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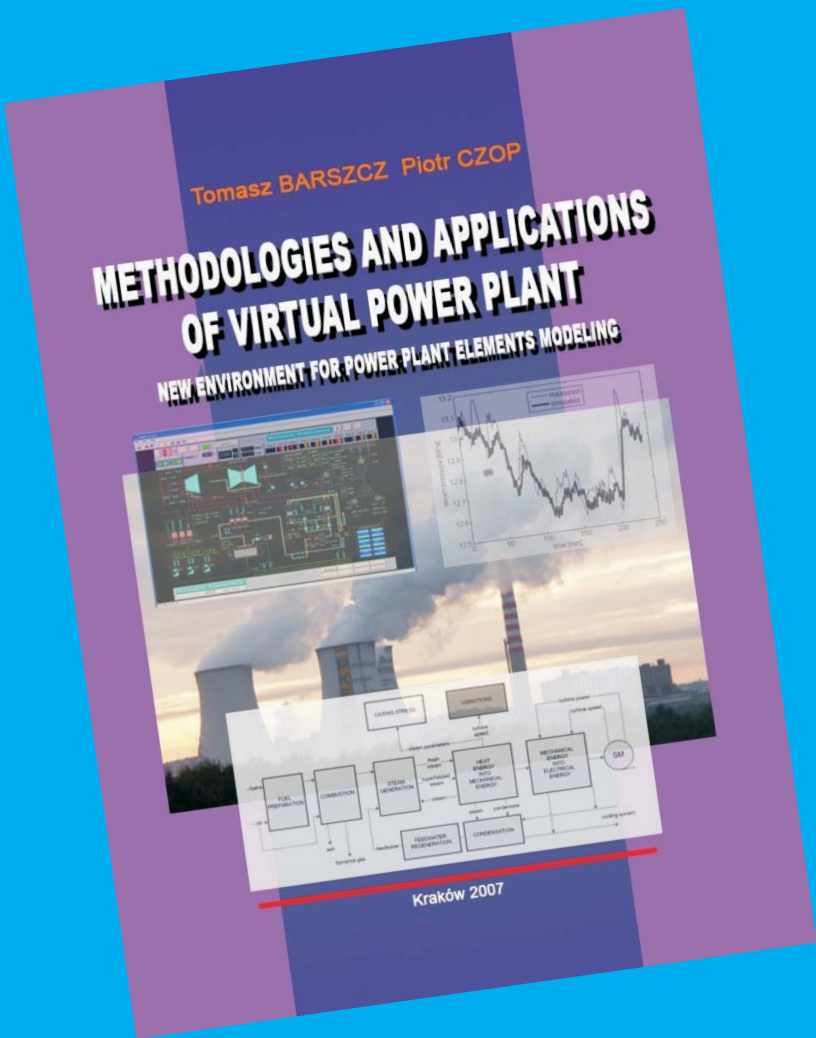

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Wszystkie opublikowane prace uzyskały pozytywne recenzje wykonane przez dwóch niezależnych recenzentów. Obszar zainteresowania czasopisma to problemy diagnostyki, identyfikacji stanu technicznego i bezpieczeństwa maszyn, urządzeń, systemów i procesów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

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JUBILEUSZ 80-LECIA prof. dr hab. inż. Lesława BĘDKOWSKIEGO

W dniu 24.10.2008 r., w Klubie Wojskowej Akademii Technicznej w Warszawie, odbyła się jubileuszowa uroczystość 80-tej rocznicy urodzin, wielce zasłużonego dla polskiego środowiska diagnostycznego, prof. Lesława Będkowskiego.

W spotkaniu tym udział wzięło ponad 60 osób – w tym najbliższa rodzina Jubilata, byli i obecni współpracownicy, liczne grono przyjaciół z różnych polskich uczelni. Uroczystość uświetnił swą obecnością Rektor WAT gen. prof. Zygmunt Mierczyk.

Sylwetkę biograficzną prof. L. Będkowskiego przybliżył zebranym – w kilkunastominutowym referacie – wieloletni współpracownik Jubilata dr hab. inż. Tadeusz Dąbrowski.

Prof. dr hab. inż. Lesław Będkowski urodził się 25 października 1928 r. w Medenicach, w województwie lwowskim. Dzieciństwo spędził w Schodnicy i Borysławiu – w centrum polskiego przemysłu naftowego. W roku 1945 został wysiedlony i zamieszkał w Złotowie, gdzie w 1948 r. uzyskał świadectwo dojrzałości. W roku 1951 ukończył studia inżynierskie na Wydziale Elektrycznym Szkoły Inżynierskiej w Szczecinie. Powołany do zawodowej służby wojskowej w 1951 roku, został skierowany do pracy w tworzonej wówczas Wojskowej Akademii Technicznej w Warszawie. W uczelni tej nieprzerwanie pracuje do dnia dzisiejszego.

Do ważniejszych faktów z kariery naukowo-dydaktycznej Jubilata zaliczyć należy: rok 1956 – uzyskanie tytułu magistra inżyniera; rok 1968 – uzyskanie stopnia doktora inż.; rok 1981 – uzyskanie stopnia doktora hab. inż.; rok 1991 – uzyskanie tytułu profesora.

W okresie pracy w WAT Jubilat zajmował kolejno następujące stanowiska: 1951÷52 – st. asystent; 1952÷57 – kier. laboratorium; 1957÷68 – st. wykładowca; 1968÷78 – adiunkt; 1978÷1991 – docent; 1992÷aktualnie – prof. zwyczajny.

Dorobek naukowy Profesora skupia się głównie wokół następujących zagadnień: teoria diagnostyki technicznej, optymalizacja procedur diagnostycznych, diagnostyka systemów antropotechnicznych, diagnostyka w ujęciu potencjałowo-efektowym, eksploatacja w ujęciu trójprocesowym, wielopoziomowe systemy dozorująco-terapeutyczne, diagnostyka bezpieczeństwa, niepewność w procesach diagnozowania. Dorobek ten wyraża się liczbą ponad 200 różnych publikacji. Na podkreślenie zasługuje fakt, że Profesor jest w Polsce pionierem udokumentowanych prac z zakresu diagnostyki technicznej – współautorem pierwszych artykułów (1965 r.) oraz autorem jednej z dwu pierwszych rozpraw doktorskich (1968 r.) z tego obszaru (autorem drugiej rozprawy jest T. Rozwadowski).

Dorobek dydaktyczny Profesora wyraża się liczbą ponad 7000 godzin zajęć audytoryjnych, 7 wypromowanych doktorów w specjalności diagnostyka, ok. 60 wypromowanych magistrów inżynierów i inżynierów. Podstawowe obszary działalności dydaktycznej obejmują: diagnostykę techniczną, podstawy eksploatacji urządzeń i systemów, niezawodność eksploatacyjną, lotnicze urządzenia elektroenergetyczne.

Jubilat aktywnie uczestniczył i nadal uczestniczy w **działalności organizacyjno-społecznej** co znajduje wyraz m. in. w pełnionych – w różnych okresach czasu – funkcjach. Ważniejsze z nich to: przewodniczący Zespołu Diagnostyki Technicznej NOT (1983÷1991); przewodniczący Zespołu Diagnostyki Cybernetycznej PTC (1983÷1991); v-przewodniczący Zespołu Diagnostyki SPE KBM PAN (1983÷1991); członek Prezydium Sekcji Podstaw Eksploatacji KBM PAN (1984÷1990); v-prezes Zarządu Głównego Polskiego Towarzystwa Diagnostyki Technicznej (1990÷1993); redaktor Działu Diagnostyki Zagadnień Eksploatacji Maszyn PAN (1983÷1992); przewodniczący Komitetu Naukowego Krajowych Konferencji „Diagnostyka Techniczna Urządzeń i Systemów" DIAG'86, '90, '95, '98; '2003 oraz członek Komitetów Naukowych wielu innych konferencji; członek Polskiego Towarzystwa Diagnostyki Technicznej (od 1990 r.); członek Komitetu Budowy Maszyn PAN (1990÷1993); członek Polskiego Towarzystwa Bezpieczeństwa i Niezawodności (od 1997 r.); przewodniczący Komisji Nauki Rady Wydziału Elektroniki WAT (1985÷2003).

Za całokształt swej działalności Jubilat był wielokrotnie odznaczany i nagradzany, m. in. posiada: Krzyż Oficerski i Krzyż Kawalerski OOP, Złoty i Srebrny Krzyż Zasługi, Medal Komisji Edukacji Narodowej, Złoty Medal „Zasłużony dla WAT", Medal „Zasłużony dla lotnictwa" i inne.

Profesor L. Będkowski zakończył służbę wojskową w stopniu pułkownika lotnictwa w roku 1994.

Pasją pozazawodową Jubilata jest turystyka piesza, historia przemysłu naftowego zagłębia borysławskiego, poezja i muzyka poważna.

Redakcja „Diagnostyki" składa
prof. L. BĘDKOWSKIEMU wyrazy szacunku
i podziękowania za dotychczasową wieloletnią
współpracę.
Życzymy panu Profesorowi wiele zdrowia
i pomyślności w życiu osobistym.

prof. Ryszard MICHALSKI
Redaktor Naczelny

VERIFICATION OF DOPPLER EFFECT REMOVAL METHOD FOR THE NEEDS OF PASS-BY RAILWAY CONDITION MONITORING SYSTEM

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Summary

The description of the experiment verifying the method of Doppler's Effect removal from the acoustic signal of moving object was discussed in the paper. Doppler's Effect was removed by dynamic resampling according to the theoretical frequency changes curve as well as with use of the curve obtained by passband filtration of the signal around the carrier frequency and differentiation of the phase of the analytic signal. Described solutions were tested in the GPS synchronised field measurements on the moving railway cars and simultaneously the stationary measurements taken next to the railway track.

Keywords: Doppler's Effect, nonstationarity, task oriented dynamic resampling instantaneous frequency, monitoring station.

WERYFIKACJA METODY USUWANIA EFEKTU DOPPLERA DLA POTRZEB PRZYTOROWEJ STACJI MONITORINGU STANU TECHNICZNEGO

Streszczenie

W pracy przedstawiono opis eksperymentu weryfikującego metodę usuwanie efektu Dopplera z sygnału akustycznego poruszającego się obiektu. Efekt Dopplera z sygnału usuwano poprzez dynamiczne przepróbowanie sygnału zarówno zgodnie z teoretyczną krzywą zmian częstotliwości chwilowej sygnału jak również z użyciem krzywej otrzymanej przez wąskopasmową filtrację sygnału wokół częstotliwości nośnej a następnie różniczkowanie fazy sygnału analitycznego. Zaproponowane rozwiązania zostały przetestowane w warunkach poligonowych podczas jednoczesnych, synchronizowanych sygnałem GPS, pomiarów na poruszających się pociągach oraz pomiarów przytorowych.

Słowa kluczowe: efekt Dopplera, niestacjonarność, zorientowane zadaniowo dynamiczne przepróbkowanie, chwilowa częstotliwość, stacja monitoringu.

1. INTRODUCTION

Doppler Effect, a change in frequency of a sound wave emitted by a moving source recorded by stationary observer, is a barrier that reduces the possibility of online diagnosing of moving vehicles, treated as the signal sources, with the use of stationary measuring equipment positioned outside the vehicle. This effect introduces the spectrum smear similar to the one caused by signal nonstationarity e.g. change of rotational velocity in rotating machines, forcing spectrum lines to shift from the proper place. A method of removal this phenomenon based on a task oriented resampling was proposed in [1]. In this paper the experimental results were shown confirming the theoretical simulation results shown in [1] and additional modifications of the method based on the field measurements were proposed. The removing of the Doppler Effect is crucial for any pass-by condition monitoring stations to correctly analyse Fourier spectrum components.

2. EXPERIMENT DESCRIPTION

Experimental measurements were taken in Żmigród on a CNTK railway test track. The testing object and a source of the signals was a four wheel drive rail vehicle WM-15A, with diesel engine of 147 kW (Fig. 1). The distance between the axles was 5.85 m and the wheels diameter 0.92 m. The measurements were taken on a cloudy day with temperature of 29 °C and moderate wind condition.

Fig. 1. WM-15A vehicle used for test measurements.

The measurements were taken on straight part of the rails on a test distance of about 30 m. The measurements were performed for different velocities of the vehicle.

For the measurement purpose the National Instruments measuring gear consisting of two independent signal recording computers (NI/PXI-8186 type) equipped with two PXI-4472B and one PXI-4462 data acquisition cards was used. Signal recordings were taken simultaneously on the pass-by ground recording station and on a moving recording station onboard of a WM-15A vehicle. Both sets of recordings were synchronised with each other using Pulse-Per-Second (PPS) signals from Garmin 18LVC GPS receivers. The GPS signal synchronisation principles used in the experiment were described separately in [2].

On the mobile station placed onboard a vehicle a total of 8 signals were recorded using PXI-4472B data acquisition card: GPS PPS signal for future synchronisation purposes, bearing vibrations (accelerations) in axial and perpendicular directions of both wheels on one side of the vehicle, acoustic pressure (noise) close to this bearings and acoustic pressure on the top of the platform as a reference signal (Fig. 2).

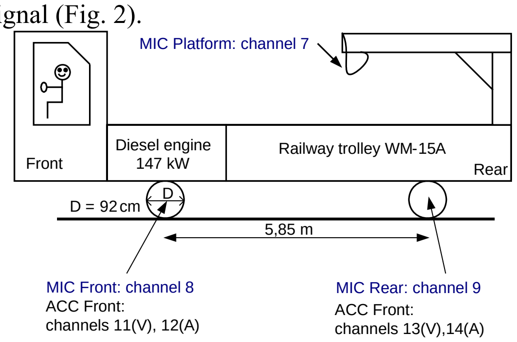

Fig. 2. Sensor placement on a mobile station used in the experiment.

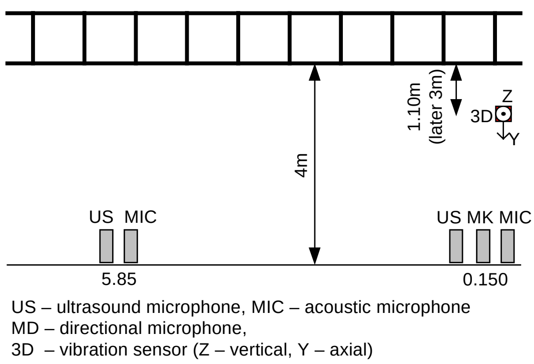

Fig. 3. Sensor placement on a ground station used in the experiment.

On the pass-by ground station besides GPS PPS signal, acoustic pressure (noise) signals using five microphones (2 conventional measuring microphones, 2 ultrasonic and one directional microphone) were recorded. The distance between microphones group's positions was selected according to the vehicle axle distance of 5,85m. Additionally the ground vibrations in two directions next to the railway track were recorded. The transducers setup of the ground pass-by station is shown schematically on Fig. 3.

3. SIGNAL POSTPROCESSING FOR DOPPLER EFFECT REMOVAL TESTS

Recorded signals were later processed to test the Doppler Effect removing method described in [1]. The described tested algorithm relies on the task oriented dynamic resampling of the recorded signal. The signal resampling was done according to the changes in the frequency of the recorded signal from a moving source (a vehicle). As was proved in [1] a frequency change of the pure tone acoustic signal moving relatively to the microphone could be described with (Fig .4)

$$f_R(t) = f_0 \cdot \frac{1}{1 - \frac{V_z}{V_d} \cdot \frac{s - V_z \cdot t}{\sqrt{h^2 + (s - V_z \cdot t)^2}}} \tag{1}$$

where:

- f_0 - real frequency of the signal source,
- f_R - instantaneous frequency of the recorded signal,
- V_d- sound velocity in the air (V_d = 343 m/s was assumed),
- V_z -velocity of the moving vehicle (signal source),
- h - distance from the microphone to the railway track,
- s - distance describing the position of the vehicle in the moment of signal recording beginning defined as a distance from the point closest to the microphone.

Having fixed f_0 frequency and $f_R(t)$ waveform one can resample the recorded signal using the new $dt(t)$ according to the formula:

$$dt_{new}(t) = \frac{f_o \cdot dt}{f_R(t)} \tag{2}$$

where dt is the sampling interval (inverse of the sampling frequency).

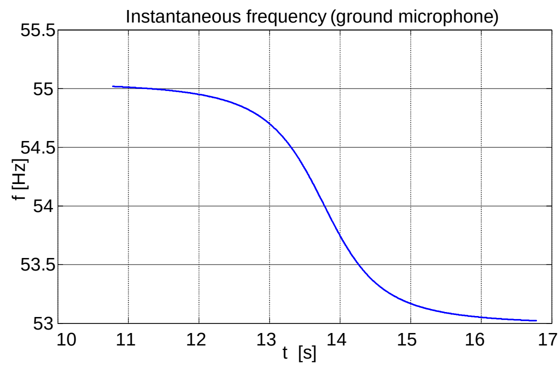

Fig. 4. Change of instantaneous frequency of 54 Hz according to equation 1.

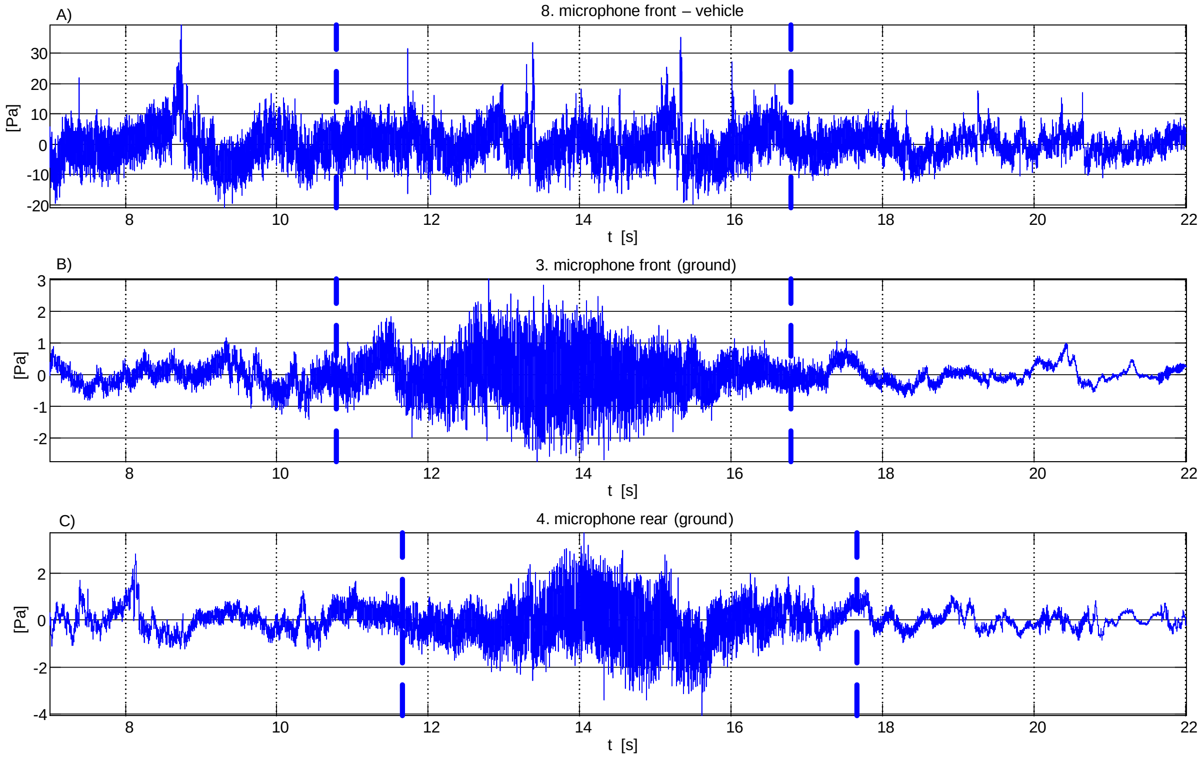

Fig. 5. Time waveforms with selected parts for removing Doppler Effect

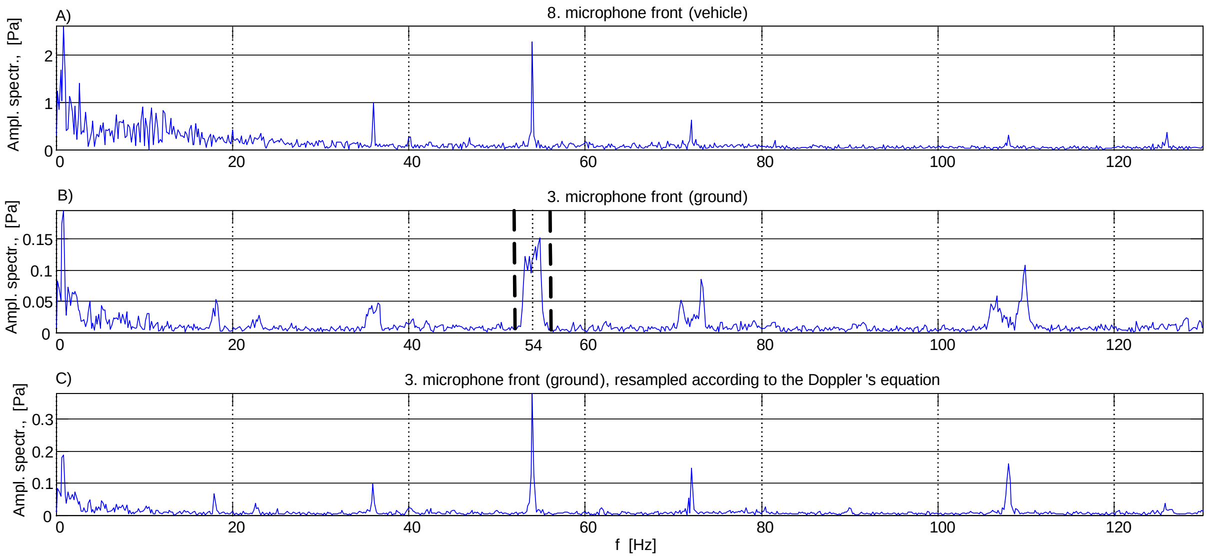

Fig. 6. Acoustic pressure amplitude spectrum for reference signal recorded
A) near the front bearing of the vehicle; B) on the front microphone of a ground pass-by station;
C) Signal from B) with Doppler's Effect removed using equations (1) and (2)

To apply this method a part of a recorded signal should be selected symmetrically to the microphone position. Any errors would result in additional frequency smear of the resampled signal. On the Fig. 5 the recorded time signals with selected parts corresponding to the front and rear microphones of the ground pass-by station as well as a bearing noise reference signal were shown. On the Fig. 6 the results of this procedure applied to the noise recordings of the vehicle moving with a velocity of 24 km/h were shown. The similarity of signal's spectra recorded with a microphone near the vehicle bearing and spectra of the front microphone on a ground pass-by station is clearly visible. Similar results were obtained for the rear ground pass-by station microphone signal. The differences in the amplitudes of the signals are due to the distance between the microphones of the ground station and the railway track (4 m).

The described method has one serious drawback. It requires the precise knowledge of the vehicle position relative to the stationary, ground microphone as well as its velocity relative to the recording microphone. This method could be modified to get rid of this flaw.

To do this an instantaneous frequency f_R should be calculated from the analytical signal of the passband filtered signal [3]

$$x_a(t) = x(t) + j \cdot H[x(t)] = |x_a(t)| \cdot e^{j \cdot \varphi(t)} \qquad (3)$$

using well known equation [3]

$$f_r(t) = \frac{1}{2 \cdot \pi} \cdot \frac{d\varphi(t)}{dt} \qquad (4)$$

The passband of the filter should be selected in such manner as to remove from the signal all the frequencies except the single smeared frequency. For the signal from Fig. 5B a passband of 52-56 Hz was selected (Fig. 6B).

It is always a problem to design a digital filter with steep enough characteristic and a very narrow passband. In this application a filtering was performed using Fourier transform, removing all the frequencies except the desired passband and then applying inverse Fourier Transform to thus modified spectrum.

Results of calculating the instantaneous frequency for both front and rear ground pass-by station microphones are shown on Fig. 7. The signals are shifted in time for the equivalence of the axle distance (see Fig. 2, 3) The great similarity of the theoretical curves calculated from equation (1) and the curves calculated from the filtered spectrum (4) are the confirmation of the correctness of the method.

The spectra of this signals look extremely similar to the one presented on the Fig. 6C.

