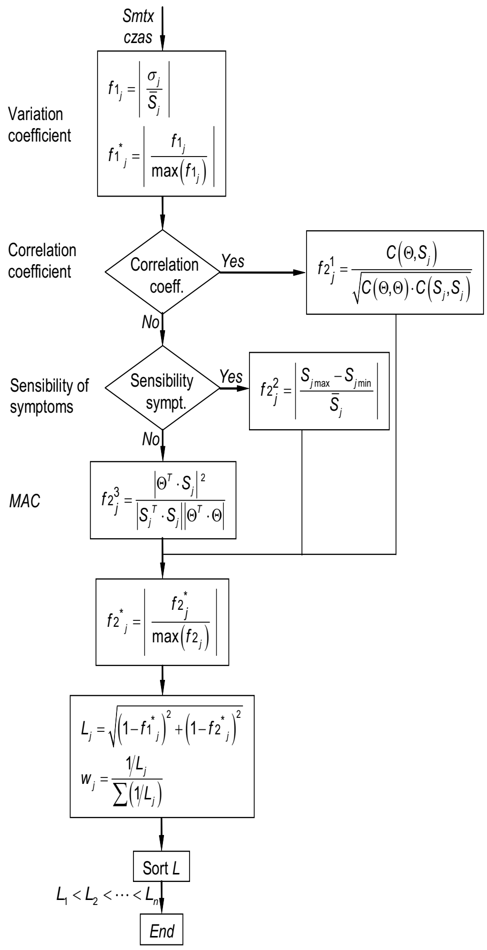


Fig. 3. Flow diagram of OPTIMUM

INPUT/OUTPUT RELATIONSHIP FUNCTIONS

Spectrum diagram

The spectrum diagram is the Discrete Fourier Transform (DFT) of the symptomatic vector S_j, computed with a Fast Fourier Transform (FFT) algorithm:

$$FFT(k)=\sum_{i=1}^{N}S_j\omega_N^{-(i-1)(k-1)}, \tag{11}$$

where, $\omega_N=e^{(-2\pi i)/N}$ is a *N* root of unity.

It is compute with a *Hanning* window:

$$\varpi[k+1]=0.5\left(1-\cos\left(2\pi\frac{k}{n-1}\right)\right), \tag{12}$$

and $k=0,\ldots,n-1$.

Transfer function

Given input signal vector *x* and output signal vector *y* of de measures matrix *Mmtx*, the relationship between the input *x* and output *y* is modeled by the linear and time-invariant transfer function $TF_{xy}(f)$. The transfer function is the quotient of the cross power spectral density $P_{xy}(f)$ of *x* and *y*, and the power spectral density $P_{xx}(f)$ of *x*:

$$TF_{xy}(f)=\frac{P_{xy}(f)}{P_{xx}(f)}. \qquad (13)$$

TF_{xy} uses a periodic *Hamming* window and estimates the transfer function at positive frequencies only; in this case, the output TF_{xy} is a function whit *(p+1)/2*, *p* is the quantity of measures. If *x* or *y* is vector whit complex elements, TF_{xy} estimates the transfer function for both positive and negative frequencies.

The cross power spectral density P_{xy} of the discrete-time signals *x* and *y* using the Welch's averaged, modified histograme method of spectral estimation. The cross power spectral density is the distribution of power per unit frequency whit 50% overlap.

Coherence

$Cohe_{xy}(f)$ finds the magnitude squared coherence estimate of the input signals *x* and *y* using Welch's averaged, modified periodogram method. The magnitude squared coherence estimate is a function of frequency domain with values a range of values $[0,1]$ that indicates how well *x* corresponds to *y* at each frequency. The coherence is a function of the power spectral density P_{xx}, P_{yy} of *x* and *y* and the cross power spectral density P_{xy},

$$Cohe_{xy}(f)=\frac{\left|P_{xy}(f)\right|^2}{P_{xx}(f)\cdot P_{yy}(f)}, \qquad (14)$$

$Cohe_{xy}(f)$ is calculated whit a periodic Hamming window of length to obtain eight equal sections of x and y, and the value to obtain and 50% overlap.

Cross correlation

It is applied the cross correlation function *XCF* between two unvaried and stochastic time series. The sample cross correlation function between *x* and *y* vectors is a vector of length *2(nLags)+1*, which corresponds to lags $\{0,\pm 1,\pm 2,...,nlags\}$. The central element of *XCF* contains the *0-th* lag cross correlation.

Optimization

The optimization procedure is realized following three basics steps:

- fitting the points to a polynomial expression,
- calculate the differential function of the polynomial expression,
- to find the roots of the differential function.

Next, it will be develop each of the steps.

Fitting the points to a polynomial expression

Given a set of *q* data, $Mmtx=\{M_1,M_2,...,M_j,...,M_{q-1},M_q\}$, where the measure vector $M_j\left(m_{1j},...,m_{ij},...,m_{pj}\right)$ have a discrete number of observations *p*, the task is calculate a new set of observations $M_j^*\left(m_{1j},...,m_{ij},...,m_{rj}\right)$, which $r>>p$, and M_j^* represent a polynomial function.

Polynomials are the approximating functions of choice when a smooth function is to be approximated locally. For example, the truncated Taylor series:

$$\sum_{i=0}^{n}(x-a)^i\ D^if(a)/i! \qquad (15)$$

provides a satisfactory approximation for $f(x)$ if f is sufficiently smooth and x is sufficiently close to a. But if a function is to be approximated on a larger interval, the degree, *n*, of the approximating polynomial may have to be chosen unacceptably large. The alternative is to subdivide the interval $[a,\ ...,\ b]$ of approximation into sufficiently small intervals $\left[\xi_j,\ ...,\ \xi_{j+1}\right]$, with:

$$a=\xi_j<\cdots<\xi_{j+1}=b, \qquad (16)$$

so that, on each such interval, a polynomial p_j of relatively low degree can provide a good approximation to **f**. This can even be done in such a way that the polynomial pieces blend smoothly. Any such smooth piecewise polynomial function is called
a spline. I. J. Schoenberg coined this term since a twice continuously differentiable cubic spline with sufficiently small first derivative approximates.

Spline interpolation

From the values of the underlying measure vector M_j at the points in the time vector *time* $\{\theta_1,...,\theta_j,...,\theta_m\}$ uses a cubic spline interpolation to find $M_j^*\left(m_{1j},...,m_{ij},...,m_{rj}\right)$, with $r=100$. It means, to involve the construction and subsequent use of a piecewise-polynomial approximation.

In the observation j-th, $,\Theta=\theta_j$ the ordered pair is $\left(M_j,\theta_j\right)$ and the spline interpolation calculate the piecewise-polynomial function f that satisfies

$$f\left(\theta_j\right)=M_j,\ all\ j. \qquad (17)$$

There are two commonly used ways to represent a polynomial spline, the *PP-form* and the *B-form*. A spline in *PP-form* is often referred to as a piecewise polynomial, while a piecewise polynomial in *B-form* is often referred to as a spline. This reflects the fact that piecewise polynomials and (polynomial) splines are just two different views of the same thing.

The PP-*form* of a polynomial spline of order *k* provides a description in terms of its breaks $\xi_j,\ ...,\xi_{j+1}$ and the local polynomial coefficients c_{ji} of its l pieces.

$$M^*(\theta)=\sum_{i=1}^{k}\left(\theta-\xi_j\right)^{k-1}c_{ji}, \qquad (18)$$

where $j=1,2,\ ...,l$.

A cubic spline is of order four corresponds to the fact that it requires four coefficients to specify a cubic polynomial.

Lagrange Interpolation

Calculate the Lagrange polynomial interpolation of *p-1* order from the measure vector $M_j(m_{1j},...,m_{ij},...,m_{pj})$

$$M_j^*(\theta) = \sum_{i=1}^{p} m_{ij} \cdot \frac{(\theta-\theta_0)(\theta-\theta_1)...(\theta-\theta_{i-1})(\theta-\theta_{i+1})...(\theta-\theta_p)}{(\theta_i-\theta_0)(\theta_i-\theta_1)...(\theta_i-\theta_{i-1})(\theta_i-\theta_{i+1})...(\theta_i-\theta_p)} \tag{19}$$

Approximation

The approximation finds the coefficients of a polynomial curve fitting $p(\theta)$ of 2, 3, 4 and 5 order that fits the data M_j, in a least squares sense. The polynomial has the expression

$$p(\theta) = p_1\theta^n + p_2\theta^{n-1} + \cdots + p_n\theta + p_{n+1}. \tag{20}$$

Differential function of the polynomial expressions

A procedure of numeric differentiation of the fitting function is realized

$$\frac{d\,M_j^*(\theta_i)}{d\,\theta} = \frac{M_j^*(\theta_{i+1}) - M_j^*(\theta_i)}{\theta_{i+1}-\theta_i}, \tag{21}$$

this procedure is a very simpler way to calculate the differential function, besides the computational calculus is really fast, and it is important when there are a lot of data. The exactitude is reasonable due to the high density of data; the function $M_j^*(m_{1j},...,m_{ij},...,m_{rj})$ result from the fitting process, then the number of observations is assured, $r = 100$.

Differential functions roots

To determinate the local maximum and minimum points of the function M_j^* is necessary solve the expression:

$$\frac{d\,M_j^*(\theta)}{d\,\theta} = 0. \tag{22}$$

The Incremental Quest method is described in Fig. 4.

Neural Network

Neural networks are composed of simple elements operating in parallel. These elements are inspired by biological nervous systems. As in nature, the network function is determined largely by the connections between elements. We can train a neural network to perform a particular function by adjusting the values of the connections (weights) between elements. Commonly neural networks are adjusted, or trained, so that a particular input leads to a specific target output (see Fig. 5).

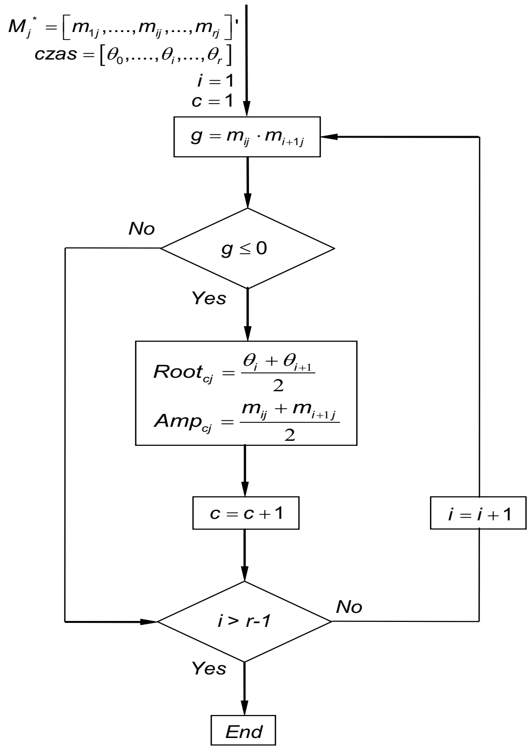


Fig. 4. Flow diagram of Incremental Quest

There, the network is adjusted, based on a comparison of the output and the target, until the network output matches the target. Typically many such input/target pairs are used, in this supervised learning, to train a network.

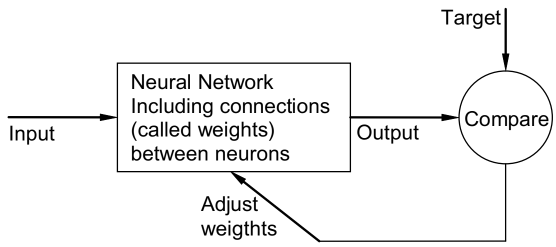


Fig. 5. Neural arquitecture

Batch training of a network proceeds by making weight and bias changes based on an entire set (batch) of input vectors. Incremental training changes the weights and biases of a network as needed after presentation of each individual input vector. Incremental training is sometimes refered to as adaptive training.

Each element of the input vector **$X=[x_1,x_2,..., x_p]$** is connected to each neuron input (see Fig. 6). The *i-th* neuron has a summer that gathers its weighted inputs and bias to form its own scalar output n_j. The various n_i taken together form an R-element net input vector *n*. Finally, the neuron layer outputs form a column vector a.

It is common for the number of elements in the input vector to a layer to be different from the number of neurons in the layer ($p \neq R$). A layer is not constrained to have the number of its inputs

equal to the number of its neurons. The developed neural network has two layers:
- in the first layer, the number of neurons is **R=2p**,
- in the second one, **R=1**.

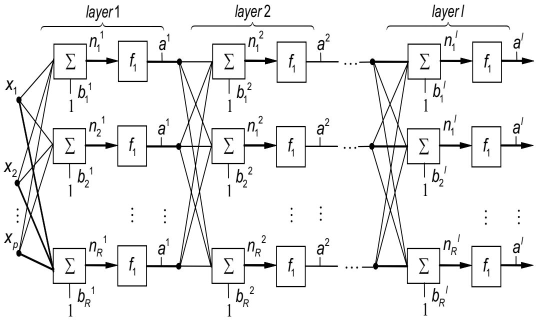


Fig. 6. Arquitecture of neural network
The sum of the weighted inputs and the bias forms the input to the transfer function *f*.

The training process requires a set of examples of proper network behavior - network inputs *x* and target outputs *y*. During training the weights and biases of the network are iteratively adjusted to minimize the network performance function. The performance function used for feedforward networks is the Sum Square Error (SSE), it means, sum squared error between the network outputs, *a*, and the target outputs t.

In the present work, the batch steepest descent training function is used. The weights and biases are updated in the direction of the negative gradient of the performance function. There is only one training function associated with a given network.

The larger the learning rate, the bigger the step. If the learning rate is made too large, the algorithm becomes unstable. If the learning rate is set too small, the algorithm takes a long time to converge.

POST-PROCESSING

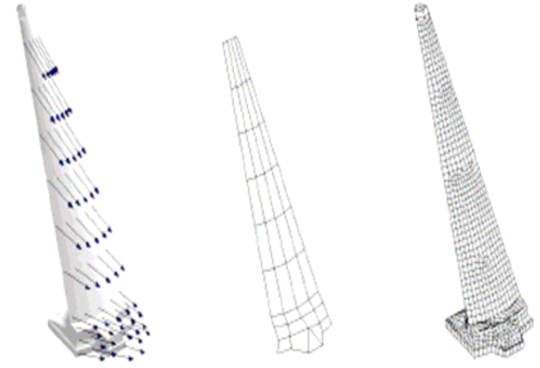
MAC procedure

Modal testing differs from system identification in the fact that responses are measured at a number of sensors which have a spatial distribution which allows the visualization of the measured motion. Visualization is key for a proper assessment of the quality of an experimental result. One typically considers three levels of models:

- Input/output models are defined at sensors.

In the fig. 7a, one represents these sensors as arrows corresponding to the line of sight measurements of a laser vibrometer. Input/output models are the direct result of the identification procedure.

- Wire frame models are used to visualize test results. They are an essential verification tool for the experimentalist. Designing a test well, includes making sure that the wire frame representation is sufficiently detailed to give the experimentalist a good understanding of the measured motion (see fig. 7b). With non-triaxial measurements, a significant difficulty is to handle the perception of motion assumed to be zero.
- Finite element models are used for test/analysis correlation. In most industrial applications (see Fig. c), test and FEM nodes are not coincident so that special care must be taken when predicting FEM motion at test nodes/sensors (shape observation) or estimating test motion at FEM DOFs (shape expansion).



a. Input/Output b. Wire frame c. Finite elements
Fig. 7. Representations of the measured motion

Correlation criteria seek to analyze the similarity and differences between two sets of results. Usual applications are the correlation of test and analysis results and the comparison of various analysis results. Ideally, correlation criteria should quantify the ability of two models to make the same predictions.

Since, the predictions of interest for a particular model can rarely be pinpointed precisely, one has to use general qualities and select, from a list of possible criterion, the ones that can be computed and do a good enough job for the intended purpose.

The Modal Assurance Criterion (MAC) and Pseudo Orthogonally Checks (POC) are very popular and useful criteria. Other criteria should be used to get more insight when you don't have the desired answer or to make sure that your answer is really foolproof. The following table gives a list of criteria.

Shape correlation tools can also be used to compare frequency responses. Thus the MAC applied to *FRF*s is sometimes called FRAC.

MAC is the most widely used criterion for vectors correlation (mainly because of its simplicity). The MAC is the correlation coefficient of vector pairs in two vectors sets, *RM* and *EM*. *RM* is the reference matrix or the observation of analytical analysis and it is defined as $RM = \{R_1,..,R_j,...,R_n\}$ where $R_j = \left[r_{1j},...,r_{ij},...,r_{mn}\right]^T$, and *EM* is the estimate matrix or experimental analysis and it is defined as $EM = \{E_1,..,E_j,...,E_n\}$ where $E_j = \left[e_{1j},...,e_{ij},...,e_{mn}\right]^T$, then MAC is given by:

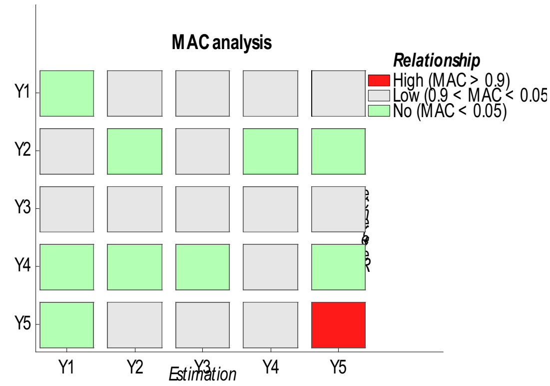
$$MAC_{ij} = \frac{\left|\{R_i\}^T \{E_j\}\right|^2}{\left|\{E_j\}^T \{E_j\}\right| \left|\{R_i\}^T \{R_i\}\right|} \qquad (23)$$

Table 2. Different correlation criteria

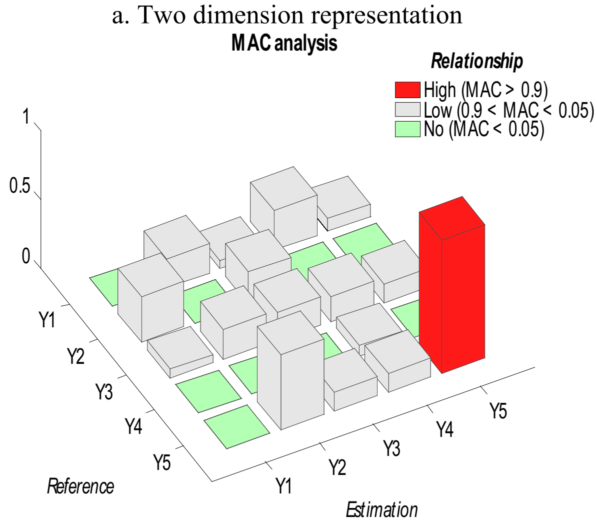
Criterion	*Description*	*Advantage*	*Limitation*
MAC	Modal Assurance Criterion. The most popular criterion for correlating vectors. Insensitive to vector scaling. Sensitive to sensor selection and level of response at each sensor.	It can be used in all cases. A MAC criterion applied to frequency responses is called FRAC.	It can give very misleading results without warning.
POC	Pseudo Orthogonally Checks. Required in some industries for model validation. This criterion is only defined for modes since other shapes do verify orthogonality conditions.	It gives a much more reliable indication of correlation than the MAC.	It requires the definition of a mass associated with the known modeshape components.
Error	Modeshape pairing (based on the MAC) and relative frequency error and MAC correlation.	The same of MAC.	The same of MAC.
Rel	Relative error. Insensitive to scale when using the modal scale factor.	Extremely accurate criterion.	It does not tell much when correlation poor.
COMAC	Coordinate Modal Assurance Criteria compare sets of vectors to analyze which sensors lead poor correlation.	A very fast tool giving more insight into the reasons of poor correlation.	It does not systematically give good indications.
MACCO	What if analysis, where coordinates are sequentially eliminated from the MAC.	It is more precise than COMAC.	It is slower.

For two vectors that are proportional $MAC_{ij} \approx 1$ (perfect correlation). If $MAC_{ij} \geq 0.9$ is generally considered as much correlated. If $0.9 < MAC_{ij} \leq 0.6$ should be considered with much caution (they may or may not indicate correlation).

Next is showed - fig. 8 - the 2D and 3D representation of MAC. The height of the patches associated to each vector pair are proportional to MAC value, the colour is relative to high and low limits. The MAC compute vector pairs for all vectors



a. Two dimension representation



b. Three dimension representation

Fig. 8. MAC diagram

in the two sets, it is means, one way to represent the analysis is, each vector from data set *RM* is compared with each vector from data set *EM.*

The product of a couple vectors is a scalar quantity. If R_j and E_j are identical the numerator and denominator are equal, giving a MAC value of 1. If the two vectors are orthogonal to one another the numerator is 0 and hence the MAC value is zero. In the Fig. is shown a two identical set of vectors non-orthogonals.

The MAC plot is an *n* x *n* grid (*n* is the number of vectors being compared) enabling comparison of all vectors from data set *RM* with all modes from data set *EM.* The leading diagonal represents the correlation between the vectors of the same number from data sets *RM* and *EM.* If the ordering of the vectors in each set is the same then the correlation here should be high.

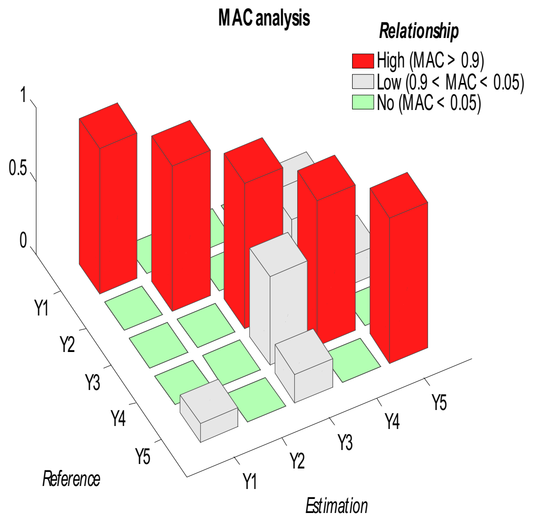


Fig. 9. MAC with identical matrix

5. SUMMARY

Initial qualities in case of machines are usually geometric features (e.g. clearance, element permanent set) and material characteristics (e.g. immediate resistance, fatigue strength) of their elements. The set of all the state features: geometric features, material and machine's functional parameters, necessary from the point of view reliability, can be treated as a multidimensional random process because many of the features change randomly in the machine's exploitation course.

The course of changes in the technical state due to external reactions, depends not only on the level of those reactions but also on the above mentioned features at the initial moment $t = 0$, i.e. on the initial technical state. The object's technical state at the moment t depends, therefore, on time which elapsed from the beginning of the exploitation, on the course of external reactions within the whole time range from t_0 to t, as well as on the initial technical state. The values of the accepted amplitude features are directly dependent on the machine's technical state. Amplitude features are qualities directly connected with the state, useful for an easy theoretical mapping of appearing (in time) changes of the object's proper functioning abilities.

Tools for the state evaluation are methods of dynamic state research, supported by modern IT technologies to which this work is dedicated. Technical reality is the result of the models analysis which describe it more or less properly. The process whose aim is to build the best operational model (mathematical or empirical) is called the identification process. It is composed of the problems: modeling, experiment, estimation and model verification.

The problems of optimization are important question. This area of investigations, in this the reduction of information quantity and search the best symptoms of destruction state elements of construction. The proposed methods of PCA, SVD, OPTIMUM permits on choice of the best measures by defined the criterions of quality usefully.

LITERATURE

1. Ameliańczyk A.: *Optimization multicriterion in problems steering and management*. Ossolineum, Wrocław 1984.
2. Bendat J. S., Piersol A. G.: *Method of analysis and measurement of random signals*. PWN, Warszawa 1996.
3. Bishop R. D., Gladwell G. M.: *Matrice analysis of tremblings*. PWN, Warszawa 1972.
4. Broch J. T.: *Mechanical Vibration and Shock Measurements*. Brüel & Kjaer, 1980.
5. Cempel C.: *Practical of vibroacoustic*. PWN, Warszawa 1989.
6. Eykhoff P.: *Identification in dynamic arrangements*. BNInż., Warszawa 1980.
7. Giergiel J., Uhl T.: *Identification of mechanical arrangements*. PWN, Warszawa 1990.
8. Giergiel J.: *Mechanical trembling.* AGH, Kraków 2000.
9. Kaczmarek J.: *Basis of theory of trembling and dynamics of machines*. WSM, Szczecin 1993.
10. Moczulski W., Ciupke K. (Eds.): *Knowledge acquisition for hybrid system sof risk assessment and critical machinery diagnosis*. Part V. ITE Radom 2008 pp.295-356.
11. Morrison F.: *Art of modeling of dynamic arrangements*. WNT, Warszawa 1996.
12. Paczkowski W. M.: *Chosen problems of discreet evolutionary optimization*. Szczecin 1999.
13. Tylicki H.: *Optimization of process of forecasting of technical state of motor vehicles*. ATR Bydgoszcz 1999.
14. Uhl T., Lisowski W.: *Practical problems of analysis of modal construction*. CCATIE, Kraków 1996.
15. Uhl T.: *By computer helped identification of models of mechanical constructions*. WNT, Warszawa 1997.
16. Żółtowski B., Niziński S.: *Modelling process of exploitation machines*. Bydgoszcz 2002.
17. Żółtowski B.: *Investigation of dynamic machine*. ISBN – 83-916198-3-4, Bydgoszcz 2002.
18. Żółtowski B., Cempel C. (red.): *Diagnostics engineering of machines*. ITE, Radom 2004.

GEAR FAULT DETECTION USING VIBRATION ANALYSIS

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Summary

The article includes results of the team's research work on vibroacoustic diagnostic of gearbox components' faults. A review of simulation and experimental researches that aimed at elaboration of methods which would enable early identification of teeth faults in the form of working surface pitting, spalling of tooth crest, crack at the tooth bottom as well as partial breaking of a tooth, is presented. Assessment of selected methods of processing the vibroacoustic signals during the detection of gear faults has been carried out while faults occur in gear bearings working under various conditions. The initially processed vibration signals analyzed within time and frequency domains constituted a basis for preparation of detection measures that were sensitive to early stages of damage. The measures obtained as a result of simulation and experimental tests were used to construct a set of neuron classifier models to diagnose the type and degree of toothed wheels faults with a validation error below 5%. The achieved qualitative and quantitative conformity of simulation and experimental research results has shown that application of an expanded and identified dynamic model of the gear in a power transmission system enables the acquisition of reliable diagnostic relations.

Keywords: gearbox, vibration, gear fault, diagnostics.

WYKRYWANIE USZKODZEŃ PRZEKŁADNI NA PODSTAWIE ANALIZY DRGAŃ

Streszczenie

W artykule zawarto wyniki prac zespołu w zakresie diagnostyki wibroakustycznej uszkodzeń elementów przekładni zębatych. Przedstawiono przegląd badań symulacyjnych i doświadczalnych, których celem było opracowanie metod pozwalających na wczesną identyfikację uszkodzeń zębów w postaci pittingu powierzchni roboczych, wykruszenia wierzchołka, pęknięcia u podstawy zęba oraz częściowego wyłamania zęba. Dokonano oceny efektywności wybranych metod przetwarzania sygnałów wibroakustycznych w procesie wykrywania uszkodzeń kół zębatych przy jednoczesnym występowaniu uszkodzeń łożyskowania przekładni pracujących w różnych warunkach. Wstępnie przetworzone sygnały drganiowe analizowane w dziedzinie czasu i częstotliwości stanowiły podstawę do opracowania miar diagnostycznych wrażliwych na wczesne stadia uszkodzeń. Miary otrzymane w wyniku symulacji oraz badan doświadczalnych wykorzystano do budowy zestawu wzorców klasyfikatora neuronowego diagnozującego rodzaj i stopień uszkodzenia kół przekładni z błędem walidacji poniżej 5%. Uzyskana zgodność jakościowa i ilościowa wyników badań symulacyjnych i doświadczalnych wykazała, że wykorzystanie rozbudowanego i zidentyfikowanego modelu dynamicznego przekładni w układzie napędowym umożliwia pozyskanie wiarygodnych relacji diagnostycznych.

Słowa kluczowe: przekładnie zębate, drgania, uszkodzenia kół, diagnostyka.

1. INTRODUCTION

Toothed gears are designed for cooperation with sources of propulsion of higher and higher power and are exposed to high external dynamic loads. In the design process, designers are trying to achieve the highest possible ratio of power transmitted through wheels to their weight. A gear working under high load should be either sporadically or constantly monitored to ensure safe operation. The techniques of diagnosing the technical condition of gears are oriented towards identification of faults of their components in the initial phase of fault occurrence.

One of the most frequently applied methods is measurement of the vibroacoustic signal and on this basis, determination of measures sensitive to different types of damage.

The rate of propagation of vibroacoustic disturbance caused by a changed condition of a gear makes the vibroacoustic methods particularly useful in diagnosing early stages of faults.

Recently, techniques of contactless measurement of vibration have developed considerably. They enable measuring the vibration speed of rotating bodies. Measurements of the vibration speed of rotating shafts make it possible to eliminate the consequences of complex and variable in time transmittance of the bearing/gearbox system, which allows obtaining effective symptoms of faults.

An essential issue in the diagnosing of gearboxes is the ability to differentiate between various phenomena influencing the vibroacoustic signal connected with both, normal operation of the gearbox and development of faults in its components.

Toothed wheels and bearings are the gearbox components most susceptible to damage. The modern diagnosing methods of gearboxes are oriented to the detection of early phases of fault occurrence, e.g. spalling of tooth crest, crack at the tooth bottom, fatigue chipping of the upper layer, or galling of the interacting surfaces. In the diagnosing of rolling bearings, detection of initial stages of damage to the bearing race or rolling elements is extremely important.

The development of computer hardware and signal processing methods enables using advanced signal analysis methods in the time-frequency plane. The methods allow observation of non-stationary impulse disturbance induced by faults in their initial stages.

Experimental research on gearboxes is difficult to carry out, as well as costly and time-consuming, and in the case of gears produced as single items, most often impossible. In such cases, it is justified to use an identified dynamic model of a gear in a power transmission system [5]. Such model will allow making a series of numerical experiments and analysis of the simulation results will enable expanding the diagnostic knowledge and obtaining higher certainty of the diagnosis.

For the monitoring of the condition of many power transmission units, expert systems are created, which use artificial intelligence components. A properly constructed and taught system can automatically recognize the existing faults. Neuron networks in the process of learning acquire the ability of generalizing knowledge, which allows detection of faults in their early phases, often not noticed during diagnosing. A basic problem while constructing such systems is to define a set of input data and acquire an appropriately large set of training data [1].

2. SIGNAL ANALYSIS METHODS IN THE DIAGNOSING OF GEARBOXES

In vibroacoustic diagnostic of gearboxes, a number of different signal analysis methods are used [2, 6, 7, 13, 14]. Figure 1 presents a general classification of the existing signal processing methods. The basis consists of a properly selected vibroacoustic signal (WA) which, in order to eliminate incidental disturbance, can be synchronously averaged and from which, by applying appropriate filtration, a differential and residual signals are obtained, as well as a signal containing only bands of meshing frequency and its harmonics. On the basis of the first two signals, numerical estimators of amplitude and dimensionless discriminants are calculated. Analysis methods are used in time domain, frequency domain, or in time and frequency domain, as well as statistical moments of higher orders. Those dimensionless discriminants which are based on statistical moments of higher orders (FM4, M6A, M8A, NA4 ...) are most often determined using differential and residual signals [1, 4, 10, 12].

In case of simultaneous occurrence of faults in wheels and bearings, it is justified to apply comb filtration, thus enabling separation of vibration signals generated by different faults [9].

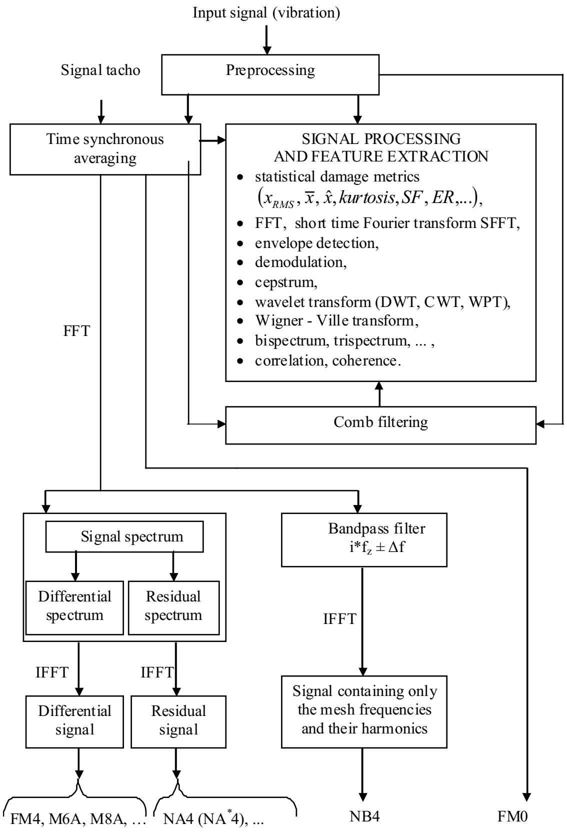

Fig. 1. Methods of vibroacoustic signal processing.

3. MODEL OF TOOTHED GEAR WORKING IN A POWER TRANSMISSION SYSTEM

In the simulation tests, a dynamic model was used representing a toothed gear working in a power transmission system (Fig.2). The model was created in the *Matlab–Simulink* environment. It takes into account the characteristics of an electric driving motor, single-stage gear, clutches and working machine.

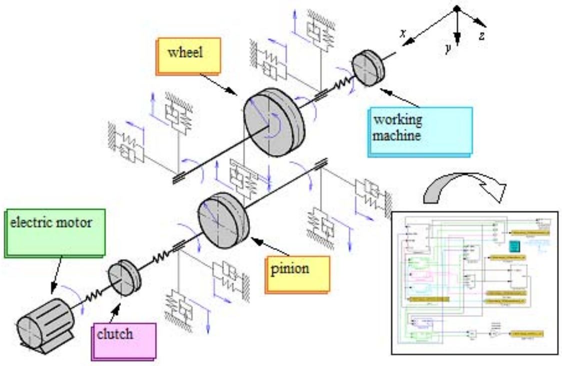

Fig. 2. Dynamic model of toothed gear in a power transmission system.

The simulation model allowed taking account, in the calculations, of cyclic and random deviations which occurred in the mesh [3, 5, 11].

The utilization of a dynamic model of gear in a power transmission system was possible owing to very good identification and tuning of the model parameters. It gave very high qualitative and quantitative consistency of simulation results with the results obtained from tests of a real object [1, 5, 6, 9].

The gear model also enabled mapping of local faults consisting of a crack at the tooth bottom or chipping of tooth crest, and faults of rolling bearings' components.