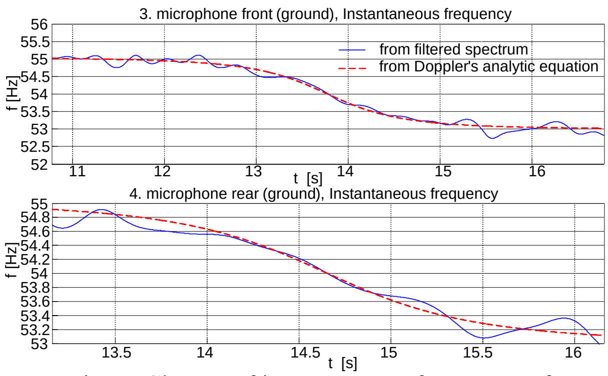

Fig. 7. Change of instantaneous frequency of 54 Hz according to equations (1) and (4)

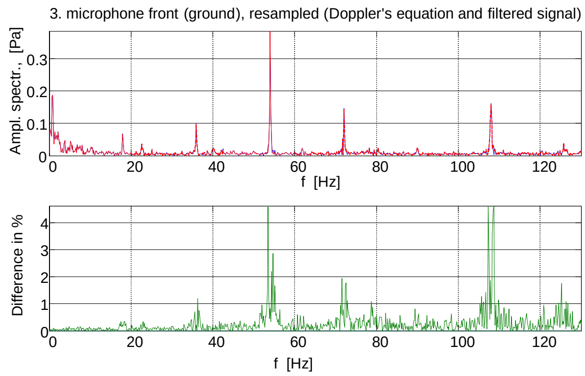

Fig. 8. Comparison of described Doppler's Effect removal methods

4. SUMMARY

Results of the experiment confirmed the possibility of Doppler Effect's removal from the real signal in the field measurements. The difference between results obtained with theoretical frequency curve and curve obtained using signal filtration differs only in maximum 5% (Fig. 8).

It was not the aim of this project to diagnose the technical state of the vehicle used in the experiment. The diesel engine used by the vehicle was noisy to such extent that it masked the bearings signals.

Described methods could be used in the development of the ground pass-by vehicle diagnostic station capable of monitoring the technical state of passing vehicles.

REFERENCES

[1] Dybała J.: *Use of task oriented dynamic resampling in reduction of signal non-stationarity.* Diagnostyka 4(48)/2008. str.25-30.

[2] Mączak J.: *Utilization of the GPS receivers for data synchronization in distributed signal acquisition systems*. In this issue.

[3] Dybała J., Mączak J., Radkowski S.: *The use of vibroacoustic signal in technical risk analysis*. Wydawnictwo Instytutu Technologii Eksploatacji PIB, Warszawa–Radom, 2006 (in polish)

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MODELING OF CYLINDER PRESSURE IN COMPRESSION IGNITION ENGINE WITH USE OF GENETIC-FUZZY SYSTEM PART 1: ENGINE FUELED BY DIESEL OIL

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Summary

This paper concerns measurement and modeling cylinder pressure in diesel engines. The aim of this paper is to build the empirical-analytical model of engine work. The experiments on engine test bench were conducted. The new genetic-fuzzy system GFSm was proposed. By means of GFSm, the engine model was built. This model allows simulation of cylinder pressure, for each allowable crankshaft speed. The model can be used to evaluate the quality of working cycles of piston engine with accuracy required in practical technical applications.

Keywords: diesel engines, modeling, fuzzy systems, genetic algorithms.

MODELOWANIE PRZEBIEGU CIŚNIENIA W CYLINDRZE SILNIKA O ZAPŁONIE SAMOCZYNNYM PRZY POMOCY ALGORYTMU GENETYCZNO-ROZMYTEGO
CZĘŚĆ 1: SILNIK ZASILANY ON

Streszczenie

Praca dotyczy pomiaru i modelowania przebiegów ciśnień w cylindrze silnika o zapłonie samoczynnym. Celem pracy jest budowa analityczno-empirycznego modelu pracy silnika. Przeprowadzono badania eksperymentalne na hamowni oraz opracowano nowy system genetyczno-rozmyty GFSm. Przy jego użyciu zbudowano model pracy silnika, który pozwala przeprowadzać symulację przebiegów ciśnień w cylindrze silnika, dla wszystkich dopuszczalnych prędkości obrotowych wału korbowego. Może także służyć do oceny jakości cykli pracy tłokowych silników spalinowych z dokładnością wymaganą w praktycznych zastosowaniach technicznych.

Słowa kluczowe: silniki o zapłonie samoczynnym, modelowanie, systemy rozmyte, algorytmy genetyczne.

1. INTRODUCTION

Internal combustion engine is a complex mechatronic device that responds to indications from many transducers. On the basis of them, the control values are generated in order to obtain required parameters of engine work: e.g. amount of fuel per cycle, injection angle or ignition angle. The control system should allow checking and manipulating the fuel supply process and combustion of the fuel during every working cycle of the engine. In order to achieve this, the measurement of cylinder pressure must be performed. Having known the changes of this physical quantity, we can calculate a series of important parameters such as: indicated power, mean indicated pressure, relative air/fuel ratio.

Time-consuming and expensive field as well as bench tests can be partially replaced by appropriate models that describe engine work. Empirical models (based on the first law of thermodynamics [9]) as well as CFD (Computational Fluid Dynamics) models [1] are well known. Expert systems, artificial neural networks, genetic algorithms, fuzzy logic and neuro-fuzzy networks [4] are used relatively rare. Neural networks are most frequently used, for several reasons. They can easily represent nonlinear systems and they have ability to self-train as well. Moreover, they can be applied in various controllers.

Most publications about internal combustion engine modeling with use of artificial intelligence methods concern the control of engine work [6] and exhaust gas emission [2, 3]. Spray penetration in diesel engine, depending on fuel pressure and density, was also modeled, by means of neuro-fuzzy system [8]. The modeling of cylinder pressure curves in diesel engines, by means of genetic-fuzzy systems, was not presented yet. The review of literature shows that existing engine work models, both numerical and analytical, have some limitations which make it difficult to use in practice. As a result, the aim of the paper was formulated following: to develop a new genetic-fuzzy system for engine work modeling.

In order to achieve this, the necessary measurements of cylinder pressure curves were made on the test bench. The engine operated in external speed characteristic and load characteristic regimes, with the crankshaft speeds from the range of 1000 to 2000 rpm. The engine was fueled by diesel oil. The results of experimental research were used to build the model of engine work.

2. TEST STAND

Experimental research was made on the test stand which consists of: diesel engine Perkins AD3.152UR, water brake and control panel. The system for engine research had 4 measurement chains, shown in Fig.1. Pressure was measured by quartz piezoelectric transducers. Measured values were recorded in function of crankshaft angle degrees (°CA). The value of angle was recorded by rotary pulse transducer and system of marking and synchronization of crankshaft position. The engine was fueled by diesel oil. Measurements were done when engine operated in external speed characteristic regime with the crankshaft speeds 1000, 1200, 1400, 1600, 1800 and 2000 rpm. Cylinder pressure values were recorded every 1.4 °CA (exactly 512 measurements for one working cycle of 4-stroke engine). At each measurement point, values of parameters were recorded, for 50 consecutive working cycles. Indicator diagrams, acquired in this way, were averaged.

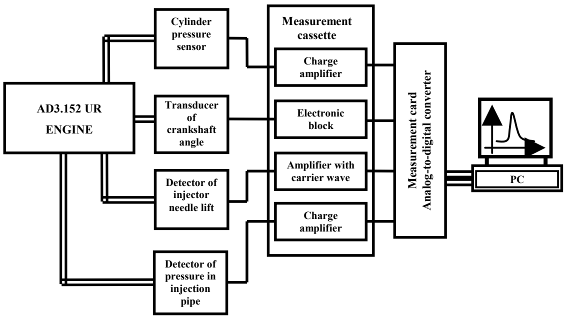

Fig. 1. Block diagram of measurement system for selected work parameters of internal combustion engine [7]

3. RESULTS OF EXPERIMENTAL RESEARCH AND MODELING OF PRESSURE CURVE

Fig. 2 shows acquired indicator diagrams of cylinder pressure, for different rotational speeds and for ranges 180-540 and 340-390 °CA. For the latter range, the differences between pressure curves for different rotational speeds are noticeable. Fast pressure increase starts at 3.5 to 4 MPa, and 353° to 359° CA. When rotational speed of crankshaft increases, maximum cylinder pressure decreases, but the crankshaft angle, at which it appears, increases. Maximum value of slope of the tangent line to the pressure curve decreases with increase of rotational speed [5]. Knowledge of first and second derivative of pressure curve with respect to crankshaft angle allows determining the start of self-ignition, which is about 352 °CA [5].

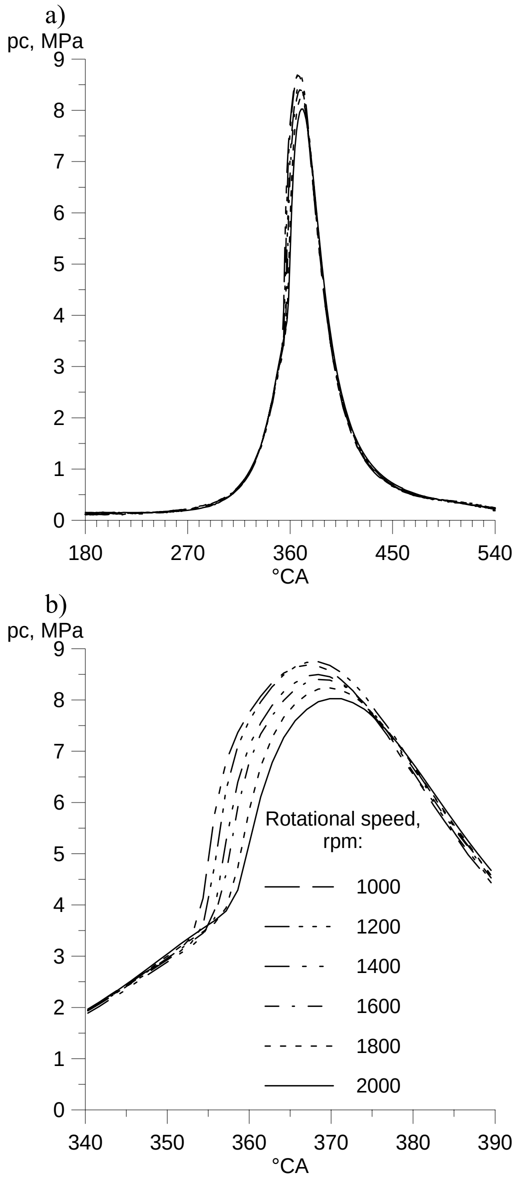

Fig. 2. Indication diagram of cylinder pressure in AD3.152UR diesel engine working at external speed characteristic and fueled by diesel oil, in function of crankshaft angle, for different CA speeds: a) in the range of 180° – 540°, b) in the range of 340° – 390°

The calculations were made by means of GFSm system[5], proposed by the authors, and rated among genetic-fuzzy systems. GFSm creates Mamdani fuzzy model (Fig.3) or Takagi-Sugeno fuzzy model, which describes relations between input and output variables, and which describes given phenomena or process. Genetic algorithm searches for solutions using mechanisms borrowed from nature: natural selection and heredity. Population of possible solutions, represented by so-called individuals or chromosomes, is changed: partially randomly and partially on the basis of "quality" of a given solution. "Good" solutions have bigger chance to reproduce, and "bad" solutions have smaller chance to reproduce. Genetic algorithm consists of several steps: 1) initial population is generated, 2) value of "fitness function" for each individual is calculated, 3) selection of solutions based on value of "fitness function" and randomness, 4) crossover (new chromosome is constructed from two others), 5) mutation (random change of small part of chromosome). Steps 2-5 are repeated until a good enough solution is found. In case of GFSm system, each chromosome represents one fuzzy model. The "fitness function" reflects the accuracy of this model and, optionally, its transparency i.e. the number of "if-then" rules in the knowledge base.

In our experiments, we used measurement data for diesel oil to create fuzzy model (and to test its accuracy) by means of GFSm system. The acquired fuzzy model had two inputs: $x1$ (crankshaft angle), x_2 (time value, proportional to rotational speed of crankshaft) and one output y (cylinder pressure value). The model predicts value of cylinder pressure (y) for all possible crankshaft angle and rotational speed values (x_1, x_2) in AD3.152UR engine fueled by diesel oil.

Relationships between input and output variables are stored in the form of so-called knowledge base, which consists of set of rules and set of membership functions of fuzzy sets used in rules. GFSm system builds the fuzzy model on the basis of training data, complying with settings for number of rules and number of fuzzy sets.

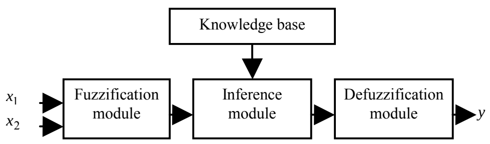

Fig. 3. Mamdani-type fuzzy model with two input variables x_1 and x_2, and one output variable y

The GFSm system created several models which had different number of rules, depending on program settings. Training data, used in experiments, contained pressure curves for speeds 1000 and 1800 rpm of CA. The single model built by GFSm describes pressure curves for all allowable crankshaft speeds. With settings "maximum number of fuzzy sets describing one input = 50" and "highest accuracy models preferred (number of rules is irrelevant)" the GFSm system created a model consisting of 40 rules. The acquired model allows to predict the value of maximum pressure with error not exceeding 5%, and the value of mean indicated pressure with error in the range of 0.3% to 13.5% (depending on rotational speed of CA). Because 13.5% error is too high for practical technical applications, a new model was created by means of GFSm system. The settings were identical like previously, but training data contained the pressure data for the range of 340° to 390° CA. The acquired model, which had 20 rules, was more precise in the above mentioned range, for all crankshaft speeds. However, in order to compute mean indicated pressure we need a model describing pressure in the whole range of 180° to 540° CA, not only in its fragment. For this reason, the next (third) model was created by means of GFSm. The settings were: "maximum number of fuzzy sets describing one input = 50", "models with small number of rules preferred" and "each rule in knowledge base must have condition (premise) regarding x_1 variable" (this variable describes the value of crankshaft angle). The acquired model is more general (only 12 rules) and also describes pressure curves for all crankshaft speeds. Fig. 4 shows "model" curves (computed with use of this model).

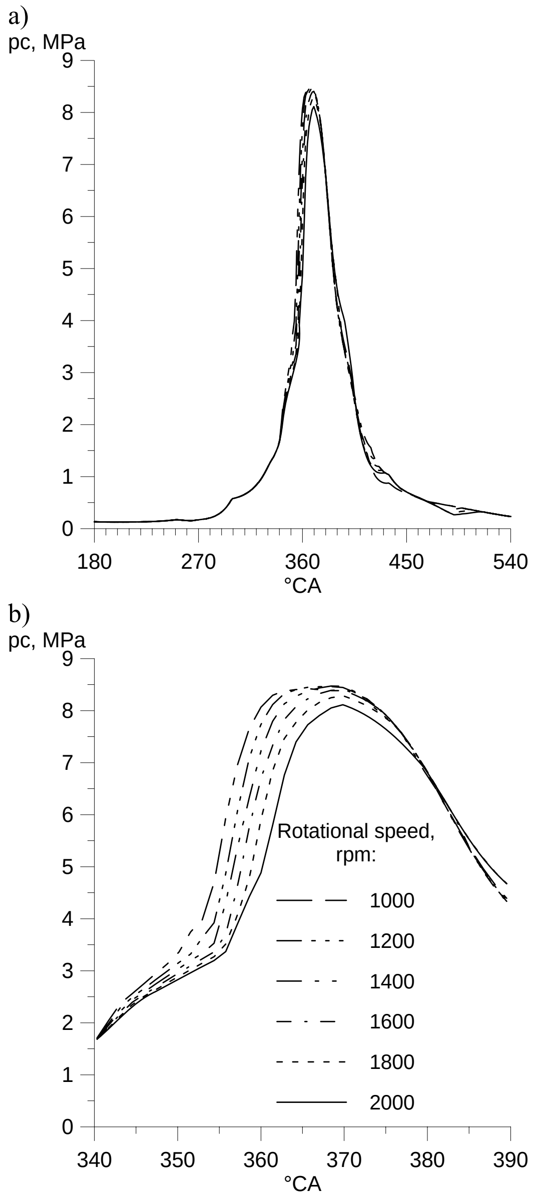

Fig. 4. Relationship between cylinder pressure in diesel engine (working in external speed characteristic regime and fueled by diesel oil) and crankshaft angle, computed by the fuzzy system, for different crankshaft speeds in the range of: a) 180° – 540° CA, b) 340° – 390° CA

The error of prediction of mean indicated pressure by GFSm model is less than 5% (with regard to experimental data) for all measured crankshaft speeds. Error of prediction of maximum value does not exceed 3.3 %. Pressure curve is calculated with high accuracy – root mean square error (RMSE) belongs to range of 0.07 to 0.13 MPa.

4. CONCLUDING REMARKS

During experimental research the cylinder pressure curves in function of crankshaft angle were recorded. The acquired indicator diagrams were analyzed in the range of 180 to 540 °CA, because then we can assume that processes in engine cylinder take place in thermodynamic closed system. The results obtained in this work can be used for regulation, evaluation and control of engine working cycle. They also give opportunity to evaluate the usefulness and relevance of fueling the engine with certain fuel. The results of experimental research acquired on engine test bench were used to build analytical-empirical model of engine work, based on fuzzy sets theory. In order to achieve this, the new genetic-fuzzy system GFSm with advanced information encoding and adjustable number of rules, being a modification of Pittsburgh approach, was designed. By using this system, three models of cylinder pressure curves were built. The best accuracy (indicated work error less than 5% for each examined crankshaft speed) was achieved by Mamdani-type GFSm model consisting of 12 rules. The model allows simulation of cylinder pressure curves with high accuracy, for all allowable crankshaft speeds. There is also a possibility to model selected fragments of pressure curves more precisely (e.g. places where pressure changes are fastest), by means of separate model. Time of computation and saving the results to disk equals 0.04 s. Proposed model can be used to evaluate the quality of working cycles of internal combustion engines, with the accuracy required in practical technical applications.

REFERENCES

[1] Amsden A. A.: *KIVA-3V: A Block-Structured KIVA Program for Engines with Vertical or Canted Valves.* Los Alamos National Laboratory, LA-13313-MS, 1997.
[2] Brzozowski K., Nowakowski J.: *An application of artificial neural network to exhaust emission modelling from diesel engine.* Journal of KONES, Internal Combustion Engines, vol. 12, 1-2, 2005, pp. 51-58.
[3] Jakubek S., Keuth N.: *A local neuro-fuzzy network for high-dimensional models and optimization.* Engineering Applications of Artificial Intelligence, vol. 19, 2006, pp. 705-717.
[4] Kalogirou S. A.: *Artificial intelligence for the modeling and control of combustion processes: a review.* Progress in Energy and Combustion Science, vol. 29, 2003, pp. 515-566.
[5] Kekez M.: *Modeling of work of compression ignition internal combustion engine with use of artificial intelligence methods.* PhD dissertation (in Polish), Kielce, 2008.
[6] Kimmich F., Schwarte A., Isermann R.: *Fault detection for modern Diesel engines using signal- and process model-based methods.* Control Engineering Practice vol. 13, 2005, pp. 189-203.
[7] Kurczyński D.: *Influence of vegetable fuels and its blends with diesel oil on parameters of work of compression ignition engine.* PhD dissertation (in Polish), Kielce, 2007.
[8] Lee S. H., Howlett R. J., Walters S.D., Crua C.: *Fuzzy logic and neuro-fuzzy modelling of diesel spray penetration: A comparative study.* Journal of Intelligent and Fuzzy Systems, vol. 18, no. 1, 2007, pp. 43-56.
[9] Rychter T., Teodorczyk A.: *Theory of piston engines* (in Polish). Wydawnictwa Komunikacji i Łączności, Warszawa, 2006.

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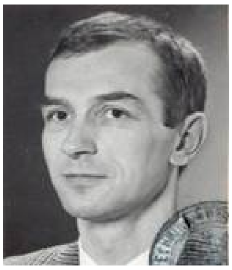

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MODELING OF CYLINDER PRESSURE IN COMPRESSION IGNITION ENGINE WITH USE OF GENETIC-FUZZY SYSTEM PART 2: ENGINE FUELED BY FAME

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Summary

This paper concerns measurement and modeling cylinder pressure in diesel engine. The main aim of this paper is to build the analytical-empirical model of work of engine fueled by different fuels. The experiments on engine test bench were conducted and a model of engine work was created by means of proposed GFSm system. In Part 1 the engine was fueled by diesel oil, and in Part 2 – fueled by methyl esters of rapeseed oil (FAME).

Keywords: diesel engines, modeling, fuzzy systems, genetic algorithms.

MODELOWANIE PRZEBIEGU CIŚNIENIA W CYLINDRZE SILNIKA O ZAPŁONIE SAMOCZYNNYM PRZY POMOCY ALGORYTMU GENETYCZNO-ROZMYTEGO CZĘŚĆ 2: SILNIK ZASILANY PALIWEM FAME

Streszczenie

Praca dotyczy zagadnień związanych z pomiarem i modelowaniem przebiegów ciśnień w cylindrze silnika o zapłonie samoczynnym. Głównym jej celem jest budowa modelu analityczno-eksperymentalnego pracy silnika zasilanego różnymi paliwami. Przeprowadzono badania na hamowni i opracowano model pracy silnika za pomocą proponowanego systemu GFSm. W części pierwszej pracy silnik zasilany był olejem napędowym, a w części drugiej - estrami metylowymi oleju rzepakowego (FAME).

Słowa kluczowe: silniki o zapłonie samoczynnym, modelowanie, systemy rozmyte, algorytmy genetyczne.

1. INTRODUCTION

Ecological fuels like FAME became very popular in recent years [1]. In comparison to diesel oil (see Table 1), FAME has higher density and kinematic viscosity and different elementary composition (FAME contains O). However, the cylinder pressure curves of engine fueled by diesel oil and FAME are similar [4]. Having known this curve, we can calculate a series of important values such as: mean indicated pressure, indicated power, start of ignition. The results of measurements for diesel oil were used to build the model of engine work, by means of the method from the field of artificial intelligence (based on fuzzy sets theory). It was presented in Part 1. Acquired model was next "tuned" for modeling of engine fueled by FAME.

The aim of this work is to build a new analytical-empirical model of diesel engine work fuelled by FAME. In order to achieve this, the measurements of cylinder pressure curves were made on the test bench. The engine operated in external speed characteristic and load characteristic regimes, with the crankshaft speeds from the range of 1000 to 2000 rpm.

Table 1. Comparison of basic properties of diesel oil and FAME [1]

Parameter	Ekodiesel Ultra D (diesel oil)	FAME
cetane number	51,4	51
heating value [MJ/kg]	43,2	36,7
density at 15°C [g/cm^3]	0,8354	0,883
kinematic viscosity [mm^2/s] (~40°C)	2,64	4,47
surface tension [N/m] (20°C)	$3{,}64 \cdot 10^{-2}$	$3{,}58 \cdot 10^{-2}$
ignition temperature [°C]	63	> 130
average elementary composition [%]		
- C	87,2	76,8
- H	12,7	12,1
- O	0	11

Literature analysis presented in Part 1 shows that existing engine work models, both numerical and analytical, have limitations which make it difficult to use them in practice. As a result, the following aims were formulated: 1) experimental research of cylinder pressure, 2) development of a new genetic-fuzzy system for engine work modeling, 3) development of methodology for "tuning" this model for other fuels.

2. TEST STAND

Experimental research was made on the test stand (presented in Part 1) built of diesel engine Perkins AD3.152UR, water brake and control cubicle. The cylinder pressure was measured by piezoelectric transducers. Measured values were recorded in function of crankshaft angle degrees (°CA). The engine was fueled by FAME. Measurements were done when engine operated in external speed characteristic regime with the crankshaft speeds 1000, 1200, 1400, 1600, 1800 and 2000 rpm. Cylinder pressure values were recorded every 1.4 °CA (exactly 512 measurements for one working cycle of 4-stroke engine). At each measurement point, values of parameters were recorded, for 50 consecutive working cycles. Indicator diagrams, acquired in this way, were averaged.

3. RESULTS OF EXPERIMENTAL RESEARCH AND MODELING OF PRESSURE CURVE

Fig. 1 shows acquired indicator diagrams of cylinder pressure, for engine work at different rotational speeds and for ranges 180-540 and 340-390 °CA. For the latter range, the differences between pressure curves for different rotational speeds are noticeable. Fast pressure increase (for FAME fuel) starts at 3.3 to 3.9 MPa, and 351° to 357° CA. When rotational speed increases, maximum cylinder pressure decreases, but the crankshaft angle, at which it appears, increases. Maximum value of slope of the tangent line to the pressure curve decreases with increase of rotational speed from 1400 to 2000 rpm [4]. Knowledge of first and second derivative of pressure curve with respect to crankshaft angle allows determining the start of self-ignition.

The calculations were made by means of GFSm system [4], proposed by the authors, which can be described as a method of generation of fuzzy models by means of genetic algorithm [2, 3]. GFSm creates Mamdani fuzzy model (Fig. 2) or Takagi-Sugeno fuzzy model. The model describes relations between input variables and output variable, which describe given phenomena or process. Model produced by GFSm predicts cylinder pressure for all possible rotational speeds in AD3.152UR engine fueled by diesel oil – this was presented in Part 1 of paper. In order to predict pressure for another fuel (like FAME), we added two scaling functions: one for input scaling and one for output scaling (Fig. 2).

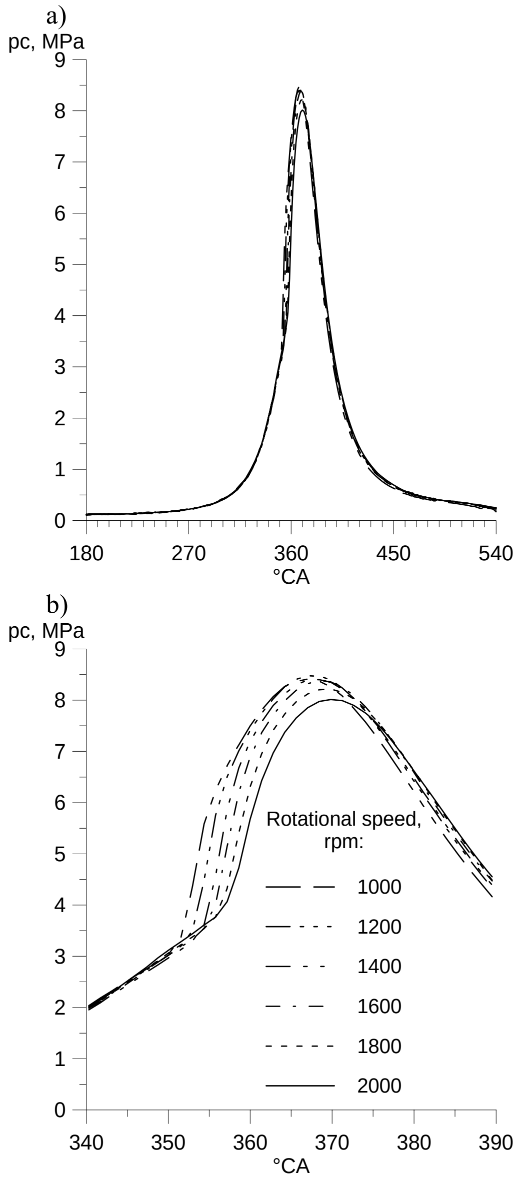


Fig. 1. Indication diagram of cylinder pressure in diesel engine working at external speed characteristic and fueled by FAME, in function of crankshaft angle, for several CA speeds: a) in the range 180° – 540°, b) in the range 340° – 390°

Parameters of these functions are different for each fuel. In order to find these values, we measured cylinder pressure curve for one rotational speed (1200 rpm) when engine was fueled by FAME. Later, we used this curve to obtain parameters of scaling functions.

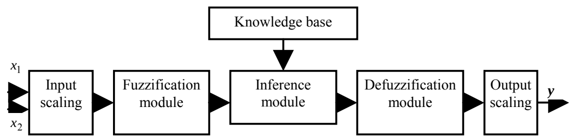


Fig. 2. Mamdani-type fuzzy model (with scaling functions), which has two input variables x_1 and x_2, and one output variable y

The output scaling function $y' = f(y)$ has the form given by the equation:

$$y' = \begin{cases} y \cdot \dfrac{a_2}{a_0} \quad \text{for } y < a_0 \\ (y - a_0) \cdot \dfrac{a_3 - a_2}{a_1 - a_0} + a_2 \quad \text{for } y \geq a_0 \end{cases} \tag{1}$$

where a_0, a_1, a_2, a_3 values are calculated in the way given in Table 2.

Table 2. Parameters of output scaling function

Parameter	Value	
a_0	p_c for α when $\left(\dfrac{d^2 p_c}{d\alpha^2}\right)_{\max}$	for diesel oil
a_2		for a new fuel (e.g. FAME)
a_1	$p_{c\max}$	for diesel oil
a_3		for a new fuel (e.g. FAME)

The idea of calculation of a_0, a_1, a_2, a_3 parameters is shown in Fig. 3. After the calculation of output scaling parameters, we also calculate a_4 parameter value for input scaling, which "moves" pressure curve along with horizontal axis. We select a value of "move" for which mean indicated pressure is calculated with highest accuracy.

The results are quite good: we acquired Takagi-Sugeno model for diesel oil, which has good accuracy (mean indicated pressure error less than 3.9% and maximum pressure error less than 2.1%, for all rotational speeds). Later, we measured cylinder pressure curve for FAME fuel, at 1200 rpm and calculated parameters of input and output scaling functions. The resulting model (Fig. 4) had also good accuracy (mean indicated pressure error less than 4.1% and maximum pressure error less than 2.6%, for all rotational speeds).

4. CONCLUDING REMARKS

During experimental research the cylinder pressure curves in function of crankshaft angle were recorded while engine was fueled with diesel oil and FAME. The results of measurements for diesel oil allowed building of model of engine work by means of GFSm system. The acquired model was later "tuned" for FAME fuel, by using input and output scaling in fuzzy model. The resulting model has good accuracy for both diesel oil and FAME (mean indicated pressure error less than 4.1% and maximum pressure error less than 2.6%).

4. CONCLUDING REMARKS

During experimental research the cylinder pressure curves in function of crankshaft angle were recorded while engine was fueled with diesel oil and FAME. The results of measurements for diesel oil allowed building of model of engine work by means of GFSm system. The acquired model was later "tuned" for FAME fuel, by using input and output scaling in fuzzy model. The resulting model has good accuracy for both diesel oil and FAME (mean indicated pressure error less than 4.1% and maximum pressure error less than 2.6%).

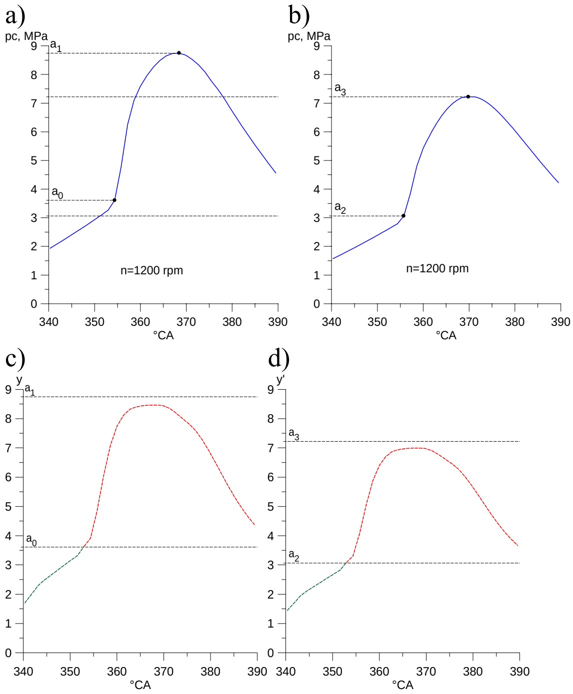


Fig. 3. Idea of calculation of parameters and work of output scaling function: a) experimental cylinder pressure curve p_c when engine operated in external speed characteristic regime at 1200 rpm and was fueled by diesel oil and idea of calculation of a_0 and a_1 values, b) experimental cylinder pressure curve p_c when engine operated in external speed characteristic regime at 1200 rpm and was fueled by a new fuel (e.g. FAME) and idea of calculation of a_2 and a_3 values, c) modeled cylinder pressure curve p_c for any given rotational speed, without output scaling (for diesel oil) d) modeled cylinder pressure curve p_c for any given rotational speed, with output scaling (for new fuel, e.g. FAME)

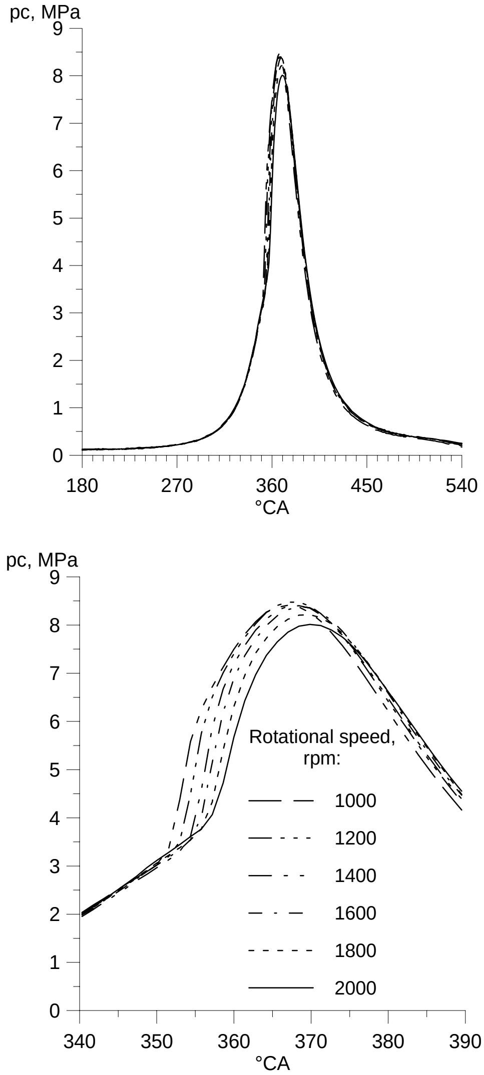
a)
b)


Fig. 4. Relationship between cylinder pressure in diesel engine (working in external speed characteristic regime and fueled by FAME) and crankshaft angle, computed by the fuzzy system, for different crankshaft speeds in the range of: a) 180° – 540° CA, b) 340° – 390° CA

REFERENCES

[1] D. Kurczyński: *Influence of vegetable fuels and its blends with diesel oil on parameters of work of compression ignition engine*. Doctoral dissertation (in Polish), Kielce, 2007.

[2] Cordon O., Herrera F., Hoffman F., Magdalena L.: Genetic Fuzzy Systems: Evolutionary Tuni*ng and Learning of Fuzzy Knowledge Bases (Advances in Fuzzy Systems – Applications and Theory*, Vol. 19), World Scientific, Singapore 2001.

[3] Cordon O., Gomide F., Herrera F., Hoffman F., Magdalena L.: *Ten years of genetic fuzzy systems: current framework and new trends.* Fuzzy Sets and Systems, vol.141, 2004, str. 5-31.

[4] M. Kekez: *Modelling of work of compression ignition internal combustion engine with use of artificial intelligence methods.* Doctoral dissertation (in Polish), Kielce, 2008.

Information on the authors is available on page 12.

APPLICATION OF HARDWARE-IN-THE-LOOP FOR VIRTUAL POWER PLANT

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Summary

The following paper presents application of the Hardware In The Loop to the Virtual Power Plant laboratory(VPP), for real time modeling of power generation unit elements. The Virtual Power Plant consists of a group of computers, which model a real power plant unit with the performance close to the real time. Application of HIL enables the laboratory to generate output signals which can be used for testing of monitoring systems or by using exciters for testing of vibration sensors i.e.: accelerometers. The paper presents implementation process of chosen module of VPP on dedicated system for real-time simulation based on DS 1103 board. Next an experimental results are discussed.

Keywords: simulation, hardware-in-the-loop, power plant, real time simulations.

ZASTOSOWANIE TECHNOLOGII HARDWARE-IN-THE-LOOP
W PROJEKCIE WIRTUALNEJ ELEKTROWNI

Streszczenie

W pracy przedstawione zostało zastosowanie technologii Hardware-In-the-Loop (HIL) projekcie Wirtualnej Elektrowni (VPP) do modelowania działania elementów elektrowni w czasie rzeczywistym. Wirtualna Elektrownia składa się z grupy komputerów które modelują działanie rzeczywistej elektrowni z wydajnością bliską czasowi rzeczywistemu. Zastosowanie technologii HIL pozwoli na generowanie w laboratorium sygnałów wyjściowych z VPP które mogą zostać wykorzystane np.: do testowania układów monitorowania bądź też, po zastosowaniu wzbudników, do testowania czujników drgań np.: akcelerometrów. Artykuł przedstawia proces implementacji wybranego modułu VPP na dedykowany układ do przeprowadzania symulacji z rygorem czasu rzeczywistego oparty na karcie DS 1103. Następnie omówione zostały uzyskane wyniki badań eksperymentalnych.

Słowa kluczowe: symulacja, Hardware-In-the-Loop, elektrownia, symulacje czasu rzeczywistego.

1. VIRTUAL POWER PLANT AND ITS ARCHITECTURE

Advances in condition monitoring, and – in the broader view – in mechanical engineering lead to the development of more and more efficient tools, which help us to better understand behavior of mechanical systems [1, 2]. Then, we can benefit from this knowledge by optimization of operation and reduction of maintenance costs, to name just a few [3]. Recently, the Virtual Power Plant laboratory (VPP) was developed within the research project DIADYN No PBZ-KBN-105/T10/2003, funded by the Polish Ministry of Science (MNiI).

VPP is the innovative work environment for technical state assessment of dynamic objects, applied to elements of the power plant unit. Such an environment should work with performance close to the real time (when necessary and technically possible). Introduction of such an environment facilitates development of models and next – the process of diagnostics. Such an environment has following benefits:

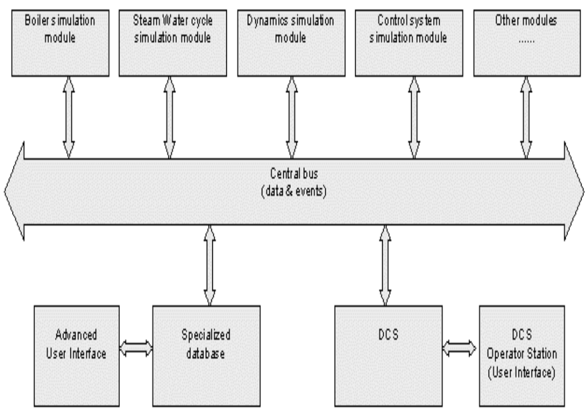

Fig. 1. The structure of the Virtual Power Plant

- flexible structure, enabling multiple configurations;
- possibility to include models in various formats (though Matlab/Simulink was chosen as the default);

- reply of malfunctions to analyze real cases from the plant;
- modeling of faulty behavior of a plant to improve the knowledge about processes in the real plant
- simulation of various modifications of the unit and effects it will have, for example in the dynamic state;
- huge resource for search of diagnostic rules, thus it will bring advances in FDI techniques;
- development of risk management algorithms;
- verification of diagnostic systems in operation on a plant.

The Virtual Power Plant [4] is the group of computers, connected by a fast computer network (see Fig. 1). Each computer plays a role of a VPP component. The largest part of the system is database, which consists of two cooperating subsystems. The first one is the database as in the typical DCS system. This allows to store the data in the same way they are stored in a real system. The second database subsystem is a specialized, fast database which is used to store data generated by modules of the VPP. This subsystem is proprietary, efficient database engine, which can also store dynamic data (e.g. vibration waveforms). The Central Bus is another computer, which is the main data exchange hub in the VPP. It provides common interface for all the modules, which allows to develop each module independent from the others. The remaining computers are used to run models of the components of the power plant. Fig. 2 presents the structure of the VPP model. The mathematical model used in the Virtual Power Plant is a compromise between the requirements of the accuracy to the real object and available computing and data processing power [5]. On the other hand, its structure allows for easy exchange of several components, depending on requirements of the application.

As presented on the Fig. 2, modeling of the dynamic state is weakly coupled with the rest of the model. There are no feedbacks and there is only one signal determining the vibration, i.e. rotational speed. Since on the list of applications presented above, the important one is verification of vibration monitoring and diagnostic systems (VMDS) in operation on a plant, there was a need to generate real-time vibration signals, which could be converted to analogue signals and fed into a vibration monitoring system. With proposed approach, it would be possible to test VMDS in various conditions, also impossible to simulate on a real power generation unit. Since the model was developed as the variable step Matlab/Simulink model, it did not generate such signals and other real time simulation techniques were necessary.

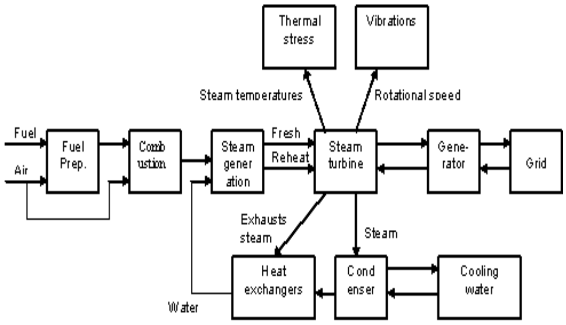

Fig. 2. The structure of the model

2. REAL TIME SIMULATIONS

Real-time system can be divided into two main categories:

- Hard real-time system - where timing correctness is critical for the system and can't be sacrificed for other benefits.
- Soft real-time systems – where time correctness is important, but not critical and can be sacrificed for other goals (for example model accuracy).

Typical real-time system consists of two parts: controller and controlled system. Depending of structure of these two parts real-time simulations can be divided into :

- Rapid prototyping of control systems;
- Hardware-In-The-Loop.

Nowadays there are two major systems used for real-time simulations:

- Systems based on FPGA systems – used mostly for fast prototyping;
- Systems based on DSP cards – used equally for fast prototyping and HIL simulations.

The system presented in the paper is based on the second solution for real-time simulations. dSPACE is one of the providers of real-time systems based on DSP's. They provide vide variety of systems designed for fast prototyping and HIL simulations. Systems offered by dSPACE varies from simple single board (DS 11xx series) to multi-board systems (dSPACE Simulator). Single board system consists of single card with processor, memory and additional input/outputs (ex.: D/A, A/D converters, DIO's, Encoder inputs). Multi-boards system consists of dedicated processor board(s – up to 20) and dedicated I/O cards connected via PHS bus. dSPACE also provides a software as a part of its system. It can be divide into 3 groups:

- Card's drivers for C/C++;
- Implementation software allows for connecting created model to dSPACE I/O boards;
- Test & Experiment Software'.

The system used during presented experiments is built using dSPACE real-time environment, based on the dSPACE's DS1103 board .

3. SYSTEM IMPLEMENTATION

Careful analysis shows, that first part of the VPP, which should be tested on real-time system is Vibration Module, as explained in the first chapter. Vibration signals, generated in real time, can be easily sent as outputs via digital outputs or D/A converters and used for example as an inputs for monitoring system or as control signal of exciter used for testing i.e.: accelerometers.

The first step in implementing Vibration Module of VPP on the real-time system was re-writing of s-function written as m-file into C-code ones. Currently, dSPACE's software doesn't support direct translation of m-file into real-time C-code that can be implemented on dedicated board. Other requirements of dSPACE's real-time system is that the simulations have to be performed with fix step. It can be obtained in two ways: translating s-function from variable step into fix step type, or by solving continuous states with chosen integration method (i.e.: Euler, Heun, Bogacki-Saphine, Runge-Knutt, Domand-Prince).

Because in C-code all variables (types, size of matrixes etc.) should be declared and defined before compilation, single 5-mode model of rotor-support was chosen for implementation. During translating m-file into C-code, algorithms were not only rewritten in C-code, but also optimized for faster calculations. Moreover, standard C-libraries does not consist matrix class variables nor matrix operation definition (addition, subtraction, multiplication and division of matrices). This is why dedicated libraries for matrix operations have been created.

After creating VPP's Vibration Module as C-code's s-function Matlab/Simulink model was built and simulated. Simulations results obtained from m-file and C-code models were compared and proved that translation process was successful (fig. 3).

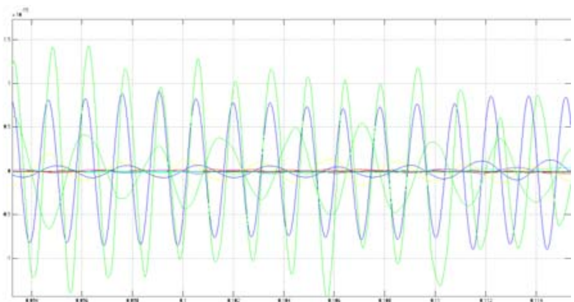

Fig. 3. Differences between vibration signals obtained from the vibration module of VPP written as M-function and in C-code

Next, created model were compiled with RTI (Real Time Interface) for the real-time system. The RTI runs through all steps necessary to prepare the application for the real-time test. The last step loads the application into the dSPACE processor. The RTW (Real Time Workshop) is used for converting Simulink's models into real-time C-code and automatically builds programs, that can be run from the real-time system environment. ControlDesk software – experiment software for managing and instrumenting experiments – is the integral part of dSPACE's real-time system,. It allows for designing experiment interfaces by easy drag & drop method. The interface designed for Vibration Module is presented in the figure 4.

The interface allows for real-time observation of simulated vibrations and changing parameters of simulations. Compiled model consists of four different types of rotor-support models (sliding bearing, nonlinear heuristic, short bearing and long bearing) and two parameters (Gravity and Damping) that can be changed using radio buttons during experiments without the need of simulation interrupting. Several experiments were performed for all four models with and without influences of gravity and damping.

First tests taken on real-time system were carried out at step size set to 0.01s , and shows that at that step size created models are unstable. Reduction of the step size allowed to achieve stable results at value 0.001 s, but good results, similar to ones obtained during simulations with variable step, were achieved at step size of 0.0002 s.

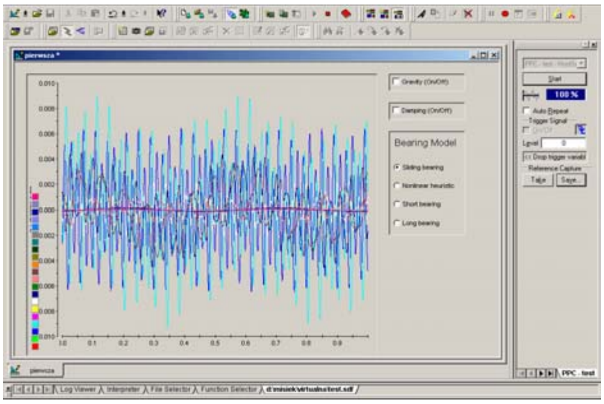

Fig. 4. Experiment interface

At this step size, the equipment used during experiments (DS 1103 board) allows only for simplest model (sliding bearing) simulation. Obtained results (fig. 5) were very similar to ones obtained from Matlab/Simulink with m-file variable step model (fig. 6), (amplitudes, phases of vibrations). Unfortunately, higher frequencies of simulated signals were cut off, due to insufficient frequency.

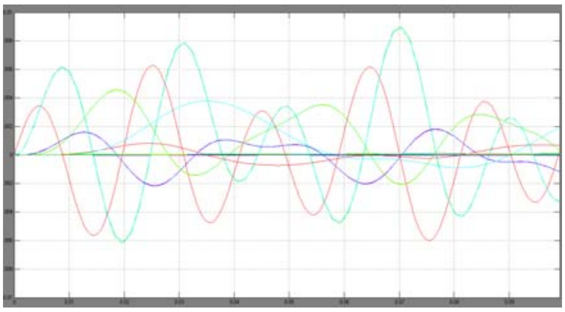

Fig. 5. Results obtained during HIL simulations

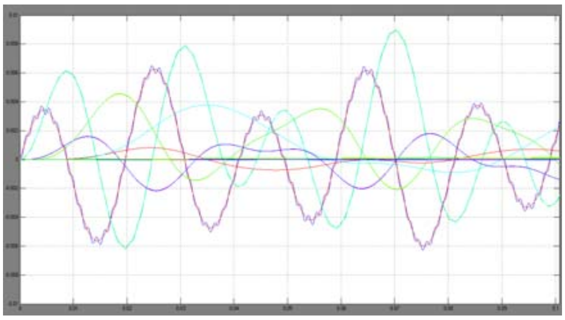

Fig. 6. Results obtained during Simulink's simulations

4. CONCLUSIONS

Application of Hardware-In-the-Loop technique for simulation of Vibration Module of the Virtual Power Plant showed promising results. It can lead to much broader application of VPP. Initial experiments proved that optimized code can lead to significant performance improvement (step size from 0.01 up to 0.0002 s). Unfortunately hardware restriction didn't allow to achieve results, which fully represent vibrations in given rotor-support model. Theoretical analysis and initial experiments proved that after equipment upgrade (change of real-time simulation system to multi-board system based on DS 1006 processor board) new hardware should provide sufficient computational power for real-time simulations of complex model.

REFERENCES

1. Flynn D. ed.: *Thermal Power Plant Simulation and Control*, Institution of Electrical Engineers, London, 2003.
2. Colonna P., van Putten H.: *Dynamic modeling of steam power cycles. Part I - Modeling paradigm and validation*. Applied Thermal Engineering vol. 27 2-3/2007, p. 467-480.
3. Gertler J.: *Fault detection and diagnosis in engineering systems*, Marcel Dekker, New York, 1998.
4. Barszcz T., Czop P.: *Methodologies and applications of Virtual Power Plant. New environment for power plant elements modelling,* ITE Radom, 2007
5. Hanselman H.: *Hardware-in-the-loop simulation as a standard approach for development, customization and production test*, SAE International Congress, Detroit, March 1-5, 1993

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TELEMATIC SYSTEM FOR MONITORING THE OPERATION OF MACHINES AND VEHICLES IN A TRANSPORT-EQUIPMENT ENTERPRISE

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Summary

The performance and the effects of applying the telematic system to the building transport-equipment enterprise were analysed in that paper. The KOMTRAX system used for this purpose allows the operation of building machinery to be continually monitored. The system provides great advantages, including the prompt completion of work tasks (about 30-40%), the reduction of vehicle maintenance costs (about 20-30%), the decrease in unauthorised mileages (about 100%) and the reduction of fuel consumption (about 20%).