The chipping of tooth crest throughout its length was modeled as tooth contact section shortened by a value equal to a predetermined part of pitch. The effect of a changing tooth contact section length on the meshing time was taken into account as well. Chipping of tooth crest in a pinion results in a premature finish of operation by a couple of teeth, whereas chipping of the reference cone apex results in a delayed start of cooperation between the couple of teeth.

A crack at the tooth bottom is accompanied by reduced rigidity of meshing. Therefore, a fault of this sort was mapped as a percentage reduction of rigidity of the cooperating couple of teeth in relation to a couple without faults.

Analysis of the effect of the crack depth in the tooth root on a change in mesh rigidity was presented in monograph [9].

Faults of working surfaces of cooperating elements of rolling bearings were modeled in a similar way, by reducing the bearing rigidity while the damaged piece of surface was in the load transmission zone [9].

4. DETECTION OF TOOTH CREST CHIPPING

Initial phases of tooth crest chipping development in a toothed gear do not significantly influence the general level of vibration. Hence, detection of damages of this type in the early phase is very difficult. It appears from the previous research that the use of a contactless laser measurement of transverse vibration speed of rotating gear shafts, combined with advanced methods of signal processing, such as Wigner-Ville distribution or continuous wavelet transform, enables detecting such fault in its initial stage. This method of measurement eliminates the influence of complex transmittance of the bearing - gear casing system [9].

Fig. 3 shows the results of time and frequency analysis *WV* of differential signal.

In the *WV* distribution, an increase of amplitude occurs within the pinion turn angle corresponding to the cooperation of the damaged tooth.

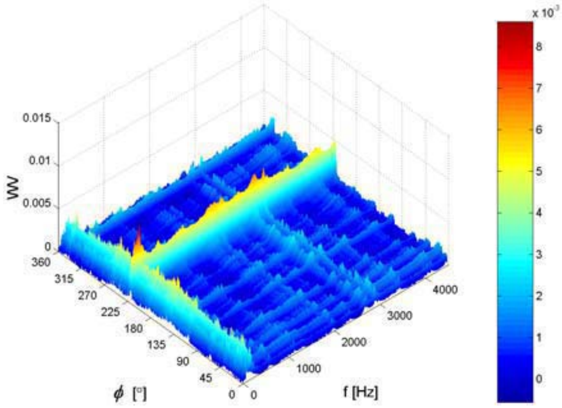

Fig. 3. *WV* Time/frequency distribution of differential signal – measurement of vibration speed of pinion shaft in the direction of the force acting between the teeth – 1 mm chip of the pinion tooth.

For easier interpretation of the results obtained, summation was performed of *WV* distribution discrete values (formula 1) in accordance with the equation:

$$S_{WV}(\phi)=\sum_{k_{WV}=A}^{B} WV(l_{WV},k_{WV}) \qquad (1)$$

$$WV(l_{WV},k_{WV})=WV(t,f) \qquad (2)$$

where:

l_{WV}, k_{WV} – discrete values of time and frequency, respectively,

A, B – discrete values corresponding, respectively, to limit frequencies of the summation interval f_A, f_B.

In the presented in Fig. 4 sum of *WV* distribution, local maxima coming from the chipping of the tooth crest in the pinion are clearly visible, which facilitates localization of the fault.

The sums $S_{WV}(\phi)$ of *WV* distributions, obtained from measurements (Fig. 4) and simulations (Fig. 5) show high consistency.

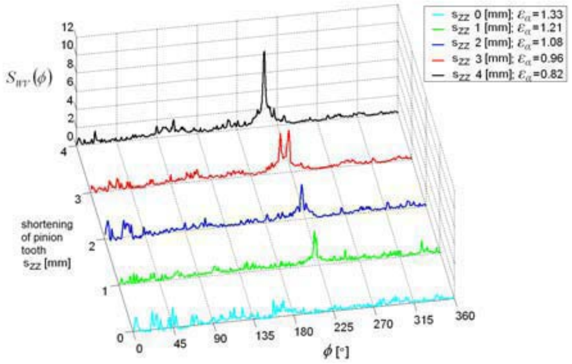

Fig. 4. The sum of time/frequency *WV* distribution in 0÷4500 [Hz] band, generated from a differential signal of pinion shaft vibration speed measured in the direction of the force acting between the teeth – experimental research result.

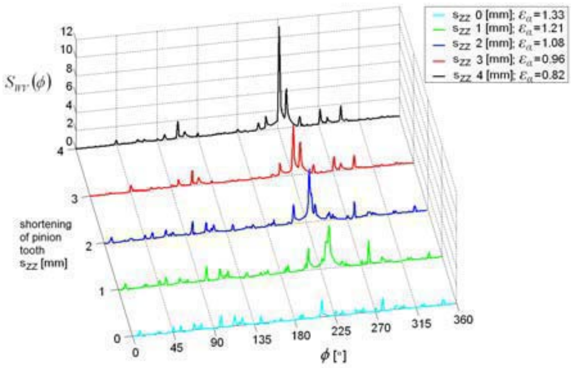

Fig. 5. The sum of time/frequency *WV* distribution in 0÷4500 [Hz] band, generated from a differential signal of pinion shaft vibration speed recorded in the direction of the force acting between the teeth – simulation result.

Based on the research, it can be affirmed that processing of the signal of transverse vibration speed of gear shafts, measured in the direction of the force acting between the teeth, and the use of analyses in, simultaneously, time and frequency, or time and scale domains (CWT), facilitate effective detection of chipping of a tooth crest. Using the sums of WV distribution (Fig. 4, 5) or scalograms [9], measures where built enabling the evaluation of the tooth chip depth.

Computer simulations of a toothed gear with damaged components, made using its expanded and identified dynamic model, made it possible to verify the measures of the case of tooth crest chipping during the operation of gears of different geometrical parameters of toothed wheels, at different rotational speeds, loads or deviations in wheel workmanship.

5. NEURON CLASSIFIER OF TOOTHED WHEEL FAULT

The results of research connected with the structure of neuron classifiers, which were taught and verified on the basis of data obtained from a simulation model of a toothed gear working in a power transmission system, were presented in monograph [1].

For constructing the models, signals of transverse vibration speed of wheel shaft, analyzed by means of *FFT* and *CWT,* were used. Based on preliminary tests, an artificial neuron network of *MLP* type was chosen as the classifier. Sets of models were built on the basis on vibration signals of a toothed gear working in the following conditions:

- $M = 138$ [Nm], $n = 900$ [r.p.m.],
- $M = 138$ [Nm], $n = 1800$ [r.p.m.],
- $M = 206$ [Nm], $n = 900$ [r.p.m.],
- $M = 206$ [Nm], $n = 1800$ [r.p.m.].

A neuron classifier was built, capable of recognizing the degree of fault in wheel teeth in the form of a crack at the tooth bottom or chipping of tooth crest in a gear working at different shaft speeds and different load torques.

It was assumed that the following classes would be recognized:

- a crack at the tooth bottom in the form of percentage reduction of rigidity of a couple of teeth in case of such fault:
  - class 1] 0 ÷ 9 %,
  - class 2] 10 ÷ 19 %,
  - class 3] 20 ÷ 29 %,
  - class 4] 30 ÷ 40 %,
- chipping of tooth crest, in the form of per cent length of pitch, by which the tooth contact section shortens as a result of such fault:
  - class 5] 0 ÷ 9 %,
  - class 6] 10 ÷ 19 %,
  - class 7] 20 ÷ 29 %,
  - class 8] 30 ÷ 40 %,

The training process and the testing validation process are presented in Fig. 6.

When using both, the models obtained from *FFT* analysis and *CWT* analysis, the authors managed to build neuron classifiers which can diagnose the type and degree of fault of a gear wheel tooth with a validation error below 5%.

Irrespective of the model building method, the testing error for data taken from a real gear was ca. 60%.

In the successive stage, apart from data taken from a dynamic model of a gear, part of data coming from tests of a real gear were added to the training set.

The testing error value obtained in that case was ca. 20% in the case where for the construction, layers of both *sigmoidal* and *tangensoidal* hidden neurons were used [1].

The research has shown that it is possible to build a neuron classifier of two fault types of wheel teeth in different stages of advancement for a gear working at different rotational speeds of shaft and with different load torques.

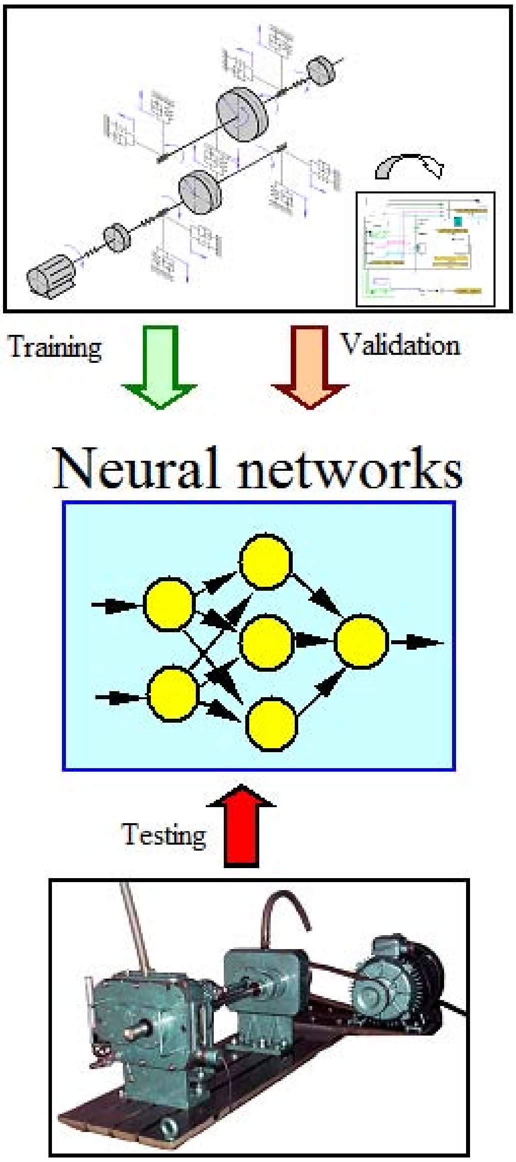

Fig. 6. Chart of the adopted methodology of working with neuron classifiers [1].

6. CONCLUSIONS

As results from the research presented in the paper, the methods applied to process the signal of transverse vibration speed of shafts, measured in the direction of the force acting between the teeth, and the use of analyses in, simultaneously, time and frequency or time and scale domains (CWT), facilitate effective detection of various faults of toothed wheels.

The achieved high qualitative and quantitative conformity of simulation and experimental research corroborates the fact that application of an expanded and identified dynamic model of a gearbox working in a power transmission system for simulating the faults of its components enables the acquisition of credible diagnostic relations.

The simultaneous application of experimental methods and computer simulations has facilitated the creation of input data to the system diagnosing local damage of wheels, working based on artificial intelligence methods. The research presented in the monograph [1] shows that artificial neuron networks, taught using data obtained from the model and from a real gearbox, offer the highest correctness of classification of the type and degree of fault in gears.

REFERENCES

[1] Czech P., Łazarz B., Wojnar G.: *Wykrywanie lokalnych uszkodzeń zębów kół przekładni z wykorzystaniem sztucznych sieci neuronowych i algorytmów genetycznych*. ITE Katowice - Radom 2007.

[2] Dąbrowski Z.: *Różne metody diagnozowania przekładni zębatych na podstawie pomiaru drgań i hałasu*. XXII Ogólnopolskie Sympozjum Diagnostyka Maszyn, Węgierska Górka marzec 1995 r., s. 35÷44.

[3] Dąbrowski Z., Radkowski S., Wilk A.: *Dynamika przekładni zębatych – Badania i symulacja w projektowaniu eksploatacyjnie zorientowanym*. Wydawnictwo i Zakład Poligrafii Instytutu Technologii Eksploatacji w Radomiu Warszawa – Katowice – Radom 2000.

[4] Lebold M., McClintic K., Campbell R., Byington C., Maynard K.: *Review of Vibration Analysis Methods for Gearbox Diagnostics and Prognostics*. 54th Meeting of Society for Machinery Failure Prevention Technology, Virginia Beach, VA, May 1-4, 2000, s. 623÷634.

[5] Łazarz B.: *Zidentyfikowany model dynamiczny przekładni zębatej w układzie napędowym jako podstawa projektowania*. Wydawnictwo i Zakład Poligrafii Instytutu Technologii Eksploatacji w Radomiu, Katowice-Radom 2001.

[6] Łazarz B., Madej H., Wilk A., Figlus T., Wojnar G.: *Diagnozowanie złożonych przypadków uszkodzeń przekładni zębatych*. ITE Katowice - Radom 2006.

[7] Łazarz B., Wojnar G.: *Detection of Early Stages of Pinion Tooth Chipping in Transmission Gear*. Machine Dynamics Problems 2003,vol. 27, No 3, s. 23÷34.

[8] Łazarz B., Wojnar G.: *Model dynamiczny układu napędowego z przekładnią zębatą*. XVII Ogólnopolska Konferencja Przekładnie Zębate, Węgierska Górka 09÷11.10.2000r., s. 101÷108.

[9] Łazarz B., Wojnar G., Czech P.: *Wibrometria laserowa i modelowanie – narzędzia*

współczesnej diagnostyki przekładni zębatych. ITE Katowice - Radom 2007.

[10] Madej H.: *Wykorzystanie sygnału resztkowego drgań w diagnostyce przekładni zębatych*. Diagnostyka, vol. 26, 2002, s. 46÷52.

[11] Müller L.: *Przekładnie zębate - dynamika*. WNT, Warszawa 1986.

[12] Stewart R. M.: *Some useful data analysis techniques for gearbox diagnostics*. Report MHM/R/10/77. Machine Health Monitoring Group. Institute of Sound and Vibration Research. University of Southampton 1977.

[13] Wilk A., Łazarz B., Madej H.: *Metody wczesnego wykrywania uszkodzeń w przekładniach zębatych*. Przegląd Mechaniczny, nr 3, 2002, s. 14÷18.

[14] Wilk A., Łazarz B., Madej H., Wojnar G.: *Analiza zmian wibroakustycznych symptomów diagnostycznych w procesach zużyciowych kół zębatych*. Materiały XXX Jubileuszowego Ogólnopolskiego Sympozjum Diagnostyka Maszyn, Węgierska Górka 03÷08.03.2003 r.

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HUMAN AND COMPUTER RECOGNITION OF NIGHTTIME PEDESTRIANS

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Summary

This study investigates recognition and detection abilities of nighttime pedestrians by observers and using a photographic method. The examination of the visibility of nighttime pedestrians is done and afterwards evaluated by two methods. In the first method observers were asked to detect a pedestrian from a slowly moving vehicle. In each attempt, detection distance was recorded. From the place of detection, a digital photography was taken from the still vehicle. Analysis of the digital photography in computer graphic software is the keystone of the second method. The article also shows potential effect of retroreflector positioning on recognition of nighttime pedestrians.

Keywords: pedestrian, recognition, detection, visibility, retroreflector.

1. INTRODUCTION

Reduced visibility is the major contributor to pedestrian accidents at night. The visible distance of dark-clad pedestrians is typically less than one-third of the stopping distance at normal highway speed. [1] Statistics show, that number of driven kilometres is minor during nighttime traffic, but accidents, which happen in dark or in lower visibility conditions are usually tragic. When scaled by the number of miles driven, pedestrian fatality rate is three times higher at night. Part of the reason is a bigger chance of driver drinking and fatigue, but the critical factor is lower visibility due to reduced ambient illumination. [3]

This study is oriented on investigating and evaluating of visibility of still object – pedestrian. Measurements were made during night. In this article, there are included: 3 measurements, in 2 different sites, with 2 different vehicles, with 2 different groups of observers. Measurements and evaluation were made using 2 methods. In the first method, let us say "human method", we measured distances, when pedestrian was recognized by observer from the moving vehicle. In the second method, let us say "computer method", digital photographs were evaluated using a computer software. These digital photographs were taken from the still vehicle right from the place, where observer had detected a pedestrian. It allowed us to compare these two methods. We could analyze applicability and reliability of computer method. Furthermore, in 2 measurements there was investigated an effect of retroreflector positioning on recognition of silhouettes of pedestrians.

2. METHOD

2.1. Task

Observers performed a recognition task while seated in the rear passenger's seat of a vehicle, with head positioned above and between front seat backs. Two vehicles were used, in each case, with low beam lamps. Specifically, an observer's task was to say stop right in the moment of recognition of a silhouette of a pedestrian. The pedestrian was standing on the right side of the road, ahead of the vehicle. In each attempt, the vehicle was stopped as soon as possible, always with the same, specially trained driver. The speed of the vehicle was being held approximately on the level of 17 km/h.

2.2. Observers

35 observers participated in this study. 31 observers were aged between 20 and 27 and 4 were aged between 45 and 60. There were 11 females and 25 males in general. All observers were licensed drivers.

2.3. Sites

There are three measurements included in this study from two different sites. The first measurement was done on 19th June 2007 in Dresden, Germany. The second and the third measurement was done on 8th December 2007 in Dolný Hričov, Slovakia.

Since other vehicles, either preceding or oncoming, would influence the visibility of the pedestrians, the measurements were conducted on rural roadway section with no traffic (Dresden) and on the landing runaway of the airport Žilina in the time without operation (Dolný Hričov).

2.4. Equipment

There were two different vehicles with different headlights used in this study. In the first measurement, we used Mercedes Benz S 500 (made in 2007) with bi-xenon factory headlights. In the second and the third measurements, we used Škoda Octavia 1,6 GLX (made in 1999) with factory headlights, but with new bulbs OSRAM Bilux H4 12V, 60/55 W.

For measuring distances, we used measuring tape and white chalk. For taking digital photographs, we used digital SLR camera Nikon D70s with lens AF-S DX Zoom-Nikkor 18-70mm f/3.5-4.5G IF ED. We used tripod.

2.5. Procedure

The observers were seated in the middle of rear seat. There were two people in the vehicle during one measurement – driver and observer. They were told that this study investigated how well drivers can recognize pedestrian at night. Particularly, the observers were instructed to say stop whenever they were sure, they recognized pedestrian as a person (silhouette was relevant). The observers had known, where the pedestrian was standing – on the right side of the road. So, they had expected, where the pedestrian were going to appear. However, they were instructed to direct their gaze primary not on the right side of the road. The pedestrian was dressed in dark clothes, as shows fig. 1: black shoes, blue/grey denim jeans, dark matte jacket, and black cap with white marking.

Fig. 1. Photography of the pedestrian

After stopping the vehicle, detecting distance was recorded and digital photography was taken. Camera was mounted on a tripod. The tripod was mounted and fixed on the right front seat.

Conditions and digital photographs parameters:

Common parameters:

Sensibility ISO: *200*, Resolution: *3008 x 2000*,
Colour space: *Adobe RGB*, File: **.NEF*, *after WB calibration converted to *.JPG*,
Long time noise reduction was activated.

Measurement 1 parameters:

Date and time: *19.6.2007*, *23:00 – 2:00*
Weather cond.: *clear sky, light wind,15-17°C*
Shutter speed: *15s*, Aperture: *9*,
WB: *3800 K,* Colour space: *Adobe RGB*
Focal length: *18mm (27mm equal to 35mm film)*

Fig. 2. Sample photography – measurement 1

Measurement 2 parameters:

Date and time: *8.12.2007, 19:40 – 21:00*
Weather cond.: *clear-somewhat cloudy, humid, foggy, stronger wind occasionally, 4-6°C*
Shutter speed: *10s*, Aperture: *5,6*,
WB: *4000 K,* Colour space: *Adobe RGB*
Focal length: *40mm (60mm equal to 35mm film)*

Fig. 3. Sample photography – measurement 2

Measurement 3 parameters:

Date and time: *18.12.2007, 19:20 – 21:00*
Weather cond.: *clear-somewhat cloudy, light wind, 1-2,5°C*
Shutter speed: *10s*, Aperture: *5,6*,
WB: *4000 K,* Colour space: *Adobe RGB*
Focal length: *44mm (66mm equal to 35mm film)*

Fig. 3. Sample photography – measurement 2

Computer method

1. *WB calibration and JPG creation.*

*.NEF file was recorded during the measurement. The reason was simple. It allowed us to make a white balance calibration. All photographs, in particular measurement, they were calibrated to the same WB value. NEF file works in 12 bit depth for each of RGB channel and also enables specific photography settings: sharpness, tone compensation, colour mode, saturation. There it was used the best configuration to distinguish pixels with the similar level of luminosity: sharpness-high, tone comp.-low contrast, colour mode-Nikon Adobe

RGB, saturation-moderate. After this process, NEF was converted and saved as JPG with the highest quality.

2. JPG processing

For JPG processing, it was used conventional graphic software – Corel Photo Paint, which provides useful statistical information about a bitmap picture. A histogram is very good tool, how to measure luminosity distribution in a picture or in a selected area. The histogram represents a bar graph of the total number of pixels that appear at different levels of luminosity. The horizontal axis represents the luminosity level, while the vertical axis represents the number of pixels at each luminosity level found within the current image. The left side of the horizontal axis represents the darkest tones within the image, while the right side represents the lightest tones within the image. The histogram provides these statistics: weighted arithmetic mean, standard deviation, median, range, … JPG file distinguishes 256 levels (8 bit) of luminosity in one pixel.

Drivers detect pedestrians by their contrast, the difference in brightness between pedestrian and background. The keystone of the computer method was to compare luminosity of the pedestrian and luminosity of the background. There was used "mask" tool, which provides possibility to cut area of the pedestrian from the background. Histogram of the pedestrian was displayed. It was used "invert mask" tool, what allowed us to display histogram of the background. The difference of weighted arithmetic means of the pedestrian and the background is the measure of the contrast.

3. RESULTS

Primary task was to measure detecting distances and compare human to computer method. Secondary task was to investigate an effect of retroreflector positioning on recognition of silhouettes of pedestrians. Graphic charts show the results – figure 4 and 5. Correlation coefficient indicates the strength and the direction of a linear relationship between two variables – detection distances and differences of weighted arithmetic means of luminosity. The problem of visibility and recognition is complex and there is a great contribution from complicating factors.

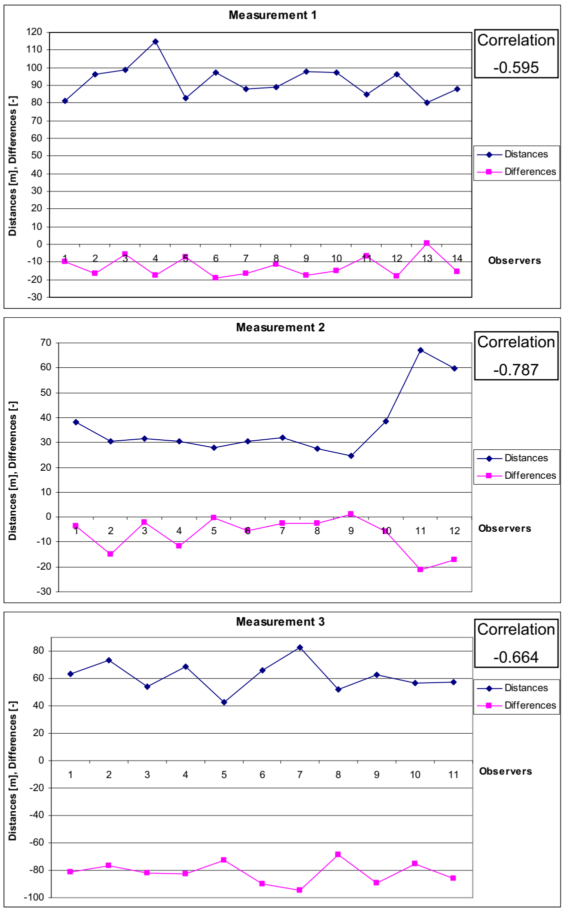

Fig. 4. Human – Computer recognition

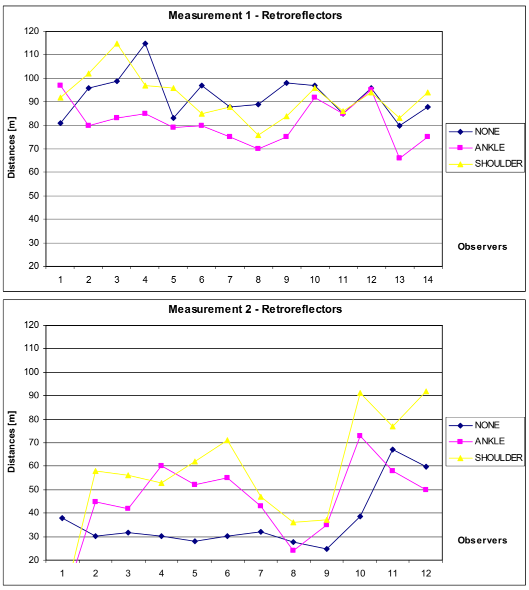

Fig. 5. Effect of retroreflector positioning

Correlatio	Negative	Positive
Small	-0,3 to -0,1	0,1 to 0,3
Medium	-0,3 to -0,5	0,3 to 0,5
Large	-0,5 to - 1,0	0,5 to 1,0

Fig. 6. Interpretation of a correlation coefficient

DISCUSSION

In the primary task we investigated recognition distances of the pedestrian in different conditions. Graphic charts – Fig. 4, shows distances, when the pedestrian was recognized by an observer. Mean recognition distances and standard deviation shows Fig. 7.

Measurement	Mean recognition distance	Standard deviation
1	**92,29 m**	9,33
2	**36,53 m**	12,66
3	**61,82 m**	10,47

Fig. 7. Arithmetic mean of recognition distances

The longest distances were measured in the measurement 1, when there was favourable weather and the measurement was done with Mercedes S with bi-xenon headlights. The shortest distances were measured in the measurement 2, when there was foggy weather and the measurement was done with Škoda Octavia. Thus, the influence of weather is evident. Foggy weather is one of the most dangerous weather conditions. It is also confirmed by the road accidents. When scaled by total number of traffic accidents, fatality rate is the highest in foggy weather.

The computer method, which we have tried, is not enough accurate. It is confirmed by a correlation coefficient. To improve accuracy, reliability and objectivity of the used method, it is necessary to improve evaluating process of the photographs. There are some proposed improvements:

a) An algorithm, which would be able to separate (automatically and reliable) pedestrian from background.
b) In the evaluation of luminosity of background, to divide it to close and far background. Another option would be to develop an integral method with stronger importance of the close background. However, there is a question what is the close background.
c) The same or similar process with pedestrian as in the case of background.

The best solution though would be to develop a method, which would be able to evaluate the contrast between pedestrian and background, reliable and quick. The existence of the algorithm, which would be able to recognize reliable the pedestrian by an analysis of an image, in visible, IR spectrum or using fused image, is the condition for developing intelligent and maybe autonomous vehicle safety system. The biggest problem is with the reliability, because there are uncountable different traffic situations in different weather conditions.

The secondary task was to investigate an effect of retroreflector positioning on recognition of nighttime pedestrians. Fig. 5. shows the results. It is necessary to point out, that we deal with static pedestrian and we tried to recognize the silhouette. We predicted, that the position of the retroreflector on the ankle would be the best for recognition. It is obvious from the Fig. 6., that the longest recognition distances were in the case of shoulder position. From the study of the photographs it is obvious and visible, that the ankle position of the retroreflector causes glare of the observer and also driver. Consequently, the ability to recognize a silhouette is reduced. There is no doubt, that the application of the retroreflector, whether fixed to shoulder or ankle, enabled visibility of the light spot from the long distance (more than 200 m).

Generally, many researches confirmed that pedestrians are visible at greater distances when they wear a reflective tag or vest. However, there are some drawbacks to reflective material. One is that reflective material sends light primarily in one direction. If the headlights hit the material at the wrong angle, the reflected light goes in the wrong direction and does not hit the driver's eye, and the reflector will appear dark. Further, if the reflective material covers a small part of the body, then the driver may detect its light but may not recognize it as being a person. Reflective material may also cause pedestrians to be overconfident. [3]

REFERENCES

[1] Luoma J., Schumann J., Traube E. C.: *Effects of retroreflector positioning on nighttime recognition of pedestrians*. The University of Michigan Transportation Research Institute, MI, USA, 1995.
[2] McCarley J. S., Krebs W. K.: *Visibility of road hazards in thermal, visible, and sensor-fused night-time imagery*. Operations Research Department, Naval Postgraduate School, Monterey, CA, USA, 1999.
[3] Green M.: *Seeing pedestrians at night*. www.visualexpert.com
[4] Kasanicky G.: Kramer F., Nitsche K.: *Zwischenergebnis zur Studie – Heutige Methoden und Verfahren zur Rekonstruktion von dunkelheitsunfällen / optische* Wahrnehmbarkeit, 2006.

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ON SOME CRITICAL MACHINERY VIBRATION MONITORING ALGORITHM AND ITS APPLICATION FOR INCIPIENT FAULT DETECTION AND LOCALIZATION

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Summary

Further development of proposed earlier [1] critical machinery vibration monitoring algorithm intended for faults early detection, unlike standard monitoring techniques, is propounded. The algorithm is founded on nondimensional S-discriminants, calculated from current amplitude-clipped vibration signal parameters referred to the ones for the machine being in good (normal) condition. These parameters have an inherent high sensibility to amplitude spikes magnitude and amount growth, which takes place at vibration signal under the machine degradation, due to suppressing intrinsic machine vibration hash. The paper shows that really effective high speed machinery condition monitoring technique based on using casing vibration data should mandatory take into account the acceleration parameters calculated both in wide and narrow frequency bands.

Keywords: vibration condition monitoring, non-dimensional discriminant, machine defect.

1. INTRODUCTION

To assure technical, ecological and human safe machinery exploration one needs to use condition monitoring and diagnostics algorithms which enable to detect operational malfunctions at the very early stage of their development, i.e. algorithms based on specific methods which detect even week changes of vibration signals originated from the incipient faults. It is the well-known fact that vibrations carry all information about machine dynamic behavior, including defects manifestation as well. The wider frequency range we use for machine problem analysis and the more diagnostics algorithms take into consideration the main specific features of machine dynamic model, the better are results. It is well-known also another fact, that generally most of machinery monitoring and protection system algorithms are based on the estimation of the RMS (root mean square) value of vibration velocity over the range of 10 to 1000 Hz, or amplitude divergence (for wide or narrow frequency band) from base line meanings under good machinery condition.

The conventional vibration velocity range (10- 1000 Hz) of high-speed-rotation machinery contains merely several first shaft rotation frequency harmonics affected only by rough machinery condition changes, for example due to unbalance, eccentricity, misalignment, part breakage, and so on. But technique of incipient fault detection (such as erosion, corrosion, pitting, scuffing, and so on) bases on some other principles, because their symptoms are situated in high frequency vibration range [1-3]. The paper gives evidences of the necessity of combined approach with incipient fault detection and diagnostics methods as its foundation. The paper presents some investigation results on the subject of safe machinery operation ensuring in atomic applications and on early detection of gas turbine engine (GTE) rolling bearing developing defects at a gas pipeline compressor station.

2. A NEW APPROACH TO THE VIBRATION MONITORING OF HIGHSPEED MACHINERY

As it is seen from practice, the more complicated is a machine unit, the more dispersion of measured parameters within general scope of similar machines proves. Due to that it is important to use the individual approach when vibration monitoring is applied.

One feasible way for the early malfunctions recognition is preliminary "passportization" of vibration spectrums and posterior comparison of measured current spectra with the passport spectral data to estimate changes derived from machine condition degradation during its exploration. The point is that the procedure is not effective enough because these changes are small and due to the procedure is not automatic.

There was suggested another way with using some non-dimensional vibration characteristics (S-discriminants) which values are independent either on machine type or vibration units, but only on type (kind) of defect and its severity. Such well-known discriminants as peak-factor X_p/σ, excess $E=(\mu_4/\sigma^4)-3$ (or kurtosis), indexes of amplitude or frequency modulation, prof. Cempel dimensionless discriminants, and so on, often have been used for this aim [1]. However above-mentioned nondimensional parameters have an essential demerit, namely – when a numerator growing along with defect development (due to the number and amplitude of vibration overshoots enlargement), a denominator behaves similarly and dependences of these characteristics on machinery time operation are nonlinear as a rule. It is known [1], that such sensitive vibration parameter to overshoots appearance as excess coefficient, having high sensitivity to any damages at an early stage with small amount of overshoots per time unit, lost its sensitivity to well-developed damage with overshoots quantity growing on.. Dependence of excess (and other standard dimensionless parameters) values from pulses number (which is modeling the machinery parts degradation degree along the operational time) is nonlinear function that means non-single-valued nature of these parameters, in contrast to S-discriminant I_d (see Fig. 1).

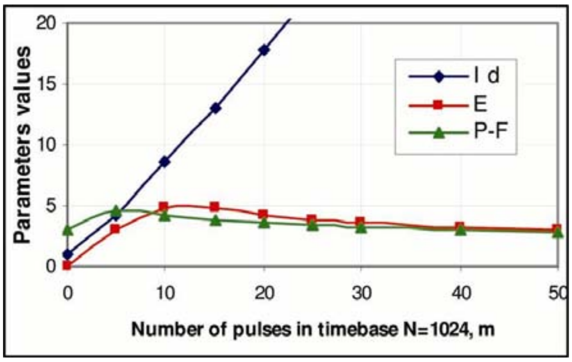

Fig. 1. Influence of pulse quantity **m** (within time realization *N*=1024) on excess *E*, peak-factor *P-F*, normalized amplitude deviation σ_t / σ_n and S-discriminant I_d values for meaning of relative pulse amplitude A / σ_s=5, where σ_s, σ_n – are standard amplitude deviations of random noise signal and reference summary noise and pulses sequence

All that is the foundation for suggestion such kind of monitoring and protective algorithms which would be more sensitive to early fault events and besides have monotonic dependence from machinery degradation state during operational time. To properly realize the "critical" machines condition monitoring and incipient fault detection techniques was proposed the algorithm of estimation of some dimensionless S-discriminant magnitude declining from the value equal to an unit that is placed in correspondence with machinery normal condition.

Analysis of machine vibration waveforms with operational damage in progress shows that vibration becomes unstable and mandatory feature of an incipient fault is an appearance of single or multiple signal overshoots (Fig. 2) deriving from interaction conjugate parts format changes due to erosion, corrosion, pitting, contact surfaces welding and scuffing, and so on.

To raise the sensitivity of the vibration features to incipient faults and minimize the influence of uninformative regular machine vibration (i.e., noise), there were suggested stochastic dimensionless characteristics (amplitude discriminants) to be formed for vibration signals, clipped above the specified amplitude clipthreshold *P* (see for example the red lines at Fig. 2 which are drawn here at amplitude values of $\pm 2\sigma_n$). Thus it is possible to get rid of the own machine vibration which is intrinsic in absence of any malfunctions, and due to it improve the parameters sensitivity.