Keywords: technical diagnostics, telematics, GPS system.

TELEMATYCZNY SYSTEM MONITOROWANIA PRACY MASZYN I POJAZDÓW W PRZEDSIĘBIORSTWIE SPRZĘTOWO-TRANSPORTOWYM

Streszczenie

W artykule przeanalizowano funkcjonowanie i efekty zastosowania systemu telematycznego w przedsiębiorstwie transportowo-sprzętowym zaplecza budowlanego. Zastosowany tam system KOMTRAX pozwala na bieżące monitorowanie pracy maszyn budowlanych. System zapewnia duże korzyści m.in. zwiększenie terminowości wykonywania zadań (o około 30-40%), zmniejszenie kosztów utrzymania pojazdów(o około 20-30%), redukcję nieautoryzowanych przebiegów (o około 100%) oraz zmniejszenie zużycia paliwa (o około 20%).

Słowa kluczowe: diagnostyka techniczna, telematyka, system GPS.

1. INTRODUCTION

The service life of transport equipment in contemporary enterprises is mainly determined by the cost account and the moral wear. Respecting the fast progress in this field and easy access to new equipment, the idea of general overhauls prolonging its life has been abandoned. The elongation of the failure-free period of operation for this equipment could be also promoted by computer-aided modern troubleshooting systems. The technical diagnostics system for technological objects has been anticipated dichotomously as supported by models and as a symptom diagnosis [1]. Especially the last one in reference to vehicles has been done more and more often using the telematic systems [2]. Under the notion of telematics we understand solutions to telecommunication, information, computer science and automatic control adapted to requirements of serviced devices – following from their tasks, infrastructure, organisation, processes of maintenance and management – and integrated with these systems [3]. Nowadays, a great interest in these systems has been observed (e.g. in Poland in 2007 the sales volume of them increased by 400% versus 2006, source: TVP News of 22.03.2008). Telematics in transportation makes it possible to influence the course of process mobility by increasing the transport capacity, improving the safety, reducing the negative effects on the environment and planning the transportation [4]. It results from long-term research carried out in the USA, Canada (and now also in Poland) that the application of telematic systems contributes the reduction of expenditures on the transport infrastructure even by 30–35% maintaining the same functionality of the system [5]. The essential element of such the system is measurement and automatic data acquisition with the use of sensors, detectors and other monitoring devices. They allow simultaneously the working processes of machines to be continuously monitored and thus immediately meet any abnormality in this scope. It brings the rational savings, rationalises the process of transportation, and facilitates operations carried out both by persons using the equipment furnished with telematic technique and also enterprises making use of this equipment [5]. The recognition of the practice in this scope with reference to machinery and other back-up facilities of a large enterprise implementing the building projects all over the state constitute the main research problem of the present paper.

2. DESCRIPTION OF A SYSTEM

The enterprise being tested applied the satellite system **Komtrax**, manufactured by Komatsu Poland Ltd. The Company Komatsu Ltd was established in Japan in 1921. Now it is a world-wide leader among producers of machinery for the building and the mining industry; it has their branches in many countries, including Poland. Komatsu is an owner of 44 factories all over the world, including 8 factories in Europe. Twenty of them produce engines, hydraulic systems, power transmission systems, whereas machines, mainly for the building industry are assembled in twenty four factories (some years ago Huta Stalowa Wola successfully manufactured bulldozers under Komatsu licence).

Komatsu Company is well-known for the implementation of state of the art technological innovations, including the satellite monitoring systems for machines such as Komtrax. According to Producer's data this system to its advanced design provides an exceptional solution on a world-wide scale. At present all over the world, there are operated 75 thousand machines equipped with a Komtrax system, and every month the next 2 thousand are introduced into operation [6]. This system is suitable mainly for machine of small or medium size and especially is useful if a machine is operated in outlaying places and hard to reach for servicing.

Nowadays the wireless communication is omnipresent. Therefore, small wonder that it is present in building machinery where helps in monitoring the process parameters. Thanks to computers it is possible to trace all the data linked with the operation of machine systems not only by operators but also supervising personnel, mechanics and owners. The system collects important operational and system data. It also provides the communication with the global positioning system (GPS), which traces its position. By GPS it transmits all the data obtained to the database management centre. Data from this centre is transmitted by the Internet to the Kamatsu's global server where is collected and analysed. Then data is sent to the local server of Komatsu distributor or "the local Internet system", where is processed according to User's requirements and formatted for displaying.

The Komtrax system due to the integrated GPS transmitter makes it possible to use a number of options, for instance determines the working areas for machines. In case of leaving this area, the Komtrax immediately initiates alarm, which is some kind of protection against theft or unauthorised use (for this reason it is possible to get some assurance discount for these machines). Since the dispatcher is able not only to cut off remotely the engine but also block its restarting. The route covered by the machine is displayed on a map or marked out with geographic coordinates (longitude and latitude). The location function makes it possible to optimise the fuel supply, planning for the maintenance service and also taking the counteraction against theft or unauthorised use.

However, the designers of the Komtrax system are mainly motivated to reduce the costs of machine operations [7]. Thus, the machine equipped with the Komtrax system transmits relevant data to the Komatsu server at regular time intervals. It enables to create an accurate work protocol at a freely specified time interval. This peculiar "CV" makes it possible for the machine to determine the load it was subjected to and detect possible faults or else optimise the equipment capacity factor.

Komtrax allows the operation-hours counter to be daily read-off. Monthly reports for this parameter could be also presented in the form of a diagram. Komtrax makes the same information available that are displayed in machines on the computer screen (depending on qualifications of the machine operator). The transmission of information between machines and the system takes place in a continuous mode by Internet. The system could be also used by service workers for remote troubleshooting. A mechanic is also able by analysing the data recorded by the Komtrax system to foresee in advance the appearance of a fault and warn the user of it. It enables to reduce the losses suffered from shutdown of machines and increase the effectiveness of their use. So, owing to the Komtrax system it is possible to determine precisely the machine capacity factor on a given building site. In the end, it is possible for the equipment to be selected optimally for execution of a given task. It also prevents the machines from overloading which significantly reduces their wear. The operation sheet provides information on the way, the time and the effectiveness of machine operation, and also the operator's efficiency. This information is presented in the form of legible bar graphs illustrating: service time of an engine, worktime – operational activities of a machine and working accessories. Due to that it is easier to eliminate the cases of unauthorised use of machines. Komtrax allows the following process parameters to be obtained: fuel level and temperature of liquid coolant. The system transmits systematically warnings about all departures from the standard of machine operation, notifies properly in advance of the necessary routine maintenance.

Reports on the machine operation could be compiled in a daily, monthly and annular cycle. A daily report describes the location of a machine, its process parameters and the technical condition of the machine from the day preceding the read-out. A fuel level diagram shows the state of filling a tank at the end of the previous day. This diagram considerably facilitates planning the fuel supply for a building site.

The technical condition of machines, the information on the value of pressure in the hydraulic system and the loads they are subjected to are helpful for monitoring. This information performs the function of the warning signals with regard to the potential overloading or underloading the machine.

Due to this fact, one can easily check whether the machines are properly matched to the task being implemented. The monthly report in the graphic form presents the total worktime, the real time and the worktime during the idle running.

The possibility of undertaking the action aimed to limit the shutdown of machines, which is connected with excessive fuel consumption. Providing the continuous documentation of its technical condition and scrupulous keeping the dates of periodical surveys prevent from appearing the serious defects, causing loses following from shutdowns. It contributes to increasing the useful life of machines and simultaneously reduces the costs connected with their routine maintenance. An undoubted advantage of this system is free of charge operation for the period of five years from the first activation [7].

3. SAMPLE SYSTEM CARDS

Examples of Komtrax system cards are illustrated in Figs. 1-6.

Fig. 1. Card „location of machine operation"

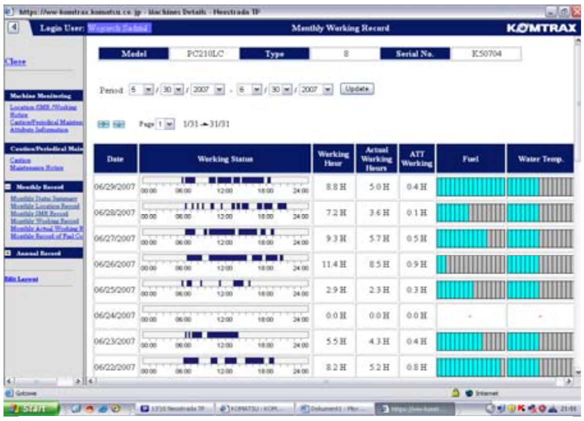

Fig. 2. Card „daily progress report"

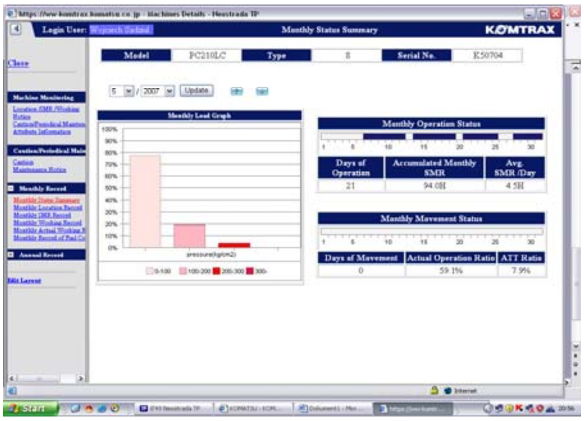

Fig. 3. Card „monthly progress report"

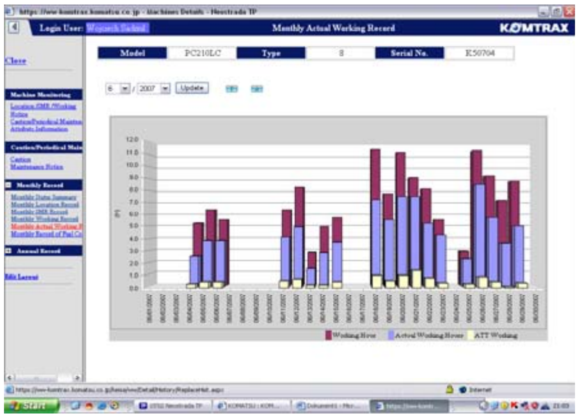

Fig. 4. Card „worktime of additional equipment"

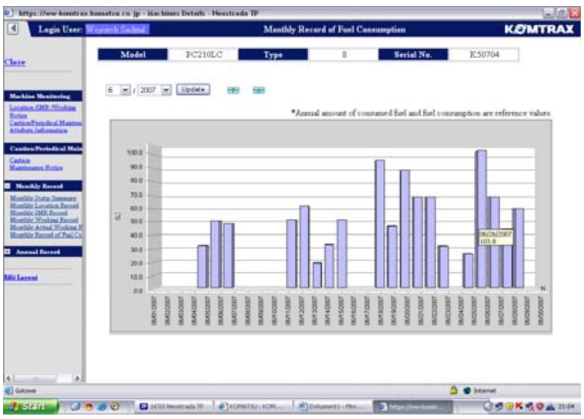

Fig. 5. Card „annual progress report"

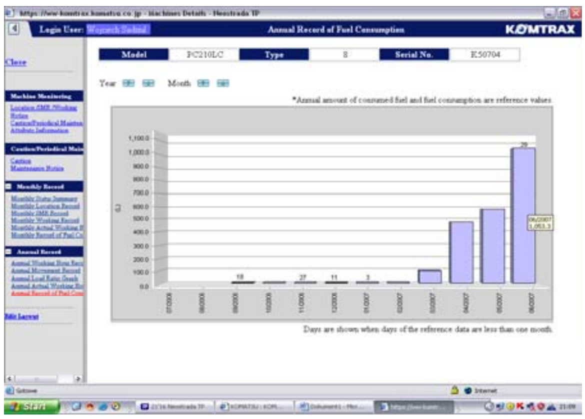

Fig. 6. Card „fuel consumption per month"

It results from analysis of applying the satellite Komtrax system to a given company, that these advantages could be divided into two groups: notable and immeasurable.

Notable advantages are more eloquent because they can be described with numbers. On the basis of own research and the experience of other users in the country it is possible to form an opinion that the system applied provides among others the prompt completion of work tasks (about 40-50%), the reduction of vehicle maintenance costs (about 20-30%), the decrease in unauthorised mileages (about 100%) and the reduction of fuel consumption (about 20%). Accurate percentage values are difficult to evaluate.

Immeasurable advantages result from the operational entirety of this system. Describing comprehensively the Komtrax system one can say that the Komtrax system provides an invaluable tool for managing and maintaining the traffic of building machines. The detailed recording of the machine route, speed, fuel level, operation of different auxiliary devices allows all the events connected with the operational use of this machine or a device to be precisely reproduced. It is a frequent problem of building enterprises that they have no control over operators, their style of work and conscientiousness. The system being offered shall put a stop to robbing the employer by dishonest operators (theft of fuel is limited). Exceptional accuracy of reports ensures the clear-cut settlement of contentious issues in this scope.

4. CONCLUSION

In Poland the telematic supervising of the building machines has not been sufficiently developed yet.

It is mostly affected by the following factors:

- obsolete stock of machines
- relatively high cost of devices,
- lack of experience in telematics,
- opportunism of managing personnel,
- high costs of mobile communications.

However, the situation starts to make a marked improvement due to undoubted advantages resulted from using this type of solution. If you want improve the output of machines, measure the punctuality and worktime you should use the satellite system. This would contribute to more efficient managing the work of operators which improve the output giving the savings in operation and cut down the "shady" routes. The system also ensures the interrupted contact of the dispatcher with operators in case of unexpected orders, failures or dispositions. More than anything else is to avoid shutdowns and guarantee the continuous contact with a customer, who wants to know at what stage is the implementation of his order.

Thus, the immeasurable advantages are equally important and maybe even more essential than calculated with a view of money.

REFERENCES

[1] Żółtowski B.: *The basics of troubleshooting for machines.* Wyd. ATR Bydgoszcz, 1996.
[2] SAT-DOG FLOTA: *Telematic system for remote supervising and protection of vehicles assisting the fleet management*, http://dest.pl/
[3] Wydro K. B.: *Telematics – meaning and definition of a term.* Telekomunikacja i techniki informacyjne, nr 1-2, I. Łączn. Warszawa 2005.
[4] Piecha J.: *Data recording and processing in telematic transport systems*. Praca zbiorowa. Wyd. Politechniki Śląskiej, Gliwice 2003.
[5] Nowacki G. I. i inni: *Analysis of Hitachi system*.. http://www.its.home.pl/.
[6] Ziemkiewicz M., Barawski J.: *Interview with Mr Takahide Oshitani, the President of The Board of Komatsu Poland Ltd.* http://www.komatsupoland.pl/
[7] *Satellite Komtrax system*. http://posbud.com.pl/.

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USE OF TASK–ORIENTED DYNAMIC RESAMPLING IN REDUCTION OF SIGNAL NON–STATIONARITY

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Summary

The article presents method of reducing the non–stationarity of a signal which relies on task–oriented dynamic signal resampling. The characteristic feature of this method is lack of preliminary assumptions regarding the phenomenon causing the eliminated non–stationarity. Thanks to this the method enables not only elimination of the non–stationarity caused by linear change of the frequency of signal but also other complex and non–linear forms of non–stationarity. The paper also includes the examples of application of the described method.

Keywords: non–stationarity, task–oriented dynamic resampling, instantaneous frequency.

WYKORZYSTANIE ZORIENTOWANEGO ZADANIOWO DYNAMICZNEGO PRZEPRÓBKOWANIA W REDUKCJI NIESTACJONARNOŚCI SYGNAŁU

Streszczenie

W artykule przedstawiono metodę redukcji niestacjonarności sygnału bazującą na zorientowanym zadaniowo dynamicznym przepróbkowaniu sygnału. Charakterystyczną cechą metody jest brak wstępnych założeń co do zjawiska wywołującego eliminowaną niestacjonarność. Dzięki temu metoda pozwala na usunięcie nie tylko niestacjonarności wywołanej liniową zmianą częstotliwości sygnału ale także i innych, złożonych i nieliniowych form niestacjonarności. W pracy zamieszczono także przykłady zastosowania opisanej metody.

Słowa kluczowe: niestacjonarność, zorientowane zadaniowo dynamiczne przepróbkowanie, chwilowa częstotliwość.

1. INTRODUCTION

In diagnostic practice we often come across the need for analyzing non–stationary signals. There can be various reasons of non–stationarity of signal. Non–stationarity can result from a special mode of operation of an object, including such elements as start–up and coasting of a machine. From diagnostic point of view the observation of the non–stationary mode of operation, which occurs during start–up and coasting, can provide a lot of diagnostically–interesting information since it enables the analysis of the behavior of object during operation at variable rotational speed, which leads to additional excitation of the signal as it encounters resonance of the structure. Moreover, during start–up there usually occur loads which enable observation of flexibility and play in bearings and clutches [2]. Non–stationarity can also be the outcome of unstable operation of the object, resulting from variability of operating conditions and demonstrating itself as fluctuation of the basic revolutions frequency of a machine. Non–stationarity of analyzed signals can be also the consequence of the adopted method of registration of these signals. Such a situation occurs when we deal with use of a stationary system for acquisition of sound signals generated by objects which are in motion. The signal registered in the conditions of relative motion of the transmitter (source of signal) and the receiver (microphone) is burdened with disturbance being the outcome of Doppler's effect [3].

Analysis of non–stationary signals generally requires special method of signal preprocessing [5], since the frequency of signal structure which changes in time, effectively hinders effective use of classical methods of signal analysis. It is important, however, that the methods applied remove only the undesirable non–stationarity of a signal while not causing at the same time the unintended, by us, elimination of other, diagnostically–useful properties of the signal. Thus a need emerges for having as useful as possible, but at the same time precisely selective, methods of reducing signal non–stationarity.

The paper will present the method of reducing signal non–stationarity which relies on task–oriented, dynamic resampling of signals. We will also present the examples of use of this method.

2. TASK–ORIENTED DYNAMIC SIGNAL RESAMPLING

The basis of a dynamic (variable in time) signal resampling is the use of variable time resolution in such a way that each subsequent (variable) period contains a permanent number of time samples [3]:

$$n = \frac{T_1}{dt_1} = \ldots = \frac{T_N}{dt_N} = \text{const} = \frac{T_W}{dt} \qquad (1)$$

which is equivalent to the following relationship:

$$n = \frac{1}{f_1 \cdot dt_1} = \ldots = \frac{1}{f_N \cdot dt_N} = \text{const} = \frac{1}{f_w \cdot dt} \qquad (2)$$

where:

- f_1, ..., f_N – represents the subsequent, instantaneous frequencies of the signal,
- dt_1, ..., dt_N – represents the subsequent, instantaneous sampling rate of the signal,
- f_w – denotes the "resultant" frequency of the modified signal,
- dt – denotes the sampling rate of the original signal.

Due to the fact that the instantaneous sampling rate of the signal can be calculated from the following relationship:

$$dt_{chw}(i) = \frac{f_w \cdot dt}{f_{chw}(i)} \qquad (3)$$

where: $dt_{chw}(i)$, $f_{chw}(i)$ represent respectively the instantaneous sampling rate and the instantaneous frequency of the signal.

While having the vector of the subsequent, determined temporal resolutions $dt_{chw} = [dt_{chw}(1), dt_{chw}(2), \ldots, dt_{chw}(m)]$, while referring to the cumulative sum we can define the modified time vector t_{chw} by means of the following relationship:

$$t_{chw}(i) = dt_{chw}(1) + dt_{chw}(2) + \ldots + dt_{chw}(i) \qquad (4)$$

The last step is to define the value of the signal at the moments in time defined by the values of the modified time vector t_{chw}. We do this through interpolation of the value of the original signal by means of polynomial splines. In the presented solution we used the cubic splines. This way we receive the modified signal whose sampling rate is identical to the sampling rate of the original signal.

Correct performance of dynamic resampling of a signal requires one to know the course of the instantaneous frequency of the signal, which defines the removed non–stationarity of the signal. Depending on the specific task there exist various possibilities of defining the required course of the instantaneous frequency. The course of frequency can be learned while relying on the knowledge of the phenomenon which causes the undesirable non–stationarity of the signal, which enables definition of the function defining the variability of the instantaneous signal frequency. The course of the instantaneous frequency can be also defined based on measuring a defined value which describes the eliminated non–stationarity of the signal (e.g. tachometric signal). There also exist methods which define the course of the instantaneous frequency based on the information contained in the signal subjected to resampling. An example of this method can be the algorithm, used by Bruel & Kjaer, which relies on the implementation of Bayes' statistical method [6, 7]. Another example of such an approach can be the method relying on the Hilbert transform. The course of the instantaneous frequency of a signal is then determined by means of the following relationship [1]:

$$f_{chw}(t) = \frac{1}{2 \cdot \pi} \cdot \frac{d\varphi(t)}{dt} \qquad (5)$$

where:

- $\varphi(t)$ – denotes an argument of the analytic signal:

$$x_a(t) = x(t) + j \cdot H\left[x(t)\right] = \left|x_a(t)\right| \cdot e^{j \cdot \varphi(t)} \qquad (6)$$

where H[·] denotes the Hilbert transform.

3. NUMERICAL EXPERIMENT – CHIRP TYPE SIGNAL

An example of a non–stationary signal generated during a start–up of machine can be a swept–frequency signal (chirp). In this experiment we used signals with two types of chirps: linear and square. Then, while relying on the presented method of dynamic resampling, we performed reduction of non–stationarity of these signals. In the case of linear chirp, the course of the instantaneous frequency of the signal was defined by a linear function while in the case of square chirp, the course of the instantaneous frequency of the signal was defined by a method relying on Hilbert transform.

The results of processing of the linear chirp are presented in figures 1, 2 and 3 (Fig. 1 – the course of instantaneous frequency as well as the original and modified time; Fig. 2 – the amplitude spectra; Fig. 3 – the Wigner–Ville time–frequency distributions, respectively for the original and the modified, dynamically resampled signal). The results of processing of square chirp are presented in figures 4, 5 and 6 (Fig. 4 – the course of instantaneous frequency as well as the original and

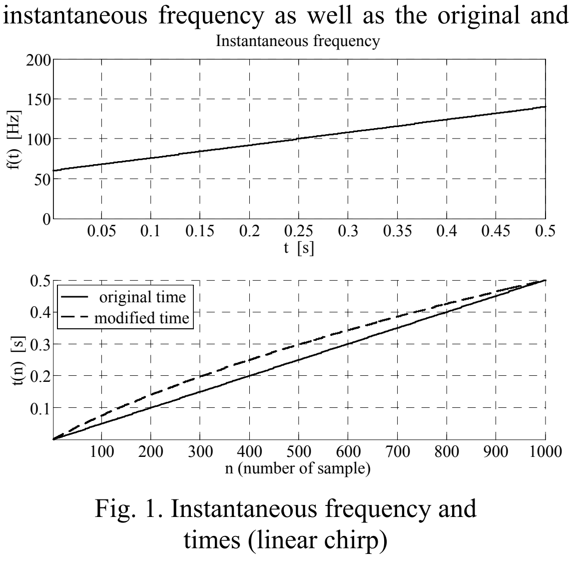

Fig. 1. Instantaneous frequency and times (linear chirp)

modified time; Fig. 5 – the amplitude spectra; Fig. 6 – the Wigner–Ville time–frequency distributions, respectively for the original and the modified, dynamically resampled signal).