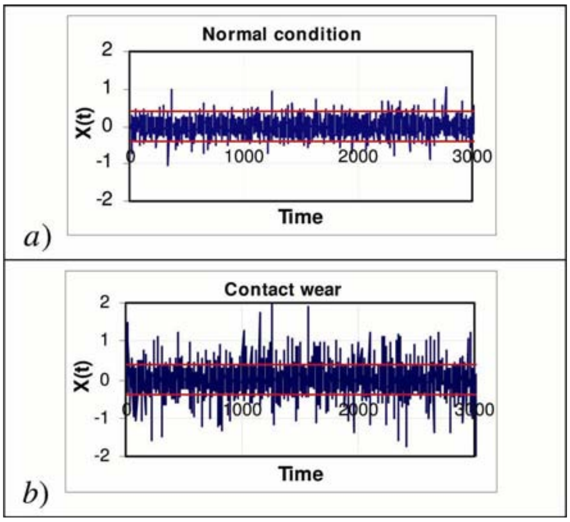

Fig. 2. Examples of vibration acceleration time histories: a) for machine in good condition, b) for machine with injured elements (scuffing in contact zone)

As a result there were formed the relative indexes from some statistical parameter of the clipthreshold exceeding for current vibration signal divided by the same characteristic of reference signal, measured under machinery normal condition. One of them is dispersion index $\mathbf{I_d}$ of threshold exceeding, formulated as follows:

$$I_d = \left(\frac{\sum_{i=1}^{N} \left[(x_i)_{(t)} = P \right]^2}{\sum_{j=1}^{N} \left[(x_j)_{(n)} = P \right]^2} \cdot \frac{K_{(t)}}{K_{(n)}} \right)$$

Here $(x_i)_{(t)}$ and $(x_i)_{(n)}$ are values of vibration amplitude components, calculated for current and reference (i.e. normal, without any faults) machine conditions; $P = \lambda \sigma_n$, (λ = 0.5 – 3.0) – amplitude clip-threshold, σ_0 – standard deviation (RMS) of vibration signal for normal (reference) machinery condition; $K_{(t)}$ and $K_{(n)}$ – are numbers of overshoots above the threshold *P* for current and normal vibration signals.

An amplitude discriminant significance equals to 1, when the machine is under its good condition, but becomes >1 or >>1, if any kind of damage would take place. Thus there were formed dimensionless amplitude discriminants, featuring high sensitivity to instability, caused by machinery operational imbalance, resulted from any fault, and noise immunity to internal machinery masking interference. Some practical (experimental) examples of S-discriminant successful application for incipient detection of multistage gearbox parts defects and of gas turbine unit rolling bearing faults are given below.

2. VIBRATION ANALYSIS RESULTS OF GAS TURBINE ENGINE (GTE) AND GEARBOX

The example below is given to clearly prove that standard monitoring technique is not effective to evaluate changes of complex high speedy machinery and is not applicable to incipient faults detection and recognition (malfunctions of bearing supports, tooth gears, compressor and turbine blades, and so on) due to practically absence of information of these machine parts operability in vibration velocity signals. Really, plant's limiting values of vibration velocity RMS within 10…1000 Hz frequency band (overall level) could be exceeded only under great machine degradation that distorts of its shaft line (bearing breakage, blade breakaway, and so on).

Accordingly with GTE failure statistics there about 80% breakdowns are the result of bearing malfunctions. Typical plot of lateral vibration acceleration spectrum being acquired at one of navy GTE type DG-90 casing measurement points is given in Fig. 3 for front support of low pressure compressor (LPC) in vertical direction [2].

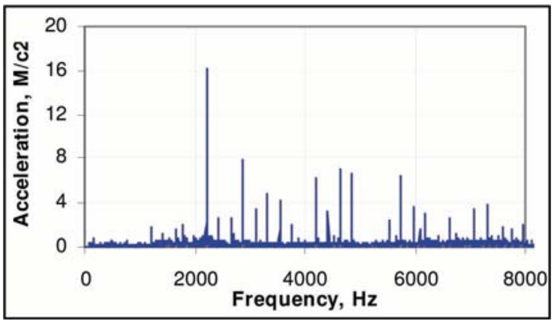

Fig. 3. GTE casing vibration acceleration spectrum

It is clear, that frequencies of bearings generated vibration lay, as a rule, exceed 1000 Hz and as a matter of fact the deterioration of LPC front support ball bearing in question had not been detected timely with the conventional on-line monitoring system because of no one vibration velocity threshold had not been exceeded.

In Figure 4 the several non-dimensional vibration parameters plots are shown under degradation process in ball-bearing of front support of low pressure compressor (LPC) of navy gas turbine engine DG-90 during operation time 01.06.04 to 19.07.04, when machinery was stopped due to metal chips appearance in lubrication.

All parameters were measured for narrow band (1.0÷1.75 kHz) case vibration acceleration – around of the inner race frequency (BPFI) [2]. The discriminant I_d actually has *max value* of _ 100, but Figure 4 scale (0 to 25) was chosen for purpose the other parameters (peak-factor *P-F*, normalized standard deviation σ_t/σ_n, excess *E*) – to be recognizable. The first significant discriminant overshoot which corresponds to dramatic change condition of ball-bearing one could see at 25.06.04 point, i.e. three weeks before the train has been stopped.

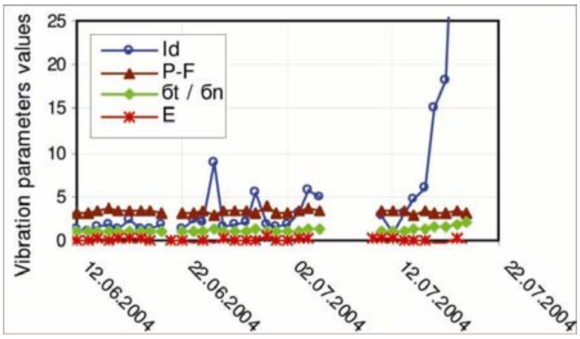

Fig. 4. Narrow band (1.0-1.75 kHz) case vibration various parameter behavior during ball bearing damage development in LPC of gas turbine engine DG-90 front support.

Some practical examples of S-discriminant application for multistage gearbox parts malfunctions are described below. Wide-band vibration discriminant analysis permits to detect informative measurement point for consequent detailed narrow-band signal analyses. In Fig. 5 there are given the dependences of discriminants from operation time of research reactor IBR-2 movable reflector-modulator [3], that are calculated for narrow frequency band (5.0-6.3 kHz) casing gearbox vibration, measured in points #1-4.

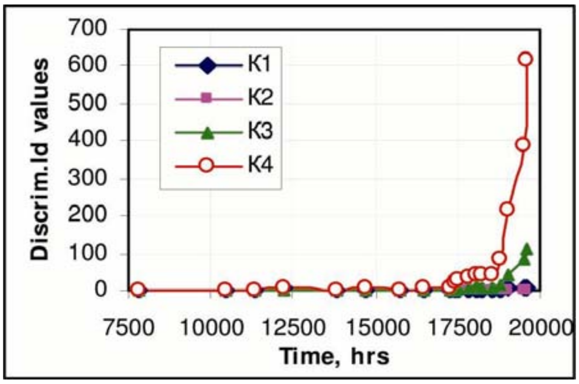

Fig. 5. Narrow-band gearbox casing vibration discriminant trends for measurement points (#1-4)

In Fig. 6 are given the amplitude modulation indexes, calculated for informative measuring point #4 on the ball bearings defect passing frequencies.

In such a way it's possible to realize the procedure of machinery deterioration development detection generally, and after that – specific malfunction localization by means of frequency identification. For objective estimation of operating machinery condition it is reasonably to estimate both wideband and narrowband vibration parameters evolution during machinery service life such as S-discriminant.

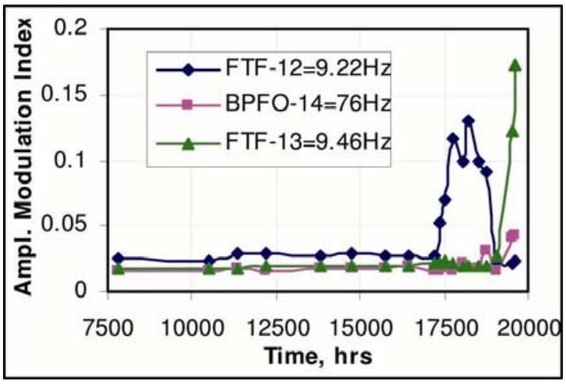

Fig. 6. Trends of ball bearings defect passing frequencies amplitude modulation indexes

Only combined utilization of a set different methods and algorithms for operating condition monitoring of critical machinery, leaning on the information, obtained with incipient failure detection methods can give a reliable estimation of its condition.

REFERENCES

[1] Sokolova A. G., Balitsky F. Ja.: *Sensitive and Noise-immune Vibration Discriminants for Instability Phenomena Detection caused by Incipient Machinery Deterioration*, Proceedings from 1st International Symposium on Stability Control of Rotating Machinery "ISCORMA-1", South Lake Tahoe, California, USA, 20-24 August 2001 (published in CD).

[2] Sokolova A. G., Balitsky F. Ja., Pichugin K. A.: *Dimensionless Machine Vibration Sdiscriminants as a Mean to Improve monitoring and Get Incipient Fault Detection*, The 9th European Conference on Non-Destructive Testing (EC NDT), Conference Proceedings / Poster Presentation N 82, 8 pp, Berlin, September 25-29 2006.

[3] Sokolova A. G., Balitsky F. Ja., Sizarev V. D.: *Detection Technique for Faults Perturbing Rotor Stability, Illustrated by Means of an Example of the Movable Reflector-Modulator of the Pulsed Research Reactor*. Proceedings of The Second International Symposium on Stability Control of Rotating Machinery-ISCORMA-2, pp 170-179, Gdansk, Poland, 4-8 August 2003.

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METHOD FOR DIAGNOSING INTERNAL COMBUSTION ENGINES WITH AUTOMATIC IGNITION ON THE BASIS OF TORQUE MEASUREMENT IN TRACTION CONDITIONS

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Summary

The paper presents a new method for diagnosing internal combustion engines with automatic ignition in traction conditions. Its substance involves determination of engine torque on the basis of recording of acceleration in road conditions. Extensive preliminary and primary experimental research has been conducted. Three variants of the internal combustion engine diagnostic model have been developed using a trivalent evaluation of states. Algorithms have been proposed to control a state and location of engine defects. The new method has been verified in traction conditions. A probability of a correct diagnosis of internal combustion engine is 0.85 ÷ 1.

Keywords: military vehicles, internal combustion piston engines, diagnostics.

METODA DIAGNOZOWANIA SILNIKÓW SPALINOWYCH O ZAPŁONIE SAMOCZYNNYM NA PODSTAWIE POMIARU MOMENTU OBROTOWEGO, W WARUNKACH TRAKCYJNYCH

Streszczenie

W pracy przedstawiono nową metodę diagnozowania silnika spalinowego o ZS w warunkach trakcyjnych. Istota polega na wyznaczeniu momentu obrotowego silnika na podstawie rejestracji przyspieszenia w warunkach drogowych. Wykonano obszerne wstępne i zasadnicze badania eksperymentalne. Opracowano trzy warianty modelu diagnostycznego silnika spalinowego, z wykorzystaniem trójwartościowej oceny stanów. Zaproponowano algorytmy kontroli stanu i lokalizacji uszkodzeń silnika. Zweryfikowano nową metodę w warunkach trakcyjnych. Prawdopodobieństwo poprawnej diagnozy silnika spalinowego wynosi 0,85 ÷ 1.

Słowa kluczowe: pojazdy wojskowe, tłokowe silniki spalinowe, diagnostyka.

1. INTRODUCTION

Based on analysis and assessment of diagnostic methods for internal combustion engines with automatic ignition, it should be stated that [3, 4, 6]:

1. tool-free methods for research and assessment of a state of internal combustion engines with automatic ignition, based on senses of eyesight, hearing and touch may be used as supplementary methods in mechanical vehicles diagnostic-servicing process, although they are not excluded to be used as primary methods in practical realization of processes for diagnosing and servicing internal combustion engines;
2. a considerable number of diagnostic methods being used for internal combustion engines with automatic ignition is characterized with complex diagnostic algorithms and a high labor consumption, which results in their low usefulness in diagnostics of those technical objects;
3. a large number of existing diagnostic methods for internal combustion engines with automatic ignition has no fixed boundary values of diagnostic parameters;
4. so far there are no objective diagnostic methods for quantitative determination of a wearing degree of piston-crank system and camshaft of internal combustion engines;
5. a need arises to develop methods for finding a genesis and forecasting a state in an aspect of possibilities for them to be used in practical realization of the internal combustion engines servicing process;
6. a significant number of existing methods stands for static and quasi-dynamic methods that are useless for applications in board diagnostic systems;
7. in our opinion, at present there is no sufficient set of diagnostic methods and means allowing for full and effective control of a state and location of damages in engine with automatic ignition both in stationary conditions and in particular while driving;
8. there is a need to develop an effective method to control a state and location of damages in internal combustion engine with automatic ignition for its further use in board diagnostic systems in conditions while a vehicle is in motion.

2. DIAGNOSTIC MODEL FOR VEHICLE ACCELERATION

2.1. Gist of vehicle acceleration process

In the vehicle acceleration process in a selected gear, internal combustion engine's torque from crank-shaft is transferred to a clutch, gearbox and further through distribution box, final drive – onto vehicle wheels. Driving force F_n, that is generated by the engine must be higher than total motion resistances force that consists of: inertia force F_b, rolling resistance force F_t, and air resistance force F_p on a horizontal route.

The higher driving velocity the higher total motion resistances force and vehicle acceleration keeps declining until stability of velocity at which driving force becomes balanced by the motion resistances force, or when a maximum rotation speed of the engine has been achieved.

2.2. Equations of vehicle motion while car acceleration

General equation of vehicle's rectilinear motion on a flat route has a form of [1, 2]:

$$F_n = F_t + F_p + F_b \tag{2.1}$$

where: F_n – driving force on vehicle wheels; F_t – rolling resistances force; F_p – air resistances force; F_b – inertia resistances force;

After its transformations, expression (2.1) has a form of:

$$F_n = fmg + \gamma C_x A v^2 + \delta m a \tag{2.2}$$

where: f – rolling resistances coefficient; m – vehicle weight; g – gravitational acceleration; ρ – air density defined by a formula:

$$\rho = \rho_0 \frac{H_T}{H_0}\frac{T_0}{T_T} \tag{2.3}$$

where: ρ_0 – air density in normal conditions = 1.189 kg/m^3; H_T – air pressure at the moment of measurements taking; H_0 – reference pressure of 100 kPa; T_T – air temperature at the moment of measurements taking; T_0 – reference temperature of 293 K; C_x – air resistances coefficient; A – vehicle face surface; a – vehicle momentary acceleration; v – vehicle linear velocity; δ – vibrating masses coefficient defined by a formula:

$$\delta = 1 + \frac{(I_s + I_T) i_c^2 \eta_m + \Sigma I_k}{r_d^2 m} \tag{2.4}$$

where: I_s - moment of inertia of engine vibrating masses; I_T – coefficient to undefined states of internal combustion engine; i_c – total ratio of driving system; η_m– driving system efficiency; I_k – driving wheels moment of inertia; r_d – real, momentary dynamic radius of wheels.

2.3. Gist of New Method

The method being proposed bases on determination of engine torque on the basis of acceleration recording while vehicle is in motion in road conditions. A simultaneous measurement of fuel consumption allows for determining hourly fuel consumption in engine's rotational speed function. It is worthwhile stressing that a concept of methodology, defined below, for determining a torque of internal combustion engine has not been applied so far in diagnostic systems of mechanical vehicles in traction conditions.

2.4. Methodology for determining a set of diagnostic parameters

A problem with determining a set of diagnostic parameters of internal combustion engines in traction conditions will be solved by the following steps:

STEP I

Measurement of vehicle linear velocity and engine rotational speed

STEP II

Determination of dynamic radius of a circle r_d from dependence:

$$r_d = \frac{v * i_c}{n_s} \tag{2.5}$$

where: v – vehicle linear velocity; i_c – total ratio of driving system; n_s – engine rotational speed.

STEP III

Attempt of vehicle free rundown. A quantity being measured is a delay a_f and a_c of vehicle motion. The gist of measurement involves acceleration of the vehicle up to a possibly maximum speed, and then setting a gear-shifting lever into neutral and recording a delay $a_f = f(t)$ until the vehicle has stopped. Motion resistances are determined at velocities below 10 km/h when influence of air resistances is ommittably small. Air resistances are determined by delay a_c recorded at velocities of 75–20 km/h.

STEP IV

Determination of motion resistances coefficient from the following formula:

$$f = \frac{a_f}{g}\left(1 + \frac{\sum I_k}{m r_d^2}\right) \tag{2.6}$$

where: a_f – vehicle motion delay; g – gravitational acceleration; I_k – driving wheel moment of inertia; m – vehicle weight.

It is worth stressing that the motion resistances coefficient includes rolling resistances and frictions in: wheel bearings, meshing of gear wheels and shafts joints.

STEP V

Determination of vehicle air resistances coefficient from the following formula:

$$C_x = \left(-\frac{m}{\rho A v^2}\right)\left(fg + a_c + \frac{a_c \sum I_k}{m r_d^2}\right) \tag{2.7}$$

where: A – vehicle face surface; a_c – vehicle motion delay; ρ – air density.

A measurable quantity is vehicle motion delay a_c being recorded at velocities of 70 ÷ 20 km/h, in a rundown attempt being realized in STEP III.

STEP VI

Measurement of vehicle acceleration and fuel consumption is started upon a minimum velocity has become stable on third gear, and then through a rapid maximum stepping on acceleration pedal the vehicle gathers speed until a maximum velocity has been achieved. Vehicle dislocation, rotational speed of engine crank shaft and fuel consumption are measured.

A measured quantity is vehicle dislocation s_p. The gist behind measuring that quantity involves a rapid acceleration of the vehicle until a maximum velocity on a give gear has been achieved and recording of dislocation $s_p = f(t)$. The vehicle motion acceleration is obtained as $a_p = \frac{d^2 s_p}{dt^2}$.

STEP VII

Having the following data: dynamic radius of circle r_d, motion resistances coefficient *f*, air resistances coefficient C_x and motion acceleration a_p, it is possible to determine torque from the following dependence:

$$M_s = \left(\frac{mgfr_d + \rho C_x A v^2 r_d + \delta m r_d a_p}{i_c \eta_m} \right) \quad (2.8)$$

where: δ – vibrating masses coefficient; a_p – vehicle motion acceleration; G_e – momentary hourly fuel consumption measured in acceleration process.

2.5. Summary

Analysis of the vehicle acceleration diagnostic model authorizes to formulate the following conclusions:

1. the basis for the new method of research and assessment of a state of internal combustion engine with automatic ignition is equation of vehicle rectilinear motion on a flat route (2.1), and dependence (2.8).
2. a set of parameters of a state of internal combustion engine with automatic ignition includes:
3. engine torque M_s;
4. hourly fuel consumption G_e;
5. diagnostic parameters of vehicle state and internal combustion engine can also be as follows:
6. dynamic radius of circle - r_d;
7. motion resistances coefficient f;
8. delay a_f;
9. delay a_c;
10. acceleration a_p.
11. it should be stressed that for the above-mentioned sets of diagnostic parameters to be symptoms of a state of internal combustion engine with automatic ignition, their usefulness should be proved in a sense of meeting the hereto criteria: sensitivity, uniqueness, stability and informativeness, using experimental research.

3. EXPERIMENTAL RESEARCH

3.1. Research goal

The preliminary research goal was [5] to:

- define properties of signals being examined;
- determine an influence of factors being tested on values of physical quantities being measured;
- determine defined research terms and conditions, required by developed method to control a state and location of 4CTi90–1 BE6 engine damages.

The goal of primary research has been specified as follows:

- to select the best diagnostic parameters due to states differentiation criterion;
- determine boundary values of diagnostic parameters for selected states of 4CTi90–1 BE6 engine;
- determine states–diagnostic parameters couplings, that is, to obtain a diagnostic model of 4CTi90–1 BE6 engine, type - informative model Is.

The purpose of laboratory research is to collect data essential for comparing their values with values of results obtained in the primary experimental research, and on their basis verify the developed method for diagnosing 4CTi90–1 BE6 engine.

3.2. Research Program

Preliminary diagnostic testing program for the engine has been presented on fig. 1.

Primary diagnostic testing program for 4CTi90–1 BE6 engine has been presented on fig. 2.

Laboratory testing program for 4CTi90–1 BE6 engine has been presented on fig. 3.

3.3. Test stand and measuring apparatus

A test stand for diagnostic testing of 4CTi90–1 BE6 engine has been HONKER make vehicle.

Individual signals have been recorded using the following apparatus:

- optoelectronic sensor of linear velocity of DLS-1 vehicle made by Corrsys-Datron company:
- sensor of rotational velocity of FS2–60 engine made by Keyence company;
- 116H type of fuel flow-meter made by Pierburg company,
- fuel temperature sensor;
- data acquisition and processing station µEEP–10 made by Corrsys-Datron company

4. PRELIMINARY TESTS RESULTS ANALYSIS

4.1. Influence of whether conditions on values of physical quantities being measured

- Analysis of performed tests results has indicated essential differences in values of physical quantities being measured in diverse weather conditions. In order to reduce uncertainty of diagnosis made, an analysis has been conducted of the weather conditions impact and correction equations have been presented allowing for referring obtained results to standard ambient conditions i.e. temp. 20º C, pressure 100 kPa.

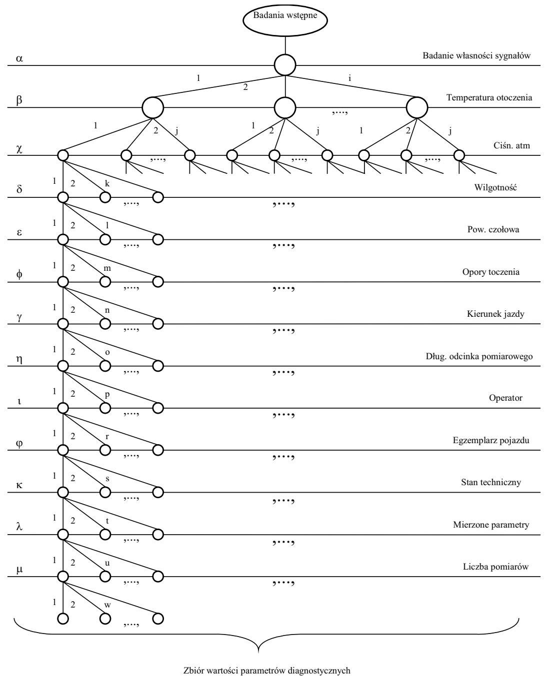

Fig. 1.Chart of preliminary diagnostic testing program for 4CTi90–1 BE6 engine

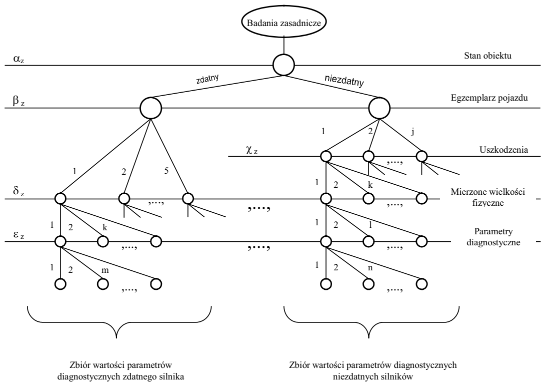

Fig. 2. Chart of primary diagnostic testing program for 4CTi90–1 BE6 engine

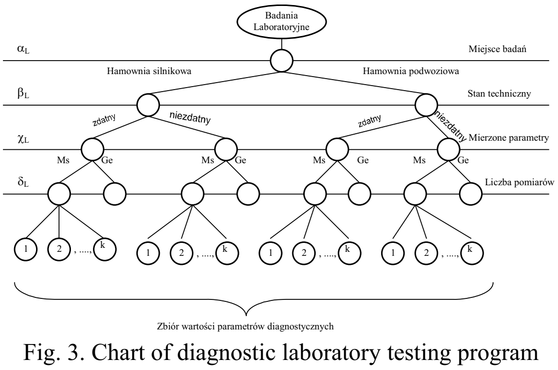

Fig. 3. Chart of diagnostic laboratory testing program for 4CTi90–1 BE6 engine

Ambient temperature

Tests performed at identical air pressure have been separated out of a set of all measurement results. Maximum values of internal combustion engine torque have been assumed for analysis. Results have been presented on fig. 4. The maximum torque value has been marked on the chart as average value and a standard deviation. This quantity characterizes a dispersion of results, that is, a statistical component of uncertainty of the measurement result (A type).

Obtained testing results are convergent with data included in technical literature. Growing ambient temperature effects in declining air density, and thus its smaller amount is sucked into the engine cylinder, which worsens a level of fulfillment and a progress of the combustion process, and therefore reduces effective pressure and engine torque.

The hereto considered process has been approximated with a straight line. Straight line inclination coefficient has been used to determine a correction equation, leading the obtained characteristics of the internal combustion engine torque to normal temperature of 20º C. The dependence takes the following form:

$$M_{sT_0} = M_s - (0{,}4060 * (T_0 - T)) \tag{4.1}$$

where: M_{sT_0} – torque corrected to temperature of 20º C; M_s – torque measured in ambient temperature *T*; T_0 – reference temperature – 20ºC;

Ambient temperature influences a temperature of fuel being delivered to engine injection pump. Injection apparatus had no temperature controlling device in the vehicle being tested. Therefore, differences in velocity characteristics of hourly fuel consumption, being measured while testing in various ambient temperatures, have been expected. Results of the performed analysis are presented on fig. 5.

A correction equation to standard ambient temperature has been determined in analogical way as that for the torque.

$$G_{eT_0} = G_e - (0{,}02142 * (T_0 - T)) \tag{4.2}$$

where: G_{eT_0} – fuel consumption corrected do temperature of 20º C; G_e – fuel consumption measured in ambient temperature *T*; T_0 – reference temperature – 20º C;

Air pressure

Corrected maximum torque values have been analyzed again due to ambient pressure value. Comparative results have been presented on fig. 6.

A correction equation of air pressure influence on torque characteristics has been determined in analogical way as that for the temperature:

$$M_{sk} = M_{sT_0} + (2{,}0042 * (p_0 - p)) \tag{4.3}$$

where: M_{sk} – torque corrected to normal conditions (temperature 20º C, air pressure 100 kPa); M_{sT_0} – torque corrected to temperature 20º C; p_0 – reference pressure (normal) reaching 100 kPa; *p* – air pressure while making measurements.

Air Humidity

Relative air humidity depends on pressure and temperature. In order to become independent from those two quantities, for the purposes of this method, a relative humidity has been measured and then converted to absolute humidity (so-called proper humidity) expressed as content of water in one kilogram of dry air. Influence of absolute humidity on torque results is presented on fig. 7.

As indicated on the above figure, absolute humidity hereto applied measurement method has no significant influence on torque value. Statistical (A type) uncertainty of results of individual measurements (performed in stable conditions) is higher than differences effecting from the impact of proper humidity.

Correction equations of the impact of weather conditions can also be determined on the basis of analysis of multiple regressions. It allows for obtaining a single equation that contains influence of all the factors being tested.

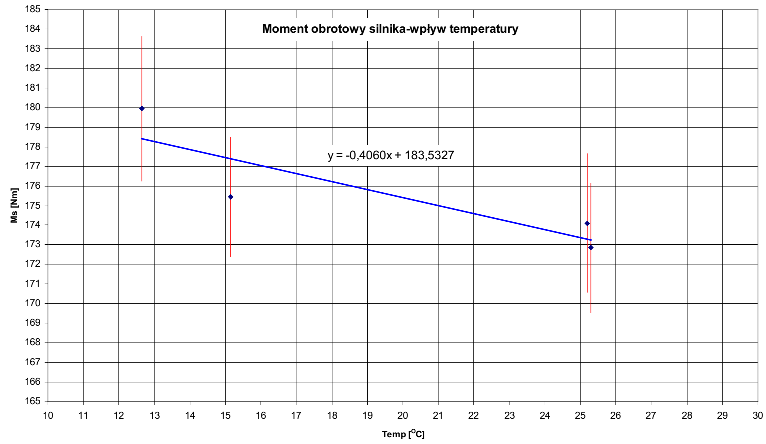

Fig. 4. Influence of ambient temperature on maximum torque values of internal combustion engine 4CTi90–1 BE6

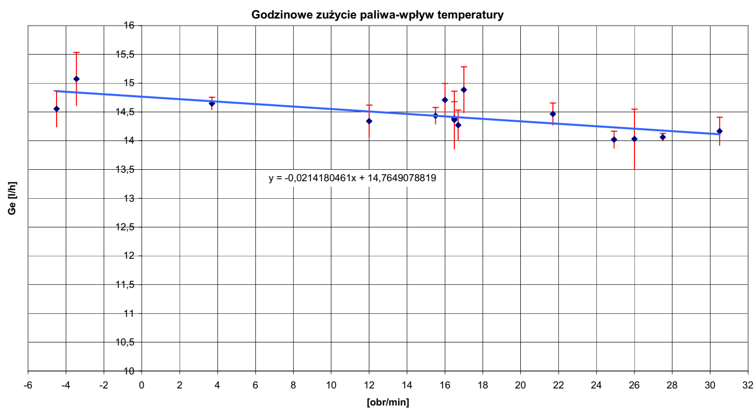

Fig. 5. Influence of ambient temperature on hourly fuel consumption of internal combustion engine 4CTi90–1 BE6

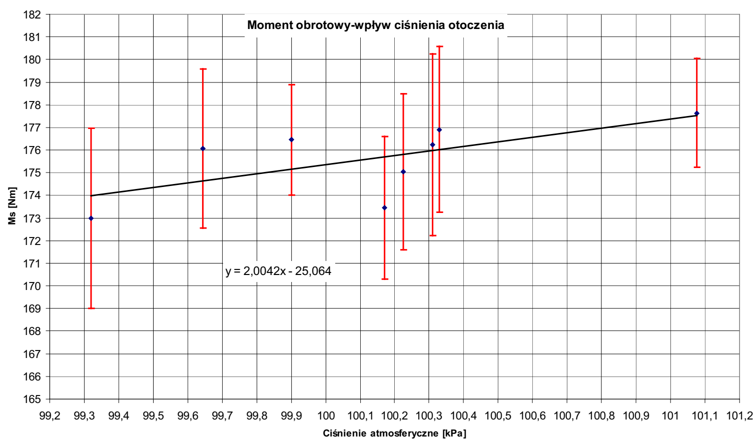

Fig. 6. Influence of air pressure on maximum values of 4CTi90–1 BE6 internal combustion engine torque

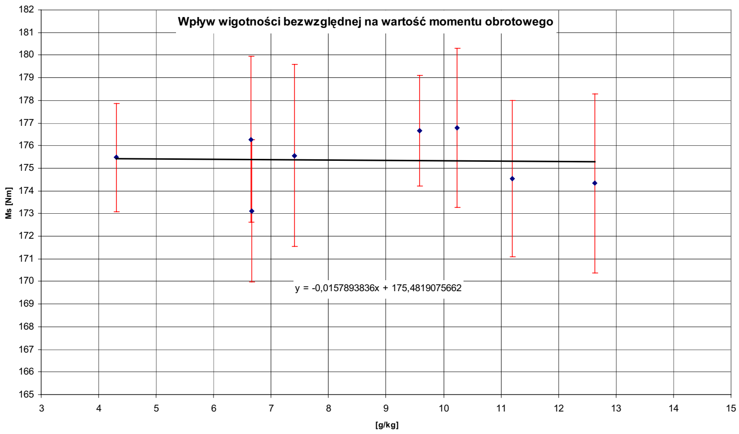

Fig. 7. Impact of air absolute humidity on obtained values of maximum torque of internal combustion engine 4CTi90–1 BE6

Summary

On the basis of performed tests and analyses of weather conditions influence on values of physical quantities being measured, it should be stated that:

1. ambient temperature has essential impact on values of parameters characterizing a process from a torque of internal combustion engine 4CTi90–1 BE6;
2. ambient pressure has a very essential influence on values of parameters related to a torque of internal combustion engine 4CTi90–1 BE6;
3. proper air humidity has a minor impact on parameters values determined for internal combustion engine 4CTi90–1 BE6 torque characteristics;
4. influence of weather conditions on parameters values related to fuel consumption by the engine is immaterial;
5. in order to obtain reliable testing results, torque and fuel consumption values being obtained should be corrected to normal conditions;
6. the most convenient method of correction to normal conditions is a use of multiple regression equations recognizing the influence of all factors being tested;
7. percentage of explained volatility for weather conditions impact on torque value is very high and exceeds 90%, and for fuel consumption 76.43%;

finally, correction equations of weather conditions influence have the following form:

- for the torque:

$$M_{sk} = M_s - (0{,}5066 * (T_0 - T)) + 2{,}1704 * \\ * (p_0 - p) + 0{,}1435 * (DP_0 - DP) \qquad (4.4)$$

where: M_{sk} – torque corrected to normal conditions (temperature 20º C, air pressure 100 kPa, reference humidity defined as dew-point 10º C); M_s – torque measure in ambient temperature *T*, pressure *p and* humidity *DP*; p_0 – reference pressure (normal) reaching 100 kPa; *p* – air pressure while making measurements; T_0 – reference temperature: 20º C; *T* – ambient temperature while making measurements; *DP* – dew-point temperature (characterizing air humidity); DP_0 – dew-point/reference temperature: 10º C,

- for fuel consumption:

$$Ge_k = Ge + (0{,}0394 * (T_0 - T)) - 0{,}8545 * \\ * (p_0 - p) - 0{,}3013 * (DP_0 - DP) \qquad (4.5)$$

where: Ge_k – fuel consumption corrected to normal conditions (temperature 20º C, air pressure 100 kPa, reference humidity defined as dew-point 10º C);*Ge* – fuel consumption measured in ambient temperature *T*, pressure *p and* humidity *DP*;

4.2. Influence of motion conditions on values of physical quantities being measured

Rolling resistances

Rolling resistances of the vehicle being tested have been changed by reducing air pressure in vehicle tires. Tests have been conducted in two variants: at pressure reaching 0.25 MPa and 0.42 MPa. They are extreme pressure values allowed for Goodyear tires G90 7.50 R16C that the vehicle being tested has been equipped in.

Trust ranges have been calculated for parameters following this dependence:

$$\overline{y_n} - t_\alpha \frac{s^2_{yn}}{\sqrt{n}} < y_n < \overline{y_n} + t_\alpha \frac{s^2_{yn}}{\sqrt{n}} \qquad (4.6)$$

where: t_α – variable t–Student for n-1 degrees of freedom, fulfilling the relation $P(-t_\alpha < t < t_\alpha) = 1 - \alpha$; $\overline{y_n}$ – parameter average value; s^2_{yn} – parameter variance defined by dependence:

$$s^2_y = s^2_{yn} = \frac{1}{n-1}\sum_{n=1}^{N}(y_n - \overline{y_n}) \qquad (4.7)$$

States differentiation test has been applied for the purposes of this study, comparing average values of parameters and trust ranges for a state of usability and non-usability. Damage identifiability has been defined via trivalent assessment of a parameter. The „0" value has been assumed for no identifiability. If a value of a tested parameter keeps declining because of damage, a checking result is „-1", and if it is rising „1". Procedure of proceeding is presented on the model:

1. definition whether a change in the parameter is identifiable upon considering the trust range:

$$\left|\overline{y_0} - \overline{y_n}\right| > t_{\alpha 0}\frac{s_{y0}^2}{\sqrt{n_0}} + t_{\alpha n}\frac{s_{yn}^2}{\sqrt{n_n}} \qquad (4.8)$$

where: $\overline{y_0}$ – parameter average value corresponding to a state of usability; $\overline{y_n}$ – parameter average value corresponding to a state of n-th non-usability; $t_{\alpha 0}\frac{s_{y0}^2}{\sqrt{n_0}}$ – half of trust range of parameter corresponding to a state of usability; $t_{\alpha n}\frac{s_{yn}^2}{\sqrt{n_n}}$ – half of trust range of parameter corresponding to a state of n-th non-usability.

2. if checking result is a number different from „0" definition whether a value of the tested parameter has declined or maybe grown as a result of damage.

Analysis of the presented results indicates that tire pressure, and effectively vehicle rolling resistances, have no influence on testing results. It allows to formulate a conclusion that the assumed methodology, recognizing real vehicle rolling resistances (determined in a free rundown attempt), make the measurement result independent from motion resistances impact.

Driving direction

Impact of driving direction on results of diagnostic parameters being obtained has been tested by conducting a series of measurements in both driving directions. While conducting tests, wind velocity has exceeded 2 m/s lengthwise of the measured section. Analysis has bee carried out separately for measurements performed for driving against the wind and with the wind.

The torque process analysis indicates that parameters values slightly differ. Trust levels remain at the same unchanged level. Noticeable is a shift of a maximum torque into directions of lower rotational speed, and a faster accumulation of a torque in range 1800 - 2500 rotations per minute. This results from phenomena occurring during cooperation of turbo-compressor with the engine. Higher motion resistance (adverse wind) cause higher load on the engine, higher combustion pressure, and thus combustion fumes that generate higher supercharge pressure at low rotational velocities. Therefore, wile driving against the wind torque is higher than that at low rotational velocities; however, upon considering trust ranges the differences are insubstantial.

The states differentiation test does not show any significant differences in values of parameters, determined on the basis of measurements made with the wind and against the wind. This proves a correctness of the assumed testing methodology.

Surface type of measured section

Research tests on influence of a surface type have been conducted on two measurement sections: local road section Halinow – Cisie with asphalt surface and on military airfield Sochaczew with concrete surface. Honker vehicle with EURO-3 engine version has been the testing object in both cases. Measurements have been taken with an interval of two days with slightly different weather conditions, therefore results have been corrected to normal conditions, following equations of (4.4) and (4.5).

The performed tests results indicate that there are no significant differences in the proposed values of diagnostic parameters.

Vehicle face surface

The analysis of vehicle face surface impact on measurements results has been conducted on the basis of measurements made on Honker and Scorpion vehicles. The face surface in the first tested object has reached 3.55 m^2, while in the second case 3.82 m^2. Characteristics have been compared and corrected to normal conditions.

Values of parameters related to engine torque slightly differ. Upon considering trust ranges, there are no differences between average values. This allows saying that the assumed methodology including in its calculations real resistances in vehicle motion is a correct one. The states differentiation test detects differences in parameters related to fuel consumption: consumption at rotational speed of maximum torque Ge_M, and maximum consumption Ge_{max}. The reason behind this situation is probably a production dispersion of engines. The two vehicles originated from different production batches: Honker from year 2002, while the vehicle marked with a cryptonym of Scorpion from year 2003.

4.3. Conclusions

Based on performed preliminary rests and analyses of results obtained, it should be said that:

1. results repeatability tests has indicated that the proposed parameters are characterized with repeatability for the engine usability state;
2. point and range estimations of research results indicate that average values of the proposed parameters are characteristic for the usability state and individual damages, which proves their usefulness for building a diagnostic model of internal combustion engine;
3. weather conditions have been found to have essential impact on engine torque values, but a small influence on fuel consumption average value;
4. based on many variances uniqueness test, it has been found that there are no basis for rejecting a hypothesis about equality of variances in tested parameters for usability state, but the torque variance value differs for individual damages;
5. on the basis of correlation analysis, a dependence has been found of average torque on weather conditions;

6. an analysis has been made of weather conditions impact and regression analysis and equations have been generated correcting the testing results to normal ambient conditions;
7. results of motion conditions influence allow for formulating the following conclusions:

- impact of rolling resistances on values of physical quantities being measured is immaterial;
- driving direction has no influence on values of physical quantities being measured;
- type of surface has no influence on values of physical quantities being measured;
- vehicle face surface has no influence on values of physical quantities being measured;

8. diagnostic parameters for usable internal combustion engine have been proposed and determined;
9. states differentiation test (4.4) has been proposed that contains trust ranges for states of usability and non-usability. This has resulted in a trivalent assessment of internal combustion engine states.

5. PRIMARY RESEARCH RESULTS ANALYSIS

5.1. Characteristics of usable engine

Characteristics of usable 4CTi90–1 BE6 engine have been determined based on 8 measuring sessions conducted in various weather conditions. Some 30 measurements have been taken during each of the sessions. Characteristics of usable engine have been presented on fig. 8. ÷ fig. 9. The charts also present trust ranges for proposed diagnostic parameters and characteristics curves equations. Trust range of a parameter has been determined from dependence (4.6).

Table 1 presents values of proposed diagnostic parameters of usable 4CTi90–1 BE6 engine, in EURO2 version, corrected to normal ambient conditions, and their trust ranges.

5.2. Influence of damages on values of physical quantities being measured

Weak links of the engine being tested, which have been determined on the basis of vehicles maintenance monitoring at military bases, have been assumed as a criterion for selection of damages to be diagnosed. Table 2 presents weak links of internal combustion engine 4CTi90–1 BE6

Testing results of individual damages impact on values of proposed diagnostic parameters, corrected to normal conditions, have been presented in a comparison with usable engine parameters. Trust ranges of proposed diagnostic parameters have been calculated for individual damages and the states differentiation test has been performed based on dependence (4.4).

Results have been presented on fig. 10 ÷ fig. 11.

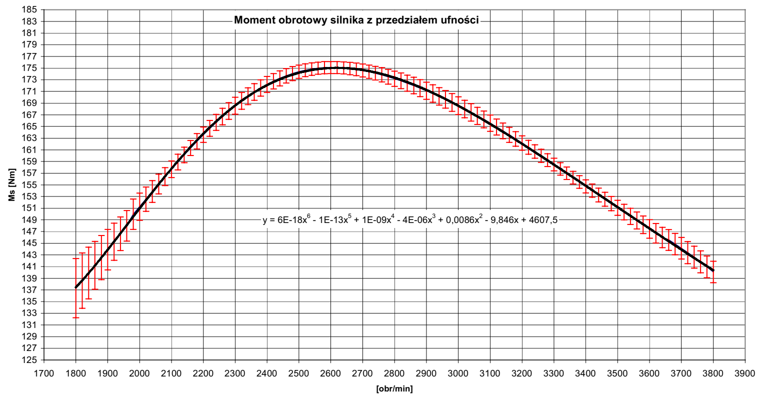

Fig. 8. Torque characteristics of usable 4CTi90–1 BE6 internal combustion engine in EURO2 version

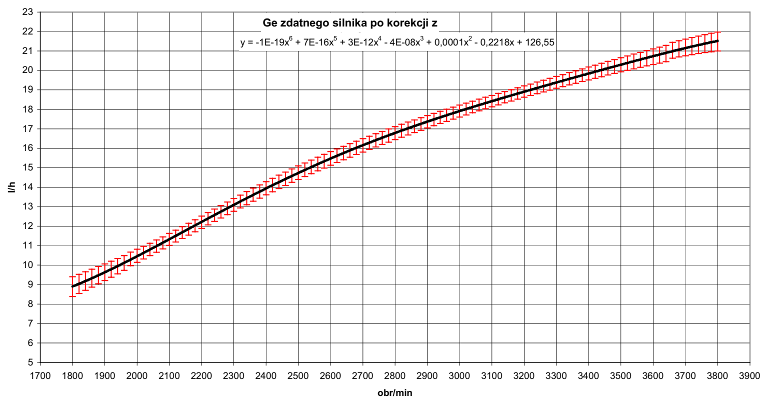

Fig. 9. Fuel consumption characteristics of usable 4CTi90–1 BE6 internal combustion engine in EURO2 version

Table 1. Proposed diagnostic parameters of usable 4CTi90–1 BE6 internal combustion engine

	Marking	Value of diagnostic parameter	Half of trust range
Average. torque [Nm]	$\overline{M_s}$	160.64	± 2.28
Max torque [Nm]	M_s	175.11	± 1.02
Torque at min. speed [Nm]	M_{s0}	137.31	± 5.07
Torque at max speed [Nm]	M_{si}	140.07	± 1.84
Rotational speed of max. torque [rotations/min]	n_M	2600	± 21
$\frac{M_{s0}}{M_{max}}$	C_{M1}	0.7842	± 0.0415
$\frac{M_{si}}{M_{s\,max}}$	C_{M2}	0.7999	± 0.0112
Average fuel consumption [l/h]	$\overline{Ge}$	16.14	± 0.74
Consumption at rotational speed of max. torque [l/h]	G_{eM}	15.48	± 0.35
Consumption at min. rotational speed [l/h]	G_{emin}	8.89	± 0.51
Consumption at max. speed [l/h]	G_{emax}	21.49	± 0.48
$\frac{Ge_M}{Ge_{min}}$	C_{Ge1}	0.5744	± 0.0343
$\frac{Ge_{max}}{Ge_M}$	C_{Ge2}	0.7204	± 0.0306

Table 2. Weak links of 4CTi90–1 BE6 engine

No	Element-	Damage probability	Non-usability state
1	injection pump	0.1	w_1^0
2	turbo-compressor	0.1	w_2^0
3	air filter	0.4	w_3^0
4	injectors	0.3	w_4^0
5	cylinder damage	0.05	w_5^0
6	timing gear system	0.05	w_6^0

Based on primary experimental research that has been conducted in traction conditions, it should be said that:

1. states differentiation test with trivalent assessment of state has been prepared;
2. a set of diagnostic parameters has been proposed and their values have been determined for usable 4CTi90–1 BE6 engine;
3. values of parameters have been determined corresponding to six selected damages;
4. states differentiation test has been made for introduced individual damages and a damage identifiability has been determined;

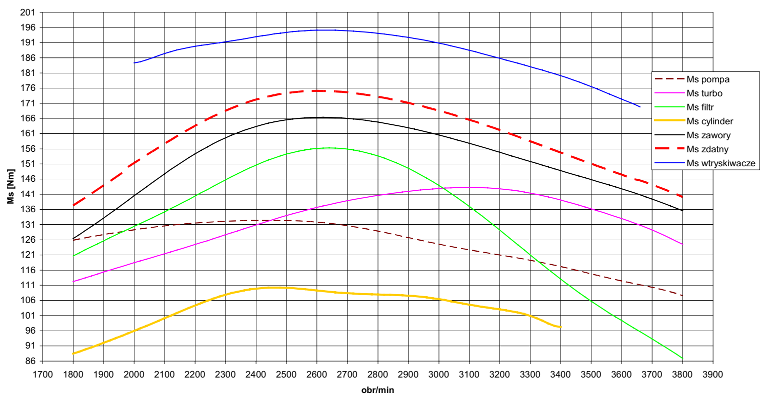

Fig. 10. A comparison of torque characteristics for usable engine and for individual damages

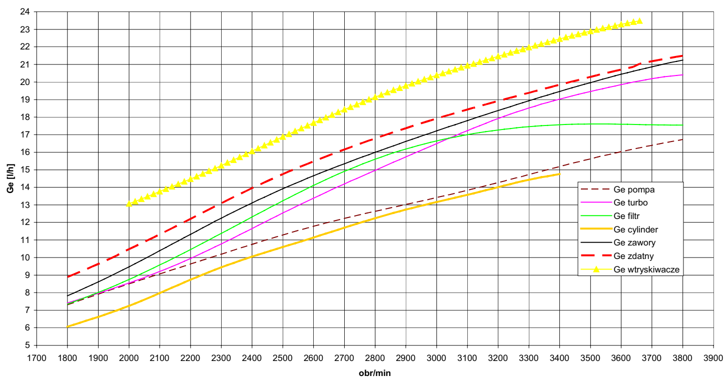

Fig. 11. A comparison of torque characteristics for usable engine and for individual damages

Table 3 presents results of the states differentiation test for individual damages. An analysis of Table 3 indicates that:

1. results of the states differentiation test for individual damages vary for specific damages, which proves that parameters have been correctly matched;
2. the most information providing parameters are: $\overline{M_s}$, M_s M_{s0}, for which a change in parameter value is differentiable in all tested damage cases;
3. the least information providing parameters are: C_{Ge2} – no differentiability for four damages, C_{M1} (see item 6.1) – no differentiability for four damages,
4. the easiest identifiable are: injection pump damage – a change in all parameters besides C_{M2} and C_{Ge2}, and injectors damage – a change in all parameters besides n_M and C_{Ge2} , however, the value of all parameters keeps growing for this type of damage;
5. the most difficult identifiable is a damage involving a leaky combustion chamber. In this case, only three parameters change: $\overline{M_s}$, M_s *and* M_{s0} (see item 6.1);
6. Table 3 is information model (diagnostic matrix) enabling a control of a state and location of selected damages of 4CTi90–1 BE6 engine.

Table 3. Information model (diagnostic matrix) of internal combustion engine 4CTi90-1 BE6

Marking	Pump corrector	Turbo	Air Filter	Injectors	Cylinder	Leaky combustion chamber	Usable
$\overline{M_s}$	0	-1	-1	-1	1	-1	-1
M_s	0	-1	-1	-1	1	-1	-1
M_{s0}	0	-1	-1	-1	1	-1	-1
M_{si}	0	-1	-1	-1	1	-1	0
n_M	0	-1	1	0	0	-1	0
C_{M1}	0	1	0	0	1	0	0
C_{M2}	0	0	1	-1	1	0	0
$\overline{Ge}$	0	-1	0	0	1	-1	0
G_{eM}	0	-1	1	0	1	-1	0
G_{emin}	0	-1	-1	-1	1	-1	0
G_{emax}	0	-1	0	-1	1	-1	0
C_{Ge1}	0	1	-1	0	1	0	0
C_{Ge2}	0	0	1	1	0	0	0

6. INTERNAL COMBUSTION ENGINE 4CTI90–1 BE6 DIAGNOSTIC METHOD

6.1. Diagnostic Model

Based on experimental research analysis results, three variants have been developed of diagnostic model of 4CTi90–1 BE6 engine. This paper will present the most extended variant. The variant is characterized with the highest precision – accuracy of diagnosis being made. Its disadvantage is a high cost and labor consumption when taking measurements. It requires fuel consumption measurement, which is associated with a purchase of expensive apparatus and time-consuming assembly inside the vehicle.

Those diagnostic parameters in the model are as follows:

1. average torque $\overline{M_s}$
2. maximum torque value M_{smax} at rotational speed n_M;
3. torque value M_{s0} at minimum rotational speed $n_0=n_{min}$;
4. torque value M_{si} at maximum rotational speed $n_i=n_{max}$;
5. placement of maximum torque on rotational speed axis - rotational speed of maximum torque n_M;
6. a ratio of torque at minimum rotational speed to maximum torque:
$$C_{M1} = \frac{M_{s0}}{M_{\max}} \tag{6.1}$$
7. a ratio of torque at maximum rotational speed to maximum torque:
$$C_{M2} = \frac{M_{si}}{M_{s\max}} \tag{6.2}$$
8. average fuel consumption $\overline{Ge}$;
9. fuel consumption G_{eM} at rotational speed of maximum torque n_M;
10. consumption at minimum rotational speed G_{emin};
11. consumption at maximum speed G_{emax} ;
12. ratio of fuel consumption at maximum torque to a minimum consumption:
$$C_{Ge1} = \frac{Ge_M}{Ge_{\min}} \tag{6.3}$$
13. ratio of maximum fuel consumption to consumption at maximum torque:
$$C_{Ge2} = \frac{Ge_{\max}}{Ge_M} \tag{6.4}$$

The research results obtained are compared to values of quantities of usable-model engine and then a parameter value is being determined:

- „0" – no changes (the parameter value corresponds to the state of usefulness);
- „1" – the parameter value has been suspended compared to the value corresponding to the state of usefulness;
- „-1" – the parameter value has declined compared to the state of usefulness.

If all parameters have „zero" value, then object is usable. If „1" or „-1" has been recorded in the results sheet, then a set of results of parameters checks is compared to combinations of results characteristic for individual damages. A non-usability state is determined on that basis and damage is located.

Then location of the damage is verified through a comparison of absolute values of obtained parameters with values corresponding to individual damages. Accuracy (probability) of diagnosis is calculated on the basis of a number of parameters that reflect changes with their character („0", „1" or „-1") and absolute value of parameters describing a given damage.

State control and 4CTi90–1 BE6 engine damages location algorithm, developed on the basis of model I, has the following form:

State control:

If ($\overline{M_s}$ = 0) and (M_s = 0) and (M_{s0}= 0) and (M_{si} = 0) and (n_M = 0) and (C_{M1}= 0) and (C_{M2}= 0) and ($\overline{Ge}$ =0) and (G_{eM} = 0) and (G_{emin} = 0) and (G_{emax} = 0) and (C_{Ge1}= 0) and (C_{Ge2}= 0) **then the state is w^1**;

Location of damage:

If ($\overline{M_s}$ = –1) and (M_s = –1) and (M_{s0}= –1) and (M_{si} = –1) and (n_M = –1) and (C_{M1}= 1) and (C_{M2}= 0) and ($\overline{Ge}$ = -1) and (G_{eM} = –1) and (G_{emin} = –1) and (G_{emax} = –1) and (C_{Ge1}= 1) and (C_{Ge2}= 0) **then the state is w_1^0**;

Supplementary test aiming at higher certainty of diagnosis

If ($\overline{M_s}$ =126,59± 1,48 Nm) and (M_s =134,44± 1,59 Nm) and (M_{s0}= 127,85± 2,03 Nm) and (M_{si}=109,56± 3,32 Nm) and (n_M =2440± 109 rotations/min) and (C_{M1}=0,9510± 0,0159) and (C_{M2}=0,8150± 0,0211) and ($\overline{Ge}$ =12,39± 0,54 l/h) and (G_{eM} =10,94± 0,57 l/h) and (G_{emin}=7,28±0,50l/h) and (G_{emax} = 16,70± 0,09 l/h) and (C_{Ge1}= 0,6653± 0,0440) and (C_{Ge2}=0,6552± 0,0504) **then the state is w_1^0**;

If ($\overline{M_s}$ = –1) and (M_s = –1) and (M_{s0}= –1) and (M_{si} = –1) and (n_M = 1) and (C_{M1}= 0) and (C_{M2}= 1) and ($\overline{Ge}$ =0) and (G_{eM} = 1) and (G_{emin} = –1) and (G_{emax} = 0) and (C_{Ge1}= –1) and (C_{Ge2}= 1) **then the state is w_2^0**;

Supplementary test aiming at higher certainty of diagnosis

If ($\overline{M_s}$ =133,54± 1,81 Nm) and (M_s =144,08± 2,33 Nm) and (M_{s0}= 113,04± 1,88 Nm) and (M_{si}=125,33± 1,80 Nm) and (n_M =3100± 83 rotations/min) and (C_{M1}=0,7846± 0,0115) and (C_{M2}=0,8699± 0,0130) and ($\overline{Ge}$ =15,11± 0,83 l/h) and (G_{eM} =17,77± 0,24 l/h) and (G_{emin} = 7,95± 0,19 l/h) and (G_{emax} = 20,94± ± 0,16 l/h) and (C_{Ge1}= 0,4473± 0,0186) and (C_{Ge2}=0,8485± 0,0328) **then the state is w_2^0**;

If ($\overline{M_s}$ =–1) and (M_s = –1) and (M_{s0}= –1) and (M_{si} = –1) and (n_M = 0) and (C_{M1}= 0) and (C_{M2}= –1) and ($\overline{Ge}$ =0) and (G_{eM} = 0) and (G_{emin} = –1) and (G_{emax} = –1) and (C_{Ge1}= 0) and (C_{Ge2}= 1) **then the state is w_3^0**;

Supplementary test aiming at higher certainty of diagnosis

If ($\overline{M_s}$ =132,78± 4,02 Nm) and (M_s =157,10± 4,47 Nm) and (M_{s0}= 121,46± 2,07 Nm) and (M_{si}=87,72± 7,35 Nm) and (n_M =2640± 67 rotations/min) and (C_{M1}=0,7731± 0,0681) and (C_{M2}=0,5584± 0,0363) and ($\overline{Ge}$ =14,80± 0,68 l/h) and (G_{eM} =14,98± 0,20 l/h) and (G_{emin} = 7,88± ± 0,07 l/h) and (G_{emax} = 18,08± 0,45 l/h) and (C_{Ge1}= 0,5263± 0,0154) and (C_{Ge2}=0,8281± 0,0363) **then the state is w_3^0**;

If ($\overline{M_s}$ = 1) and (M_s = 1) and (M_{s0}= 1) and (M_{si} = 1) and (n_M = 0) and (C_{M1}= 1) and (C_{M2}= 1) and ($\overline{Ge}$ =1) and (G_{eM} = 1) and (G_{emin} = 1) and (G_{emax} = 1) and (C_{Ge1}= 1) and (C_{Ge2}= 0) **then the state is w_4^0**;

Supplementary test aiming at higher certainty of diagnosis

If ($\overline{M_s}$ =187,76± 1,51 Nm) and (M_s =195,14± 1,53 Nm) and (M_{s0}= 184,33± 1,59 Nm) and (M_{si}=169,85± 1,98 Nm) and (n_M =2620± 39 rotations/min) and (C_{M1}=0,9446± 0,0054) and (C_{M2}=0,8704± 0,0205) and ($\overline{Ge}$ =18,89± 0,70 l/h) and (G_{eM} =17,83± 0,08 l/h) and (G_{emin} =13,07± 0,09 l/h) and (G_{emax} = 23,49± 0,08 l/h) and (C_{Ge1}=0,7328± 0,0121) and (C_{Ge2}=0,7591± 0,0123) **then the state is w_4^0**;

If ($\overline{M_s}$ =–1) and (M_s = –1) and (M_{s0}= –1) and (M_{si} = –1) and (n_M = –1) and (C_{M1}= 0) and (C_{M2}= 0) and ($\overline{Ge}$ =–1) and (G_{eM} = –1) and (G_{emin} = –1) and (G_{emax} = –1) and (C_{Ge1}= 0) and (C_{Ge2}= 0) **then the state is w_5^0**;

Supplementary test aiming at higher certainty of diagnosis

If ($\overline{M_s}$ =104,54± 1,32 Nm) and (M_s =111,07± 2,77 Nm) and (M_{s0}= 89,27± 2,33 Nm) and (M_{si}=98.02± 2,39 Nm) and (n_M =2460± 115 rotations/min) and (C_{M1}=0,8037± 0,0248) and (C_{M2}=0,8825± 0,0494) and ($\overline{Ge}$ =11,41± 0,58 l/h) and (G_{eM} =10,92± 0,08 l/h) and (G_{emin} =6,60± 0,12 l/h) and (G_{emax} = 15,29± 0,16 l/h) and (C_{Ge1}=0,6048± 0,0340) and (C_{Ge2}=0,7141± 0,0497) **then the state is w_5^0**;

If ($\overline{M_s}$ =–1) and (M_s = –1) and (M_{s0}= –1) and (M_{si} = 0) and (n_M = 0) and (C_{M1}= 0) and (C_{M2}= 0) and ($\overline{Ge}$ = 0) and (G_{eM} = 0) and (G_{emin} = 0) and (G_{emax} = 0) and (C_{Ge1}= 0) and (C_{Ge2}= 0) **then the state is w_6^0**;

Supplementary test aiming at higher certainty of diagnosis

If ($\overline{M_s}$ =153,50± 2,21 Nm) and (M_s =167,19± 1,24 Nm) and (M_{s0}= 127,22± 1,49 Nm) and (M_{si}=136,42± 2,93 Nm) and (n_M =2620± 32 rotations/min) and (C_{M1}=0,7609± 0,0086) and (C_{M2}=0,8159± 0,0165) and ($\overline{Ge}$ =15,99± 0,79 l/h) and (G_{eM} =15,34± 0,12 l/h) and (G_{emin} =8,36± 0,12 l/h) and (G_{emax} = 21,78± 0,11 l/h) and (C_{Ge1}=0,5451± 0,0090) and (C_{Ge2}=0,7040± 0,0135) **then the state is w_6^0**;

Probability of a accurate diagnosis is calculated on the basis of the following expression:

$$p_d = \frac{n_1}{n} * 100\% \geq p_{dgr} \qquad (6.5)$$

where: n_1 – a number of diagnostic parameters whose value is convergent with a value set for a given damage; n – total number of diagnostic parameters; p_{dgr} – boundary probability of diagnosis accuracy $p_{dgr} = 0{,}85$.

6.2. Method Verification

The method for diagnosing internal combustion engines with automatic ignition, based on torque measurement in traction conditions, has been verified using:

- tests of smokiness of usable engine fumes and at selected damages;
- traction tests of a vehicle with usable engine and with selected damages.

Accuracy of a diagnosis made in torque measurement method in traction conditions is an assessment criterion. Verification tests results allow for making a conclusion that diagnosis accuracy probability is above 85%.

7. SUMMARY AND FINAL CONCLUSIONS

Summing up this paper on **„Method for diagnosing internal combustion engines with automatic ignition based on torque measurement in traction conditions,"** the following should be stated:

1. analysis and assessment of existing diagnostic methods have been conducted and on the basis of which it has been found that there is a need to develop a new diagnostic method allowing for making a diagnosis of internal combustion engine in real road conditions and that may become applicable to both board and external diagnostic systems;
2. theoretical assumptions have been presented of a new diagnostic method the gist of which is vehicle acceleration process in traction conditions. A set of state parameters includes: engine torque Ms and hourly fuel consumption Ge;
3. algorithm for determining diagnostic parameters has been developed;
4. algorithm for research method structure and assessment of states of internal combustion engines with automatic ignition has been developed:
5. preliminary experimental research have been conducted under which the following have been realized:
6. primary experimental research in traction conditions have been conducted;
7. primary experimental research in conditions of engine and chassis test benches have been conducted:
8. a total uncertainty of torque measurement and fuel consumption have been estimated under the method for diagnosing internal combustion engine in traction conditions;
9. based on performed tests and analyses of their results, a three-variant 4CTi90–1 BE6 engine diagnostic model has been developed;
10. diagnostic models have become the basis for development of algorithms to make a diagnosis – assessment of a state and location of 4CTi90–1 BE6 engine damages;
11. research conducting conditions have been presented that guarantee maintenance of assumed probability to make accurate diagnosis;
12. the method has been verified on the basis of: a comparison of results to combustion fumes smokiness research results, and through tests of a vehicle with introduced damages in traction conditions. On the basis of verification tests it has been found that the diagnosis accuracy probability obtained in the course of verification is not lower than 85%.

REFERENCES

1. Arczyński S.: *Mechanika ruchu samochodu*. WNT, Warszawa 1994.
2. Dębicki M.: *Teoria samochodu*, WNT, Warszawa 1969.
3. Hebda M., Niziński S., Pelc H.: *Podstawy diagnostyki pojazdów mechanicznych*. WKŁ, Warszawa 1984.
4. Niziński S. and others: *Diagnostyka samochodów osobowych i ciężarowych*. Dom Wydawniczy Bellona, Warszawa 1999.
5. Niziński S., Michalski R.: *Diagnostyka obiektów technicznyc*h. Wydawnictwo Instytutu Technologii Eksploatacji. Warszawa-Sulejówek-Olsztyn-Radom 2002.
6. Żółtowki B.: *Podstawy diagnostyki maszyn*. Wydawnictwa Uczelniane Akademii Techniczno-Rolniczej w Bydgoszczy, Bydgoszcz 1996.

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WEIGHT AND SIGNIFICANCE OF OBJECT DYNAMIC MODELS IN CONSTRUCTING MONITORING SYSTEMS

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Summary

The author's approach to tasks of constructing monitoring systems of the state changes of machines, devices and structures is presented in the paper. The weight and significance of the identification process of the monitored object dynamic model – as a factor which in an universal and coherent way preserves the realisation process of several tasks assigned to this system operations – is emphasised. Purposefulness of applying methods of the technical stability testing for estimation of dynamic behaviours of the monitored object, was indicated. Its usefulness for the selection of the proper monitoring symptoms, for determining their criterion values and for the estimation of their exceeding the permissible values - are shown in the paper.

Keywords: monitoring of machine technical state, the algorithms of monitoring procedures, modelling of dynamic state, stability, signal processing and analysis.

ROLA I ZNACZENIE MODELI DYNAMICZNYCH OBIEKTU
W BUDOWIE SYSTEMÓW MONITORUJĄCYCH

Streszczenie

W artykule zaproponowano autorskie podejście do zadań konstruowania systemów monitorujących zmiany stanów maszyn, urządzeń, konstrukcji. Zwrócono uwagę na rolę i znaczenie procesu identyfikacji modelu dynamicznego monitorowanego obiektu, jako czynnika, który w sposób uniwersalny i spójny zabezpiecza proces wykonawczy szeregu zadań przypisanych funkcjonowaniu tych systemów. W szczególności, wskazano na celowość zaangażowanie metod badania stateczności technicznej do oceny zachowań dynamicznych kontrolowanego obiektu. Pokazano jej użyteczność dla procesu realizacji wyboru właściwych w procesie monitorowania symptomów, określenia dla nich wartości kryterialnych, jak i tworzenia procedur ocen wyjścia ich poza dopuszczalne granice.

Słowa kluczowe: monitoring stanu technicznego, algorytmy procesu monitorującego, modelowanie stanu dynamicznego, stateczność, analiza i przetwarzanie sygnałów

1. INTRODUCTION

Monitoring of state changes of machines and devices – corresponding to the recognition of early stages of defects and identification of disturbances in their operations – is a complex research task. In practice, it is realised the most often via measuring and tracing dynamic changes of processes occurring in the object under inspection. This is done by the properly selected sensors in the monitoring system.

The construction process is related to:

- Selection of measuring rules and recording of the determined process variables,
- Selection of the conversion methods for recognition of causes of the observed states,
- Assuming relevant analytical algorithms of their trends,
- Establishing criterion references enabling the proper classification of the recognised states.

Procedures of filtration of measurement disturbances, algorithms of change predictions of controlled signals or expert systems allowing for a certain automation of the diagnostic changes occurring in the monitored machine - are more and more often implemented in solutions. Their realisations are based on various model formalisms determining their functioning as well as on the knowledge collected during their operations. The proper selection of algorithms in the construction process is decisive for the universality and functionality of the monitoring system.

Currently, in the collection of construction rules of the monitoring systems available in the market, there is none coherent theory enabling the proper connection of conditions of loosing the ability to safe operations with the rules of selecting diagnostic symptoms. Constructional and exploitational features of the inspected object corresponding to the requirements of undisturbed estimation of the monitored processes and prediction processes with a determined time advance - are not sufficiently taken into account in the construction of monitoring systems. Trials of looking for solutions, in which the essence of operating of the monitoring system constitute relationships between the state of the inspected system and the form of the monitored signal [3, 4, 7] conjugated with the criteria selection for the alarm signals [5, 6] or for switching off - are not numerous.

Thus, it seems that an important realisation approach to the construction of monitoring systems is its coupling with the identification of the dynamic model of the inspected object and with the analysis of its technical stability [11]. Such approach ensures the possibility of undertaking and solving several tasks in the building process of the monitoring system. The frame of constructional operations related to the building of the monitoring system, it means related to the selection of proper diagnostic symptoms, of the levels of their quantification for the purpose of diagnostics decisions or the requirements of the filtration of measuring disturbances – can be based on them.

The aim of this paper is to indicate certain possibilities within this scope. It does not pretend to show all results of the author researching these problems, but aims to indicate the existence of the universal platform giving the possibility of undertaking and solving several tasks in constructing monitoring systems – referring to the common modelling formalisation.

2. OBJECT MODELLING – THE BASE FOR CONSTRUCTING MONITORING SYSTEM

Several tasks determining functioning of monitoring systems, can be reduced to the problem of analysis the possible trajectories of the inspected dynamic system under the influence of disturbances in the exploitation process, caused by undesirable exploitation inputs (loads and external disturbances), or by changes of structural parameters (it means: mass, elastic and damping parameters) due to failures.

They determine the possible solutions of the set of differential equations modelling state changes in the monitored object and related to them the estimation of changes of the monitored dynamic processes.

Their forms result from the selected model formalisation of the inspected object, it means, from the description of the set of elements being in a mutual cooperation with the surroundings, which is characterised by a set of measurable features (containing the total information on the state of the inspected object), which are changing with time.

Generally the model describing the cooperation can be represented by a pair (**X** , **f**), in which **X** denotes the vector of state space, while ***f*** is a vector of this space representation:

$$\dot{x}_i = f_i\,(t, x_1, x_2, \ldots, x_n)\ , \quad i=1,2,\ldots,n \qquad (1)$$

in which functions f_i are determined in a space:

$$t \geq 0, \qquad (x_1, \ldots, x_n) \in G \subset E_n$$

where E_n denotes the linearly normalised n-dimensional space.

When using the identified model of the monitored object it is possible to recognise theoretically its behaviour under the influence of disturbances. The deviations of the inspected processes versus the programmed ones and caused either by parameter changes or by variability of inputs acting on the object - are classified.

Taking into account their model connections with the measuring observations the Kalman [15] model formalism can be assigned to them, ensuring the realisation process of the optimal filtration and prediction tasks of the monitored diagnostic signals.

The identified model of the inspected object given by Equation (1), under conditions of acting random disturbances, allows - in addition - the estimation of the time when the analysed operation enters into zones assigned to alarm states [19, 20]. The assigned for them analyses can be related to the existing analytical methods of the dynamic systems stochastic trajectories, including solutions based on the method of „*functionals supporting the obtainable zone*„. The analysis of the monitoring process of the state changes of the hydrodynamic bearing [1, 2] being the part of the dynamic system: '*Rotor – Bearings – Supports – Foundation'* can constitute a good example.