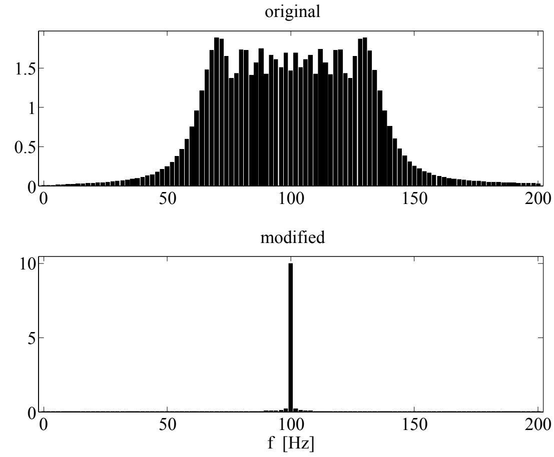

Fig. 2. Amplitude spectra (linear chirp)

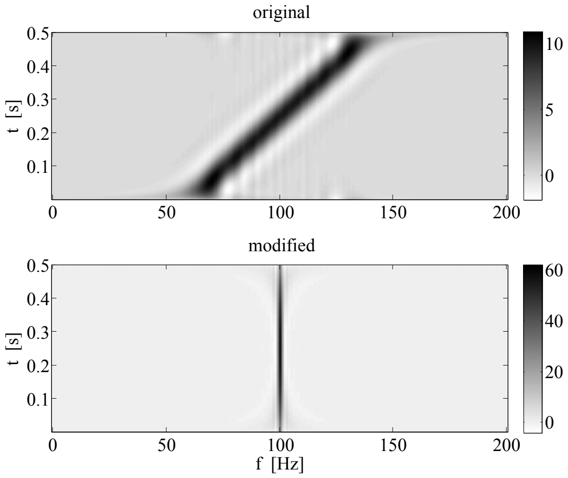

Fig. 3. Wigner–Ville distributions (linear chirp)

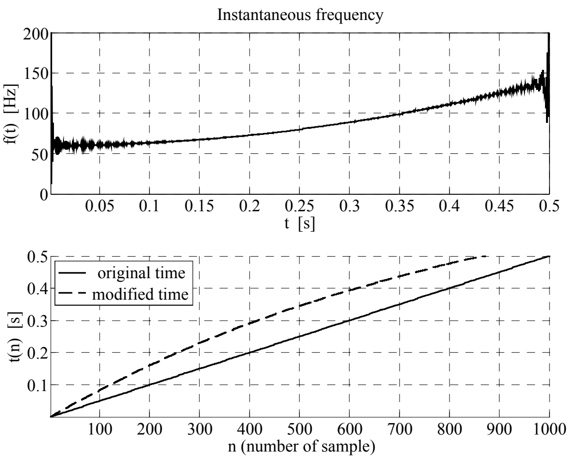

Fig. 4. Instantaneous frequency and times (square chirp)

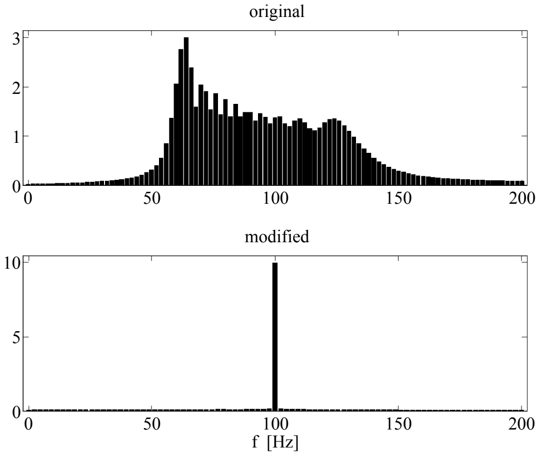

Fig. 5. Amplitude spectra (square chirp)

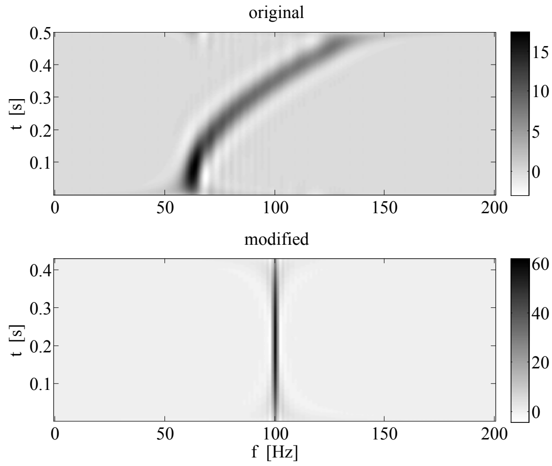

Fig. 6. Wigner–Ville distributions (square chirp)

4. NUMERICAL EXPERIMENT – A SIGNAL WITH FREQUENCY FLUCTUATION

A signal with fluctuating frequency can be an example of a non–stationary signal generated during unstable mode of an operation of object. In this experiment we used a signal with harmonic fluctuation of frequency. Then, with the use of the presented method of dynamic resampling, we performed reduction of the non–stationarity of signal. The course of the instantaneous frequency of the signal was defined with the use of the method relying on Hilbert transform.

The results of processing of the signal with the use of harmonic frequency fluctuation are presented in figures 7, 8, 9 (Fig. 7 – the course of the instantaneous frequency as well as the original and modified time; Fig. 8 – amplitude spectra; Fig. 9 – the Wigner–Ville time–frequency distributions, respectively for the original and the modified, dynamically resampled signal).

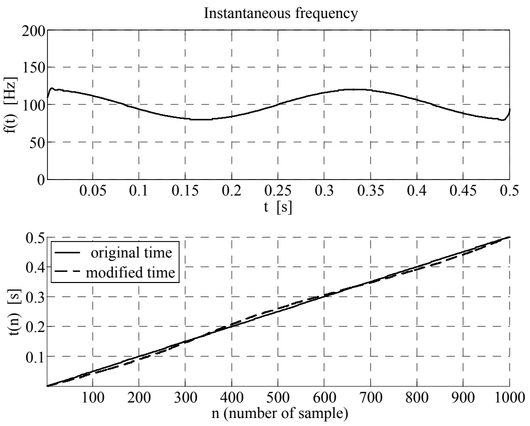

Fig. 7. Instantaneous frequency and times (frequency fluctuation)

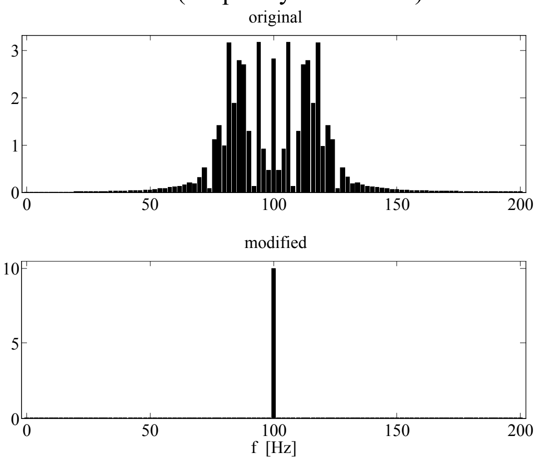

Fig. 8. Amplitude spectra (frequency fluctuation)

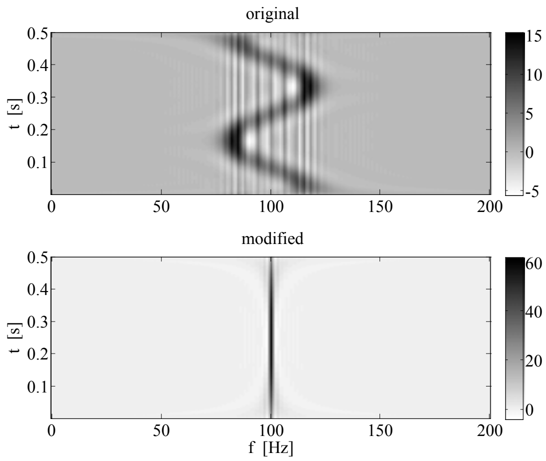

Fig. 9. Wigner–Ville distributions (frequency fluctuation)

5. NUMERICAL EXPERIMENT – A SIGNAL WITH AMPLITUDE–FREQUENCY (PHASE) MODULATION

In this experiment we have used a signal with amplitude–frequency modulation. The signal was then dynamically resampled. The course of the instantaneous frequency of the signal was defined with the use of the method relying on Hilbert transform.

The results of processing of the signal with the use of amplitude–frequency modulation are presented in figures 10, 11 and 12 (Fig. 10 – the course of the instantaneous frequency as well as the original and modified time; Fig. 11 – amplitude spectra; Fig. 12 – the Wigner–Ville time–frequency distributions, respectively for the original and the modified, dynamically resampled signal).

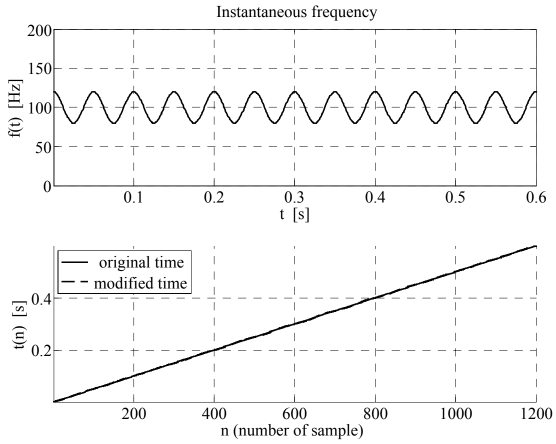

Fig. 10. Instantaneous frequency and times (amplitude–frequency modulation)

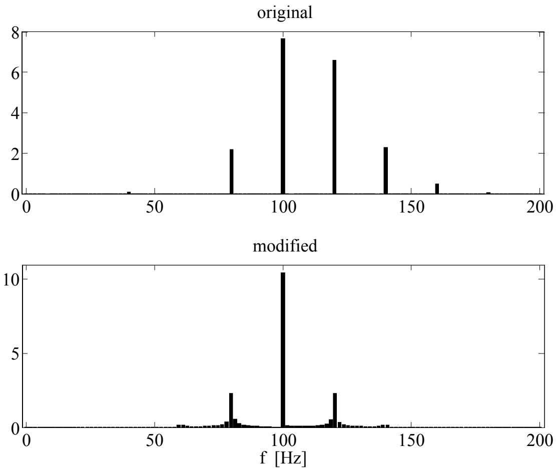

Fig. 11. Amplitude spectra (amplitude–frequency modulation)

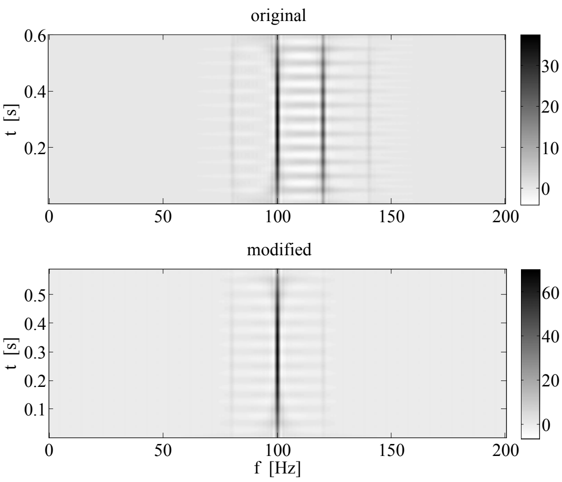

Fig. 12. Wigner–Ville distributions (amplitude–frequency modulation)

6. NUMERICAL EXPERIMENT – A SIGNAL WITH DOPPLER'S EFFECT

In this experiment we modeled the operation of a stationary system of acquisition of sound signals generated by an object in motion. An assumption was made that the object moves at a constant speed in a straight line. The diagram of the modeled situation is presented in Fig. 13.

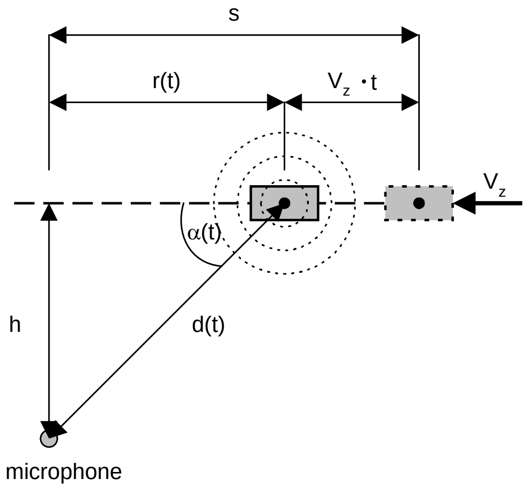

Fig. 13. Diagram presenting the modeled measuring situation

The following notation has been adopted:

- V_z – speed of the object (source of signal),
- h – distance separating the microphone from the path of object,
- s – distance defining the moment when signal registration starts (the distance between the object and the place in which the object is closest to the microphone).

The signal registered by a microphone in the conditions of relative motion of the object (the source of the signal) is burdened with noise being the result of the Doppler's effect [4]:

$$f_R = f_0 \cdot \frac{1}{1 - \frac{V_z}{V_d} \cdot \cos \alpha(t)} \tag{7}$$

where:

- f_0 – the frequency of the source of the signal,
- f_R – the frequency of the registered signal,
- V_d – velocity of propagation of sound in the air (V_d = 343 m/s was assumed),
- $\alpha(t)$ – the angle between the vector of the speed of object and the line between the object and the microphone.

While taking into account that:

$$\cos \alpha(t) = \frac{r(t)}{d(t)} = \frac{s - V_z \cdot t}{\sqrt{h^2 + (s - V_z \cdot t)^2}} \tag{8}$$

we obtain:

$$f_R(t) = f_0 \cdot \frac{1}{1 - \frac{V_z}{V_d} \cdot \frac{s - V_z \cdot t}{\sqrt{h^2 + (s - V_z \cdot t)^2}}} \tag{9}$$

Thus one can see that in the presented measurement situation we will be registering a signal whose frequency will change during the measurement.

As part of the measurement we performed a computer simulation of signal registration based on the following assumptions f_0=100Hz, s=8.3m, h=1m, V_z=33.3m/s (120km/h). Then, with the use of the presented method of dynamic resampling, we performed reduction of the non–stationarity of signal. To determine the course of the instantaneous frequency of the signal we used the functional relationship describing the change of the frequency of the signal when caused by a Doppler's effect (formula 9).

The results of processing are presented in figures 14, 15, 16 (Fig. 14 – the course of the instantaneous frequency as well as the original and modified time; Fig. 15 – amplitude spectra; Fig. 16 – the Wigner–Ville time–frequency distributions, respectively for the original and the modified, dynamically resampled signal).

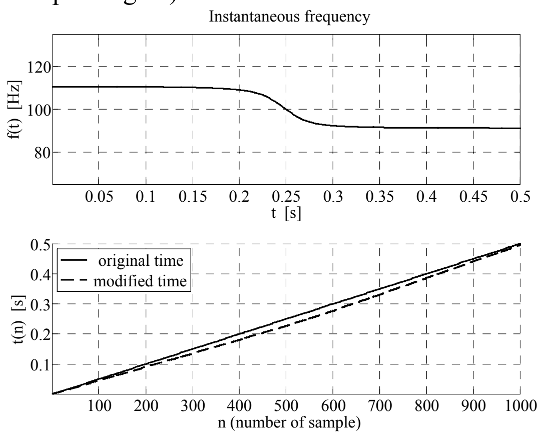

Fig. 14. Instantaneous frequency and times (Doppler's effect)

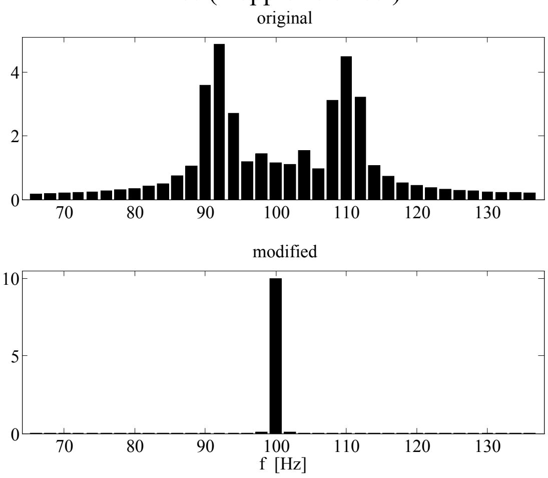

Fig. 15. Amplitude spectra (Doppler's effect)

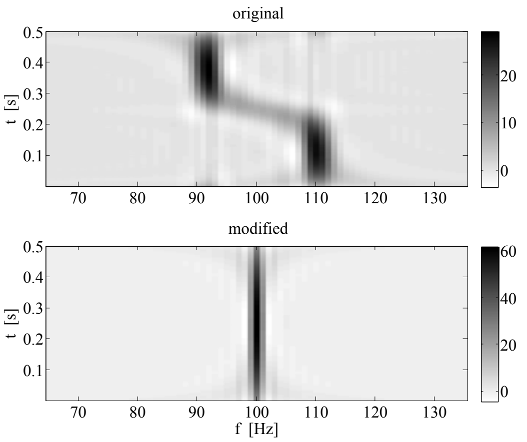

Fig. 16. Wigner–Ville distributions (Doppler's effect)

7. SUMMARY AND CONCLUSIONS

The computer simulations we conducted demonstrate that the method of task–oriented dynamic signal resampling, that was presented in this paper, effectively reduces the non–stationarity of a signal. The characteristic feature of the method is lack of preliminary assumptions as regards the phenomena causing non–stationarity. The simulations we conducted demonstrate that the possibilities of this method are not restricted to eliminating the non–stationarity caused by linear change of a frequency of signal only. The method also enables elimination of other, complex and non–linear forms of non–stationarity.

Effective reduction of various forms of non–stationarity is conditioned by the availability of the course of instantaneous frequency of which defines the eliminated non–stationarity. It is this very course that defines the task while leading to a situation where the method becomes oriented on eliminating the non–stationarity indicated this way.

The method of determining the course of the instantaneous frequency of signal is discretionary (free), independent of the method itself. Usually, however, it is conditioned by a specific task and form of the removed non–stationarity. One of the applied methods can include determination of the course of a instantaneous frequency by means of a method relying on the Hilbert's transform. This method is effective particularly in the case of signals characterized by non–complex frequency structure. If the method is used for more complex signals, then the course of instantaneous frequency should be defined in a specifically selected frequency band [1].

This restriction is not necessary since the method seeks all the forms of changes of the instantaneous frequency and not only the changes of the frequency we intend to eliminate. Thus, the outcome of applying this method of determining the frequency could be elimination of the frequency modulation of signal which was not intended by us (see the experiment with the amplitude and frequency modulated signal). Hence, if the method relying on the Hilbert' transform is used, then we should select carefully the frequency band to be used for determining the course of the instantaneous frequency, so that the bandwidth contains the form of the non–stationarity of signal that we really want to eliminate.

8. LITERATURE

[1] Bonnardot F., El Badaoui M., Randall R. B., Danière J., Guillet F. *Use of the acceleration signal of a gearbox in order to perform angular resampling (with limited speed fluctuation)*. Mechanical Systems and Signal Processing 19, pp. 766÷785, 2005.

[2] Dybała J., Mączak J., Radkowski S. /red./ *Wykorzystanie sygnału wibroakustycznego w analizie ryzyka technicznego*. Wydawnictwo Instytutu Technologii Eksploatacji PIB, Warszawa–Radom, 2006.

[3] Gałęzia A. Gontarz Sz.: *Zastosowanie metody redukcji efektów zjawiska Dopplera w stacjonarnym stanowisku diagnostycznym*. Praca dyplomowa magisterska, Politechnika Warszawska, Warszawa, 2004.

[4] Jaworski B. M., Dietłaf A. A.: *Fizyka. Poradnik encyklopedyczny*. Wydawnictwo Naukowe PWN, Warszawa, 2004.

[5] Krzyworzeka P., Adamczyk J., Cioch W.: *Metody synchroniczne w diagnozowaniu maszyn*. (w: Żółtowski B., Cempel Cz. /red./ Inżynieria diagnostyki maszyn. Rozdz. 14, str. 264÷278, Wydawnictwo Instytutu Technologii Eksploatacji PIB, Warszawa, Bydgoszcz, Radom, 2004).

[6] Brüel & Kjær magazine: *Międzynarodowy Magazyn Aktualności, Autotracking – analiza śledząca rzędów w czasie rzeczywistym bez sygnałów tachometrycznych*. str. 11, Nr 2, 2005.

[7] Brüel & Kjær, *Enhanced Order Analysis with Autotracking*, http://www.bksv.com/default.asp?ID=3986

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SYNCHRONISM AIDED RECOVERY OF PHASE MODULATION IN NON-STATIONARY SIGNAL – COMPARISON OF TWO METHODS

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Summary
The paper discusses an compares some properties and possibilities of two methods called PLL and OT in relation to PM demodulation of non-stationary machine VA signal due to repeatable operation mode of certain technical systems. Simulation experiment proved PLD efficiency. Case of OT needs synchronization with carrier cycle to get OT even better, but only if PM carrier signal is to recover, otherwise PM demodulation fails.

Keywords: synchronism, decimation, order analysis, demodulation.

WSPOMAGANIE SYNCHRONICZNE DEMODULACJI KĄTA DRGAŃ MASZYN W STANACH NIESTACJONARNYCH

Streszczenie
Porównywano skuteczność transformacji rzędów OT oraz procedury liniowej decymacji PLD we wspomaganiu asynchronicznej procedury demodulacji drgań maszyn cyklicznych w stanach niestacjonarnych. Badania symulacyjne wykazały zadawalającą skuteczność PLD i niekiedy nawet większą dla OT pod warunkiem synchronizacji cyklem nośnym, w praktyce diagnostycznej trudno dostępnym. Standardowa OT nie wykrywała PM.

Słowa kluczowe: synchronizm, decymacja, analiza rzędów, demodulacja.

1. TIME-SCALE TRANSFORMATION

Time scale in which:
- variability description becomes simpler,
- essential characteristics of informational variability are preserved,
- non-informational variability is reduced,

can facilitate diagnosing in variable operational conditions.

Local time scales are synchronized with marker event sequences determined by some characteristic $\psi(\Theta)$ of kinematics cycle, here by:
1. instantaneous cycle Θ;
2. short-term linear approximation of Θ;
3. carrier cycle Θ_C.

The above leads to known procedures formalizes as PLD and OT (see glossary)

Widely [2, 3, 7, 8] discussed, they don't need detailed presentation. The principle of TS conversion (see Fig. 1) shows the main difference between order transform and linear decimation.

2. DIFFICULTIES OF PM RECOVERY

A number of detailed researches [1, 2, 5] indicate the occurrence of angle modulation PM and its pulse version PPM as early as in the first stages of damage evolution.

However, if the case of unintended PM of machine vibrations several current methods of PMD, created and optimized for carrier signals of a specified form and constant frequency, turn out to be inefficient.

The problems originate from:
- non-informative carrier-frequency changes;
- inference rather than knowledge of modulation type and its parameters;
- inaccessibility of carrier signal
- unknown current form of the signal.

If and for what can they be overcome? One of the solution is to transfom original PM signal using local time scale synchronized with $\psi(\Theta)$.

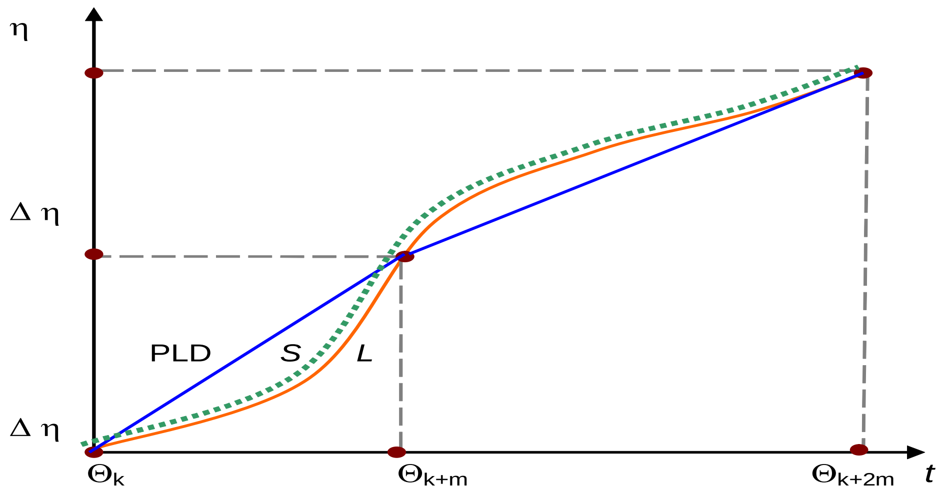

Fig. 1. PLD split instantaneous **L**(Θ) into several line segments S with constant growth rate, while OT leads to 3rd order spline approximation of **L**

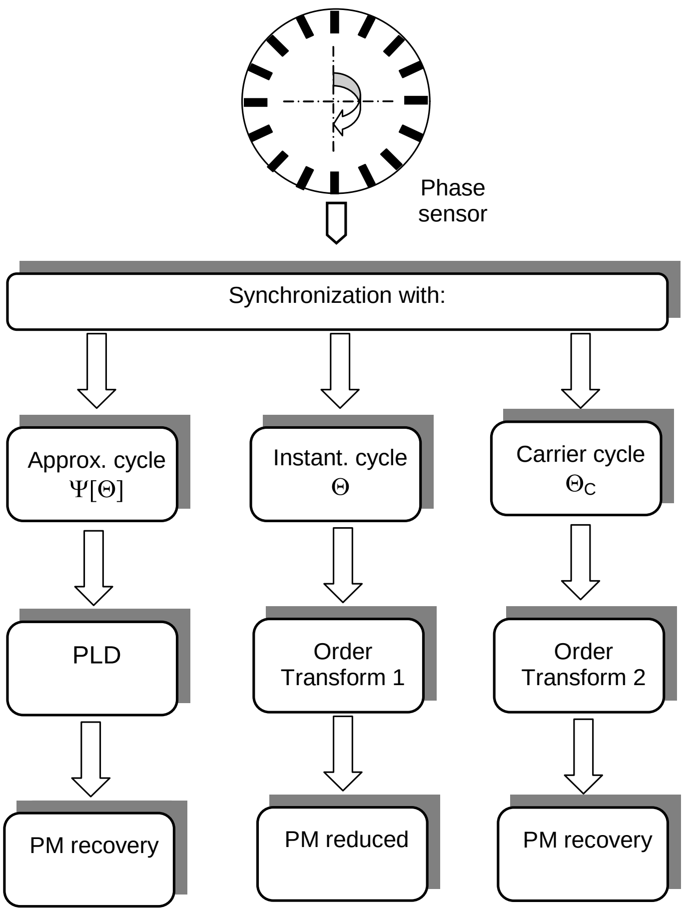

Fig. 2. Synchronization of time scale conversion in relation witch applied conversion procedure:
a) procedure of linear decimation PLD; b) order transform, standard version;
c)order transform synchronized with carrier cycle

3. SIMULATIONS

The efficiency of both methods has been tested using simulated PM signals and procedures disposed on Fig. 2.