The model describing dynamic behaviours of the object, when its steady state is disturbed, can become the basic tool at constructing the monitoring system. It generates indications concerning the symptoms selection for the observation of the object state changes as well as the selection criterion values protecting the classification of undesirable state changes. Realisation of this operations results from analysis of dynamic behaviours of the object done when testing its stability. Various understanding of the stability notion and methods of its testing properly related to the required functional properties of the monitored object – can be applied [11, 13, 14].

The criterion of the technical stability [11] can be a good testing criterion for realisation of several tasks, which appear in processes of constructing monitoring systems. It widens the notation of stability in the Lagrange's and Lapunow's meaning into conditions, which can appear in the investigated technical reality. They seem to be especially essential for selecting the method of the monitored state changes realisation in the inspected object. It takes into account the quantification of motion disturbances characteristic for the tasks assigned by the monitoring system. They are – from the point of view of the correctly functioning inspected object - conditioned by the assumed permissible perturbations of input forces, or object characteristics as well as by the permissible changes of initial conditions – related to the acceptable changes of the structure parameters of the monitored object.

In the case when the solutions of the technical stability theory are applied for the realisation the monitoring of the object state it is necessary to assume:

- Permissible deviations of the motion trajectory from the steady state (related to the safe exploitation of the analysed object);
- Permissible range of the initial conditions changes;
- Levels of expected external and internal disturbances permanently acting on the inspected object, which dynamic behaviours are described by the equation:

$$\dot{x} = f\,(x, t) + R\,(x, t) \qquad (2)$$

in which **x**, **f**, **U** are vectors determined in space $\Re^n$:

$$\boldsymbol{x} = \begin{bmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{bmatrix} \quad \boldsymbol{f} = \begin{bmatrix} f_1 \\ f_2 \\ \dots \\ f_n \end{bmatrix} \quad \boldsymbol{R} = \begin{bmatrix} R_1 \\ R_2 \\ \dots \\ R_n \end{bmatrix} \qquad (3)$$

and their functions *f(t,x) R (t,x)* are determined in the zone contained in the $(n+1)$ dimensional space:

$$t > 0,\ x \subset G \subset E_n \qquad (4)$$

It is assumed that input functions of permanently acting disturbances *R (t,x)* in the zone (4) is limited:

$$\left\| \boldsymbol{R}\,(t\,,\boldsymbol{x}) \right\| < \delta \qquad (5)$$

where δ is a positive number, while $\left\| \bullet \right\|$ denotes the Euklides norm of vector ***R(t,x)***.

At this type of model dynamic behaviour the notion of technical stability for the system modelled is understood as follows:

Let there be two zones Ω and ω - contained in *G*. Zone Ω is closed, bounded and contains the origin of the system, while ω is open and contained within Ω.

Let us assume, that the solution of the analysed system (2) is $x(t)$, of an initial condition: $x(t_0) = x_0$.

If for every x_0 belonging to ω, ***x(t)*** remains in zone Ω for $t \geq t_0$, at the disturbance function satisfying inequality (5), the system (2) is *technically stable* due to zones ω, and the limited, constantly acting disturbances (5).

According to this definition of the technical stability, each motion trajectory, which exits zone ω, has to remain in zone Ω for $t \geq t_0$.

For the monitored objects, for which instantaneous exits of the monitored signals outside levels considered permissible - are safe, the notion of the technical stability can be weakened into the condition, in which each trajectory of motion which exits zone ω has to remain in zone Ω for $t_0 \leq t \leq T_0$, where $T - t_0$ is a time of motion. At such condition we are dealing with the ***technical stability in a finite time***.

Realisation of the monitoring process of changes of the inspected object state can be also looked for on the grounds of the ***stochastic technical stability*** definition introduced by W. Bogusz [11].

It is formulated as follows, in reference to the object described by the model:

$$\dot{x} = f\,(\,x, t, \xi(t, \alpha\,)\,) \qquad (6)$$

This model takes into account random disturbances α, acting on it, in a form of a certain stochastic process $\xi(t,\alpha)$ of the following features:

$$\xi(t, \alpha\,) \;=\; \sup_{x \in G} \left| \boldsymbol{R}\,(t\,, \boldsymbol{x}, \boldsymbol{\alpha}) \right| \qquad (7)$$

In reference to such conditions of functioning of the inspected object, two zones Ω and ω contained in E_n are defined, such that zone ω is limited and open, Ω is limited, closed and contains origin of coordinates and also takes into account the condition $\omega \subset \Omega$. Let us assume that the positive number ε satisfying inequality 0 <ε<1 exists. Initial conditions for $t = t_0$ are $x(t_0) = x_0$, while the solution assigned to them: $x(t, t_0, x_0)$. If each solution $x(t, t_0, x_0)$ of initial conditions belonging to zone ω belongs also to zone Ω with the probability higher than $1 - \varepsilon$, the analysed object is technically, stochastically stable it means: ***stochastically stabilised*** versus zones ω, Ω and process $\xi(t)$ with the probability $1 - \varepsilon$:

$$P\,\{\,\boldsymbol{x}(t,\,t_0,\,\boldsymbol{x}_0) \in \Omega\,\} > 1 - \varepsilon \quad \text{for} \quad \boldsymbol{x}_0 \in \omega \qquad (8)$$

The presented above mathematical formalisation of the problem of monitoring state changes of the object described by model (2), supplemented by relevant statements facilitating technical stability testing, can be used as the approach methodology to constructing monitoring system. Thus, it forms the logical frames for solving problems occurring at searching for the proper constructions of monitoring systems.

3. METHODS OF TESTING THE TECHNICAL STABILITY – TOOLS IN CONSTRUCTING MONITORING SYSTEMS

Realisation of the idea of utilising solutions of the technical stability theory in the process of constructing monitoring systems [5, 6] means introducing – into their solutions – algorithms of testing conditions of loosing the technical stability by the inspected object. This requires the identification of the dynamic model of the monitored object, being the grounds for comparative references of the observed states. Algorithms of testing the technical stability enable their classification. The main determinants of the monitoring process are identifications of the dynamic model of the inspected object. The identification process should be conjugated with the selected methods and algorithms of testing the technical stability, which can become the useful tool for the recognition of alarm states in the inspected object.

Solutions included in the so-called 'topologic' methods of solutions of differential equations can be applied in the constructing of monitoring systems. They require examination of trajectories, it means curves [$x(t),\ \dot{x}(t) = y$] on the phase plane $x,\ \dot{x}$, related to the dynamic model of the monitored object. Their analysis can constitute the basis for determination of the permissible dynamic behaviour of the monitored object, at the described level of permanently acting disturbances and allowable perturbations of the steady state. Those perturbations are related to changes of the parameters value, which might be significant for appearing of defects, including their early stages.

The investigating procedures are based on certain topologic facts, related to certain invariants of homomorphic rearrangements, formulated in the form of statements. They enable the qualitative estimation of dynamic behaviours of the analysed object and conditions for the technical stability loss - corresponding to them.

The Lapunow's method [11, 16, 17] is the most often applied procedure. The properties of the scalar function $V(x,t)$ - properly selected for the dynamic description of the inspected object - are used. Investigating its derivative along solutions (behaviours) of the system (2) determines its stability.

This law states: if there is a scalar function $V(x,t)$ of class C^1 determined for each $\boldsymbol{x}$ and $t \geq 0$ in the vicinity of the equilibrium point, meeting the conditions:

- $V(\boldsymbol{x},\ t) > 0$, for $x \neq 0$
- $\dot{V}(x,t) \leq 0$ along solutions (4) , for $\boldsymbol{x} \notin \boldsymbol{G} - \omega$ (9)
- $V(\boldsymbol{x_1},\ t_1) < V(\boldsymbol{x_2},\ t_2)$ for $\boldsymbol{x_1} \notin \boldsymbol{\omega}$ and $\boldsymbol{x_2} \notin \boldsymbol{G} - \boldsymbol{\Omega};$ $t_1 < t_2$

then the object described by (2) and meeting conditions (3-5) is technically stabilised.

Referring the results of this law to the problem of realisation assumptions for the monitoring systems of the machine state, the Lapunow's function $V(x,t)$ should be formulated and by means of the experimentally determined trajectories x, y of the object under testing, the conditions given by Equation (9) verified.

Essential, helpful element in the process of building a state classifier can be the results of the law given in paper [15], since it provides an estimation of the velocity with which the dynamics of the monitored system proceeds to the zero equilibrium point.

The law states that, in the case when the Lapunow's function: $V(x) > 0,\ x \in \Re^n,\ x \neq 0,$ is such that $V(x) < 0$ for $x \in \Re^n,\ x \neq 0$ at which the following relation occurs:

$$\gamma = \max_x(-V(x)/\dot{V}(x)),\ x \in \Re^n,\ x \neq 0$$

the inequality:

$$V(x,t) \leq V(x,0)e^{-t/\Upsilon} \qquad (11)$$

which allows to estimate the velocity, with which the analysed dynamic system proceeds to the zero equilibrium point – is the true one.

The results of this law enable to select properly the delay time of the monitoring system for reacting for an instantaneous disturbance.

Another way of investigating properties of the monitored trajectories – estimating the dynamic system stability – is using two functions [12]:

$$\Phi\ (x,y) = xy + \dot{x}\dot{y}\ ;\ \Psi(x,y) = x\dot{y} - \dot{x}y \qquad \Phi \qquad (12)$$

The first function is a derivative of the square vector of the distance of the point on the trajectory from the origin of coordinates, while the second is the value of the phase velocity moment versus the origin of coordinates, which positive or negative determinant allows to estimate the character of the monitored motion. Their values, positive or negative, enable assigning to the trajectory points the directions characteristic for input, output or slip points versus the analysed curve, which allows to determine G and Ω zones within the monitored phase space.

Assumptions for building quantifiers of the monitored trajectories properties (from the point of view of their stability) can be also looked for on the basis of the topologic retracting method, Ważewski [18]. In this method, developed by W. Bogusz [9], the zones bounded by curves of input and output points of the system *(2)* from areas considered to be permissible - are constructed.

As it results from the synthetic presentation of the examination methods of the technical stability [9], their application in constructing the monitoring system is related to three tasks [5]:

1. Identification of the dynamic model of the monitored construction node of the object under inspection.
2. Creation of the measuring instrumentation protecting observations of trajectory changes of the dynamic behaviour of the monitored object node, determined by the measurement:
$$x(t),\ \dot{x}(t) = y$$
3. Constructing quantifiers for the monitored courses by the implementation of algorithm of

examining the technical stability, based either on the method of the Lapunow's function, or two functions $\Phi(x, y)$ and $\psi(x, y)$, or the retracting method.

The solution of the first and second task does not generate significant difficulties in the realisation of the monitoring system. More difficult is assigning of positively or negatively determined Lapunow's function to the dynamics describing the monitored object, given by the identified set of differential equations.

An essential element of estimation the usefulness of phase trajectories in the defect recognition process is the requirement of tracing changes in the trajectory shape of the inspected processes. Its realisation, in the case of using the currently available – in the market – monitoring systems for inspecting vibrations of machines, devices or constructions, would require the reorganisation of their functioning. There would be a need of securing the possibility of measuring phase trajectories, which means measuring displacements and vibration velocities on the selected constructional nodes of machines. Analysis of their changes is the basic information carrier, which enables tracing the technical stability loss of the monitored object, caused by inadmissible disturbances in its proper functioning.

Thus, an essential task in the estimation of usefulness of the technical stability theory in the development of diagnostic systems is the verification of behaviours of phase trajectories of the monitored objects under conditions of defect occurrences [9, 10]. Computer simulation experiments provide certain directions and information [8] on changes of phase trajectories caused by defects.

4. CONCLUSIONS

The author's approach to tasks of designing and constructing of the systems monitoring changes of machines, devices and structure states – is presented in the paper. The attention was directed towards the importance of the dynamic model identification process of the monitored object. Its presence in the constructing procedure of the monitoring system preserves - in an universal and coherent way - the realisation process of diagnostic tasks. It enables the possibility of the simulation base formation for the recognition of inefficiency of the monitored objects, protects the optimal filtration and prediction of changes in the processes under inspection and formulates methodological guidelines for the realisation of the monitoring process.

Application of methods of technical stability investigations for assessments of dynamic behaviours of the tested object generates selection indications of symptoms necessary in the monitoring system, determination their criteria values as well as formation of estimation procedures of their exceeding the permissible values.

As it seen from the short review given above, several problems related to constructing the assigned algorithms remains still unknown and constitutes an interesting research field. The author hopes, that the indicated research idea will be developing and the results will produce more effective rules of monitoring the state changes in machines, structures and devices.

5. REFERENCES

1. Banek T., Batko W.: *Time Estimation of Disturbance Occurrences in Monitoring Systems*. Zeitschriftt f. angew. Math. u..Mech. (ZAMM), 77, s.1-8, 1977**.**
2. Banek T., Batko W.: *Method of Supporting Functional in the Estimation of Alarm Conditions in Systems of Vibration Monitoring*. Mechanika Teoretyczna i Stosowana No 4, Vol. 32, 1994. pp .931-944.
3. Banek T., Batko W.: *Estimation of Disturbances in Monitoring Systems*, Publishing House AGO, Kraków, 1997 (in Polish).
4. Batko W.: *Development of monitoring solutions weakly-sensitive for disturbances*. Report of the KBN Project No PB 582/3/91. 1991-1993 (Warsaw University of Technology) (in Polish).
5. Batko W.: *Stability in Technical Diagnostics*, Diagnostyka No 4 (44), 2007, p. 69-72.
6. Batko W.: *Technical stability – a new modeling perspective for building solutions of monitoring systems for machine state*. Zagadnienia Eksploatacji Maszyn, z. 3 (151), Vol. 42, s.147-157, 2007.
7. Batko W., Banek T.: *Noise filtering in monitoring systems*. Journal of Applied Mathematics and Computer Science 1993,vol.3, No.3, 509-517.
8. Batko W., Dąbrowski Z., Kiciński J.: *Nonlinear phenomenal in Vibroacoustics Diagnostic*, Publishing House of the Institute of exploitation Technology (ITE) Radom 2008. (in Polish).
9. Batko W., Majkut L.: *Damage Identification in Prestressed Structures Using Phase Trajectories*, Diagnostyka, No 4(44), 2007, p. 63-68.
10. Batko W., Majkut L.: *The Phase Trajectories as the New Diagnostic Discriminates of Foundry Machines and Devices Usability*, Archives of Metallurgy and Materials, Vol. 52, 2007.
11. Bogusz W.: *Technical Stability*. PWN, Warszawa, 1972 (in Polish).
12. Bogusz W.: *A Two Tensor Method for Investigation Nonlinear Systems*, Proceedings of Vibration Problems, Warszawa, 2, No 3, 1961.
13. Busłowicz M.: *Resistant Stability of Linear Dynamic Stationary Systems with Delays*, Publishing House of the Białystok Technical

University, Warszawa-Białystok, 2002 (in Polish).
14. Byrski W.: *Observations and Control in Dynamic Systems.* Scientific and Didacting Publishing House, AGH, Kraków, 2007 (in Polish).
15. Kalman R. E.: *A new approach tolinear filtering and prediction problems*. Jour. of Basic Eng. Trans. Of ASME, vo. 82D, 1960.
16. Mitkowski W.: *Stabilisation of Dynamic Systems*. Publishing House of AGH, Kraków, 1991 (in Polish).
17. *Stability Problems in Discrete Systems*, Team work, Publications of IPPT PAN, No 49, 1970 (in Polish).
18. Ważewski T.: *Sur un principe topologique de l'examen de l'allure asymptotique de integrals de equations differentiates ordinaries*, Ann. Soc. Polon. Math., No. 20, 1947.
19. Zabczyk J.: *Stable Dynamical Systems under Small Perturbations*. Preprint 353, December 1985, Institute of Mathematics PAN.
20. Zabczyk J.: *Exit Problem and Control Theory*. Systems and Control Letters, 6, 1985, pp.163-172.

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MECHATRONICS IN DIAGNOSTICS

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Sumamry

This paper deals with current problems of diagnosing mechanical structures. The structural diagnostics have been presented as an interdisciplinary area integrating the fields of mechanics, electronics, computer science and materials engineering. The analogy between mechatronics and structural diagnostics will be discussed. The diagnostic methods contain three basic elements: measurements, including sensors designing and signal processing, procedures and diagnostic algorithms as well as structure properties prediction. The main issues within monitoring and structural diagnostics will be presented in the paper.

Keywords: mechatronics, diagnostics, structural health monitoring.

MECHATRONIKA W DIAGNOSTYCE

Streszczenie

W pracy przedstawiono współczesna problematykę diagnozowania konstrukcji mechanicznych. Przedstawiono diagnostykę konstrukcji jako dziedzinę interdyscyplinarną, stanowiącą integrację mechaniki, elektroniki, informatyki i inżynierii materiałowej. Pokazana zostanie analogia pomiędzy mechatroniką, a diagnostyką konstrukcji. Metody diagnostyki zawierają trzy podstawowe elementy; pomiary, w tym konstrukcja czujników, przetwarzanie sygnałów; metody i algorytmy oraz przewidywanie własności konstrukcji. W ramach referatu przedstawione zostaną podstawowe problemy z dziedziny monitorowania i diagnostyki konstrukcji.

Słowa kluczowe: mechatronika, diagnostyka, monitorowanie stanu konstrukcji.

1. INTRODUCTION

New terms have recently appeared in the technical literature: SHM (Structural Health Monitoring) and structural damage detection [1, 3, 48]. Structural damage consists in such changes introduced into structure properties that have led or will lead in the future to the loss of operating properties. This term includes continuous monitoring of structure material condition (in real time) for structure elements as well as for the entire structure conducted during its operation. The structure material condition should meet the requirements specified in the design process. The requirements concerning material condition must take into account changes caused by normal wear and tear during operation, changes caused by the influence of environment in which the structure is used and accidental events affecting material condition. Due to the fact that the monitoring is carried out in a continuous way during operation, full operation history is available and these data can be used to forecast condition, breakdowns and time of structure safe use. In several titles, SHM is defined as a new method of Non-Destructive Testing [3, 15, 35]. The novelty of this approach consists in continuous monitoring of material condition while operating a given device. It requires some structural and operational solutions typical of this new field of structure testing. SHM constitutes a combination of such fields as sensorics, teleinformatics, electronics (microprocessor engineering in particular), mechanics and materials engineering [1, 7]. It has been schematically presented in fig. 1.

Systems implementing SHM processes should be embedded in the structure and act independently. Installation and use of such systems bring two kinds of benefits:

- for design engineers: it enables introduction of structural changes so that the breakdown probability is minimal,
- for users: guidelines for such management of structure use to minimize breakdown risk, treating the structure as a part of a bigger system.

As it is shown in the presented diagram of SHM process, its structure is very similar to mechatronics and it is completed with issues related to materials engineering.

The main functions of SHM system are as follows:

1. Monitoring of structural coherence (e.g. material condition);
   - A function connected with the type of physical phenomenon that constitutes a quantity measured by sensors and a failure mode;

- A function connected with the type of physical phenomenon used by built-in sensors for signal generation;

2. Monitoring of structure wear and tear – load cycles, influence of environment;
3. Prognosis of residual lifetime of the structure (function1+function2+damage mechanisms);
4. Managing the structure condition (maintenance activities, repair works, etc.).

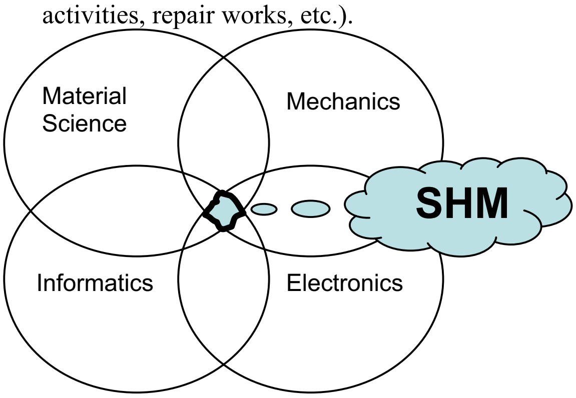

Fig. 1. Diagram of fields' integration in SHM systems

As a result of this multifunctionality, SHM systems have a hierarchical structure [9, 19, 28]. The first layer of the SHM system is a monitoring layer determined by the type of physical phenomenon monitored by sensors and connected with structure damage and by the type of physical phenomenon used by sensors in order to generate a signal, most frequently an electric one, containing information about damage and subject to recording and processing. A few or a few dozen sensors usually work in such a system. They are connected and create a network of sensors measuring also environmental factors that affect the structure condition and operation. Most frequently considered structural sensors currently include: light pipe technology-based sensors [2, 49], the so-called Bragg gratings used in aviation and construction industry, wireless sensors and their networks [4, 11, 13, 18, 21, 23, 47, 51, 59], sensors in the form of piezoelectric elements embedded in the structure [11, 18, 23, 47] and vision systems based on classic cameras [21, 59].

Data from all the sensors and historical data along with data from other, similar structures enable a fusion of diagnostic information on the structure condition (signal fusion). By linking this information with data from the base on structure damage and wear phenomena, a forecast of its condition and data on the range of necessary repair can be obtained. More and more frequently, simulation systems are applied for these purposes. The systems enable |a very fast generation of results similar to those obtained from the network of sensors on the basis of known damage models (structure virtual operation).

Methodology of data collection and selection of information on an object condition constitutes a crucial element of SHM procedures [15, 19, 44]. Two fundamental approaches may be currently listed in this area: statistical and based on image recognition techniques. They support the decision-making process on the current condition of the monitored structure. Due to the fact that contemporary SHM systems are embedded in the structure, the selection of inference algorithms and analysis of available measurement information must be specialized and possible to implement on processors with limited capacity. A review of these procedures can be found in the next chapter of this paper. The highest level of SHM systems contains procedures of forecasting condition of a monitored object. It is, undoubtedly, the most difficult and error-prone process implemented within SHM systems. The suggested diagnostic procedure has been presented in figure 2.

As the above diagram shows, the crucial role in the diagnostic process is played by two models: a global model describing structure behavior and a local model within simulation of material behavior, its degradation or other phenomena connected with loss of properties.

Application of such systems is encouraged by:

- possibility of avoiding catastrophic breakdowns,
- possibility of optimizing the operational process (minimization of emergency shutdowns),
- obtaining information for design engineers, which is necessary for structure modification,
- possibility of minimizing maintenance costs and increase in the device availability thanks to applying condition-based repair methodology and avoiding disassembly and replacement of undamaged or unworn elements,
- possibility of avoiding operator's mistakes in structure condition assessment.

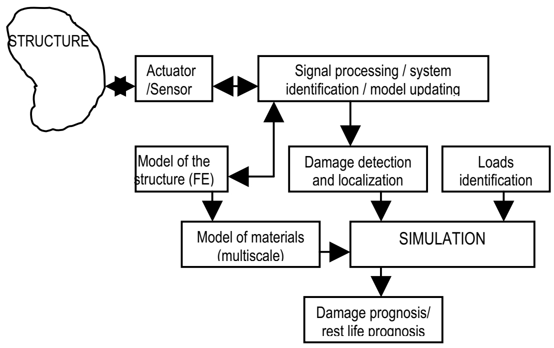

Fig. 2. Diagram of SHM process

Such systems are used in air force and civil aviation, military equipment, building infrastructure as well as critical machines in the industry (e.g. power engineering, chemistry, etc.) [1, 37, 48].

Economic reasons constitute a very significant factor influencing the universality of SHM systems' use. Such justification can be found in several papers [1]; it consists in comparing maintenance costs and structure availability. In the case of a structure with no SHM systems installed, the costs increase with operation time but the structure availability decreases. Installation of such systems enables to keep constant maintenance costs accompanied by constant availability of the structure. There is, however, one precondition for applying SHM systems which limits universality of their implementation. The cost of the system itself must be lower than the positive economic result connected with its use.

The necessity to reduce the costs of SHM systems is currently related to the application of intelligent materials and structures [3]. They enable to integrate the structure and built-in sensors into one system. To make such activities effective, they need to be undertaken at the stage of structure designing. Tendencies to apply intelligent structures have been observed since early 80s, particularly in aviation and construction industry. Their characteristic feature is adaptation of these structures' properties to operational conditions. This adaptation takes place independently in intelligent structures. Intelligent structures include: structures sensitive to operational conditions, structures controllable within their properties and auto-adaptive structures adjusting their properties to the operational needs. In practice, homogeneous materials frequently applied in structures are replaced by composite materials or other multimaterials (materials composed of layers with different physical properties). Intelligent materials and structures include: structures with controlled geometry (shape), structures with controlled vibrations and structures with controlled condition. The last structure type, in particular, is closely connected with SHM techniques [1, 4, 27, 40, 56]. It is most often expressed in the form of embedded sensors made of intelligent materials or embedded actuators aiming to soften the effects of a breakdown. The purpose of such actuators is to generate the structure deformations in order to reduce stresses in the areas of their concentration [34, 55]. Nowadays, scientists are searching for phenomena and methods of their measurement that would enable to conduct continuous structural health monitoring through monitoring of the structure material condition.

Research within SHM systems' development is very often inspired by discoveries in biology and biomimetics [8]. Very similar research is conducted in medicine and SHM methods' development [16]. SHM systems can be applied not only during structure operation but also during its manufacture, transport and assembly. They enable proper management of structure lifetime through a suitable selection of mission that can be performed and maintenance activities it needs to safely meet all the requirements imposed. More and more frequently, specialists search for methods that could be used in each stage of a product lifetime, as most economically effective and easiest to implement.

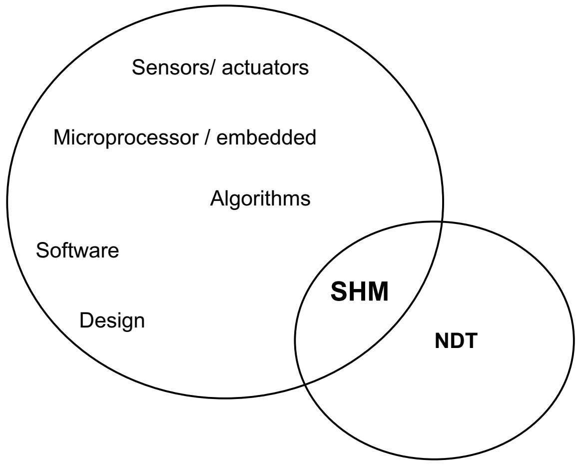

Fig. 3. Diagram of structural health monitoring (SHM) process – basic elements of the process

What is typical of SHM systems, it is their integration with a structure. Very often, sensoric elements constitute a part of the structure performing also other functions; it is usually made by using intelligent materials.

Summing up the above review of the issues connected with SHM, one may say that it is a new interdisciplinary field concentrating such detailed areas of science as mechatronics, materials engineering, electronics, computer science, physics, optics and many other, applied in operation of structures in aviation, construction industry, automotive industry and power engineering, including nuclear power engineering. The range of application is wider and wider.

2. SENSOR TECHNOLOGY FOR STRUCTURE DIAGNOSTICS

Development of SHM methods and applications results from a rapid development of measurement techniques enabling collection, archivisation and processing of measured signals. The crucial role in these systems is played by sets of sensors that enable to directly measure the quantities connected with material and structure degradation phenomena. Sensors of this type include: optical sensors, piezoelectric sensors and contactless sensors used more and more frequently to test and analyze structural health. Another method of sensors' classification is the manner of transferring measurement results to the system of data collection and analysis. This division includes wireless sensors and sensors connected to the system by means of cables. Due to the size of monitored structures and nature of currently built monitoring systems in the form of dispersed layouts, application of wireless sensor networks is more and more frequent.

Optical sensors [2] used in SHM are based on light pipe techniques whose development is connected with rapid growth in application of light pipes in telecommunications. The advantages of light pipes used for measurements in SHM systems include: resistance to electromagnetic interference, very small weight, high definition, wide transfer band, large information capacity and relatively low cost. Application of light pipes to implement sensors can be divided into three categories:

1. Sensors based on light intensity measurement
2. Sensors based on phase modulation (interferometers)
3. Sensors based on light wave length modulation.

The first group of sensors includes proximitors to measure displacements of whirling shafts [37]. These sensors enable to measure displacements with a definition better than 3 μm. Another example of a light intensity measurement-based sensor is a pressure sensor, in which the light pipe is located between two rough surfaces subject to loading resulting from differential pressure between them. As a result of surface irregularity, the light pipe is bent and one can observe bigger optical losses than in case of unbendable light pipe. Thus, it is possible to measure pressure. Various light sources as well as various light detectors are applied in these sensors.

Another group of sensors enable currently the most detailed laboratory distance measurements. The principle consists in measuring the power of optical signal of a monochromatic light wave reaching the detector inside the light pipe. The power of the signal of two waves overlapping each other and running inside the light pipe (a wave generated by the source and a reflected wave) depends on the phase displacement between the waves and for a displacement by 180^o it may equal zero. The change in one wave path against the other results in their mutual phase displacement and it indirectly changes the power of the signal reaching detector. Light pipe, interferometric sensors enable distance measurement with a definition of up to 10 nm.

Another area of activity of light pipe-based sensors is application of Bragg gratings [3]. Bragg grating placed inside the light pipe, most frequently on the length of 10 mm, constitutes a periodic modulation of refraction coefficient. It leads to light wave diffraction and consequently, to the change in the optical wave length according to the diffraction (Bragg's) law for a wave running in the light pipe:

$$\lambda_b = 2\overline{n}_e T$$

where: λ_b is the length of a light wave after going through Bragg grating, $\overline{n}_e$ is the averaging refraction coefficient, T is the period of light pipe properties' modulation.

In the case of a change in properties' modulation (Bragg grating period), the length of a light wave is also changed. It means that Bragg grating acts as an optical filter whose parameters depend on elongation or shortening of the light pipe measuring length. The dependence between relative strains and change in wave length may be expressed in the following form:

$$\Delta\lambda_b = \lambda_b \xi \varepsilon$$

where: ξ is photoelasticity constant (1.13 pm/με for the light 1550 nm), ε is average strain on the grating length.

The measurement of strains consists in tracking the displacement of wave length for the given grating.

The initial modulation of a light pipe is given in the production process. For one light pipe, one can place as many as 3000 gratings, obtaining the possibility of distinguishing from which grating the given wave length comes. In practice, the used strain sensors have a definition (theoretically) of approx. a few nε, however due to the influence of temperature, which should be compensated, their definition amounts to 1 με. Particular solutions differ in the method of measurement of wave length displacement. The most frequently used ones include: WDM interferometer, Fabry – Perota filter, optoacoustic tuned filter, CCD linear sensor, hybrid tuned filter. The choice of measurement method depends on the accuracy required and frequency of changes of the measured quantity. In the majority of Bragg grating cases, the measuring band is limited to 100 Hz. This frequency is completely sufficient to monitor structure condition. Light pipe sensors with Bragg gratings are used as elements embedded in composite structures, in reinforced concrete structures to monitor strains in reinforcement. The advantages of sensors constructed in this way include a possibility of application in explosive environments, long-lasting stability of work, small dimensions, small weight, possibility to multiplex sensors on one light pipe (usually, 10 Bragg gratings on one light pipe), relatively low cost of the sensor and resistance to strong electromagnetic fields. Light pipe sensors are used to measure distribution of structure strains in such objects as bridges, aircrafts and ships. Possibility of tracking local changes in strains' distribution constitutes an advantage as regards SHM systems. Several structure damages in the initial nucleation stage do not modify global strains in a measurable way but only cause some slight local changes.

Research on development of sensors using light pipes with Bragg gratings on them is conducted very intensively all over the world. These sensors have a wide range of described commercial applications in SHM systems.

Other sensors largely used in SHM systems are, due to the possibility of easy integration with monitored structure, piezoelectric sensors [1].

The techniques using piezoelectric sensors may be classified into three groups:

1. Passive techniques,
2. Active techniques,
3. Mixed techniques.

These techniques have been schematically presented in fig. 4.

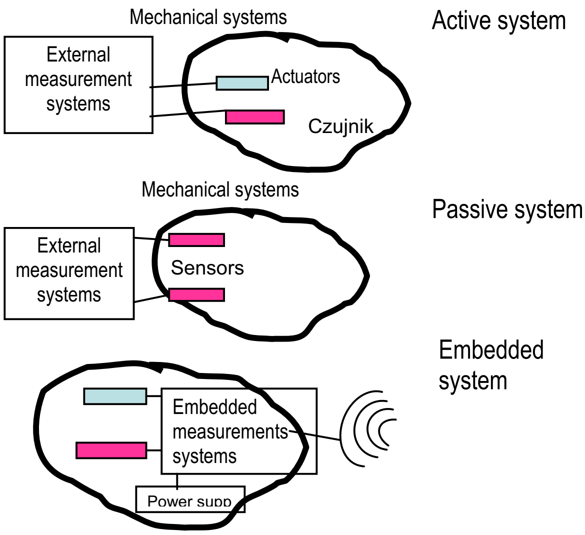

Fig. 4. Schematic presentation of typical SHM systems

The SHM systems presented in fig. 4 use various physical phenomena taking place in structures. The phenomena most frequently applied in SHM systems include: acoustic emission [1], propagation of ultrasounds (including Lamb waves) in structure [17] and a change in electromechanical impedance as a result of damage [34].

One of the advantages of applying piezoelectric elements is the possibility to use them as sensoric elements measuring structure response and simultaneously, as elements exciting vibrations within high frequencies. Excitation conducted by piezoelectric systems is characterized by relatively considerable force but small displacement.

Piezoelectric sensors are made of materials showing piezoelectricity effect connected with electric charges generation as a result of stresses taking place in the material. Such properties are typical of quartz crystals and different kinds of ceramic materials, the most popular ones include lead zirconate titanate (PZT), barium titanate, polyvinylidene fluoride (PVDF).

For a typical piezoelectric element with the shape of a disc of d thickness, τ voltage generated as a result of stress is expressed by the following formula:

$$V = gd\tau$$

where: g is the voltage coefficient defined as a ratio of voltage to stress for a unitary thickness of a disc. The dependence between dipole moment and mechanical deformation of a piezoelectric element may be expressed by means of the following formulas:

$$\sigma = E\varepsilon - eE_o$$
$$D = \varepsilon_o E_o + e\varepsilon$$

where: σ is mechanical stress, ε is relative strain, E_o is electric field intensity, D is density of electric field flux, E is material Young's module, e is piezoelectric constant, ε_o is permittivity of free space.

The efficiency of piezoelectric materials can be measured by means of electromechanical coupling coefficient K^2, determined from the following dependence:

$$K^2 = \frac{e^2}{E\varepsilon_m}$$

where: e is piezoelectric constant, E is Young's module, e is piezoelectric material permittivity.

The advantage of piezoelectric sensors is that they generate loads with no power supply, and the disadvantage is that they work only with dynamic loads and below Curie temperature. In practice, piezoelectric materials are not ideal dielectrics and this is the reason for difficulties in measuring very low frequencies (leakage conductance of loads).