OT has been synchronized with both carrier and instantaneous cycle. Some of conclusive results are shown below (Fig. 3 and 4) [8].

Corruption of of original PM spectra as well as efficiency of PM side-lobes recovery degree are there evident.

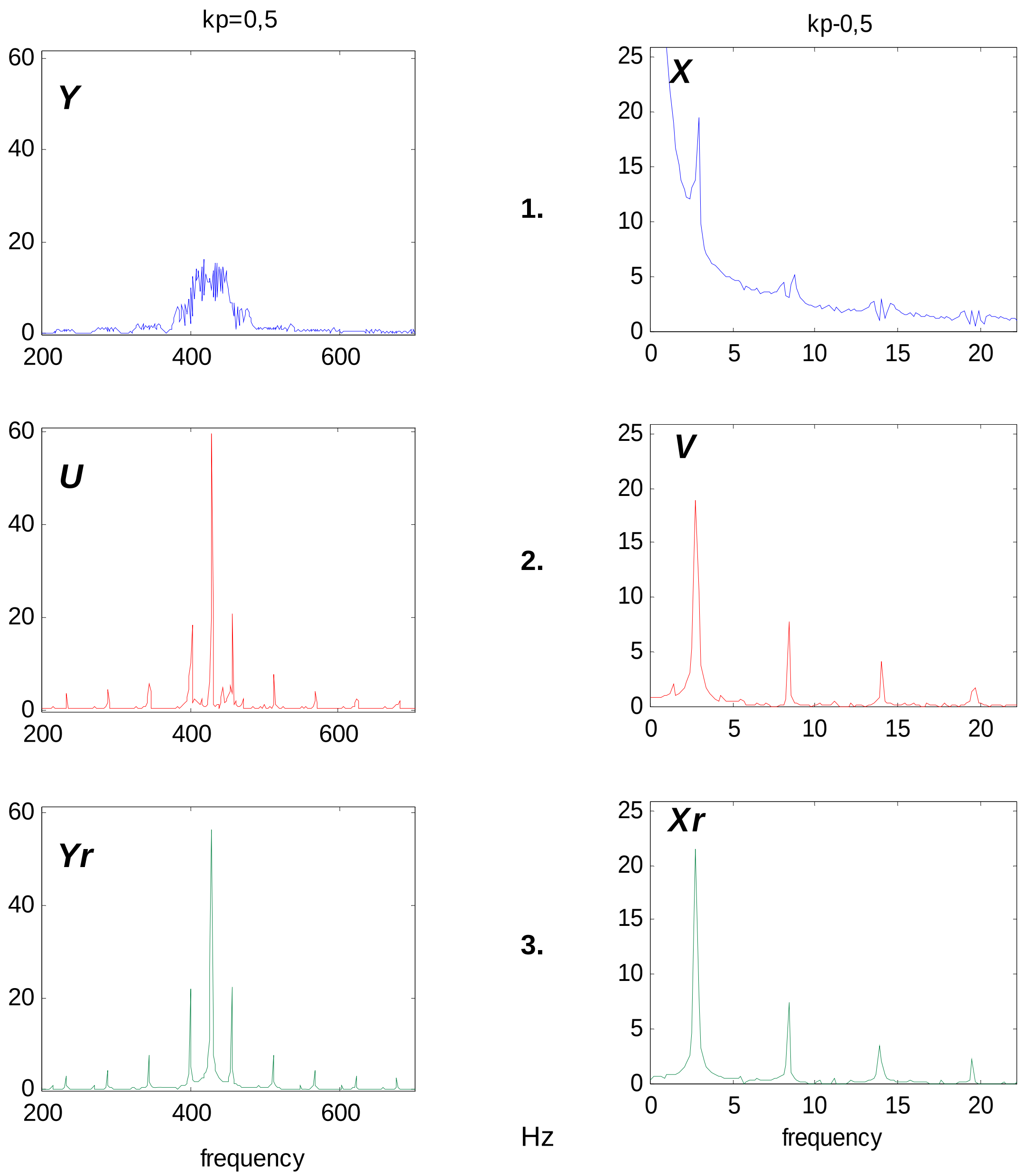

Fig. 3. Spectra of PM signal (A), and demodulation results (B).
1) real time signal; 2) after PLD transform; 3) real time reference signal, constant carrier frequency

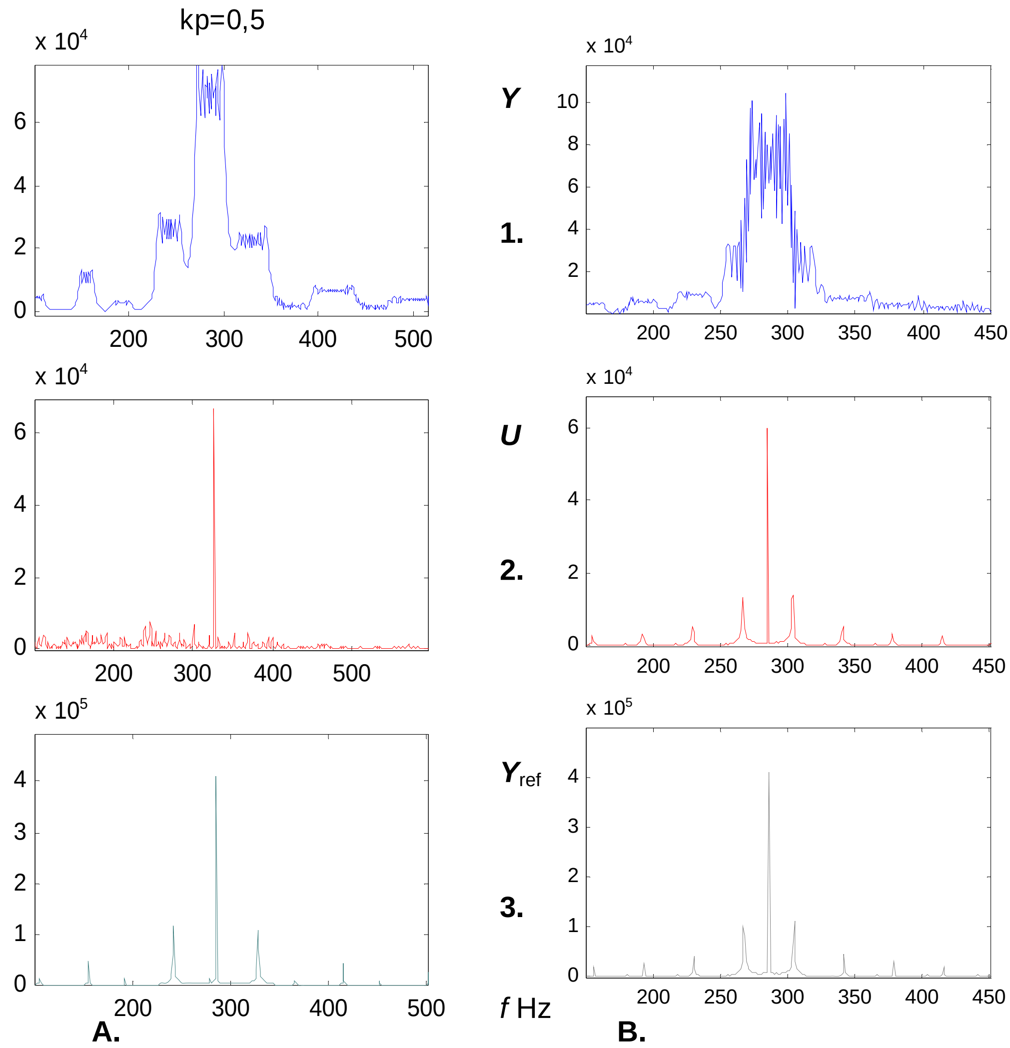

Fig. 4. Spectra of PM signal, side-lobes represent PM recovery.
A - order transform, standard version; B - order transform synchronized with carrier cycle
1) real time signal; 2) after time scale transform; 3) real time reference signal, constant carrier frequency

4. CONCLUSIONS

The results seems to confirm certain conclusions resulting from the model of machine signal PM modulation proposed once by author [4], Therefore:

– Both PLD and OT reduced leakage of FFT spectra.
– PLD offers generally lower FFT accuracy, but satisfactory in the case of monotonic carrier frequency trend; furthermore:
  - get DPM easy to synchronization
  - does not require the precise carrier cycle approximation;
  - does not require complex calculations;
  - is simple in on-line implementation.
– Order transform synchronized by signals with cycle closed to instantaneous cycle reduces PM effect (see Fig 4. A) [3].
– OT recover well PM spectral side-lobes, but only when synchronized with carrier cycle Θ_C, generally unknown in the case of real machine signal PM (see Fig 4. B).

5. REFERENCES

[1]. Cioch W., Krzyworzeka P.: *Modulacje niezamierzone w diagnozowaniu głośnika*. Diagnostyka, vol. 28, 2003, 29 – 36.
[2]. Cioch W., Krzyworzeka P.: *PLD aide demodulationof starting vibratios In rotating machinery*. Diagnostyka, vol. 43, 2007, 105 – 110.
[3]. Korbiel T. *Order analysis in the diagnostic of nonstatinary VA process*: Diagnostyka, vol. 43, 2007, p. 99 – 104.
[4]. Krzyworzeka P.: *Demodulacja drgań maszyn przy zmianach prędkości obrotowej*. Diagnostyka, vol. 31, 2004, 21 – 28.
[5]. Krzyworzeka P.: *Wspomaganie synchroniczne w diagnozowaniu maszyn*: Kraków-Radom. BPE, Wyd. ITE . 2004.
[6]. Radkowski St.: *Wibroakustyczna diagnostyka uszkodzeń niskoenergetycznych*: W-wa, Radom, WITE, 2002.
[7]. Piotrowski A., Stankiewicz A., Balunowski J., Solbut A.: *Diagnostics symptoms forming in the rotating machine monitoring based on the order tracking analysis*. II International Congress of Technical Diagnostics, Diagnostika'2000, Poland, Warsaw 19-22 September 2000.
[8]. Korbiel T., Krzyworzeka P.: *An application of splines In synchronous analysis of nonstationary machine run*: Diagnostyka, vol. 43, 2007, 105 – 110.

Abbreviations & Symbols

DPR	–	dynamic residual process
MVS	–	machine vibration signal
OT	–	Order transform
PDI	–	Diagnostic identification procedure
PLD	–	Procedure of linear decimation
PM	–	Phase modulation
PMD	–	Phase demodulation procedure
TSC	–	Time scale conversion
$\psi(\Theta)$	–	synchronizing cycle characteristic
$\Delta\varphi$	–	angular step of synchronization
Θ	–	instantaneous cycle
Θ_C	–	carrier cycle
$\boldsymbol{y}$	–	original measured signal
$\boldsymbol{u}$	–	final signal after TSC
'η'	–	local time scale
't'	–	real time scale
$\boldsymbol{s}_F$	–	characteristic signal
T	–	Time width of observation window
η	–	PLD or OT time
z_k	–	referential event

APPLICATION OF MORPHOLOGICAL ANALYSIS FOR GEAR FAULT DETECTION AND TRENDING

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Summary

Frequency domain based signal processing methods such as cepstrum analysis, Hilbert Transform based demodulation, cyclostationary analysis, etc have been shown to present a quite effective behaviour in the detection of defects, when applied to the analysis of vibration signals, resulting from gear pairs with one or more defective gears. However, these methods typically require some complex and sophisticated analysis, which renders their application cumbersome for applications requiring unskilled personnel or automated fault detection and trending. Alternatively to these methods, morphological analysis for processing vibration signals has been proposed, addressing the issues of how to quantify the shape and the size of the signals directly in the time domain. Morphological analysis and the resulting morphological index is applied in this paper to a set of twelve successive vibration measurements resulting from a gearbox prior to tooth breakage. As shown, the morphological index is able monitor the evolution of the potential fault, providing a clear warning prior to the breakage of the tooth.

Keywords: defective gears, morphological processing, fault trending, vibration analysis.

1. INTRODUCTION

Gearboxes are widely used in industrial applications. A sudden and unexpected failure of a gearbox may cause significant losses, not only from the economic but also from the human life point of view. Thus, it is very important to find early symptoms, which may indicate an approaching gearbox destruction. Typical faults of gears include pitting, chipping and more seriously, crack. The development of a local fault at a gear often introduces both amplitude and phase modulations at the vibration signals [1].

Since the increase of the number and of the amplitude of the sidebands often indicates faulty conditions, many frequency domain based signal processing methods have been proposed for gear fault detection, such as cepstrum analysis [2], envelope analysis [3], cyclostationary analysis [4], deconvolution filters [5] or combined time frequency analysis methods, such as wavelets [6, 7].

Although these methods have been shown to present a quite effective behavior in the detection of defects, they typically require some complex and sophisticated analysis, which renders their application cumbersome for applications requiring unskilled personnel or automated fault detection and trending.

Parallel, a number of traditional methods exist, requiring only a direct processing in the time domain, such as the root mean square of the signal, the crest factor, the kurtosis, the shape factor and the impulse factor, or the more recently introduced morphological analysis. Morphological signal processing comprises a broad collection of theoretical concepts and mathematical tools for signal analysis, non-linear signal operators, design methodologies and application systems that are related to mathematical morphology [8, 9, 10]. Morphological signal processing was first used to analyze binary image data and was extended to grey level images. Since its launching, it has grown rapidly. This growth is a consequence of the great variety of applications which can be treated by mathematical morphology. The traditional tools of linear systems and Fourier analysis are of limited use for solving geometry-based problems because they do not directly address the issues of how to quantify the shape and the size of the signals. Contrarily, morphological signal processing is perfectly able to quantify all aspects, related to the geometrical structure of the signals. However, applications of morphological filters to one-dimensional time series have been quite limited, restricted practically to biomedical signals [11, 12, 13, 14].

Morphological signal processing of vibration signals resulting from defective rolling element bearings has been proposed in [15]. The basic concept of the proposed method is to modify the geometrical features of the signals in the time domain, in order to construct a kind of envelope, which accentuates information corresponding to the impulse series produced by the fault. As a result, a morphological index can be defined, able to monitor the evolution of the defects. As shown [16], this index presents a number of advantages over other traditional time indices, such as the root mean square of the signal, the crest factor, the kurtosis, the shape factor and the impulse factor, such as increased robustness to added noise, variations of the resonance frequency and damping ratio, rotation speed, etc.

This paper further proceeds to the application of this morphological index for the processing of vibration signals resulting from defective gears.

First, a revision of the basic concepts of morphological processing of signals is provided, resulting to the definition of the morphological index to be used. Then, morphological processing is applied to a series of twelve successive vibration signals, resulting from a gearbox under an evolving defect, just prior to a tooth breakage. The results indicate that the morphological index is able to monitor the evolution of the defect, being able to provide an early warning just prior to the breakage of the tooth.

2. BASIC CONCEPTS OF MORPHOLOGICAL PROCESSING OF SIGNALS

Morphological operators are indices that are sensitive to the geometric characteristics of the signals and they are a result of morphological signal processing. The fundamental concept of morphological signal processing [8, 9] is the modification of the shape of the signal through its interaction with another object, called the structuring element. The basic morphological operations of set erosion, dilation, opening and closing are related to Minkowski set operations and are used to construct morphological filters. Using the definitions for Minkowski addition and subtraction between functions, the four basic morphological operations are defined as:

$$dil(f,g)=\left(f\oplus g^{r}\right)(x)=f(x)\oplus g(-x)= =\sup_{y\in D}\{f(y)+g(y-x)\} \quad (1)$$

$$er(f,g)=(f\ominus g)(x)=f(x)g(x) =\inf_{y\in D}\{f(y)-g(y-x)\} \quad (2)$$

$$cl(f,g)=(f\bullet g)(x)=\left[\left(f\oplus g^{r}\right)\ominus g\right](x) \quad (3)$$

$$op(f,g)=(f\circ g)(x)=\left[\left(f\ominus g^{r}\right)\oplus g\right](x) \quad (4)$$

where $g^r(x)$ denotes the reflected (symmetric) function $g(x)$ with respect to the origin of the x-axis.

Equations (1) - (4) can be significantly simplified, if $g(x)$ is an even function, i.e. $g(x)=g(-x)$, and if sampled functions are used. For a signal $f(k)$, defined over a domain D_f, and for a function $g(u)$, called the structuring element, which is of length L and defined over a domain D_g, the dilation and the erosion of the signal $f(k)$ by the element $g(u)$ are defined as:

$$dil(k)=(f\oplus g)(k)= \max_{u\in Dg}\{f(k+u)+g(u)\} \quad (5)$$

$$er(k)=(f\ominus g)(k) =\min_{u\in Dg}\{f(k+u)-g(u)\} \quad (6)$$

Similarly, based on erosion and dilation, the closing and the opening operations of the signal $f(k)$ by the element $g(u)$ are further defined as:

$$cl(k)=(f\bullet g)(k)=er(dil(k)) \quad (7)$$

$$op(k)=(f\circ g)(k)=dil(er(k)) \quad (8)$$

3. THE MORPHOLOGICAL INDEX

The Morphological Index results by the application of a closing process to a signal, using a flat structuring element [15].

The flat (zero) structuring elements are selected because they present the simplest structuring element with a straightforward application, since the only parameter which must be selected for their application, is their corresponding length L. Additionally, morphological operations using flat structuring elements seem to be quite appropriate for the detection of peaks of impulsive type vibration signals, resulting by faulty bearings or gears.

After the closing operation, a local maxima algorithm is further implemented, in order to evaluate the impulsive information contained in the closing. According to this algorithm, an impulse series $p(i)$ can be obtained by retaining only the local maxima of the closing $cl(i)$ of the signal f(i), located at the time instants i which satisfy:

$$\begin{cases} p(i)=cl(i), if \\ f(i)>f(i-1)\wedge f(i)>f(i+1)\wedge f(i)>tr \\ p(i)=0 \quad \text{, otherwise} \end{cases} \quad (9)$$

where tr is a threshold value, used to suppress low amplitude peaks, which are typically attributed to noise effects.

The morphological index MI is then expressed as the RMS value of the impulses $p(i)$ detected by the closing operation and characterizes the amount of energy involved in the pulse series caused exclusively by the bearing or the gear defect.

A detailed analysis on the effect of the length and the shape of the structuring element is performed in [15]. According to this analysis, a flat structuring element with a length in the range of 60%-70% of the impulse repetition period minimizes the noise effects. Thus a value of the structuring length equal to 60% of the impulse repletion period is further chosen in this paper. According to extensive analysis results, the optimal range for the threshold value is typically between 25 to 35% of the maximum impulse amplitude.

4. EXPERIMENTAL APPLICATION

The contact fatigue strength of gear steels and the performance of gear lubricants can only be determined by running gears at sufficiently high torque to cause contact fatigue or lubricant breakdown.

This often results in the need for high power and long test durations. For this reason, contact fatigue testing of gears can be carried out fast and more easily on back-to-back, or 'power recirculating' test rigs.

Thus, a series of twelve (12) measurements were performed on a back-to-back test rig (Figure 1) at the Vibroacoustic Laboratory of Warsaw University of Technology. The last one of them was obtained just prior to the breakage of the gear tooth. Two test gearboxes of identical gear ratio and centre distance are joined by torsionally compliant shafts (torsion bars), with an actuator in one shaft. This rotates the shafts to induce equal and opposite torques in the test gears at each end.

A small variable speed motor drives both gearboxes, the power required being only equal to the total mesh friction, windage and churning losses of the gears.

Each measurement consists of 8192 samples and the sampling rate is equal to 24 KHz. The shaft rotation frequency is approximately 21 Hz and the expected gear mesh frequency is approximately 670 Hz.

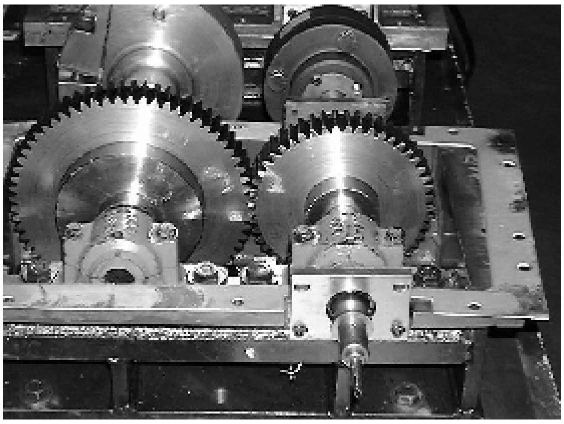

Fig. 1. Test rig used

Initially, the raw measured signals were processed using Fourier Transform. Their time waveforms and their corresponding spectra are presented respectively in Fig 2 and Fig. 3.

No significant changes of the measured signals related to the evolution of the defect can be observed, either in the time or in the frequency domain, with the slight exception of the last measurement.

Then, in order to apply morphological analysis, a soft-thresholding de-noising procedure is used at the first step, using wavelet analysis.

The purpose of this procedure is to remove as far as possible the random signal information and the amount of white noise, since morphological analysis is very sensitive to these effects. A soft thresholding procedure is performed using the db2 wavelet and level 2. The selected threshold settings are according to the minimax rule and the single level rescaling method.

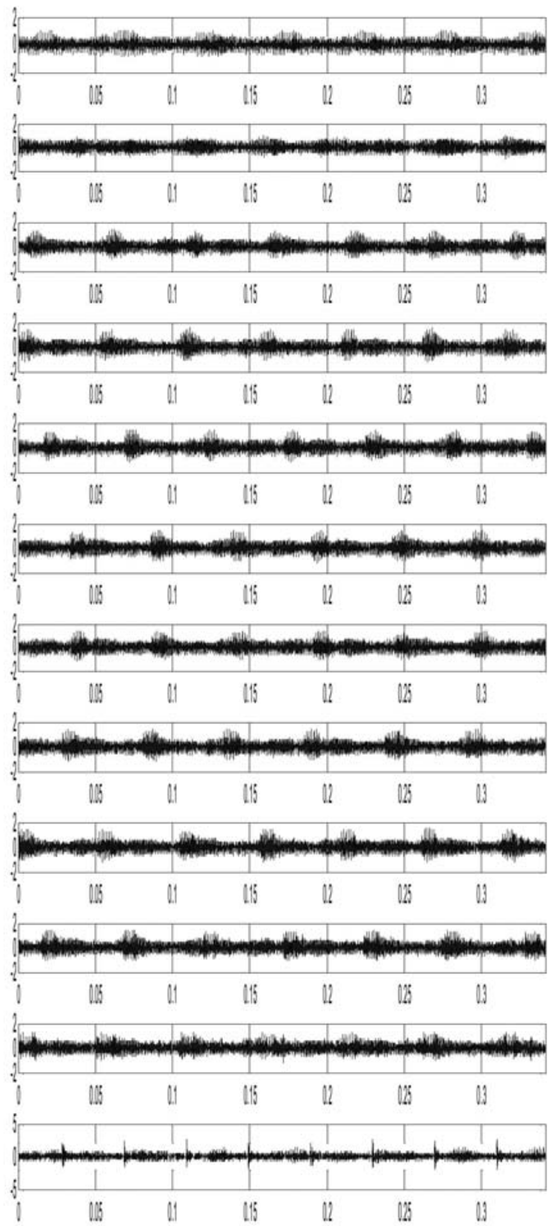

Fig. 2. Time waveforms of the raw signals.

The effect of denoising is minimal and the resulting signals keep almost the same periodic form as the original signals. However, the denoised signals appear more regular, as the presence of white noise and random components is limited, and they present a smaller amplitude and less noise. This can be observed in the spectral peaks of the frequency analysis of the signal from measurement 12 (Fig. 4), in the waveforms of the signals from measurement 12 (Fig. 5) and from measurement 2 (Fig. 6). The raw signals are presented with a solid black line and the de-noised ones with the dot gray.

Then, morphological closing was applied on all the original and de-noised signals, using a flat structuring element. The basic idea of the implementation of the morphological analysis on signals emitted by gears is to extract information from the time domain shape of the produced envelope.

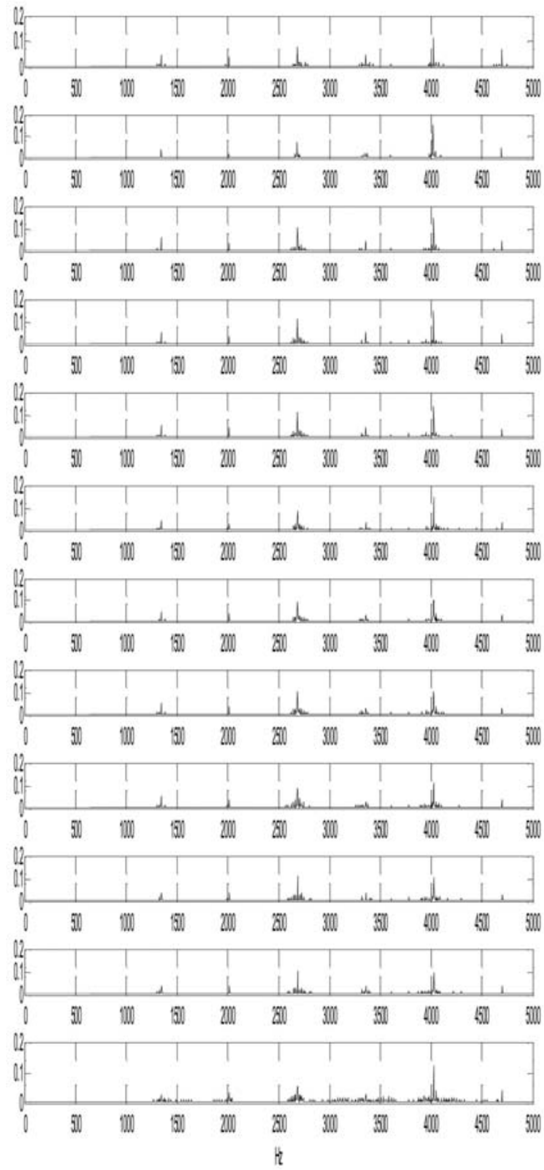

Fig. 3. Spectra of the raw signals.

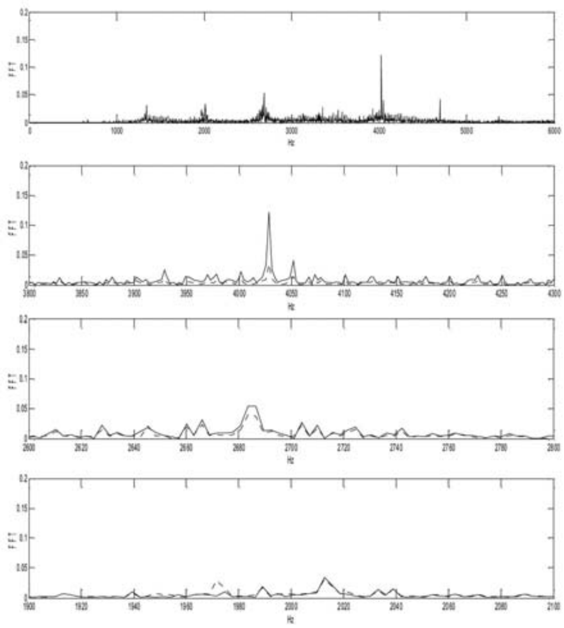

Fig. 4. Frequency regions of the spectrum analysis of the original and the de-noised signal 12.

Gear mesh frequencies are often very sensitive to load, but high GMF amplitudes do not necessarily indicate a problem if the side band frequencies remain at low level. Thus, the length of the structuring element was selected as 67% times the assumed repetition period, which corresponds to the inverse of the rotation frequency as the side bands around the GMFs spaced at this frequency.

The resulting signals after the closing operation are shown in Fig. 7, where the original and the denoised envelopes appear superimposed. Parallel, Figs 5 and 6 show detailed presentation of the resulting signals from the closing operation. As can be observed, a characteristic shape like an envelope appears above the original signals, presenting periodic lobes related to the rotation speed. The solid line envelopes which result from the implementation of the morphological analysis on the de-noised signals and the dot line envelopes result from the raw signals.

The difference between the envelopes from the raw and the denoised signals is minimal, due to the limited values of added noise.

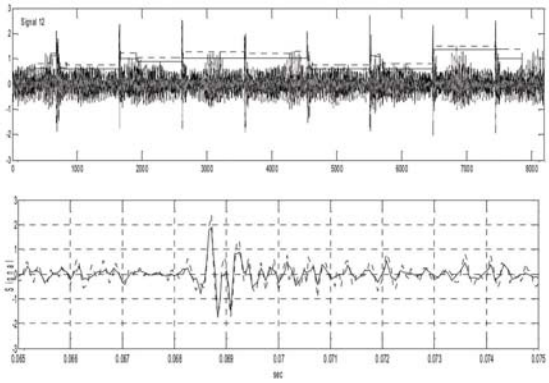

Fig. 5. Time waveform and closing of the raw and the de-noised signal 12.

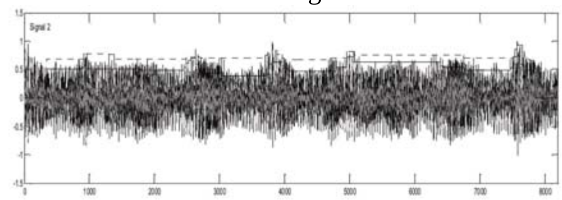

Fig. 6. Time waveform and closing of the raw and the de-noised signal 2.

After the closing operation, a local maxima algorithm is further implemented, in order to evaluate the impulsive information contained in the produced envelopes. According to this algorithm, an impulse series is obtained by retaining only the local maxima of a closing.

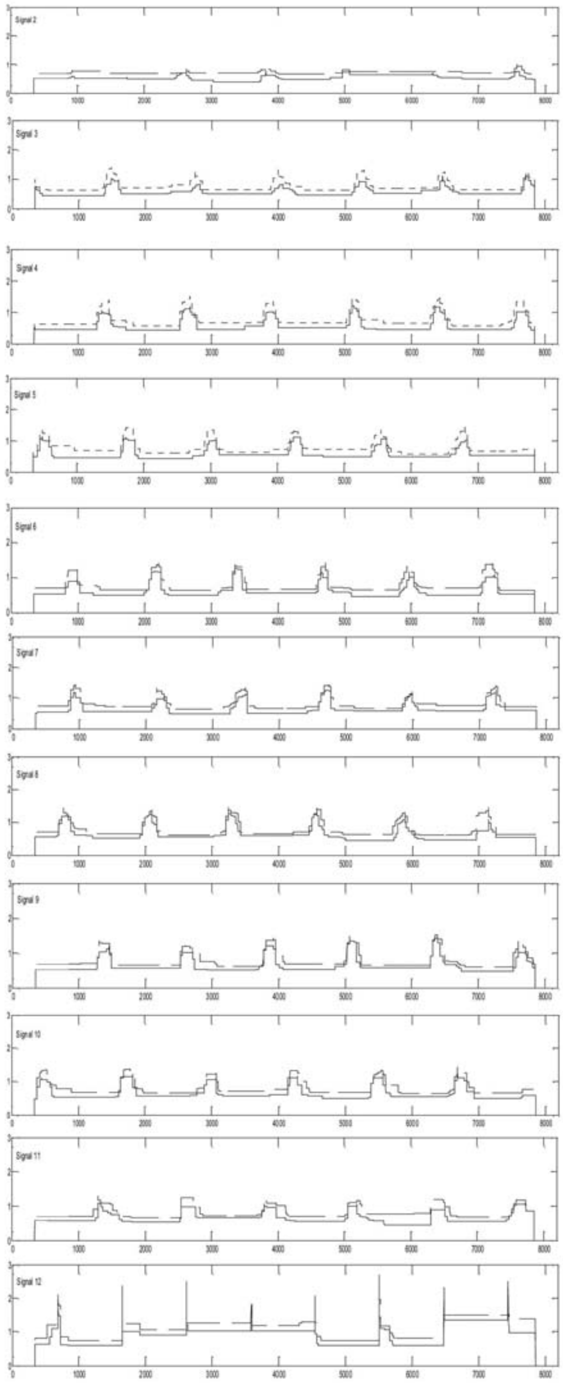

Fig. 7. Envelopes produced by morphological analysis of the raw and de-noised signals.

The morphological index MI is then calculated as the RMS value of the impulses detected by the closing operation. The MI characterizes the amount of energy involved in the pulse series caused exclusively by the gear defect. The resulting Morphological Index is presented in Fig. 8. As it can be observed, the MI follows monotonically the progress of the defect.

The closing of the signal exhibits an interesting property: it presents a kind of envelope, the shape of which is clearly related to an impulse sequence, which occurs periodically, with a frequency determined by the geometry of the defective component and the rotation speed.

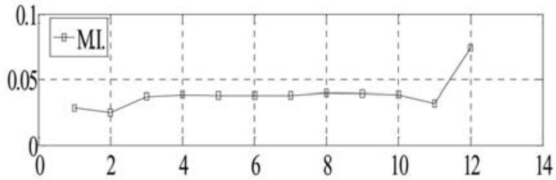

Fig. 8. Evolution of the Morphological Index with the progress of the fault

As observed in Fig. 7, the envelope produced by the closing operation is characterized by peaks. These peaks allow the detection of the time instants, at which the impulses occur. This periodic time duration is related to the inverse of the rotation frequency. As also observed in Fig. 7, the peaks tend to be sharper and their amplitude increases as the gear wear deteriorates.

Thus, according to the proposed procedure, the changes in the time domain shape of the signals obtained by the closing operation are shown at a first stage to be able to offer a visual inspection on the resulting envelope of the wear evolution. At a second stage, a quantitative indication of the evolution of the defect can be obtained by the evolution of the Morphological Index.

CONCLUSION

The morphological closing using a flat structuring element results to the extraction of a kind of envelope with a series of impulses corresponding to the impulses generated by a defective gear. This series can offer a better visual inspection of the impulsive nature of the signal. Parallel, they contain sufficient quantitative information about the repetition period and the intensity of the impacts.

Based on this envelope, the Morphological Index can be defined, providing a quantitative measure for the evolution of the defect.

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REFERENCES

1. McFadden P. D.: *Detecting fatigue cracks in gears by amplitude and phase modulations of the meshing vibration*, ASME Transactions, Journal of Vibration, Acoustics, Stress and Reliability in design, 1986,n 108, 165-170.
2. Randall R. B.: 1987, *Frequency Analysis*, Bruel & Kjaer, 3rd Ed.
3. Wang W.: *Early detection of gear tooth cracking using the resonance demodulation technique*,

Mechanical Systems and Signal Processing, 2001, 15(5), 887-903
4. Capdessus C., Sidahmed M., Lacoume J. L.: *Mechanical Systems and signal processing*, 2000, 14, 371-385, "Cyclostationary processes:Application in gear faults early diagnosis".
5. Endo H., Randall R. B.: *Enhancement of autoregressive model based gear tooth fault detection technique by the use of minimum entropy deconvolution filter*, Mechanical Systems and Signal Processing, 2007, 21, 906-919.
6. Jafarizadeh M. A., Hassannejad R., Ettefagh M. M, Chitsaz S.: *Asynchronous input gear damage diagnosis using time averaging and wavelet filtering*, Mechanical Systems and Signal Processing, 2008, 22, 172-201.
7. Halim E. B., Choudhury S. M. A. A., Shah S. L., Zuo M. J.: *Time domain averaging across all scales: A novel method for detection of gearbox faults*, Mechanical Systems and Signal Processing, 2008, 22, 261-278.
8. Maragos P., Schafer R.: *Morphological filters – Part I: their set-theoretic analysis and relations to linear shift invariant filters*. IEEE Transactions on Acoustics, Speech and Signal Processing ASSP, 35, 1987, 1153-1169.
9. Maragos P.: *The Digital Signal Processing Handbook on Morphological Signal and Image Processing*. Boca Raton: CRC Press, 1998. p.74.1- 74.26., FL, USA.
10. Meyer F., Maragos P.: *Non-linear scale space representations with morphological leveling*. Journal of Visual Communication and Image Representation. 2000, 11, 245-265.
11. Nishida S., Nakamura M., Miyazaki M., Suwazono S., Honda M., Nagamine T., Shibasaki H.: *Construction of a morphological filter for detecting an event related potential P300 in single sweep EEG record in children*. Medical Engineering Physics, 1995, 17, 425-430.
12. Nishida S., Nakamura M., Shindo K., Kanda M., Shibasaki H.: *A morphological filter for extracting waveform characteristics of single sweep evoked potentials*. Automatica, 1997, 35, 937-943.
13. Nishida S., Nakamura M., Ikeda A., Shibasaki H.: *Signal separation of background EEG and spike by using morphological filter*. Medical Engineering Physics, 1999, 21, 601-608.
14. Sedaaghi M. H.: *ECG wave detection using morphological filters*. Applied Signal Proccesing. 1998, 5, 182-194.
15. Nikolaou N. G., Antoniadis I. A.: *Application of morphological operators as envelope extractors for impulsive-type periodic signals*. Mechanical Systems and Signal Processing, 2003, 17(6), 1147-1162.
16. Patargias T. I., Yiakopoulos C. T., Antoniadis I. A.: *Performance assessment of a morphological index in fault prediction and trending of defective rolling element bearings*, Nondestructive Testing and Evaluation, 2006, Vol. 22, No 1, pp 39-60.

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POWER TURBO-SETS VIBRATION STATE DIAGNOSING

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The paper presents automatic system of turbo-sets vibration state analysis and diagnosing. The turbo-set shaft line is considered as main object for diagnosing. The system is equipped with sufficient sensors to measure vibratory signals from the rotor line and non-vibratory data. Computer system enables efficient real-time analysis and post-processing of measured values. Methods of operation states assesment are applied to provide analysis during the rotor turning, run-up/run-down, idle running and loading conditions. A special attention is payed to investigations of torsional vibrations as indicator of some defects. An example of computer simulation of shaft crack is presented showing their usefulness. A technique for the rotors torsional strains check and assessment at the turbo-set shaft line rotation is introduced into the presented system to determine fatigue phenomena.

Keywords: diagnostics, vibration state, technique and systems, power machinery, turbo-set.

DIAGNOZOWANIE STANU DYNAMICZNEGO TURBOZESPOŁÓW ENERGETYCZNYCH

Praca przedstawia automatyczny system analizy i diagnostyki stanu dynamicznego turbozespołów energetycznych. Linia wirników została przyjęta jaki główny obiekt diagnozowania. System jest wyposażony w odpowiednie czujniki mierzące sygnały drganiowe i inne wielkości. Komputerowa obróbka sygnałów umożliwia efektywną analizę w czasie rzeczywistym oraz postprocessing zmierzonych wartości. Zastosowane metody dają możliwość analizy w różnych stanach operacyjnych maszyny, jak obracanie wirnika, rozbieg/wybieg, bieg jałowy, bieg pod obciążeniem. Zwrócono specjalną uwagę na badania drgań skrętnych jako wyróżnika diagnostycznego niektórych defektów. Podany przykład badań symulacyjnych pęknięcia wirnika pokazuje ich użyteczność. Zaprezentowano technikę wyznaczania naprężeń skrętnych w celu określania zjawisk zmęczeniowych.

Słowa kluczowe: diagnostyka, stan dynamiczny, technologia i systemy, maszyny energetyczne, turbozespół.

1. INTRODUCTION

Nowadays the importance of problems regarding increase of steam power plant's and thermo-electric plant's turbo-set safety operation becomes very important. This is a result of the turbo-sets technical state when most of them completed their fleet life, their operational conditions at transient and peak modes in the conditions of power market which are nor foreseen by the design and realized, as a rule, with deviations from normal technological processes. Because of additional low-cyclic and high-cyclic loadings such modes result in accelerated accumulation of fatigue damages and appearance of latent defects, first of all in elements of the shaft line. Methods and techniques for the turbo-sets technical state analysis and diagnosing by vibration parameters are important for estimation of damages initiation and growth.

Collected numerical and experimental data show that appearance of the dangerous vibration is possible if the following take place: a crack of essential size in the rotor where the opening angle more than 0.25π or its depth equals 15-20% of the rotor diameter; damages in shaft couplings of rotors and non-centering of supports; in stability of the shaft line rotation and progress of self-exited oscillations; essential unbalance (mechanical or thermal) of shaft line rotating elements; breaking off or damage of rotor elements or its catching the stator; defects of elements and parts of the generator electromagnetic system [1-6].

Investigations [2-5] on the determination of information and diagnosing parameters and indicators of dangerous damages show that they influence on the change of the general vibration level of supports and rotor necks as well as on its separate harmonic and spectral components. Initiation and growth of most of dangerous defects and damages results first of all in specific changes of parameters of rotational harmonic component, in appearance and progress of parameters of the double rotational harmonic component and in the specific enrichment of vibration spectrum by high frequency (HF) components of 3, 4 and higher order at the progress of defects and damages till the dangerous level. Here, the specific enrichment of the spectrum by low frequency (LF) oscillations of the shaft line is observed at presence of elements defects and damages and under the influence of forces of hydrogasodynamical nature in the turbine flow passage and in the oil layer of plain bearings.

For example, if the amplitude and phase of the rotational component do not depend on operation modes (load, stem temperature, etc.) and the amplitude excesses essentially the amplitudes of other spectrum components, the possible reason is mechanical unbalance of shaft line rotational elements. In cases of their dependence on operation modes one can speak about a symptom of the thermal unbalance. Monotonic variation of rotational component parameters in time can indicate the crack growth, and stepwise one – breaking off or failure of turbo-set shaft line elements.

Presence of double rotational frequency harmonic component can be induced by the rotor double stiffness (because of presence and growth of the crack in the rotor or damage in shaft couplings), design peculiarities of generators bipolar rotor and effect of the electromagnetic field between rotor and stator.

High frequency vibration components arise, as a rule, simultaneously with rotational and double rotational components and can be indicators of the bending of rotor joints, rotor crack, rotor catching the stator, etc.

For determination of defects and damages of the diagnosed turbo-set it is necessary to form information-diagnosing arrays and trends of parameters taking into account operation modes and factors at continuous automotive analysis of these parameters. This is realized by the automotive system of turbo-sets vibration state analysis and diagnosing developed at the Institute for Mechanical Engineering Problems NASU. Experimental versions of the system operate on two power units 300 MW of Zaporozhje Steam Power Plant, at Kiev Thermo-Electric Plant-5 and Kharkov Thermo-Electric Plant-5. The block diagram of the system is presented in Fig. 1. To develop the system the experience of long-term investigations is used. Among them one can describe the following results.

Methods and developed equipment for contact and contact-less measurement of turbo-sets rotors and elements oscillations with utilization of eddy current converters with frequency modulated output signal which meet the requirements of Standards by their technical data. They have increased error probability for electromagnetic fields influence and do not require adjustment on the metal of object, type and length of the cable of the communication line and not sensitive for side metal that describes their advantages in the comparison with analogous devices of recognized companies. This has permitted to increase error probability and truth of obtained initial information on vibration parameters [7, 8, 9].

2. ASSESSMENT OF VIBRATION PARAMETERS

A method of assessment of the operation modes influence on the vibration parameters variation is described in [10, 11]. A method of identification of turbo-sets shaft line models calculating parameters by experimental amplitude-frequency characteristics of the diagnosing turbo-set which permits to build adequate calculating model of the system for numerical determination of its defects influence on the turbo-set's vibration parameters is described in [12].

Computer technologies of operation of the system of automotive analysis and diagnosing of vibration state in real time and post-analysis on the parameters correspondence with norms for vibrations at all operation modes to determine reasons of their deviations [13, 14].

Methods of the analysis and assessment of turbo-sets vibration state and reasons of its variation by amplitudes and phases of harmonic components of vibrations of rotors and shaft line bearings supports as well as by current spectral order characteristics and their variations in time (trends) [15].

A technique for the rotors torsional strains check and assessment at the turbo-set shaft line rotation which permits to determine fatigue phenomena [16, 17].

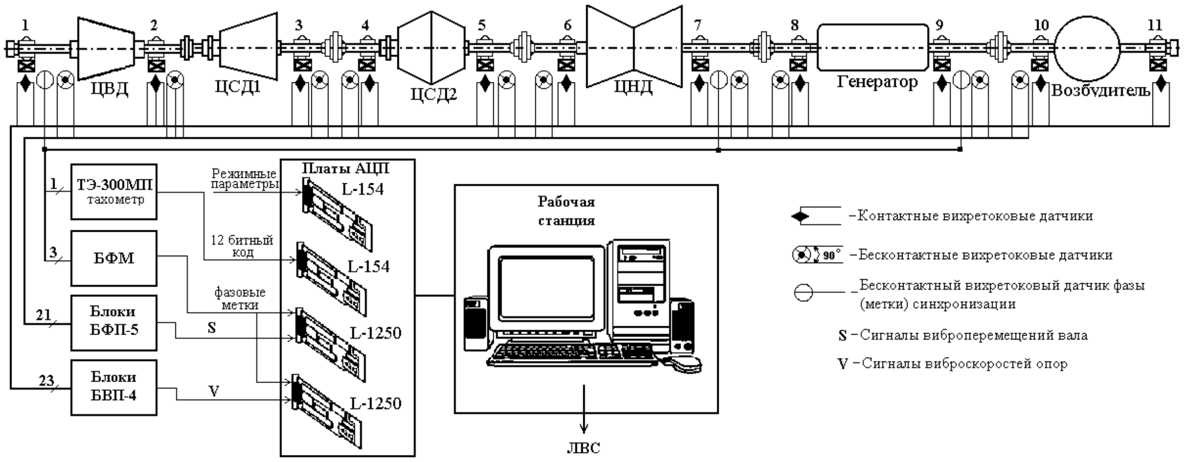


Fig. 1. The block diagram of the system.

Initial vibration data are signal of instantaneous values of relative displacements (gap variations) of all shaft line rotors necks in bearings recesses and vibrations of all bearings supports at least in two orthogonal directions. Collection of vibration signals is carried out simultaneously (in parallel by all channels), continuously and synchronously with the shaft line rotation. Synchronization of the signals receiving and treatment, check of rotation frequency and torsional strains are carried out by signals from marks on shaft line rotors. Necessary thermo-mechanical and non-vibration parameters are formed by signals from converters and measuring devices of the automatic process control system. The turbo-set shaft line is considered as main object for diagnosing because most probable defects and faults mentioned above are connected with its vibration state.

A technique of the turbo-set vibration state diagnosing at start-up procedures (rotor turning, speed-up–acceleration, no-load and loading) is intended for identification of thermal and mechanical rotor deflection, misalignment of rotors and supports as well as defects of mounting and repair.

Instantaneous values of necks displacements $S_{xi}(t)$ and $S_{yi}(t)$ are measured and registered continuously on the shaft line in each bearing at two orthogonal radial directions x and y, and maximal moduli of necks displacements are calculated

$$S_{i\max} = \max\sqrt{S_{xi}^2(t) + S_{yi}^2(t)} \qquad (1)$$

as well as their direction $\psi_{i\max}$. Orbital movements of all rotor necks in bearings and numerical values of $S_{i\max}$ and $\psi_{i\max}$ are displayed on the monitor. Following the experience of investigations the tolerated value of $S_{i\max}$ after the warm-up should not exceed 20 µm.

If after satisfied warm-up $S_{i\max}$ does not decrease till tolerated level, the reason can be non-removed defects of mechanical nature of mounting or repair. It can be seen from the mnemoline of the shaft line "bending" obtained on the monitor by $S_{i\max}$ of necks taking into account directions $\psi_{i\max}$ of their displacements in bearings (see Fig. 2).

A peculiarity of vibration state analysis and diagnosing at speed-up and acceleration modes is the following. They are carried out continuously in real time at variable rotational speed. Developed hardware, software and methods realize necessary speed of signals receiving and treatment as well as output of information in required amount on variation of controlled vibration parameters. This permits to receive and store frequency characteristics at speed-up and acceleration by general level of rotors and supports vibrations as well as by amplitude-phase-frequency characteristics of their harmonic components. Threshold levels of shaft and supports vibrations at speed-up are set by actual mean-statistic acceleration characteristics.

Rotors relative vibration displacement check on critical frequencies permits to prevent crushing of seals in the turbine flow passage and conserve present efficiency and reliability of the turbo-set operation. At the excess of the threshold level at least of one of rotors it is useful to interrupt the speed-up till clearing and removal of corresponding reasons. Besides, parameters of spectral and harmonic characteristics of turbo-set shaft line rotors and supports vibrations are used. To do it ordinal spectra (by numbers of harmonic components) are introduced which contain data on vibration amplitude and phase as functions of harmonic number which permits to check the variation of harmonics amplitudes and phases in the process of the turbo-set (see Fig. 3).

Operative assessment of the turbo-set state at operation modes (after loading and connection to the power network) is guaranteed by the way of continuous check of rotors and bearing supports vibration parameters on their correspondence with their normal levels.

At these modes information-diagnosing arrays and trends by adopted list of vibration parameters are formed. To do it samples of values of rotors relative vibration displacements and shaft line supports vibration speeds are synchronously formed each second with discreteness of 80 μs and values of vibration displacement span as well as root-mean-square value of vibration speed are calculated. By each of these parameters on the interval of 20 s arrays updated each second are formed. After averaging for 20 s their values are compared with normal values. The excess of the threshold level is indicated by the change of the color of the bar with simultaneous audible signal (see Fig. 4).