Piezoelectric sensors play a significant part in structural health monitoring. They are applied to measure structure vibrations within low frequencies (0- 20 kHz), within ultrasound frequencies (above 20 kHz), as well as those connected with acoustic emission (above 100 kHz). In continuous monitoring systems, which are typical of SHM, piezoelectric sensors are embedded in the structure. Such solutions are used in both methods based on vibration measurement and active methods of condition monitoring based on generation and measurement of waves in structures.

In case of many monitored structures, the cost of monitoring system is high due to the necessity of installing cables that supply sensors and enable signal transmission from the sensor to the data collection station. In order to reduce these costs, several companies and research laboratories work on wireless transmission of data [28, 51]. Recently, there has been a significant increase of interest in wireless sensors. Moreover, we can observe irregular development of such sensors' production technology.

Modern wireless sensors constitute an independent system of data collection with a built-in microprocessor dedicated to measuring data processing and to managing wireless communication [51]. The sensors are very often equipped with systems to recover energy from vibrations by means of piezoelectric effect [42, 43]. Such a system is integrated with a sensoric element which enables to minimize the amount of information sent. An outline of a wireless sensor has been presented in fig. 5.

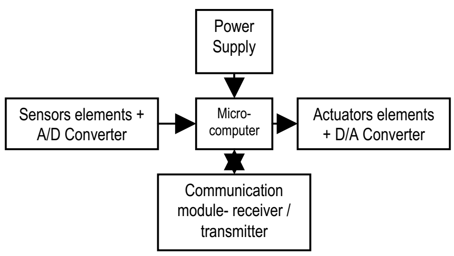

Fig. 5. Schematic structure of a wireless sensor

Technological development of wireless sensors applied to structural health monitoring goes towards implementation of monitoring algorithms directly in the sensors and of the so-called local SHM algorithms.

3. RESEARCH METHODS IN STRUCTURE DIAGNOSTICS

There are three groups of SHM methods: vibration measurement based methods, methods based on testing wave phenomena and methods using other phenomena accompanying structure operation, e.g. generation of a changeable temperature field as a result of structure damage [46]. The use of active methods is more and more frequent. These methods consist in generating phenomena whose course is influenced by potential damage in the tested structure. The basic methods within structure diagnostics include:

- Methods based on vibrations measurement (low-frequency, structure modal parameters) [6, 8, 12, 40, 36]
- Methods based on measurement of elastic waves propagation (the most frequently used ones include Lamb waves) [22, 1, 48, 17, 38, 39, 61];
- Methods based on strain measurement (more and more often, with the use of light pipe technique – Bragg grating) [2];
- Methods based on measurement of other phenomena (more and more frequent application of active thermovision) [46];
- Methods based on impedance measurement (measurement of input function and response in one point) [34].

The listed methods are not the only ones used in practice. They are, however, most frequently applied methods with existing and available monitoring systems.

A model based method schematically presented in fig. 6 is one of the methods more and more often applied in structure monitoring [32].

This method is more and more widely used due to development of operating modal analysis techniques and loads identification methods basing on the solution to the identification inverse problem [15, 52, 54, 50].

4. DAMAGE DETECTION ALGORITHM

Several various algorithms used to detect damage in structures have been described in literature. As regards their use in SHM systems, these should be algorithms not requiring too strong design power and optimized for embedded-type application.

Only two selected algorithms have been presented in this paper: the one based on modal filter [33, 60] and the other one based on regressive models [25, 28].

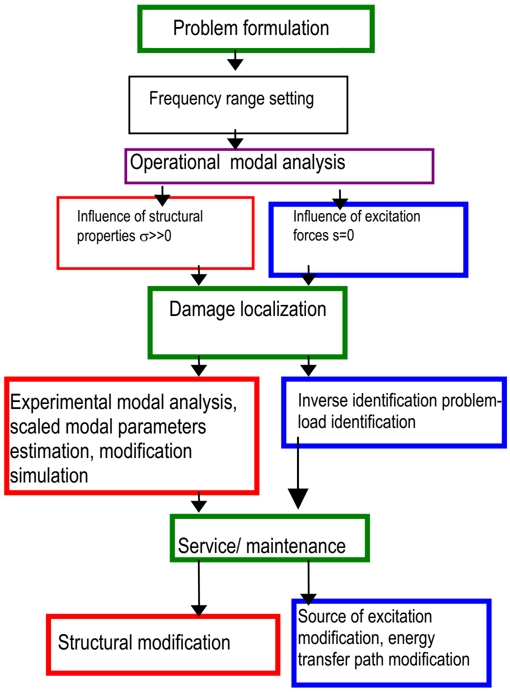

Fig. 6. Diagram of structure monitoring and diagnostics method based on a modal model.

One of the main methods in SHM practice is a method based on tracking changes in structure modal parameters, as it is shown in fig. 6. However, in many practical cases, such environmental parameters as a change in ambient temperature, humidity, etc., have a greater influence on structure parameters than the arising damage. Therefore, this influence should be filtered out. A modal filter constitutes one of the methods that enable to filter environmental parameters' influence on structure modal parameters. The basis of modal filter theory has been presented for the first time in [31, 57, 60]. Its application to diagnose structure condition has been presented in [8, 33]. The idea of modal filter method consists in transforming physical coordinates (generalized) into modal coordinates connected with particular forms of structure vibrations. For this purpose, new modal vectors have been defined – the so-called reciprocal modal vectors. According to the definition, reciprocal modal vectors are orthogonal towards all modal vectors except for one on which the filter is tuned. Thanks to that, modal filter may be used to disintegrate the system response to particular modal coordinates η_r.

$$\eta_r(\omega) = \Psi_p^{\ T} \cdot \{x(\omega)\} \qquad (1)$$

where: Ψ_p – matrix of reciprocal modal vectors
$\{x(\omega)\}$ – system response vector.

Determination of r modal vector corresponding to r pole of transition spectral function is based on the assumption that the modal residue R_{rpp} has an imaginary value:

$$R_{rpp} = j \cdot 1 \qquad (2)$$

In the next step, it is assumed that the transition spectral function $H_{pp}(\omega)$ for the system with one degree of freedom is expressed in the following form:

$$H_{pp}(\omega) = \frac{R_{rpp}}{j\omega + \lambda_r} + \frac{R_{rpp}^{\ *}}{j\omega + \lambda_r^{\ *}} \tag{3}$$

where: $\lambda_\rho -$ r pole of the system.

For the given frequency range, the above transition function is determined by the vector of k value:

$$H_{pp}(\omega) = \left[H_{pp}(\omega_1) \quad H_{pp}(\omega_2) \quad \cdots \quad H_{pp}(\omega_k)\right]^T \tag{4}$$

Assuming that there is one input function in the system and that the response is measured in N points on the structure, the matrix of transition function has the value k x N;

$$H_{kN}(\omega) = \begin{bmatrix} H_1(\omega_1) & H_2(\omega_1) & H_N(\omega_1) \\ H_1(\omega_2) & H_2(\omega_2) & H_N(\omega_2) \\ \vdots & & \\ H_1(\omega_k) & H_2(\omega_k) & H_N(\omega_k) \end{bmatrix} \tag{5}$$

On the basis of the transition function matrix formulated in this way, the matrix of reciprocal modal vectors Ψ_p is determined from the following dependence:

$$\Psi_p = H_{kN}^{\ +} \cdot H_{pp} \tag{6}$$

In the case of damage in the structure, the structure rigidity is usually changed locally, which is reflected in the change in values of rigidity matrix elements, and which consequently affects the change in frequency of free vibrations and modal vectors.

In this case (damaged system), the filter tuned for a structure with no damage will respond in a completely different way than for a structure with no damage. Additional maxima different from structure poles will be created at the output.

In the case of a change in structure properties (frequency of free vibrations), as a result of change in structure temperature or humidity, the filter response will be different as regards quality. It results from the fact that temperature change is accompanied by a change in all the elements of rigidity matrix proportionally to the change in temperature, or in the elements of mass matrix as a result of change in ambient humidity, which do not change the shape of vibrations' form but only natural frequencies. In this case, the response of a modal filter tuned for an undamaged structure will remain unchanged [57, 34, 45]. Modal filter implementation constitutes the subject of a project conducted at the Department of Robotics and Mechatronics at the Cracow University of Science and Technology. In the case of analyzing nonstationary systems (here, with changeable parameters) to process and filter signals, a wavelet transform is applied [26, 20].

The second algorithm mentioned is based on signal modeling (in case of measuring response only) or structure modeling when input and output measurements are available (for active methods) [6]. This algorithm has two basic advantages. Firstly, it can be decentralized which means that it can be used locally for particular sensors independently. Secondly, it does not require great design power. This algorithm is dedicated to be used in embedded systems. The algorithm first step is estimation of parameters of AR (ARX) models, which can be conducted using the least squares method, known from the linear systems theory:

$$\Theta = \left[\Phi^T \Phi\right]^{-1} \Phi^T Y \tag{7}$$

where: Θ – is parameters' vector, F is regression matrix containing results of input function measurements, Y is output vector.

Thanks to the knowledge of regressive model parameters for an undamaged structure and during operation, their difference may be determined. Various kinds of metrics are applied here. One of the possibilities is application of difference standard deviation. If it exceeds a certain, specified level, damage arises in the structure.

In another approach [6, 24, 45], basing on the knowledge of AR (ARX) model parameters, discrete system poles are determined solving a characteristic equation. Basing on the knowledge of these poles, structure modal parameters are determined in the form of natural frequencies and modal damping coefficients [20, 53]. On the basis of their variation, it is possible to estimate if there is any damage in the system. Low requirements as regards design power and possibility to implement them in the form of recurrent procedure constitute the advantages of this method. Basing on this method, the team of specialists at the Department of Robotics and Mechatronics at the Cracow University of Science and Technology has developed a device to evaluate flutter margin (on-line), on the basis of measurements of an aircraft's vibrations during flight [53].

5. STRUCTURAL HEALTH FORECASTING

Structural health forecasting in SHM systems is a new problem based particularly on simulation of structure life on the basis of a model of a monitored object and identified loads. The issue of load identification is defined as an identification inverse problem which, in most practical cases, is an incorrectly defined problem [54, 41] and special methods are required to solve it. The majority of these methods are based on regularization [54] or dynamic programming [41]. For forecasting purposes, the following models of monitored objects are used: models built on the basis of crack mechanics rules (physical model), metamodel (a model in the form of experience-based dependence) or multi-scale, adjoint models that can be used to simulate phenomena of cracking or wear and tear in the macro and micro scale at the atoms level [30, 55]. This development of simulation methods enables to forecast the time of object correct use in a more and more precise manner.

6. SUMMARY

Basing on the presented review of structural monitoring and diagnostics issues, this research area can be treated as an interdisciplinary field in which correct integration of a monitoring system with structure plays a more and more significant role. More and more frequently, implementation of this process involves application of built-in systems that work independently and are fully embedded in the monitored object. Therefore, structural monitoring, diagnostics and mechatronics have several common features whereas methods and tools used in mechatronics are largely applied in monitoring and diagnostics.

BIBLIOGRAPHY

1. Adams D. E.: *Health Monitoring of Structural Materials and Components,* Wiley, Chichester, 2007.
2. Ansari F.: *Fibre Optic Sensors for Construction Material and Bridges,* Lancaster, PA, Technomic, 1998.
3. Balageas D., C. P. Fritzen, A. Gumes (Ed.), *Structural Health Monitoring,* ISTE, London, 2006.
4. Basheer M. R., Rao V., Derriso M.: *Self-organizing Wireless Sensor Networks for Structural Health Monitoring*, in Proceedings of the 4th International Workshop on Structural Health Monitoring, Stanford, CA, September 15–17, 2003, 1193–1206.
5. Beynon J. H., Das S., Howard I. C., Shterenlikht A.: *Extending the Local Approach to Fracture; Methods for Direct Incorporation of Microstructural Effects into Finite Element Model of Fracture*, Proc. Conf. ASME2002, ed., Brust F. W., Vancouver, 2002, 229-237.
6. Bogacz M., Uhl T.: *Real-time Modal Model Identification and Its Application for Damage Detection,* Proceedings of ISMA 2004 Conference, Leuven, (2004), pp. 1065- 1075.
7. Chang P. C., Flatau, A., Liu S. C.: *Review Paper: Health Monitoring of Civil Infrastructure*, Structural Health Monitoring, Vol. 2 (3), pp. 257-267, 2003
8. Deraemaeker A., Preumont A.: *Vibration-based Damage Detection Using Large Array Sensors and Spatial Filters*, Mechanical Systems and Signal Processing, Volume 20, 2006. Issue 7, 1615-1630.
9. Doebling S. W., Farrar C. R., Prime M. B.: *A Summary Review of Vibration-based Damage Identification Methods*, Shock and Vibration Digest, Vol. 30, No. 2, 1998, pp. 91–105.
10. Farrar C. R., Sohn H., Robertson A. N.: *Application of Nonlinear System Identification to Structural Health Monitoring,* in Proceedings of the 2nd European Workshop on Structural Health Monitoring, Munich, Germany, 2004, pp. 59–67.
11. Fritzen C. P., Mengelkamp G., Guemes A.: *A CFRP Plate with Piezo-electric Actuators and Sensors as Self Diagnosing Intelligent Structure,* in Proceedings of the International Conference on Noise and Vibration Engineering, Leuven, Belgium, 2002, pp. 185 191.
12. Fugate M. L., Sohn H., Farrar C. R.: *Vibration-Based Damage Detection Using Statistical Process Control*, Mechanical Systems and Signal Processing, 2001, 15 (4) pp.707–721.
13. Giurgiutiu V., Buli X., Cuc A.: *Dual Use of Traveling and Standing Lamb Waves for Structural Health Monitoring*, in Proceedings of the 23rd International Modal Analysis Conference (IMAC XXIII), Orlando, Florida, USA, 2005, pp. 361 – 368
14. Hermans L., Van der Auweraer H., Coppens P., Mathieu L.: *Modal Parameter Extraction from In-Operation Data*, XV IMAC, Orlando, pp. 531–539, 1996.
15. Inman D. J., Farrar C. R., Steffan V. Lopes (ed.): *Damage Prognosis for Aerospace, Civil and Mechanical Systems*, Wiley, New York, 2005.
16. Karbhari V. M., Guan H., Sikorsky C.: *Web-based Structural Health Monitoring of a FRP Composite Bridge*, in Proceedings of the International Conference on Structural Health Monitoring and Intelligent Infrastructure, Tokyo, Japan, November 13–15, Vol. 1, 2003, pp.217–225.
17. Kessler S. S., Spearing S. M., Soutis C.: *Damage Detection in Composite Materials using Lamb Wave Methods*, Smart Materials and Structures, 2002, 11(2) pp. 269–278.
18. Kim J. S., Vinoy K. J., Varadan V. K.: *Wireless Health Monitoring of Cracks in Structures with MEMS–IDT Sensors*, in Smart Structures and Materials, San Diego, CA, March 18, Proceedings of the SPIE, Vol. 4700, 2002, pp. 342–353.
19. Klein L. A.: *Sensor and Data Fusion: Concepts and Application*, SPIE Press, 1999.
20. Klepka A., Uhl T.: *Application of Wavelet Transform to Identification of Modal Parameters of Nonstationary Systems,* J. of Theoretical and Applied Mech., Vol. 43, (2005), pp. 277-296.
21. Kohut P, Holak K, Uhl T.: *Structural Health Monitoring Using a Vision System*, Materials of XIVth School of Modal Analysis, Cracow, 2008.
22. Leonard K. R., Malyarenko M. K.: *Hinders, Ultrasonic Lamb Wave Tomography,* Inverse Problems, vol. 18, 2002, pp. 1795–1808.
23. Lin M., Chang F.-K.: *The Manufacture of Composite Structures with a Built-in Network of Piezoceramics,* Composites Science and Technology 62 (2002), pp. 919–939.
24. Ljung L., Söderström T.: *Theory and Practice of Recursive Identification*, MIT Press, Cambridge, 1985.
25. Lu Y., Gao F.: *A Novel Time-Domain Auto-Regressive Model for Structural Damage*

Diagnosis, Journal of Sound and Vibration, Vol. 283, 2005, pp. 1031–1049.
26. Lucero J., Taha M. M. R.: *A Wavelet-Aided Fuzzy Damage Detection Algorithm for Structural Health Monitoring*, *in Proceedings of the 23rd International Modal Analysis Conference (IMAC XXIII), Orlando*, Florida, USA, 2005, pp.. 78 – 84.
27. Luo H., Hanagud S.: *Dynamic Learning Rate Neural Network Training and Composite Structural Damage Detection,* AIAA Journal, Vol. 35, 1997, pp. 1522–1527.
28. Lynch J. P.: *An Overview of Wireless Structural Health Monitoring for Civil Structures*, Phil. Transactions R. Society A, vol. 365, 2007, pp. 345-372.
29. Lynch J. P., Sundararajan A., Law K. H., Kiremidjian A. S., Carryer E.: *Embedding Damage Detection Algorithms in a Wireless Sensing Unit for Operational Power Efficiency*, Smart Materials and Structures, Vol. 13, No. 4, 2004, pp. 800–810.
30. Friswell M. I., Penny J. E. T.: *Crack Modeling for Structural Health Monitoring*, International Journal of Structural Health Monitoring 2002, 1, pp. 139–148.
31. Meirovitch L., Baruh H.: *Control of Self-adjoint Distributed Parameter System*, Journal of Guidance Control and Dynamics, 8 (6), 60-66. 1982.
32. Mendrok K., Uhl T.: *Overview of Modal Model Based Damage Detection Methods*, *Proceedings of 2004 ISMA*, Leuven, Belgium.
33. Mendrok K., Uhl T.: *Application of Modal Filter for Damage Detection.* Proceedings of III ECCOMAS Thematic Conference on Smart Structures and Materials, Gdansk 2007., Poland
34. Park G., Sohn H., Farrar C., Inman D. J.: *Overview of Piezoelectric Impedance Based Health Monitoring and Path Forward*, Shock and Vibration Digest, vol. 35, 2003, pp. 451-463.
35. Park J. M., Kong J. W., Kim D. S., Yoon D. J.: *Nondestructive Damage Detection and Interfacial Evaluation of Single-Fibers/ Epoxy Composites using PZT, PVDF and P(VDF-TrFE) Copolymer Sensors*, Composites Science and Technology, Vol. 65, 2005, pp. 241–256.
36. Parloo E., Guillaume P., Van Overmeire M.: *Damage Assessment Using Mode Shape Sensitivities*, Mechanical Systems and Signal Processing, Vol. 17, 2003, pp. 499–518.
37. Pi Y. L., Mickleborough N. C.: *Modal Identification of Vibrating Structures Using ARMA Model,* Journal of Engineering Mechanics 115, 1989.
38. Ryles M., McDonald I., Ngau F. H., Staszewski W. J.: *Ultrasonic Wave Modulations for Damage Detection in Metallic Structures*, Proceedings of the Third European Workshop on Structural Health Monitoring, Granada, 2006, pp.275–282.
39. Ryles M., I. McDonald, F. H. Ngau, Staszewski W. J.: *Ultrasonic Wave Modulations for Damage Detection in Metallic Structures*, Proceedings of the Third European Workshop on Structural Health Monitoring, Granada, 2006, pp.275–282.
40. Silva J. M. M., Gomes A. J. M. A.: *Crack Identification of Simple Structural Elements through the Use of Natural Frequency Variations: The Inverse Problem*, in Proceedings of the 12th International Modal Analysis Conference (IMAC XII), Honolulu, Hawaii, USA, 1994, pp. 1728–1735.
41. Simonian S. S.: *Inverse Problems in Structural Dynamics*, Int. Journal on Numerical Methods in Engineering, vol. 17, pp. 357-365, 1981.
42. Sodano H. A., Inman D. J., Park G.: *A Review of Power Harvesting from Vibration Using Piezoelectric Materials*, Shock and Vibration Digest, Vol. 36, No. 3, 2004, pp.197–205.
43. Sodano H. A., Park G., Leo D. J., Inman D. J.: *Use of Piezoelectric Energy Harvesting Devices for Charging Batteries*, in Smart Structures and Materials: Smart Sensor Technology and Measurement Systems, San Diego, CA, March 3–6, Proceedings of the SPIE, Vol. 5050, 2003, pp.101–108.
44. Sohn H., Farrar C.: *Damage Diagnosis Using Time Series Analysis of Vibrating Signals*, Smart Materials and Structures, vol.10, no.3, 2001, pp. 446-451.
45. Sohn H., Worden K., Farrar C. R.: *Statistical Damage Classification under Changing Environmental and Operational Conditions*, Journal of Intelligent Material Systems and Structures, 2003, 13(9) pp. 561–574.
46. Szwedo M., Uhl T., Bednarz J.: *Application of Vibrothermography for Damage Detection in Mechanical Structure*, Proc. of IV EW SHM, Cracow, 2008.
47. Spencer B. F. Jr., Ruiz-Sandoval M. E., Kurata N.: *Smart Sensing Technology: Opportunities and Challenges*, Journal of Structural Control and Health Monitoring, Vol. 11, No. 4, 2004, pp. 349–368.
48. Staszewski W., Boller C., Tomlinson G. (Ed.): *Health Monitoring of Aerospace Structures,* Wiley, Chichester, 2004.
49. Todd M. D., Nighols J. M.., Trickey S. T., Seaver M., Nichols C. J., Virgin L. N.: *Bragg Grating Based Fiber Optic Sensors in Structural Health Monitoring,* Phil. Trans. R. Soc. A, vol. 365, 2007, pp. 317-345.
50. Trujillo D. M.: *Application of Dynamic Programming to the General Inverse Problem,* International Journal on Numerical Methods in Engineering, vol.23, pp.613-624, 1987.
51. Uhl T., Hanc A., Tworkowski K., Sękiewicz Ł.: *Wireless Sensor Network Based Bridge Monitoring System*, Key Engineering Materials, 2007 vol. 347 pp. 499–504.
52. Uhl T., Lisowski W., Kurowski P.: *In-operation Modal Analysis and Its Application*, AGH, Cracow, 2001.

53. Uhl T., Petko M., Peeters B.: *Embedded Systems for Real Time Flight Flutter Testing,* in Structural Health Monitoring 2007, ed. Fu-Kuo Chang, DSTech, Lancaster,2007, pp. 272-280.
54. Uhl T., Mendrok K.: *Identification Inverse Problem and Its Application*, ITE, Radom, 2005.
55. Wang K., Inman D. J., Farrar C. R, *Modeling and Analysis of a Cracked Composite Cantilever Beam Vibrating in Coupled Bending and Torsion*, Journal of Sound and Vibration, Vol. 284, 2005, 23–49.
56. Wu F., Chang F-K.: *A Built-in Active Sensing Diagnostic System for Civil Infrastructure Systems*, in Smart Structures and Materials, San Diego, CA, March 5–7, *Proceedings of the SPIE*, Vol.4330, 2001, pp.27–35.
57. Yan A. M., Kerschen G., De Boe P., Golinval J. C.: *Structural Damage Diagnosis under Varying Environmental Conditions*, Part I: *A Linear Analysis, Mechanical Systems and Signal Processing*, Vol. 19, 2005, pp. 847–864.
58. Zang C., Friswell M. I., Imregun M.: *Structural Health Monitoring and Damage Assessment Using Measured FRFs from Multiple Sensors, Part II: Decision Making with RBF Networks*, in Proceedings of the 5th International Conference on Damage Assessment of Structures (DAMAS 2003), Southampton, England, UK, 2003, pp.141–148.
59. Zaurin R., Catbas F. N.: *Computer Vision Oriented Framework for Structural Health Monitoring of Bridges*, in *IMAC XXV. Society for Experimental Mechanics*, 2007, Orlando, FL, pp. 213-218.]
60. Zhang Q., Allemang R. J., Brown D. L.: *Modal Filter: Concept and Applications*, Proceedings of International Modal Analysis Conference, Kissimmee, 1990, pp. 487-496.
61. Zhongqing S, Lin Y, Ye L.: *Guided Lamb Waves for Identification of Damage Incomposite Structures: A review*, Journal of Sound and Vibration vol. 295 (2006) pp.753–780

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ABOUT NEED FOR USING NONLINEAR MODELS IN VIBROACOUSTIC DIAGNOSTICS

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Summary

The paper discussed the thesis that in vibroacoustic diagnostics using the nonlinear mathematical model is necessary. Natural specification of machine degradation is the frequency response function change and "additional" inputs related to defects remain usually as self-exited vibrations, which require the application of nonlinear description. Very often a new machine can be described with an adequate accuracy by a linear model. During exploitation certain nonlinear disturbances related to wear and tear - occur. Thus, an observation of nonlinear effects allows solving a diagnostic task.

Keywords: nonlinear effects, vibroacoustic diagnostic.

O KONIECZNOŚCI STOSOWANIA W DIAGNOSTYCE WIBROAKUSTYCZNEJ MODELI NIELINIOWYCH

Streszczenie

W artykule przedyskutowano potrzebę stosowania w diagnostyce wibroakustycznej modeli nieliniowych. Naturalnym opisem degradacji maszyny jest zmiana funkcji odpowiedzi częstotliwościowej, a „dodatkowe" wymuszenia związane z uszkodzeniami pozostają z reguły jako drgania samowzbudne, co z założenia wymaga zastosowania opisu nieliniowego. Bardzo często nową maszynę możemy opisać z dobrą dokładnością modelem liniowym. W trakcie eksploatacji pojawiają się i wzrastają nieliniowe zaburzenia związane ze zużyciem. Tym samym obserwacja efektów nieliniowych pozwala na rozwiązanie zadania diagnostycznego.

Słowa kluczowe: efekty nieliniowe, diagnostyka wibroakustyczna.

The problem of assessment of the machine state by means of vibrations and noise analysis is based – from the theoretical side – on the statement that, the vibroacoustic energy dissipation increases during the machine exploitation. Therefore a certain vibration or noise measure should exist, which in the moment - when further exploitation is dangerous – exceeds the permissible value. Such reasoning results from the adaptation of a model assuming an increase of dissipated energy during wear and tear as well as on the assumption that energy of parasitic vibroacoustic processes is proportional to the total dissipation of energy. Now-a-days the assumption of a general increase of energy consumed is not doubtful. We may assume that this is the proved law of nature. However, there is still a problem of developing the easiest mathematical notation and looking for the "optimal" model.

It is well known, that the statement of proportionality of vibroacoustic energy to the total parasitic energy is a simplification from which might be – and actually are – exemptions. Examples, where a periodical lowering of the vibration level indicates a dangerous defect and where the "waving" of a trend of changing values being the measure of the vibroacoustic process occurs, are considered in the paper. It should be assumed that those phenomena are accompanied by increases of dissipation energy in other processes, mainly thermal ones, but also electric and hydraulic (e.g. an oil leakage from the damaged bearing can cause damping of vibrations). In the complicated structure of the mechanical system the effect of an apparent "self repairing" can occur and it may periodically lower the amount of dissipated energy and change proportions in between dissipation forms. It is presented pictorially in Figure 1.

If, according to this short reasoning, we assume that there are cases when an increased level of vibrations and noises (in the whole observable range or in the selected bands) is not proportional to a wear, it will still not indicate that vibroacoustic processes are insensitive to it. **The assumption arises, that the change of proportion in between individual forms of the dissipated energy can have its representation in the observed form of vibrations (even when the level remains constant or lowered).** This phenomenon was investigated at analysing defects of rolling bearings, where – at the constant general level – the proportions between the dominating amplitudes in the spectrum were changing. Similar results were obtained at checking hydraulic elements when investigating a multi-symptom index (vibrations + heat) and at diagnostics of a tool wear in the machining process. The mentioned phenomena have been observed during passive as well as active diagnostic experiments. Having an accurate recording of several symptoms – during the whole life-time – for the statistically representative sample of specimens one can establish significant dependencies. However, the difficult problem of assuming the proper model still remains to be solved.

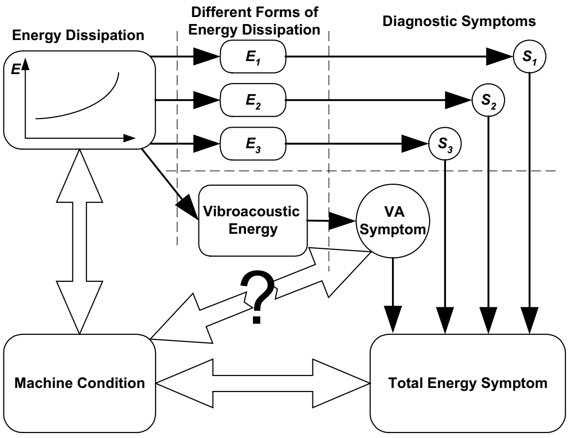

Fig. 1. Utilising the diagnostic symptom in a machine diagnostics.

Let us discuss the example presented in Figure 2 showing the spectrum of vibration accelerations of the rolling bearing. An average value and average square value are the same as measurement accuracy.

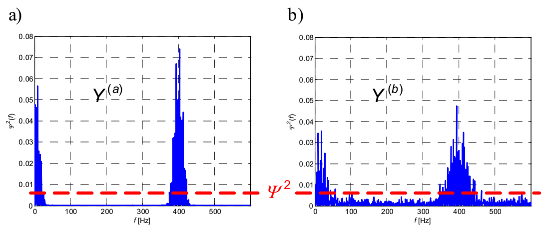

Fig. 2. Example of „iso-energy" evolution of a spectral power density of the vibration acceleration during the machine wear (rolling bearing).

A frequency distribution is – of course – completely different. Taking into account only the module, or more precisely the spectral power density and disregarding phase shifts, let us discuss which transformation should be applied to the dynamic system in order to transform spectrum "a" into spectrum "b". Let us assume, at first, that the system is linear and discrete. Both spectra were obtained from the observation of the machine steady state, it means under conditions when inputs are stable processes of the dominating participation of determined and periodical components. Let us neglect – for the time being – random disturbances. Let the system has n degrees of freedom. Both spectra, "a" and "b", concern "normal" working conditions. Thus, neither a loss of stability nor a loss of continuity of solution as a function of parameter changes occurs. Such situation would correspond to the essential defect of a device. During the time elapsing between both observations the system evolution could have occurred and probably have done so. This evolution manifested itself by small changes of coefficients; it means elements of matrix of inertia, damping and rigidity and by an occurrence of new – generally weak – excitations and also by eventual decreasing of previous forces. This last phenomenon can be omitted as being of a low probability. Let us assume further, that there are m poly-harmonic inputs (where $m < n$). The amplitude spectrum for a linear system is formed as the result of the following transformation:

$$Y(f) = \sum_{i=1}^{m} P_i(f) \cdot H_i(f, m_j, k_j, c_j) \quad j = 1 \div n \quad (1)$$

where:

P_i – Fourier transform of excitation moments,
H_i – Transmittance.

Each transmittance, and more accurate its module – it means the coefficient of amplification, has as many extremes as degrees of freedom of the system (natural frequencies). The set of transmittances is explicitly determined by $3 \cdot m$ parameters. Equation (1) must be satisfied for each frequency of the output spectrum. At assuming a spectrum discretisation into k elements we have k+2 equations. An addition of number 2 results from the postulate of the average and average square value conservation. At the assumption that the system inputs were not changed and that all coefficients (parameters) of mass, rigidity and dissipation could have changed, the minimum number of degrees of freedom of the linear system enabling transformation of the response $Y^{(a)}(f) \to Y^{(b)}(f)$ equals:

$$n = \frac{k+2}{3} \quad (2)$$

Equation (2) regardless of the fact, that it requires generating a huge number of equations, has only a formal meaning. It determines precisely the minimum number of degrees of freedom enabling – at the preserved model structure – the possibility of the given change of the frequency response structure without changing inputs and at assuming the application of outside forces in each degree of freedom and the possibility of a free selection of all coefficients. Physical realisability of such system is practically impossible. In the actual diagnostic tasks, investigating an evolution of a device, the change of a dynamic response structure depends on changes of the insignificant part of parameters (the ones responsible for the defect). Thus, the number of the necessary equations should be multiplied by coefficient λ, defined by the ratio of invariable elements (degrees of freedom), to the ones in which certain number of parameters are changing (usually not all) and by coefficient λ_1, which denotes the ratio of all degrees of freedom to the ones receiving energy from outside. When the number of spectral lines, taken into account, is limited to 100 the number of degrees of freedom of the system should amount to several thousands. This is the condition for the identificability of the system; it means that changes of actual parameters (in our example: state variables) should be transformable by the determined and mutually explicit procedure into the model parameters changes. However, regardless of the mentioned difficulties, there is a possibility of obtaining such solution. Therefore the application of the linear software FEM has allowed to solve several problems described analytically as nonlinear. Simplifying a little the consideration, we can state that the presented operations are based on **reducing the globally nonlinear influences to locally linear ones** and the increase of the number of degrees of freedom of the system results from decreasing the zone considered to be the "local" area – up to the determined limit of error. This linearisation corresponds de facto to the approximation of a curve by a certain number of segments.

Let us return now to our assumptions. We have assumed at the beginning, that the response $Y^{(a)}(f)$ was the result of linear transformations of inputs, which means that the sum of inputs and outputs from the system should fill the same frequency bandwidth. Thus, each harmonic component of the input corresponds to one and only one harmonic component of the response, which usually has different amplitude, slightly changed frequency (because of damping) and different phase shift (what was not taken into account in our reasoning) but surely will not decompose into a sequence of components. In the discussed example no spectrum of the system response $Y^{(a)}(f)$ nor $Y^{(b)}(f)$ can be obtained at inputs of a smaller number of components. In diagnostic tests – during machine exploitation - new harmonic components appear very often and the value of their amplitude is considered the symptom. Such transformation in a linear system requires applying a new excitation, which – in the diagnostic test – would need a postulate that each defect (wear) constitutes such force. This is an evident contradiction. We assumed at the beginning, that the transformation of spectral concentration $Y^{(a)}(f) \to Y^{(b)}(f)$ is isoenergetic (Ψ^2=const), whereas each defect would have been described by the energy "inflow" from outside. However, supporters of a linear description for any cost (which really means: for the cost of a tremendously increased number of motion equations) could find the solution of the problem by assuming simultaneous decrease of primary inputs caused by other means of energy loss due to wear, but the model obtained in such manner would not be identifiable.

Natural specification of machine degradation is the frequency response function (transmittance) change and "additional" inputs related to defects remain usually as self-exited vibrations, which require the application of nonlinear description, etc.

The presented above considerations lead to the conclusion that a classic diagnostic task very often requires application of a nonlinear description. The following postulate can be formulated on the basis of numerous papers: A new ("after an initial usage") machine can be described with an adequate accuracy by a linear model. During exploitation certain nonlinear disturbances related to wear and tear – occur. Thus, **an observation of nonlinear effects allows solving a diagnostic task.**

This postulate is also true for technical devices, which operations require a nonlinear description from the 'very beginning' (e.g. piston-and-crank mechanism). In such situation we will observe an increase of nonlinear disturbances. Besides, "a diagnostic" model does not need to be a fully "dynamic" model.

Let us solve now a simple example. An ordinary differential equation of the 2nd order in a form of a simple harmonic oscillator – is given:

$$\ddot{x} + \omega_0^2 x = P(t)$$

with an input:

$$P(t) = P\cos 2\Omega t .$$

An evident singular solution is a well-known "school type" dependency:

$$x(t) = \frac{P}{\omega_0^2 - \Omega^2}\cos 2\Omega t \tag{3}$$

Let us check whether finding the singular solution of a frequency being equal e.g. to the half of the input frequency Ω in the form: $x = A\cos\Omega t$ is possible. By substitution we obtain the following equation:

$$A\cos\Omega t(\omega_0^2 - \Omega^2) = P\cos 2\Omega t , \tag{4}$$

which satisfaction for each t requires zeroing of the input amplitude at the arbitrary amplitude of response. Thus, it leads to an obvious triviality. Let us assume the possibility of modification of the basing equation by introducing an arbitrary nonlinear function of variable $x(t)$ and let us check whether now obtaining the response of the frequency equal half of the input frequency is possible. The task is as follows:

$$P\cos 2\Omega t \to x = A\cos\Omega t : \ddot{x} + \omega_0^2 x + f(x) = P\cos 2\Omega t \quad . \quad (5)$$
$$f(x) = ?$$

Proceeding in an identical fashion as previously and transforming the input we will obtain:

$$-A\Omega^2\cos 2\Omega t + A\omega_0^2\cos 2\Omega t + f(A\cos\Omega t) = \frac{1}{2}P(\cos^2\Omega t + 1) \quad . \quad (6)$$

This equation is much better and at the proper selection of $f(x)$ function its identity satisfaction is possible. E.g. assuming:

$$f(x) = k\left(x^2 + 1\right)$$

we will obtain:

$$\bigwedge_t (\omega_0^2 - \Omega^2)A\cos 2\Omega t + kA(\cos^2\Omega t + 1) =$$
$$= \frac{1}{2}P(\cos^2\Omega t + 1) \Leftrightarrow \Omega^2 = \omega_0^2$$
$$P = 2kA \quad . \quad (7)$$
$$P = 2k$$
$$A = 1$$

This is a special case, relatively difficult – however possible at the appropriately selected kinematics – for the technical realisation. It corresponds to the situation when the properly selected input force amplitude of the resonance frequency instead of increasing the first harmonic "releases" vibrations of a different frequency. This, in turn, corresponds to changing the phase trajectory into a certain limiting cycle and constitutes a certain form of self-exited oscillations, in which a restitution function described by an even function ("full" parabola) becomes an "amplifier". However, the discussion of the obtained results is not significant in this case. The example should be treated as a mathematical "plaything", which indicates – in a very simple manner – the possibility of generating, by a nonlinear system, the response of the frequency different than the input frequency.

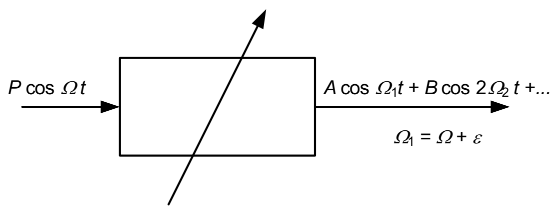

Fig. 3. Nonlinear system as frequency transformer.

Much more physically real would be an example of a double frequency response – according to the schematic presentation from Figure 3, but finding function $f(x)$ is not simple, similarly as a function causing a sub-harmonic response, for various amplitudes and frequencies of inputs. A solution of such problem requires an application of analytical approximate methods or simulation methods, exactly the same as applied at solving nonlinear differential equations. Mathematical laws are not to be avoided. A solution of nonlinear problem is obtained in an approximate form "in both ways", the most often in a series and infinite form. The fact, that the first and the second approximation are usually confirmed by experiments indicates that nonlinear models are worth to be applied now a days when calculation tools are highly developed. Features of nonlinear models are as follows:

1. Principle of superposition is not binding;
2. The system response can have and generally has the different frequency distribution that the input;
3. System transmittances depend on themselves and on inputs (they are not system invariables);
4. Local transient states can occur (example of „bended" amplitude-frequency characteristics is known from each text-book on the vibration theory);
5. Resonance responses can occur at frequencies being an arbitrary linear combination of input and natural frequencies, including an effect of the so-called internal resonance;
6. Self-exited vibrations can occur.

Diagnostics specialists know all mentioned above features from the observation of actual objects. The situation presented in Fig. 2 is a typical example of a frequency conversion.

Resonant increases of the amplitude in bands, in which the vibration level in a new machine was low, local losses of motion stability, generation of self-exited vibrations, as well as strong dependence of parasitic vibration processes on the load – are typical symptoms frequently utilised in vibroacoustic diagnostics.

Thus, purposefulness of application nonlinear descriptions seems to be doubtless similarly as looking for vibration measures (more precisely: methods and techniques of signal analysis) sensitive to the nonlinear disturbances evolution.

REFERENCES

Many examples of the applications of this thesis and theoretical discuss as well you can find in book:

1. Batko W., Dąbrowski Z., Kiciński J.: *Nonlinear Effects in Vibroacoustic Diagnostic*, Institute for Sustainable Technologies – National Research Institute, 2008.

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VIBROACOUSTIC MONITORING OF MECHANICAL SYSTEMS FOR PROACTIVE MAINTENANCE

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Summary

A relevantly defined operational strategy has decisive influence from the point of view of the ability to maintain and improve reliability and safety as well as from the point of view of maintaining manufacturing quality. The paper presents the main tasks and the method of implementing pro-active operation. Particular attention is paid to the issues of selection and adaptation of the methods of diagnosing the low-energy phases of defect development as well as use of a posteriori diagnostic information. Attention is paid to the importance of technical risk analysis.

Keywords: proactive maintenance, vibroacoustic diagnostic, low-energy stage of failure, bayesian updating.

MONITORING WIBROAKUSTYCZNY SYSTEMÓW MECHANICZNYCH W PROAKTYWNEJ STRATEGII EKSPLOATACJI

Streszczenie

Odpowiednio określona strategia eksploatacji ma decydujący wpływ na utrzymanie i poprawę niezawodności, bezpieczeństwa oraz utrzymanie jakości produkcji. W pracy przedstawiono główne zadania i sposób realizacji proaktywnej eksploatacji. Szczególną uwagę zwrócono na zagadnienia doboru i adaptacji metod diagnozowania niskoenergetycznych faz rozwoju uszkodzeń oraz wykorzystania aposteriorycznej informacji diagnostycznej. Zwrócono także uwagę na znaczenie prowadzenia analizy ryzyka technicznego.

Słowa kluczowe: proaktywna strategia eksploatacji, diagnostyka wibroakustyczna, niskoenergetyczna faza rozwoju uszkodzenia, bayesowskie uaktualnianie.

1. INTRODUCTION

The fact that the need for implementing the principles of harmonious development is treated as a rule of the development of modern economy creates a whole series of new challenges for more and more fields of science and technology. From the point of view of machine construction and operation this means adoption of design and operation principles which account for Life Cycle Engineering while rejecting the current, reactive principles of design, operation, maintenance and management which are focused on maximization of short-term effect. Now the goal is to maximize the long-term effects. This means adoption of an operational strategy whose integral elements include technical condition diagnosis as well as predictive models of functional tasks' realization and principles of pro-active machine maintenance and operation.

Thus the defined strategy accounts for a whole series of aspects of harmonious development, starting from economic analysis of individual lifecycles, ecological requirements, ergonomic requirements and cultural requirements, with the technical component of the management system being distinguished by its predictability, holistic approach and openness.

The predictive nature of the system means its ability to forecast the technical condition and the quality of realization of functional tasks by the system and by its individual elements.

The criteria of harmonious development and the resulting necessity of holistic approach become the basis for planning the maintenance-and-repair processes. The system's open nature means both the possibility of using selected modules of the system in specific applications as well as the possibility of using selected methods both within the system itself as well as autonomously, for the tasks realized outside the system. This last feature is the outcome of the assumption that that system development and adaptation are intended to fulfill the needs and meet the expectations of its users. This in particular concerns accommodation of the subsystem responsible for data registration preprocessing, development and adaptation of technical condition models, functionality assessment methods as well as the methods of optimization and analysis of maintenance and repair processes. Due to the predictive nature of the system and the inherent burden of uncertainty it is the analysis of probability distribution, while analyzing the condition as well as the development and use of degradation process models, that become particularly important. The scope of changes associated with the proposed approach is illustrated by the definition of a technical object's maintenance process which says that it is a combination of all technical and associated administrative actions taken during an object's lifetime in order to maintain that object or its element in a condition enabling performance of the expected functional tasks. The predictive nature of the proposed strategy defines in each case the scope and the nature of the activities. In practice various scopes of analysis are applied, depending on the method of defining the control, accounting for or not accounting for the consequences of failures or accidents [1].

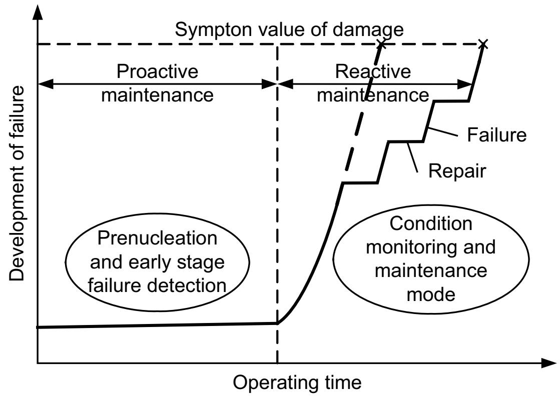

Fig. 1. Comparison of technical diagnostics goals in proactive maintenance versus reactive maintenance

From this point of view it is the implementation of proactive operational strategy that becomes particularly important. As is presented by Fig. 1, the essence of such an approach boils down to anticipation of preventive actions, in equal degree prior to defect emergence as well as during the period of development of low-energy phases of defects. This calls for developing and adapting relevant methods of diagnosis which are supported by relevant diagnostic models.

2. CHARAKTERISTICS OF A PROACTIVE OPERATIONAL STRATEGY

Let us note that the essence of thus defined a strategy is the extensive use of monitoring, diagnosis, forecasting and decision-making models for creating the possibilities of taking maintenance-and-repair actions while anticipating problems [2]. This denotes the need for developing and applying advanced monitoring, presentation of information on emergency states and values, selection of methods and means enabling monitoring and on-line inference in a way enabling early detection of growing disturbances and extracting from general signals the information on anomalies in operation which are characteristic of defects; controlling the defects and taking corrective actions by the operator in order to minimize and in particular to avoid undesirable developments leading to serious consequences; development of a forecast of future events based on current observations and registered permanent changes of parameters which have been detected by analyzing the results and the measurements collected in the database. The last item is particularly important when monitoring the condition of mechanical elements and units as well as the remaining components which are subject to degradation and wear and tear for which the detection of early phases of defect development may help prevent the occurrence of the catastrophic phase of defect development, including destruction of the whole system.

Thus reduction of the uncertainty of reliability estimations becomes a critical issue in the process of making the decisions which are intended to ensure technical safety of the system and minimize the costs.

One of the essential methods of reducing the epistemological uncertainty is to develop models and diagnose the degradation and wear and tear processes, thus reducing the variance of evaluations of the residual period until the occurrence of a catastrophic defect.

Realization of this goal calls for assessment of structural reliability of the system while accounting for detection and analysis of degradation processes affecting all the components during the previous and current period of use. This requires development of a relevant database containing information on potential defects of the system's components, knowledge gathered based on the experience acquired by relevantly trained personnel as well as procedures which account for the feedback and adaptation changes occurring in the system.

In the process of estimating the probability of of defect occurrence, the above enables us to account for the influence of operational conditions on the possibility of defect occurrence, the influence of earlier defects, quality, scope and intervals between inspections, the probability of defect occurrence in specific time in the future. The consequences are estimated in a similar manner, especially the magnitude of loss and the probability of worst case scenario occuring. Thus developed risk matrix serves as the basis for defining risk category, priority and scope of inspections, ways of changing the architecture of the monitoring system.

Idea of proactive maintenence system algorithm, was presented in literature [1, 2, 3] (Fig. 2).

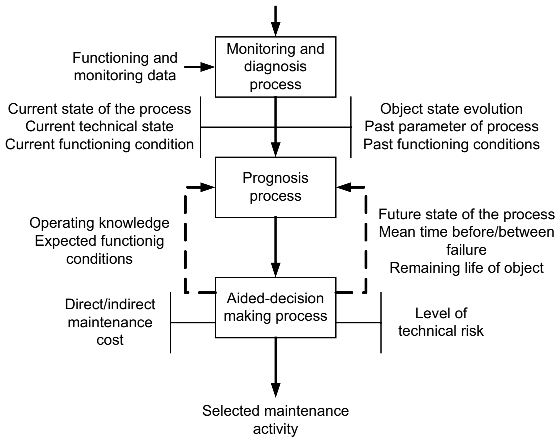

Fig. 2. Architecture of the proactive maintenance system

Let us note that estimation and modelling of the degradation process is one of the most effective methods of defect development anticipation and maintenance of system operation in terms of nominal parameters. In reality such an approach denotes compilation of several conventional methods of forecasting – probabilistic behavioral models and event models in particular. Probabilistic behavior and degradation models enable analysis of the type and extent of uncertainty which conditions forecasting reliability. Event models are a kind of a combination between the contemplated models and the actual system and they make up the basis for constructing and analyzing causal models which enable assessment of degradation and determination of the optimum scenario of maintenance-and-repair work.

Let us note that subsequent stages of the forecastng procedure make references to various models and types of knowledge. The a priori knowledge gathered from experiments serves as the basis for developing stochastic models of degradation processes while technical diagnosis and process monitoring are used for developing the indicators of an object's technical condition.

Interaction between the elements of the monitored object is described and forecasted with the use of cause-and-effect relations based on laws of physics in the form of model-aided forecast. In accordance with the definition [3], behavioral models contain both the description of functioning as well as the dynamics of a system. In the first case the system is analyzed as a set of many processes analyzed from the point of view of flow of materials, energy and information. The purpose of the system dynamics model is to offer description of conditions in which failures occur – in this case the modeling process points to two phases – in the first one the cause-and-effect relations are defined between the degradation process, the cause and the consequences. This is often done with the use of the EMECA method [4].

The estimation of probability of defect occurrence accounts for the influence of operating conditions on the possibility of defect occurrence, the influence of earlier defects, the quality and the scope of operational inspections, the probability of defect occurrence in specified time in the future. The consequences are estimated in a similar way, especially the gravity of loss and the probability of the worst-case scenario occurring. Thus, the developed risk matrix serves as the basis for determining the risk category, the priority and scope of the inspection as well as the method and directions of changes in the operation maintenance procedures. An exemplary division into categories is presented in [5] (Fig. 3).

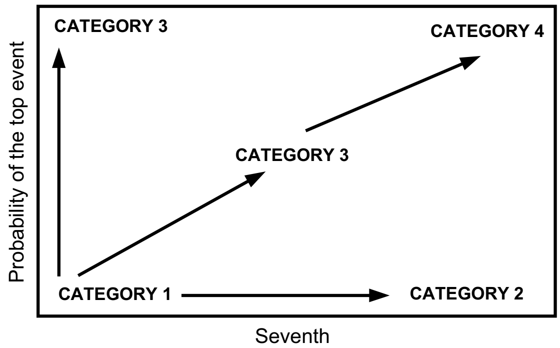

Fig. 3. Risk categories

The following scope of activities is assigned to each category respectively:

- category 1 – (acceptable),
- category 2 – (acceptable, inspection required),
- category 3 – (undesirable),
- category 4 – (not acceptable).

The influence of various degradation processes, including wear, cracking and corrosion, is modeled in the second phase.

In the to-date contemplated models the probability of defect occurrence was being defined on the assumption of invariability of examined distributions during operation of the object. In reality, as a result of wear and tear processes and associated changes of conditions of mating elements and kinematic pairs, we observed conditional probability distributions, however the relationship demonstrated itself both in quantitative terms (change of the parameters of probability density function) and in qualitative terms (change of the function describing the distribution). In addition the degradation processes accompanying the performance of functional tasks can cause similar variability of distributions of the probability which describes load capacity. In this case one can expect that the location of the separating line and the probability of defect occurrence will not only depend on the time of operation of an object but on the new dynamic feedbacks in the system, associated in particular with the development of non-linear relations and non-stationary disturbance.

3. VIBROACOUSTIC SIGNAL AS THE SOURCE OF DIAGNOSTIC INFORMATION

The central issue is how to extract the relevant diagnostic information and use it in the forecasting process. Thus the research focuses in particular on the methods of analyzing the relations between various frequency bands and their links to various types of defects or phase of their development. The value of the information contained in the bi-spectrum consists of, among others, the fact that it enables examination of statistical relations between individual components of the spectrum as well as to detect the components generated as a result of occurrence of non-linear effects and the additional feedback associated with the emerging defects. This results from the fact that in contrast with the power spectrum, which is positive and real, the bi-spectrum function is a complex value which retains the information on both the distribution of power among individual components of the spectrum as well as the changes of phase. Let us note that the bi-spectrum enables one to determine the relations between essential frequencies of the examined dynamic system. High value of bi-spectrum for defined pairs of frequency and combinations of their sums or differences will point to the existence of frequency coupling between them. This may mean that the contemplated frequencies, being the components of the sums, have a common generator, which in the presence of non-linearity of higher order may lead to synthesizing the aforementioned new frequency components.

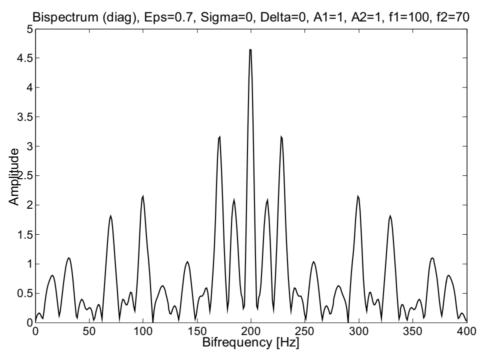

Fig. 3. Illustration of diagonal bi-spectrum in the case of square non-linearity

An example of using the diagonal bi-spectral measure for the qualitative and quantitative determination of the effect of non-linearity evolution is presented in Fig. 3÷5.

The confirmation of the importance of the changes of phase coupling is offered by the analysis of the process of diagnostic information generation during the low-energy phases of development [6].

While attempting to develop a model oriented on such defects one should on the one hand consider the issue of examining the signal's parameters from the point of view of their sensitivity of to low-energy changes of the signal and, on the other, the issue of quantification of energetic disturbances occurring in the case of defect initiation.

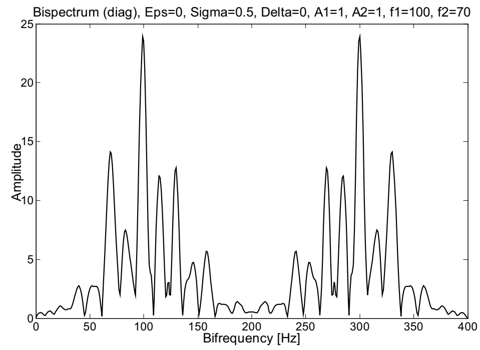

Fig. 4. Illustration of diagonal bi-spectrum in the case of the third order non-linearity

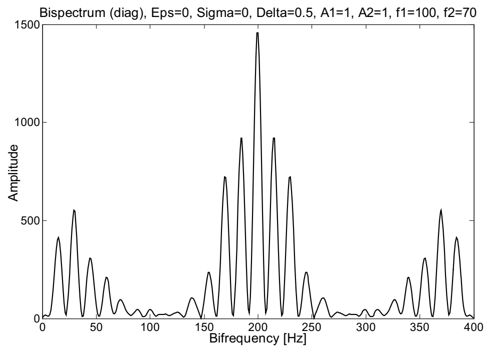

Fig. 5. Illustration of diagonal bi-spectrum in the case of the fourth order non-linearity

Let us assume that the degree of damage D is the dissipated variable that covers the changes of the structure's condition due wear and tear:

$$\mathrm{d}E_d(\Theta, D_0) = = \frac{\partial E_d(\Theta, D_0)}{\partial D}\mathrm{d}D + \frac{\partial E_d(\Theta, D_0)}{\partial \Theta}\mathrm{d}\Theta \qquad (1)$$

where:

$$\mathrm{d}E_d = \frac{df(D, \Theta, \gamma(\Theta))}{d\Theta}$$

$\gamma(\Theta)$ - the parameter describing how big a part of the dissipated energy $\mathrm{d}E_d$ is responsible for structural changes,

Θ - operating time.

Bearing in mind the possibility of diagnosis of the origin and the development of low-energy phases of defect formation, when the extent of the original defect can be different in each case, let us analyze this issue more precisely.

To examine this problem let us recall here the two-parameter isothermal energy dissipation model proposed by Najar [7] where:

$$\mathrm{d}E_{d_s} = \mathrm{d}E_d - \mathrm{d}E_{dq} = T\mathrm{d}s = \sigma_\Theta \mathrm{d}D \qquad (2)$$

where:

$\mathrm{d}E_{d_q}$ - energy transformed into heat,
$\mathrm{d}E_{d_s}$ - energy responsible for internal structural changes,
T - temperature,
$\mathrm{d}s$ - growth of entropy.

The expression (2) shows that the growth of the dissipated variable D is attributable to the $\mathrm{d}E_{d_s}$ part of energy, which is the dissipated part of $\mathrm{d}E_d$ energy, that causes the growth of entropy $\mathrm{d}s$.
The role of the multiplier determining the relation between the increments of dissipated variable and the entropy is played by the dissipation stress σ_Θ.
The assumption of $T = \text{constans}$ results in independence of dissipation-related loss $\mathrm{d}E_{d_s} = \mathrm{d}E_{\Theta_s}$, thus following integration the expression (2) takes the following form:

$$E_{d_s} = T\Delta s \tag{3}$$

The derivative of defect development energy related to D, when $E_f(D_0) \le \frac{1}{2}E\varepsilon^2$, means the boundary value of deformation energy and takes the following form:

$$\frac{\mathrm{d}E_{d_s}}{\mathrm{d}D} = \frac{E_f(D_0)(1-D_f)(1-k)D^{-k}}{D_f^{1-k} - D_0^{1-k}} \tag{4}$$

For a defined initial defect of D_0 and for a defect leading to damage D_f, relationship (5) will have the following form:

$$\frac{\mathrm{d}E_{d_s}(D)}{\mathrm{d}D} = (1-k)E_{D0,f}(k)D^{-k} \tag{5}$$

Let us note that parameter $E_{D0,f}$ is an exponential function of power k, similarly as the whole derivative. While referring to the second rule of thermodynamics for irreversible processes we will assume the following in the contemplated model:

$$\frac{\mathrm{d}E_{d_s}(D)}{\mathrm{d}D} \ge 0 \tag{6}$$

Thus for the assumed model to be able to fulfill condition (6), the exponent must meet the requirement of $k \le 1$. In addition, while referring to the rule of minimization of dissipated energy, the conditions of permissible wear process show that the change of exponent k is possible as the defect develops.

To examine this problem let us assume that the exponent shows a straight line dependence on the extent of damage:

$$k(D) = a + bD \tag{7}$$

For damage of small magnitude the linear approximation seems to be sufficient and enables description of defects whose emergence is characterized by small growth of defect energy (see Figure 6).

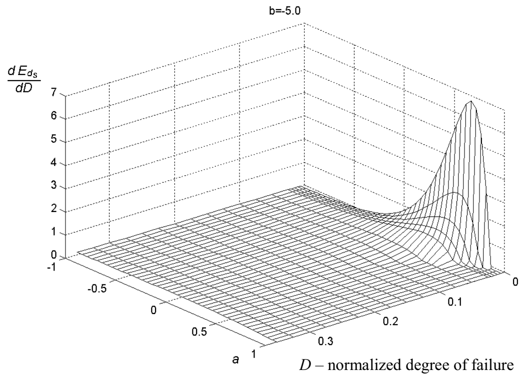

Fig. 6. Change of energy of defect development for small D

Thus while defining the set of diagnostic parameters we should pay attention to the need for selecting such a criterion so that it will be possible to identify defects whose emergence is characterized by small growth of defect-related energy.

While contemplating this issue let us assume that vibroacoustic signal is real and meets the cause-and-effect requirement, which means that it can be the base for creating an analytical signal.

In accordance with the theory of analytical functions, the real and the imaginary components are the functions of two variables and meet Cauchy-Riemann requirements.

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Please be reminded that the analysis of the run of the analytical signal will be conducted while relying on the observation of changes of the length of vector A and phase angle φ:

$$z(x,y) + jv(x,y) = A(\cos\varphi + j\sin\varphi) \tag{8}$$

Thus,

$$\begin{aligned} z\big(x(\tau), y(\tau)\big) &= A(\tau)\cos\varphi(\tau) \\ v\big((x(\tau), y(\tau)\big) &= A(\tau)\sin\varphi(\tau) \end{aligned} \tag{9}$$

means that the signal measured is the orthogonal projection of vector A on real axis.

Ultimately, while exploiting the Cauchy-Riemann conditions for variables $A(\tau)$ and $\varphi(\tau)$ we will obtain:

$$\frac{dz}{d\tau} = \frac{dA}{d\tau}\cos\varphi - A\sin\varphi\frac{d\varphi}{d\tau} \qquad (10)$$

As we expected the obtained relationship presents an equation that enables the analysis of the measured signal while observing A and φ. At the same time it should be noted that for low-energy processes, when we can neglect the changes of the vector's length and assume $A \cong \text{const}$, the whole information on the changes of the measured signal is contained in the phase angle, or more precisely in the run of momentary angular velocity.

While accounting for the obtained results of the analysis of the process of low-energy defect emergence and detection of diagnostic information associated with the changes of momentary values of amplitude and angular velocity, let us analyze the conditions that must be fulfilled by a diagnostic model intended to enable observation of the influence of such disturbance on the form of the system's dynamic response.

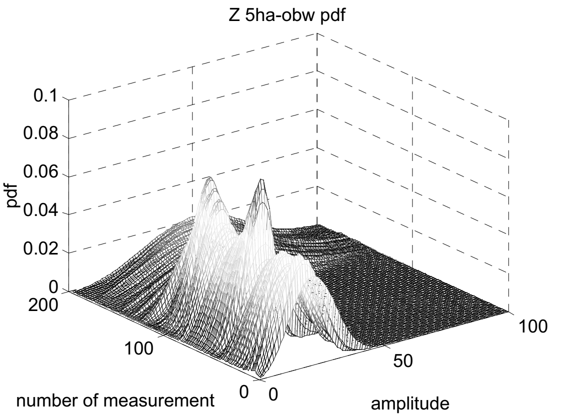

Fig. 7. Function of density probability distribution oh the envelope of 5th harmonics meshing frequency

This illustrates the problem of effective use of results of diagnostic observations in the task of diagnosis of early stages of defect development.
While referring to [8] we quoted the example of evolution of probability density distribution function for the value of vibroacoustic signal envelope, precisely the fifth harmonic frequency of meshing as calculated for the width of the frequency band corresponding to twice the frequency of the input shaft (Fig. 7). Fig. 8 and Fig. 9 accordingly present the values of shape and scale parameters corresponding to these changes. Let us note that both parameters depend on defect development while their values, the value of shape factor in particular, does not change monotonously.

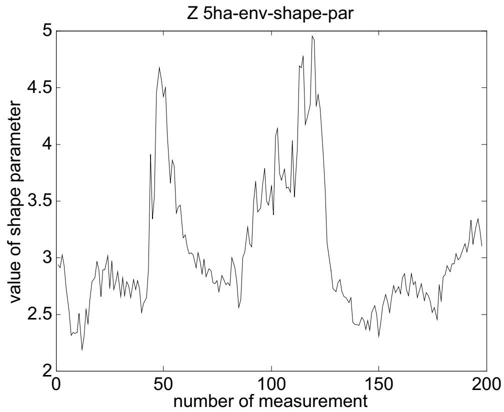

Fig. 8. Parametr of shape in function of mesurement number

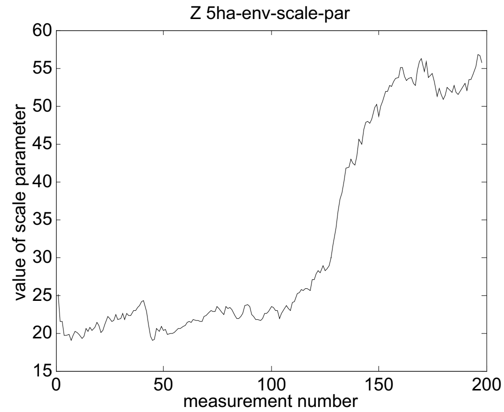

Fig. 9. Parametr of scale in function of mesurement number

In order to achieve higher efficiency in application of the results of vibroacoustic diagnosis, we should take into account, in a much bigger degree, the individual vibroacoustic characteristics which as defined during preliminary measurements and analysis.

Such an approach fully meets the requirements of Bayes methodology [9], including:

- the possibility of adopting randomness of the examined parameter in a probabilistic model;
- the possibility of obtaining the a posteriori estimate of the parameter based on the observation and measurement of a vibroacoustic signal as well as the a priori distribution in accordance with the requirements of Bayes' theorem;
- selection of the optimum estimator of a parameter in the sense of Bayes decision-making theory.

Assuming that detection, identification and location of changes of vibroacoustic properties of the monitored object is the outcome of vibroacoustic monitoring, the a priori distribution of probability of parameters can be determined on the basis of pre-defined vibroacoustic characteristics.

A good illustration of the discussed method of using the Bayes formula for evaluation of changes of distribution parameters based on the diagnostic information is offered by Cruse's paper [10] in which Bayes theorem is used for determining the value of parameters describing the growth of fatigue-related defect while accounting for the observation of crack development.

The essence of this approach involves updating of estimated parameters of the probabilistic model so as to achieve bigger alignment between the results of modeling and observations.

In accordance with the above presented assumptions it is assumed that unknown or uncertain parameters of distribution are random variables. Uncertainty of estimation of results can be linked to variability of random variables by means of Bayes theorem [11].

Then, while assuming that we will be estimating the parameters of a priori distribution of parameter a of the function of probability density $f(a)$ and that D is an observation set enabling reduction of a priori uncertainty on the condition of the results of the observation being included, we should be able to conduct the estimation of a posteriori distribution parameters by means of the following formula:

$$f(a/D) = \frac{f(D/a)f(a)}{f(D)} \tag{11}$$

Where:

$$f(D) = \int_{-\infty}^{\infty} f(D/a)f(a)da$$

In addition we can assume that the denominator, which is described by the integral of the a posteriori probability density function, is constant and that $f(D/a)$ is the probability of observation which can be expressed by the credibility function. In such a case equation (11) can have the following form:

$$f(a/D) = K_B \cdot L[D/a] \cdot f(a) \tag{12}$$

where:

K_B – standardizing constant

$L[D/a]$ – credibility function

To be able to determine the probability of a defect in the analyzed timeframe, the information contained in the observations should account for both, occurrence of a defect and non-occurrence of a defect. For the exponential form of the function describing the distribution, the credibility function will be noted in the following form:

$$L[D/a] = \prod_{i=1}^{n} p(\theta_f / a) \times \prod_{j=1}^{m} [1 - P(\theta_f / a)] \tag{13}$$

where:

n – denotes the set of detected defects

m – denotes the set of events defining non-existence of a defect.

Let us note that Bayes formula can be simplified by accounting for proportionality of a posteriori and a priori distributions only :

$$f(a/D) = \frac{f(D/a)f(a)}{f(D)} \propto f(D/a)f(a) \tag{14}$$

In a similar way the probability density is proportional to the square root of Fisher's information matrix factor [12]:

$$f(a) \propto (\det \mathrm{I}(a))^{1/2} \tag{15}$$

where:

$\mathrm{I}(a) = -E\left[\frac{\partial^2 \ln f(D/a)}{\partial a^2}\right]$ – is calculated as the matrix of average second derivatives from the credibility function logarithm based on the results of the experiment.

Thus formula (11) is finally written in the following way:

$$f(a/D) \propto L(D/a)(\det \mathrm{I}(a))^{1/2} \tag{16}$$

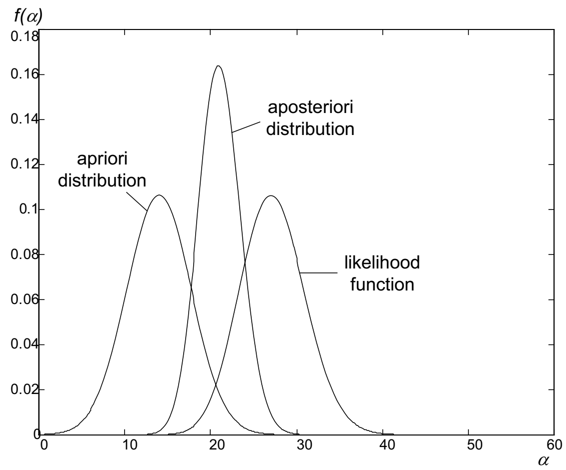

Fig. 10. An example of using diagnostic information in bayesian updating

Thus the presented method of using the risk analysis method, supported by vibroacoustic diagnosis, in the process of making operational decisions refers on the one hand to the definition of risk and the associated estimation of probability of occurrence of undesirable incident as well as to estimation of the extent and value of loss accompanying such an incident. On the other hand it refers to the possibility of using the results of a diagnostic experiment in the task of reducing the uncertainty related to estimation of parameters of a posteriori distribution of intensity of defects. Use of Bayesian models enables direct application of the results of diagnostic observation in Bayesian estimation of a posteriori distribution as well as tackling the problem of selecting the a priori distribution. The results of such an analysis are presented in Fig. 10. As has been demonstrated in this example, such use of diagnostic information enables one to solve the problem of determining the conditional probability distribution for the parameters of defect intensity while relying on the results of the diagnostic experiment.

4. CONCLUSIONS

While summing up the methodology of a pro-active system of operations based on risk evaluation, attention should be drawn to the necessity of tackling the following issues:

- Identification of elements of the system as well as factors and persons responsible for controlling the system and its functioning;
- Defining a wide area system for control and analysis of the system's functioning;
- Development of the behavioral model of the system accounting for the physical mechanisms of degradation processes affecting the system's elements and their mutual interactions,
- Modeling of events, incidents and defects in the system in a way enabling inclusion of the results in the decision-making processes,
- Development of a forecasting model enabling integration of the models of events with the behavioral model of the system,
- Developing a man-machine communication program focused on psycho-physical capabilities of the operator.

The methodology of designing and implementation of a proactive operational strategy, developed according to such assumptions, relies on a combination of probabilistic models of development of degradation processes and dynamic monitoring architecture accounting for changes in the models of events as supplemented by developed man-machine communication systems.

BIBLIOGRAPHY

[1]. Muller A., Suhner M. C., Iung B.: *Maintenance alternative integration to prognosis process engineering.* Journal of Quality in Maintenance Engineering (JQME), Vol. 2, 2007.

[2]. Muller A., Suhner M. C., Iung B.: *Formalisation of a new prognosis model for supporting proactive maintenance implementation on industrial system*, Reliability Engineering & System Safety, Vol. 93, 2008, pp 234÷253.

[3]. Tian Han, Bo-Suk Yank. L *Development of an e-maintenance system integrating advanced techniques.* Computers in Industry, Vol. 53, 2006, pp. 569÷580.

[4].Radkowski S.: *Safety technique fundamentals*. Oficyna Wydawnicza Politechniki Warszawskiej, 2003 (in polish).

[5]. Radkowski S.: *Use of the diagnostic information in safety oriented maintenance*. Diagnostyka, Vol. 2(38), 2006, pp 85÷92 (in polish).

[6]. Radkowski S.: *Nonlinearity and intermodulation phenomena tracing as a method for detecting early stages of gear failures*. Insight Non-destructive Testing and Condition Monitoring, August 2008 (in press).

[7]. Najar J.: *Continuous damage of in: Continuum damage mechanics theory and applications*. Editors: Krajcinovic D., Lemaitre J. International Centre for Mechanical Sciences Courses and Lectures, 295, 1991, pp. 234÷293.

[8]. Gumiński R., Radkowski S.: *Use of aposteriori diagnostic information in technical risk analysis*. Diagnostyka (in press).

[9]. Grabski E., Jaźwiński J.: *Bayesian methods in reliability and diagnostics*. Wydawnictwa Komunikacji i Łączności, Warszawa, 2001 (in polish).

[10]. Cruse T. A.: *Reliability Based Mechanical Design*, Marcel Dekker, Inc, New York, 1997.

[11]. Gumiński R., Radkowski S.: *Diagnostics and uncertainly decreasing of technical risk evaluation*. Materiały Szkoły Niezawodności, Szczyrk, 2006, pp 133÷140 (in polish).

[12]. Jeffreys H. J.: *Theory of Probability*, Oxford Clarendon Press, 1961.

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SUBSTANTIATION OF STRUCTURE AND PARAMETERS OF HYDRAULIC STANDS WITH RECUPERATION OF CAPACITIES FOR DIAGNOSTICS OF ADJUSTABLE HYDROMACHINES

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Summary

Set of parameters which objectively characterize a technical condition of the hydromachine can be received at their bench tests. Considering the set forth above features of hydromachines, for reception of the maximal volume of the information at the minimal expenses of time and energy at tests apply stands with recuperation of capacities. Essentially new designs of stands with recuperation of capacities for test of hydraulic machines and mechanical units are offered and patented. The basic structures of test beds with recuperation capacities and bases of a choice of their parameters which allow testing adjustable hydromachines in a wide range of their parameters are considered. The developed stands allow raising quality of diagnosing of adjustable hydromachines essentially.

Keywords: hydromachine, stand, recuperation, control, test.

1. INTRODUCTION

Greater part of modern mobile technique - build-road, agricultural, communal et al produced with hydraulic drives a to 90% engine power is utillized in which. The technical level of modern gidrodrive is determined the parameters of his basic power aggregates – pumps and motors. In spite of ap-preciation of value of hydraulic drives, application of the managed power aggregates instead of fixed volume allows to extend an adjusting range, decrease the swept volume of pump and increase his frequency of rotation to frequency of rotation of billow of drive engine without intermediate mechanical transmis-sions, that on the whole diminishes sizes and mass of transmission and promotes its reliability.

One of important technological operations at making and repair of knots, aggregates and machines there are their tests and rolling. Tests provide the estimation of conforming to of producible good the requirements of designer and normative and technical documents, and also exposure of weak points in a construction and technology with the purpose of development of measures on their removal. Rolling allows in the process of making and repair substantially to promote reliability indexes, that promotes quality of producible wares in same queue. For organization of these technological operations at a production it is necessary operatively and objectively to estimate the state of aggregate which is tested. Diagnostics allows to define the actual consisting of technical object, and also character of change of him of time [1]. Knowledge of the real state of aggregate at tests allows to optimize time of tests and rolling, and also to expose and remove the lacks of construction, and also technologies of making of aggregates, knots and details.

2. OBJECTS AND PROBLEMS

The feature of hydraulic drive of mobile technique at tests and rolling is that variety of its kinds, and also different and difficult external environments are required by applications of different types of tester equipment. Creation and introduction of universal tester equipment allows to execute on him a test and rolling of aggregates of different type in the wide range of office hours.

Stands for the tests of aggregates de bene esse are divided by two classes: with the direct stream of power and with rekuperatsiey of power. Most modern are stands with rekuperatsiey of power with a hydraulic drive. Advantages of hydraulic stands with rekuperatsiey of power it is been [2]:

- smooth regulation of speed and parameters of loading;
- change of a direction loading in the process of tests and rolling;
- reliable protection of examinee aggregates from an overload;
- possibility of complete automation of tests and rolling, and also remote control the parameters of stand;
- small labour intensiveness of setting of equipment and examinee aggregates.

The row of constructions of hydraulic stands is developed with rekuperatsiey powers [3, 4, 5] which allow to execute tests and rolling, both hydraulic equipment and mechanical aggregates. Hydraulic stands can be executed on the opened chart, when the suction hydraulic line of pump and weathering gidrodvigatelya is connected with a tank, or on the closed chart, when foregoing hydraulic lines are united between itself.

On fig. 1 the hydraulic chart of universal tent-bed test is presented with rekuperatsiey of power [3]. A stand is contained by an engine 2, which is a drive for the managed pump 1, pressure hydraulic line 5 last reported through the managed throttle 4 with loading motor 3, and suction hydraulic line with a tank 13. Coupled hydromachines 6 and 7 connected by between itself a pressure hydraulic line 8, and their shafts are mechanically connected by a transmission 10. In the presented chart hydromachine 6 is a pump, and hydromachine 7 is a motors. Weathering hydraulic line of motors 9 and suction hydraulic line pump 6 and motor 7 connect with a tank 13. In addition, shafts of hydromachines 6 and 7 through a transmission 10 mechanically connected with the shaft of loading motors 3.

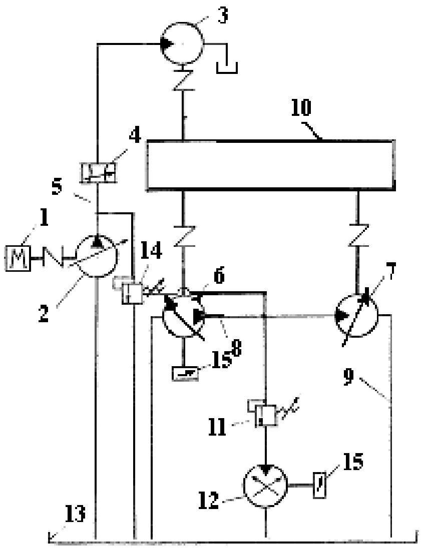


Fig. 1. The principle hydraulic scheme of stand.

Pressure hydraulic line 8 reported through a loading valve 11 and flowmeter 12 with a tank 13, and pressure hydraulic line 5 through a loading valve 14 reported with a tank 13. Loading valve 14 executed a differential, here his managing cavity is united with pressure hydraulic line 8. Hydromachine 6, loading motor 3 and flowmeter 12 supplied the sensors of angular speed 15. Pressure hydraulic line 5 and 8 supplied the sensors of pressure.

A hydraulic stand works as follows. At including of engine 2 pump 1 gives through a throttle 4 on a pressure hydraulic line 5 working liquid in a loading motor 3, which drives to the rotation a transmission 10. Rotation through a transmission 10 passed on the shaft of pump 6, which forces a working liquid on pressure hydraulic line 8 in a motor 7, which passes a rotation on a transmission 10, what and recuperation of power at stand is provided.

Transmission 10 must provide speed of rotation of billow of pump higher, than at gidromotora 7, in order that serve of working liquid of pump 6 was higher consumable expense by a motor 7. Surplus of working liquid given a pump 6 given on weathering in a tank through a loading valve 12 and flowmeter 15. Change of tuning of loading valve 14 provides the change of pressure in a pressure highway 8, and, consequently moment on the billows of gidromashin 6 and 7.

Change of serve of pump 2 or tuning of throttle 4 changes frequency of rotation of loading motor 3, and consequently, through a transmission 11, changes frequency of rotation of billows of gydromachines 6 and 7. Setting of differential loading valve 14 with a management from pressure in the pressure highway of 8 gydromachines 6 and 7, provides the changes of moment on the billows of examinee aggregates at their permanent frequency of rotation or provides the change of frequency of rotation of billows of examinee aggregates at a permanent moment.

3. MAIN SECTION

Hydraulic, kinematics and power calculations of hydraulic stand with rekuperatsiey of power executed the known methods. The feature of calculation is a choice of gear-ratio of transmission and determina-tion of drive engine power.

Flow of working liquid of hydromachine working in the mode of pump:

$$Q_н = n_н \cdot q_н \cdot \eta_{н0}, \qquad (1)$$

where $n_н$ - frequency of rotation shaft of pump, $q_н$ - displacement of pump, $\eta_{н0}$ - volumetric efficiency of pump.

In a kind recuperation of power on a stand will present the serve of pump in a kind:

$$Q_н \geq (Q_м / \eta_{0м}) + Q_{нк} = \alpha \cdot Q_м \qquad (2)$$

where $Q_м$ - rate of flow in motor, $\eta_{0м}$ - volumetric efficiency of motor, $Q_{нк}$ - flow of working liquid through a loading valve, α - coefficient flow of pump.

At such denotation $\alpha - 1$ is a relative amount of working liquid, which does not pass through gidromotor.

Frequency of rotation shaft of pump is determined from dependence:

$$n_н = n_м \cdot i_m, \qquad (3)$$

where $n_м$ - frequency of rotation shaft of motor, i_m - a transfer relation of transmission.

Taking into account dependences (1) (2) will get

$$i_m \geq \alpha \cdot (q_м / q_н) \cdot (\eta_{0м} / \eta_{0н}), \qquad (4)$$

In this case the required power drive of stand is determined on dependence:

$$N_n = \frac{\Delta p}{\eta_m} \cdot (Q_н \cdot (1-\eta_н) + Q_м \cdot (1-\eta_м) + Q_н \cdot (\alpha - 1)), \quad (5)$$

where $\Delta p_к$ - an overfall of pressure on a loading valve, $\eta_н, \eta_м, \eta_m$ - general efficiency of pump, motor and transmissions accordingly.

Taking into account the accepted denotations and foregoing dependences will transform a formula (5)

$$N_n \geq \frac{\Delta p}{\eta_m} \cdot n_н \cdot q_н \cdot \left[\alpha - \eta_н + \frac{q_м}{q_н} \cdot (1 - \eta_м) \right], \quad (6)$$

In case if $q_м = q_н$ power of drive of stand on dependence (6) appears in a kind

$$N_n \geq \frac{\Delta p}{\eta_m} \cdot n_н \cdot q_н \cdot (\alpha + 1 - \eta_н - \eta_м), \quad (7)$$

For example, at the use as power aggregates of drive of stand axial piston hydromachine (APH) hydrodrive type GST-90 with nominal power pump and motor of $N_м = N_н =$ 46 kWt and displacement $q_н = q_м =$ 90 sm^3, $\eta_н = \eta_м = 0{,}92$, accept $\alpha = 1{,}15$. Consequently, $i_m \geq 1{,}15$, and drive power of stand of 14,3 kVt. According to dependence (7) $N_n \geq 0{,}31 \cdot N_н$. At the tests of every aggregate individually on the opened chart the total expenses of power make $N_n \geq 92$ kWt, that consumable power at tests goes down in 6 times. Taking to account that a hydraulic drive is provided in a chart (Fig. 1), a that decline of power will be a few less than.

For drafting of diagnostic model of drive of stand the method of formalization of functioning is accepted on the basis of generalized three key element [6]. The power aggregates of hydraulic drive can be presented charts which have three entrance variables, functionally related to other elements. As variables for knots accepted: knot taking of power, knot entrance of working environment and knot taking of working environment. Thus every element is described the system from 3 equalizations.

One of signs of change of the technical state of aggregates of hydrodrive, both in the conditions of exploitation and at tests and rolling there is power efficiency. For the aggregates of by volume hydrodrive select three indexes, which represent power efficiency: complete, volume and mehanical efficiency. The analysis of these indexes at tests allows simply to determine the technical state of aggregate, and the dynamics of their changes allows operatively to set duration of tests, and also to set reasons of low quality of good. Therefore as a basic sign of the state at the tests of power hydraulic aggregates efficiency is accepted.

Important direction of perfection power aggregates of hydraulic drives is an increase and stabilizing of efficiency in all of range of operating parameters. The increase of technical level hydraulic drives of mobile technique is provided the increase of nominal pressure to 30..45 MPa, by the increase of nominal frequency of rotation of pumps to frequency of rotation drive engine, and also by application of the managed power aggregates with the purpose of diminishing of losses of power in a transmission. Forcing power of machines on results in the decline of their efficiency, that requires development of additional complex of structural and technological measures for providing of his increase and stabilizing. Application of the automated facilities of diagnostics at the tests of new or modernized constructions allows substantially to shorten time of polishing of pre-production models to the serial making.

The methods of determination efficiency of rotor pнdromachinyi are known, which are based on the theory of similarity [7]. In obedience to this theory, general efficiency of pump is determined on dependence:

$$\eta_н = \frac{1 - k_{y1} \cdot \sigma_1}{1 + k_{f1} + (k_{\mu 1} / \sigma_1)}, \quad (8)$$

where $k_{y1}\sigma_1$ – specific power from the losses of working liquid; k_{f1} – specific power which is lost on a dry friction; $k_{\mu 1}/\sigma_1$ – specific power of losses on a viscid friction in a pump; $\sigma_1 = p/\mu \cdot \omega_н$ – a criterion of similarity of flow of viscid liquid in an equivalent crack for a pump, which is named the Zommerfel's function, p – pressure in a general pressure line, μ – dynamic viscidity of working liquid, $\omega_н$ – angular speed of shaft of pump.

For motorts general efficiency is determined on dependence:

$$\eta_м = \frac{1 - k_{f2} - (k_{\mu 2} / \sigma_2)}{1 + k_{y2} \cdot \sigma_2}, \quad (9)$$

where k_{f2} – specific power which is lost on a dry friction in a motor; $k_{\mu 2}/\sigma_2$ – specific power of losses on a viscid friction in a motor; $k_{y2}\sigma_2$ – specific power from the losses of working liquid in a motor; $\sigma_2 = p/\omega \cdot \omega_м$ – a criterion of similarity of flow of viscid liquid in an equivalent crack for a motor; $\omega_м$ Q angular speed of motor billow.

Taking to account for (8) and (9) $\omega_н = i_m \cdot \omega_м$, that $\sigma_1 = i_p \cdot \sigma_2$.

The values coefficients of specific powers losses of energy in power aggregates are determined on the characteristic sizes of hydromachines:

- from the losses of working liquid

$$k_{yi} = \frac{C_{yi}}{e_i} \left(\frac{\delta_i}{\bar{q}_i} \right)^3 \quad (10)$$

where: C_{yi} Q coefficient of losses; $0 \leq e_i \leq 1$ - adjusting parameter; δ_i – equivalent gap; $\bar{q}_i = \sqrt[3]{\frac{q_i}{2 \cdot \pi}}$ – characteristic size of hydromachine.

− from losses on a dry friction:

$$k_{\mu_i} = \frac{C_{\mu_i} \cdot \overline{q}_i}{e_i \cdot \delta_i}, \qquad (11)$$

where: C_μ − coefficient of losses on a viscid friction.

In the above-mentioned dependences $\overline{q}_i$ for concrete type of hydromachine the characteristic volumes $\overline{q}_i$ of size are permanent, all of other are determined the structural features of units and details of hydromachines, and also technology of their making, as a rule are variable at tests.

Investigation change of the state aggregate which is tested is a change of signs the state. Thus basic sources of uninvariance there is an object of diagnosing. As a result of break-in process details of aggregates takes a place changes of internal factors, that is reflected at the level general efficiency of aggregates. Descriptions of drive of stand at tests have statistical changeability the analysis of which allows to estimate the basic sign of diagnosing. For the analysis of the state of aggregates which test apply two indexes: mean value and dispersion of general efficiency of aggregates for period of their test. The size of mean value allows to set conforming to of aggregate the normative requirements, and an analysis of dispersion is time of break-in process.

4. RESULTS OF RESEARCHES

On the presented stand in joint-stock company «Strojhydravlika» managed bent axis APH trimot type 403.112 is tested. His issue accustoms from 2008 for application in the hydraulic transmissions of build-travelling and agricultural technique. The distinctive feature of new series is possibility of providing of the discrete adjusting of the displacement. Thus two workers of volume, maximal $q_{\max}$=112 sm^3, and the minimum displacement is set depending on the technical terms of customer. By undeniable advantage of hydraulic drives with discretely managed motors is providing of two workings speeds, and also possibility of putting in these speeds without the stop of machine, that promotes the productivity and management quality substantially.

A standard pumping unit and original adjuster is applied in the construction of APH type 403.112. With the purpose of verification of capacity of gidromashiny its tests were conducted on a stand with rekuperatsiey of power, which is presented on fig. 2, and setting two managed machine 403.112 on a stand shown, on fig. 3.

Fig. 2. The stand with recuperation of powers for tests APH 403.112

Fig. 3. Setting of two hydromachines 403.112 at the stand.

Treatment of values of parameters of tests allowed continuously to determine the signs of the state of hydromachin: mean value and dispersion of efficiency. The analysis of these signs allowed to define accordance of the technical state of aggregates the requirements of technical document for development of machines, and also to specify time of their break-in process. The additional task of tests was verification of longevity by work of regulator of number of cycles of switching, which would provide his tireless durability at the base number of cycles of loadings, what corresponded continuous work of hydromachine during the set interval of time with switching of regulators of every aggregate.

The given stand also can be applied at tests and break-in process mechanical units. In this case units which are tested are installed instead of transmission 10 (fig. 1).

The loading cycles APH 403.112 at the stand are presented on diagrams which are shown on fig. 4. On diagrams are shown Q_1 – rate of flow the hydromachine, which works in a mode of the motor, and Q_2 - rate of flow the hydromachine, which works in a mode of the pump. Switching of operating modes was provided with hydraulic allocators which conditionally are not shown on the basic scheme fig. 1.

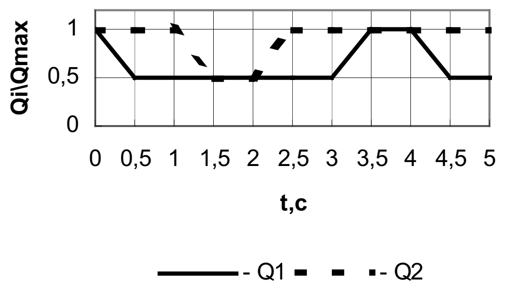


Fig. 4. The loading cycles of hydromachines

The results of the conducted tests were confirmed by a capacity and longevity of the developed construction of managed variable displacement hydromachines 403.112. with the discrete adjuster.

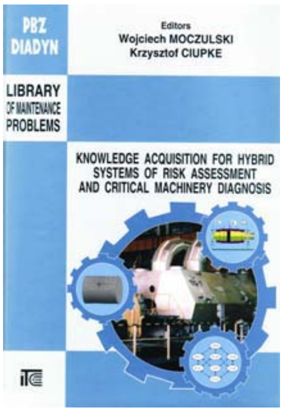
5. CONCLUSIONS

For providing of diagnosing of the technical state of power aggregates of hydraulic drives at their tests and break-in process it is suggested to apply hydraulic stands with recuperation of power.

The row of constructions of such stands is developed. The method of calculation parameters of hydraulic stand with recuperation of power is offered. At the tests of hydraulic aggregates of expense of power on their conducting go down in some times. Continuous analysis of signs of the state of aggregates which test apply two indexes: mean value and dispersion of general efficiency of aggregates for period of their test.

REFERENCES

1. Sjiricin T.: *Reliability of gidro- and pnevmodrives*. M: Machinostroenie, 1981 (in Russian).
2. Volkov D., Nikolaev S.: *Reliability of build machines and equipment.* M: Vysh. school., 1979 (in Russian).
3. Gorbatij V., Nikolenko I. and other:. *The stand for tests of hydromachine with recuperation of power*. – A.s. USSR № 1606750. Bul. № 42., 1990 (in Russian).
4. Gorbatij V., Nikolenko I. and other: *The stand for tests of hydromachine*. A.s. SSSR № 1613683. - Bul № 46., 1990 (in Russian).
5. Nikolenko I., Komarov A.: *The hydraulic stand for test of mechanical units*. Patent of Uraine № 64366/ Bul. № 2, 2004 (in Ukrainian).
6. Berengard Ju., Gajcgori M.: *Algorithm of forming of mathematical model of hydrodrive of arbitrary structure*. Engineering science. № 1, 58 – 65., 1977 (in Russian).
7. Kondakov L., Nikitin G., Prokofiev V. and others: *Machine-building hydrodrive*. – M.: Machinostroenie, 1978 (in Russian).



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Knowledge acquisition for hybrid systems of risk assessment and critical machinery diagnosis

ITE Radom 2008

The work contains the results of research activity of seven teams from six research centers. Parallel proceeding of these teams has been part of the research carried out within the framework of the research project "Integrated dynamic system for risk assessment, diagnostics and control of technical objects and processes" (project acronym: DIADYN) supported by the Polish Ministry of Science and Higher Education (formerly Polish Committee for Scientific Research) from year 2005 until 2008. The steering group of the project decided to manage the project in the form of a package of groups of tasks (GTs). The presented book integrates the results of two GTs and has been mainly concerned on knowledge acquisition for hybrid systems capable of dealing with risk assessment and diagnostics of critical machinery.

The book will be interesting for industrial engineers, scientists and students as well who wish to pursue the risk assessment and advanced technical diagnostics issues of safety-critical machinery.

The last paragraph explains the main objective of the work that we have edited. The goal of the teamwork of the seven research groups has been to address several issues of knowledge acquisition for hybrid systems of risk assessment and critical machinery diagnosis. The book has been composed of parts that correspond to the issues of research groups, each of them being an original insight to the title topic of the monograph.

The first part concerns a system for acquiring diagnostic knowledge of selected faults of critical rotating machinery, and contains results of collaboration between the research groups from the Department of Fundamentals of Machinery Design, Silesian University of Technology at Gliwice, and from the Institute of Fluid Flow Machinery, Polish Academy of Sciences. After dealing with the issues of knowledge acquisition with special attention paid to knowledge discovery in databases, selected faults in rotating machinery were described together with employed methods of their modeling and simulation. Then the results of simulation experiments were presented in the form of prototype diagnostic relations. Further on, a system for knowledge acquisition was presented and several results of system verification for one distinguished kind of fault, i.e. cracks in shafts were documented as well.

The part ends with a concept of adapting the system to changing operating conditions and varying overall technical state of the machine. The second part prepared by the group from the Institute of Fundamental Technological Research, Polish Academy of Sciences, presents other approach to a specific kind of faults of rotating machinery which are cracks in shafts of machines. The method involves a stochastic attempt that takes advantage of Monte-Carlo simulation. In order to detect and locate individual cracks the knowledge base of multiple cases of cracks developing at different locations was used. Moreover, some issues concerning durability of cracked machine shafts were discussed.

The third part of the monograph was elaborated by the scientific group from the Chair of Building and Operation of Vehicles and Machinery, the University of Warmia and Mazury in Olsztyn. This work was targeted at a system for operational risk assessment. Implementation of the system concerned several objects operated in the food industry. The system includes identification of risks to be met within operation of the selected machinery. Further on, a survey of methods of risk analysis was carried out. Finally, the method for assessment of operational effectiveness in the risk aspect was presented.

The fourth part is the result of work of the team from the Department of Vibroacoustics and Biodynamics of Systems, Poznań University of Technology, and concerns a diagnostic agent for critical machinery. The main issue was based on a multi-agent approach. The part includes examples of applications of the elements of the system to the diagnostics of rotating machinery and vehicles.

The next part prepared by the scientific group of the Department of Vehicles Engineering and Transportation, the University of Technology and Life Sciences in Bydgoszcz, concerns issues of the diagnostics through identification. This software-oriented approach takes advantage of the theory of technical diagnostics. A novel software tool developed within the DIADYN project was described. The part ends with the description of an on-board diagnostic system for critical machinery.

Finally, the last part of the book, authored by the group of the Institute of Fundamental Technological Research, Polish Academy of Sciences, is devoted to numerical identification of loads. Two approaches were concerned: model-less identification based on pattern recognition methods, and methods taking advantage of numerical models, which allowed reconstruction of load, and continuous identification of loads. Another problem addressed thorough the work concerns optimal location of sensors upon the mechanical system.

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Zjawiska nieliniowe w diagnostyce technicznej

ITE Radom 2008

Efektywne funkcjonowanie dowolnych systemów działania na przykład: przemysłowych, rolniczych, wojskowych i innych jest zdeterminowane stanem maszyn i urządzeń technicznych. Stanem zdatności funkcjonalnej i zadaniowej obiektów technicznych należy sterować. Narzędziem sterowania są metody diagnostyki technicznej.

Maszyny to systemy techniczne z przepływem masy, energii i informacji. Są to systemy transformujące energię z nieodłączną ich dyssypacją: wewnętrzną i zewnętrzną. Nośnikiem informacji
o stanie maszyn są procesy:

- robocze, w których zachodzi przetwarzanie jednego rodzaju energii w inny lub jej przenoszenie;
- towarzyszące (resztkowe) na przykład: nagrzewanie się elementów, zanieczyszczenie oleju, a w szczególności procesy wibroakustyczne.

Niestety, pomimo wielkich dokonań wielu badaczy, na dzień dzisiejszy nie poznano dokładnie natury generacji procesów wibroakustycznych, zatem nie rozwiązano problemu podstawowego, to jest przyporządkowania wybranych składowych sygnału, konkretnym parom kinematycznym i mechanizmom maszyn. Przykładem może być brak efektywnych metod wibroakustycznych badań o ceny stanu: silników spalinowych, przekładni hydromecha-nicznych, czy mostów napędowych pojazdów mechanicznych. Taki stan rzeczy wynika z faktu, że nie dysponujemy odpowiednimi modelami diagnostycznymi maszyn. Z reguły stosowane są modele liniowe, które odzwierciedlają stan obiektów rzeczywistych z pewnym przybliżeniem.

Model, w którym występują zależności między: parametrami sygnałów diagnostycznych, masami, elementami sprężystymi, tłumiącymi oraz wymuszeniami nazywa się diagnostycznym modelem strukturalnym obiektu technicznego. Modele diagnostyczne nie wyznaczają stanu obiektu, lecz są podstawą budowy określonych algorytmów diagnozowania, za pomocą których ustala się dopiero jego stan.

W czasie eksploatacji maszyn pojawiają się i narastają zaburzenia nieliniowe związane z ich starzeniem fizycznym. W związku z tym istota zagadnienia tkwi w tym, że należy opisać maszyny diagnostycznymi modelami nieliniowymi, które mogą rozwiązać problem diagnozowania (monitorowania), prognozowania i genezowania stanu maszyn, za pomocą symptomów wibroakustycznych.

Biorąc pod uwagę niektóre przedstawione informacje dotyczące diagnostyki wibroakustycznej maszyn należy stwierdzić, że opiniowana praca Panów Profesorów Jest bardzo aktualna i wypełnia lukę dotyczącą tej trudnej problematyki. Autorzy podstawili sobie bardzo ambitne, trudne do realizacji zadanie: rozpatrzenie i dokonanie analizy niektórych zjawisk nieliniowych występujących w diagnostyce maszyn. Konsekwentnie starają się wykazać użyteczność różnego rodzaju dynamicznych modeli strukturalnych do opisu zjawisk nieliniowych, których ewolucja może stanowić wiarygodny symptom diagnostyczny. Taki sposób postępowania nazywają diagnostyką według modelu.

W drugim rozdziale pracy Autorzy w sposób wyczerpujący i precyzyjny przedstawili następujące zagadnienia:

- pojęcie nieliniowości;
- diagnostykę maszyn według modelu (defekty, model teoretyczny układu, symptomy, relacje diagnostyczne);
- filtracja i predykcja obserwowanego sygnału;
- relacja sygnał ↔ model.

Trzeci rozdział pracy jest poświęcony istotnemu zagadnieniu, tzn. identyfikacji dynamicznego modeli nieliniowego, która trafnie zdefiniowano następująco: „identyfikacją modelu matematycznego nazywamy wszelkie działania, w wyniku których proponowany model matematyczny odpowiada rzeczywistości (obserwacji) w sensie jakościowym i ilościowym zgodnie z przyjętymi kryteriami i zachowuję tę odpowiedniość przy przewidywanym zakresie dopuszczalnych zmian, to znaczy pozwala na wnioskowanie o aktualnym obserwowanym fragmencie rzeczywistości, z zadana dokładnością”.

Inne niektóre rozpatrzone zagadnienia tego rozdziału to:

- identyfikacja modelu liniowego;
- rozwiązanie układu słaboliniowych równań różniczkowych zwyczajnych;
- badania symulacyjne odpowiedzi nieliniowych w warunkach zakłóceń;
- identyfikacja relacji sygnał ↔ model za pomocą filtracji Kalmana.

W rozdziale czwartym pracy rozpatrzono proste modele nieliniowe, układów wirujących, a w szczególności:

- nieliniowy model ruchu wirnika na sztywnych podporach;
- model wirnika na podporach elastycznych;
- model dynamiczny układu przenoszenia mocy.

W rozdziale piątym opracowania w sposób oryginalny przedstawiono problem wykorzystywania filtracji Kalmana w diagnozowaniu ruchów czopaw panwi łożyska hydrodynamicznego. Rozwiązano zadanie eliminacji zakłóceń w systemie monitorującym drgania czopa wału w panwi łożyska hydrodynamicznego, będącego częścią systemu dynamicznego: „wirnik – łożyska – podpory – fundament". Zaprezentowano wyniki symulacji filtracji zakłóceń i ich odniesienie do rzeczywistych wyników pomiarów. Uzyskane wyniki wskazują nowy obszar możliwych w tym zakresie rozwiązań.

Rozdział szósty pracy omawia zagadnienia funkcji koherencji jako miary zaburzenia nieliniowego, lokalizacji uszkodzeń struktury kompozytowej obiektu. Stwierdzono, że analiza koherencyjna pozwala na obserwację propagacji uszkodzenia struktury masztu kompozytowego z dokładnością, co najmniej porównywalną z metodą rentgenograficzną i może być zarówno podstawą identyfikacji modelu matematycznego jak i znalezienia miary symptomowej uszkodzenia.

W rozdziale siódmym Autorzy pokazali w jaki sposób można wykorzystać rozwiązania teorii stateczności technicznej w procesie konstruowania systemów monitorujących zmiany stanów: maszyn, urządzeń, konstrukcji, bądź procesów. Jak wykazały badania symulacyjne, warto uwzględnić w konstrukcji systemu monitorującego, warunek potrzeby kontrolowania zmian portretów fazowych. Mają one dużą wrażliwość na zmiany stanu nadzorowanego obiektu. Podkreślono, że nie da się zbudować nowoczesnego systemu monitorującego bez podejścia systemowego, tzn. uwzględniającego: wiedzę diagnostyczną, metody analizy dynamiki badanego obiektu, analizę jego zachowań nieliniowych i związanych z nimi ocen ich stateczności.

Ważnym elementem pracy jest rozdział ósmy, w którym Autorzy przedstawili opracowany nieliniowy model diagnostyczny turbozespołu, obejmującego między innymi następujące zagadnienia:

- model struktury maszyny wirnikowej i algorytm realizacji obliczeń dynamicznych;
- model konstrukcji podpierającej;
- transformację zespolonych charakterystyk podatnościowych konstrukcji podpierającej do rzeczywistych charakterystyk masowo – tłumiąco - sztywnościowych;
- algorytm obliczeń nieliniowych układu: linia wirników – konstrukcja podpierająca z wykorzystaniem funkcji wagowych.

Rozdział dziewiąty pracy Autorzy poświęcili realizacji cyfrowej nieliniowości modelu turbozespołu małej i dużej maszyny wirnikowej. Linia wirników skupia na sobie oddziaływania wszystkich podzespołów maszyny wirnikowej, tzn. oddziaływania łożysk ślizgowych i konstrukcji podpierającej, wyrażone w formie współczynników sztywności i tłumienia filmu olejowego i macierzy współczynników sztywności i tłumienia mas pozostałych elementów.

Przedstawiono została własna oryginalna metoda określania współczynników sztywności i tłumienia łożysk ślizgowych, oparta na modelach nieliniowych łożysk ślizgowych i zmodyfikowanej metodzie perturbacji. Razem stanowi to bardzo zaawansowany, kompleksowy i wzajemnie spójny model dynamiczny złożonego układy typu: linia wirników z imperfekcjami-konstrukcja podpierająca, do analizy zarówno w zakresie liniowym, a przede wszystkim w zakresie nieliniowym. Nie jest znany inny odpowiednik takiego modelu.

Opracowany model układu: linia wirników-łożyska ślizgowe-konstrukcja podpierająca stanowi zestaw wielu równań i zależności o bardzo złożonej strukturze. Otwiera on nowe możliwości w badaniach tego typu maszyn.

Pracę kończy rozdział dziesiąty poświęcony określeniu przedziału adekwatności opracowanego modelu turbozespołu. Wobec niemożliwości uzyskania analitycznego opisu „przekształcenia odwrotnego", jedynym sposobem osiągnięcia pozytywnych efektów w zadaniu identyfikacji modelu jest określenie przedziałów, dla których wyznaczone charakterystyki dynamiczne są właściwe (tzw. przedziałów adekwatności).

Przedstawiono wyniki badań dwóch obiektów: wirnika „laboratoryjnego" i turbozespołu dużej mocy. W badaniach teoretycznych i eksperymentalnych wykorzystano eksploatacyjną analizę modalną. Zostały określone przedziały adekwatności jak i charakterystyki dynamiczne badanych obiektów. Wyniki obliczeń przedstawione zostały w formie kart diagnostycznych, wspomagających określenie stanu badanych elementów maszyn wirnikowych.

Reasumując opinię o pracy należy stwierdzić, co następuje:

1) książka jest pierwszą krajową publikacją poświęconą zjawiskom nieliniowym w diagnostyce wibroakustycznej ;
2) praca wnosi nowe wartości poznawcze i utylitarne do nauki o badaniach i ocenie stanu maszyn, w szczególności diagnostyki wibroakustycznej;
3) publikacja wytycza nowy kierunek działań w badaniach właściwości i zastosowania procesów wibroakustycznych w iagnozowaniu (monitorowaniu), prognozowaniu i enezowaniu stanów maszyn;
4) sądzę, że monografia będzie podstawą dalszych prac opracowania nieliniowych modeli diagnostycznych i ich pełnego wykorzystania w procesach utrzymania maszyn.


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