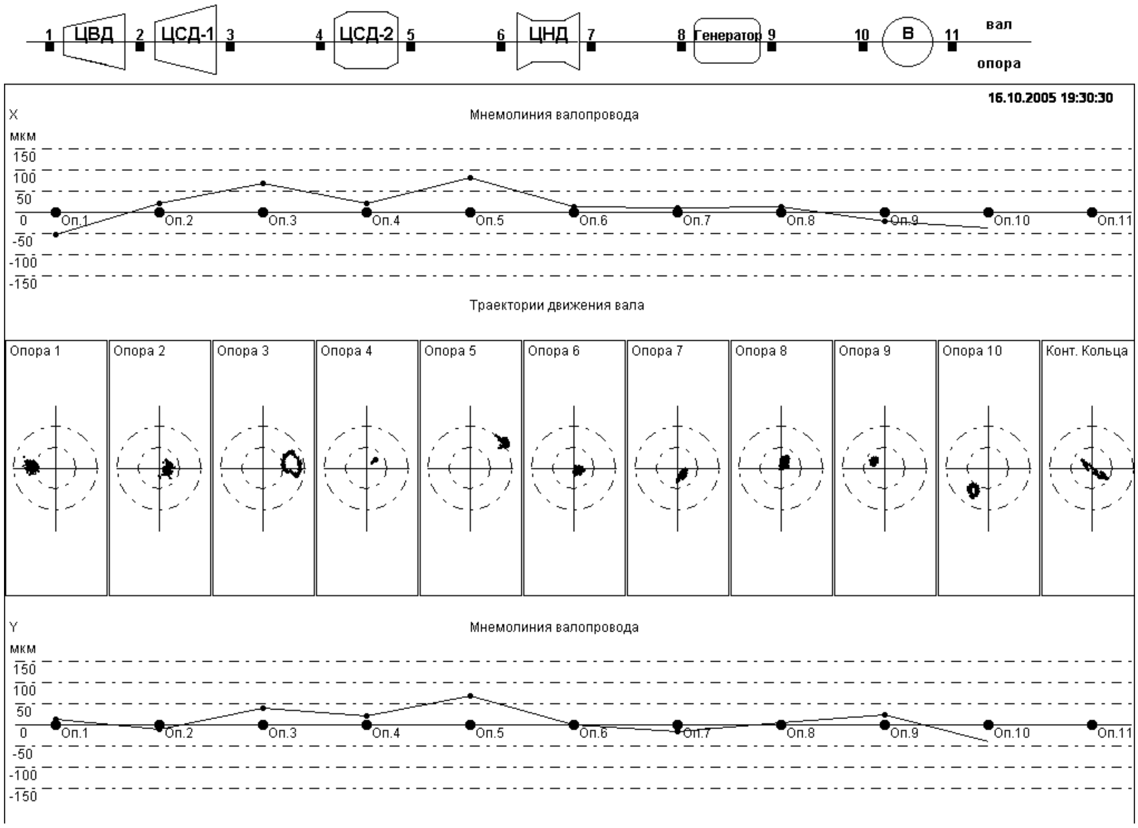


Fig. 2. Shaft line mnemoline.

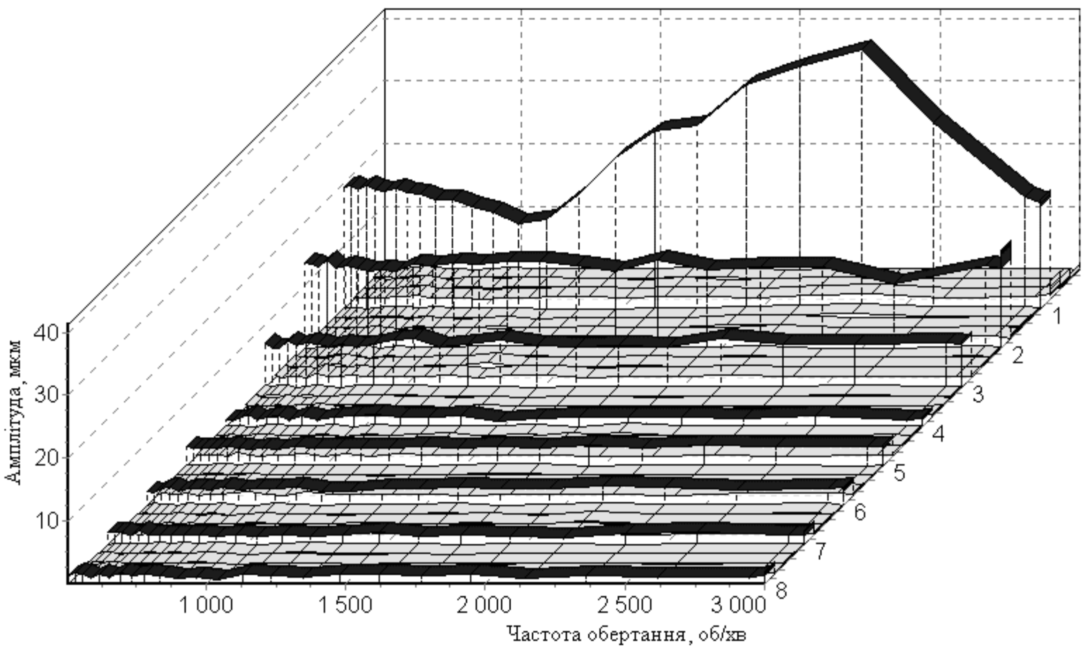


Fig. 3. Ordinal spectra of acceleration by harmonic components.

These arrays are initial to determine unexpected (stepwise) vibration variation because of breaking off or failure of shaft line rotating parts as well as sub-harmonic and super-harmonic components.

For the turbo-set vibration state diagnosing statistical arrays and trends of vibration parameters are formed with period of averaging of 20 s, 90 s, 1 h and 24 h. Using values averaged for 24 h trends are form for a month, a quarter, a season, a year, an inter-maintenance period, etc.

Besides, the system archives informational-diagnosing arrays and trends of the following parameters:

– amplitudes and phases of rotors vibration displacement rotation frequency harmonic component and bearing supports vibration speed, as well as their ratios by orthogonal directions of the same rotor necks and bearing supports;
– amplitudes and phases of double rotation frequency harmonic component of amplitude values for the 3-rd, 4-th and 5-th harmonics, as well as their ratios;
– amplitude of the sub-harmonic component with half rotation frequency of rotors and supports vibration displacement and vibration frequency;
– spectra of LF rotors and bearing supports vibrations in the frequency interval of (5– $F_0/2$) Hz (where F_0 – rotation frequency);
– spectra of HF rotors and bearing supports vibrations in the frequency interval higher $2F_0$.

By data of these arrays the spectral analysis of vibration signal with step of 3 Hz is carried out, besides the forming of the trajectory of rotors necks movement in plain bearings as well as phase portrait of the supports vibration speed is carried out (see Fig. 5).

The mentioned arrays of parameters are formed depending on rotation frequency, loading variation (active and reactive power and current of the generator rotor), steam parameters (pressure and temperature in the chamber of the regulating stage), temperature state of turbo-set elements including oil at input and output of supporting and thrust bearings and metal of the high-pressure cylinder (top-bottom), vacuum in the condenser, rotors and cylinders thermal expansions and some other parameters.

It permits to determine in time fast and slow vibration parameters variations taking into account influence of technological and operation factors and identify appearance of dangerous faults.

For the numerical analysis of defects influence on shaft line vibration parameters a dynamical model of the shaft line built by the way of the approach of results of vibration characteristics calculation to data of experimental investigations is used [12] (see Fig. 6).

Here the inverse problem of theory of oscillations is solved by searching of partial solutions. Nowadays special attention is paid to investigations of large turbo-sets torsional vibrations. Necessity of their investigations is determined by a number of accidents because of fatigue damages of rotors [4, 18, 19].

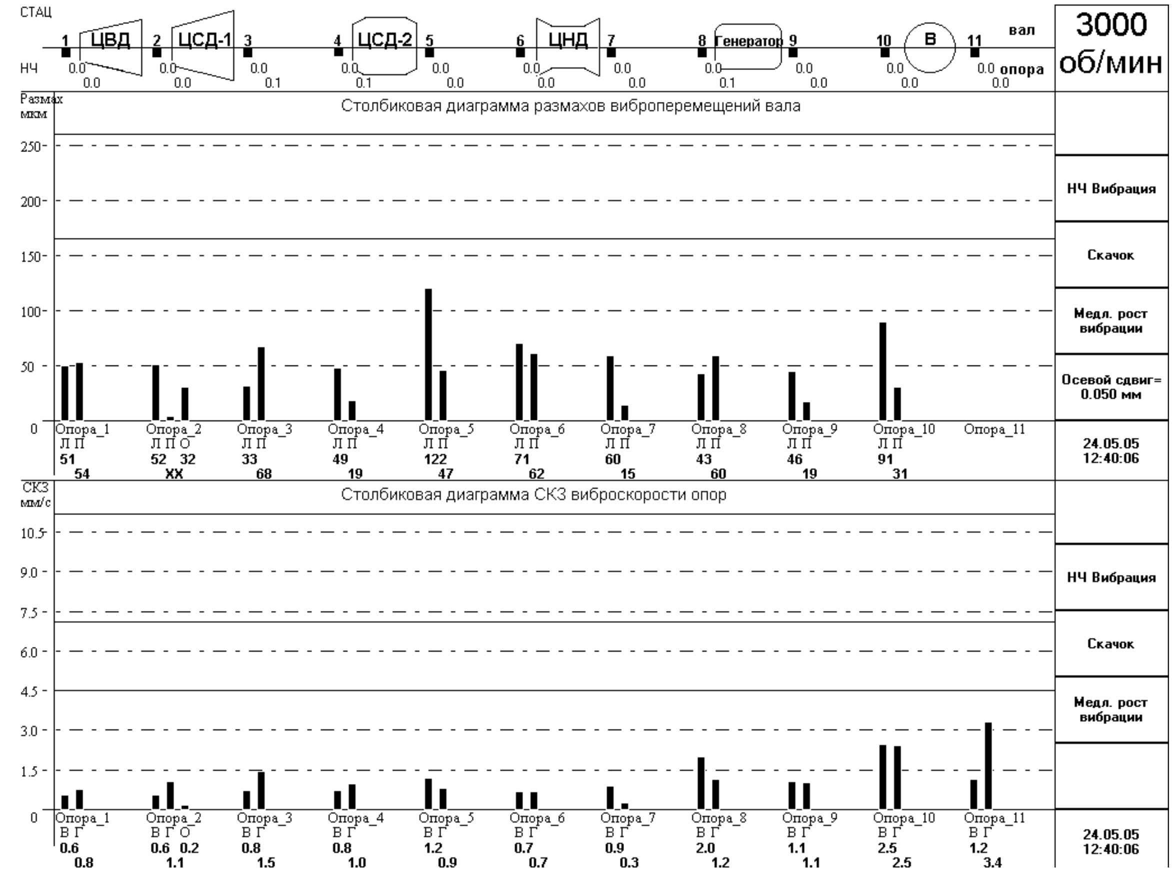


Fig. 4. Bar diagram of turbo-set vibration parameters.

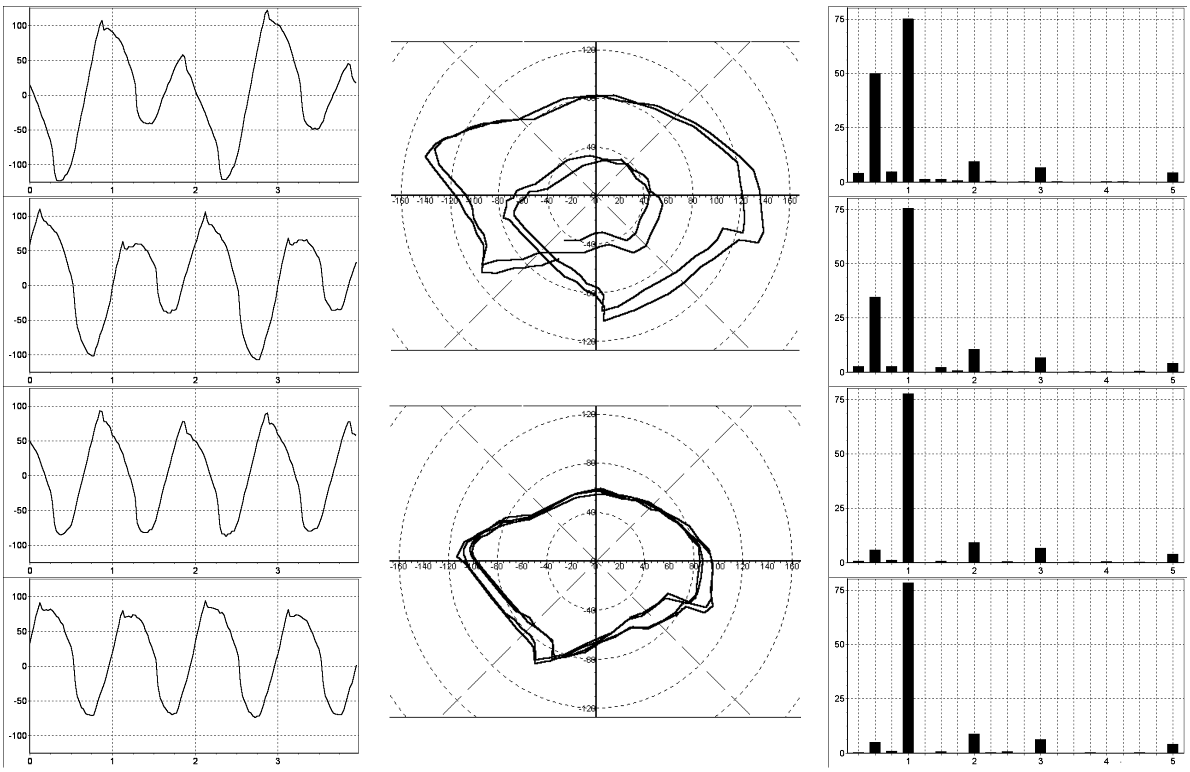
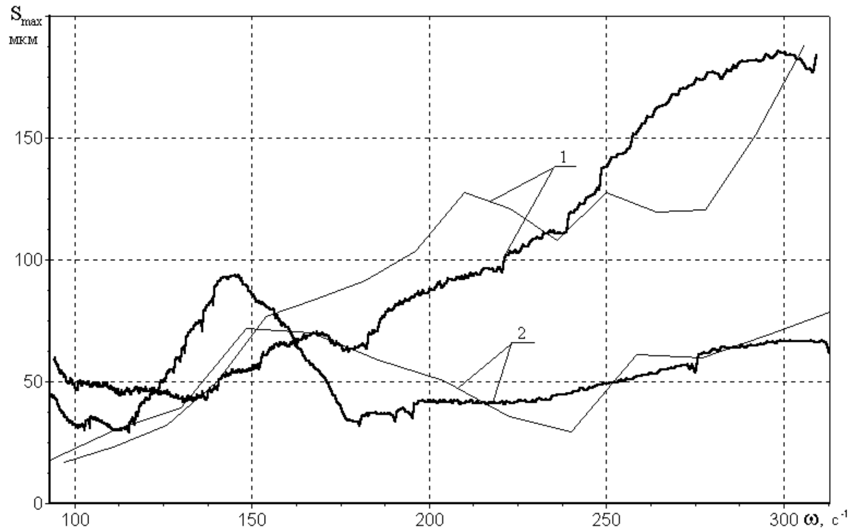
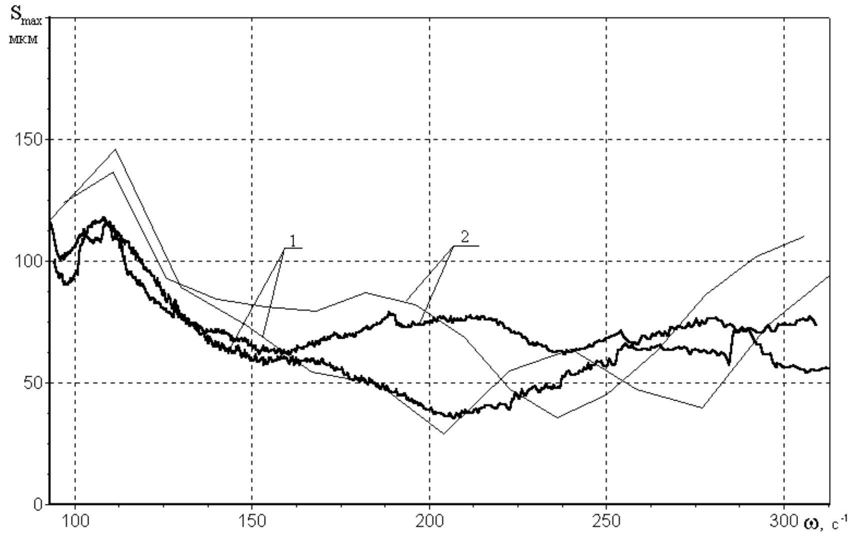


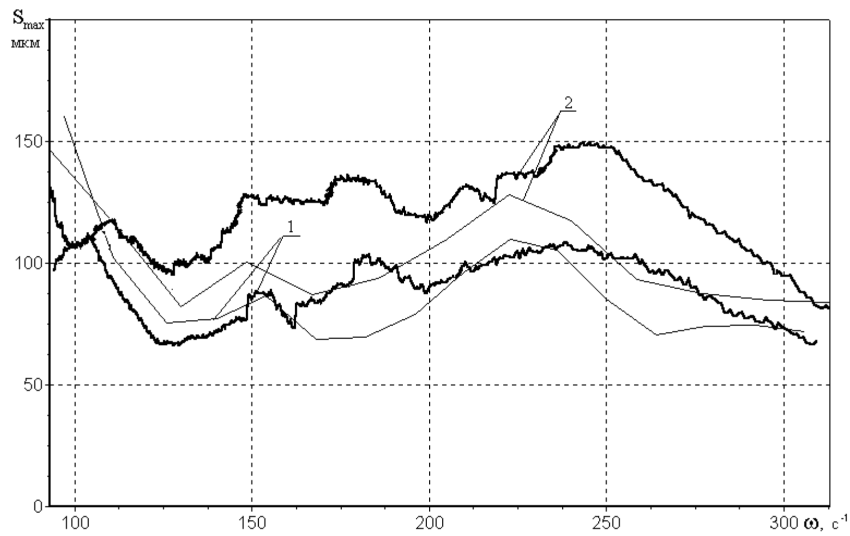
Fig. 5. Shaft line vibration characteristics.



a)



b)



c)

Fig. 6. Amplitude-frequency characteristics at acceleration:
a) support 1; b) support 4; c) support 7;
▬ – experimental values; — – calculated values:
1 – before repair, 2 – after repair

3. TORSIONAL VIBRATIONS AS DIAGNOSTIC INDICATOR OF SHAFT CRACK – COMPUTER SIMULATION

Investigations carried out at the Institute of Fluid-Flow Machinery PASci. (IFFM) show that by using methods of torsional vibrations spectral analysis it is possible to find initiation and growth of a cross crack [20]. They were based on simulation calculations. The NLDW computer code is utilized to perform the simulations. It is a part of computer code environment MESWIR that allows to model multifarious phenomena in rotating rotors founded on slide bearings. It bases on non linear methods to model interactions in the rotating machine between shaft, bearings and supporting structure. The core of this environment is strongly non-linear, diathermal model of slide bearing. This model encompasses Reynolds equation, energy equations, equations describing heat transfer in the lubricating gap, etc., giving as an output non-eliptical trajectories of displacements of nodes of the model and their spectra. A shaft is modeled with typical Timoshenko beam elements with 6 DOF's per node. It allows to take into account transverse, axial and torsional loads of the shaft, to obtain displacements in those directions and analyze couplings between them.

Crack is modeled with Knott model. It is typical two-state model of the slot. The appearance of the crack amends the form of the stiffness matrix in such a way that additional influences appear, which are responsible for coupling of the bending and axial vibrations as well as bending and torsional or two-dimensional bending vibrations [20-22].

$$K_e = T_t\,(L + L_d)^{-1}\,T \tag{2}$$

where the index ***t*** denotes the matrix transposition and ***-1*** means matrix inversion.

The matrix of additional flexibilities $\boldsymbol{L_d}$ is calculated using the form of elastic deflection energy of the beam element, which emerges from the transverse crack [22]. It can be proven that it can be written in a form, where non-diagonal elements describe couplings between displacements in different directions:

$$\boldsymbol{L_d} = \begin{bmatrix} c_{11} & 0 & 0 & 0 & 0 & c_{16} \\ & c_{22} & 0 & c_{24} & c_{25} & 0 \\ & & c_{33} & 0 & 0 & c_{36} \\ & & & c_{44} & c_{45} & 0 \\ s & y & m & & c_{55} & 0 \\ & & & & & c_{66} \end{bmatrix} \tag{3}$$

Crack depth is described by the crack coefficient W_P (4). It can be also called a "relative crack depth" which is absolute crack depth divided by the shaft diameter (both in the length units). It is convenient to user to apply it into NLDW data.

$$W_P = \frac{a}{D} \tag{4}$$

Transformation of the stiffness matrix of the beam element with a crack to the system turned by an arbitrary angle α has been presented in Fig. 7 [20].

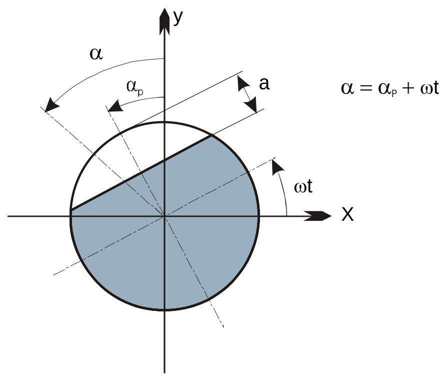


Fig. 7. Beam element with the crack turned with respect to the y axis by an arbitrary angle αp determining the initial location of the crack in the x-y plane.

This angle is a sum of the angle describing initial location of the crack with respect to the reference system α_P and the angle resulting from rotation of the shaft ωt. Applying simple mathematical transformations we obtain the stiffness matrix for the beam element with the crack turned in the x-y plane by the angle α_P.

As an example we can see the investigations of two different (separate) crack locations in the rotor of 200 MW turbogenerator (see fig. 8).

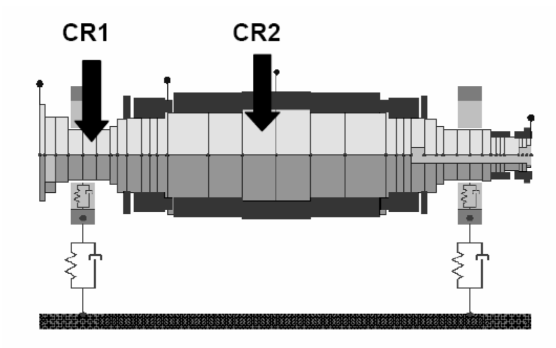


Fig. 8. The assumed crack positions in rotor of 200 MW turbo-set (scheme of generator - section between bearings No. 6 and 7).

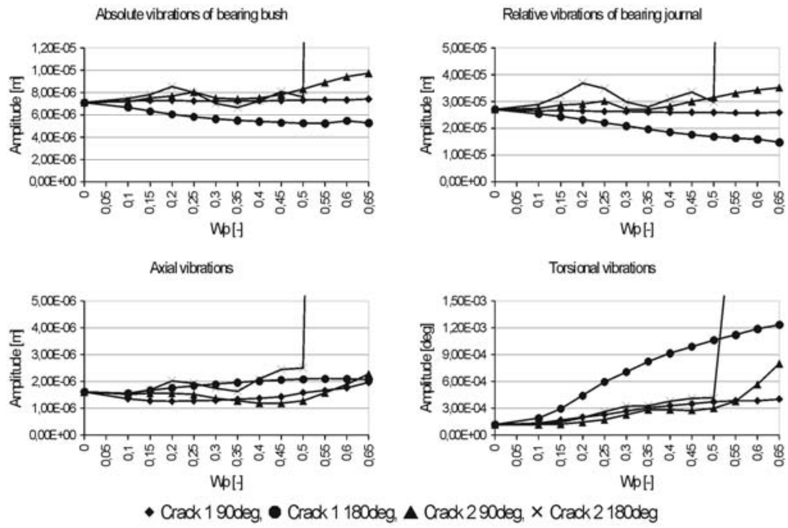


Fig. 9. The crack propagation influence on the machine dynamic state - amplitudes obtained for bearing No. 6 in selected cases

The analysis of fig. 9 leads to interesting conclusions. In some cases we can find some local resonances of bending vibrations for W_P=0.2-0.25. In other cases, bending vibrations doesn't exhibit such a phenomenon. They may even decrease. On the other hand, torsional vibration are the most sensitive to the crack. Their increase is the largest – in the case of CR2, α_P=180^O they increase over 30 times (not shown on the drowing because of the scale).

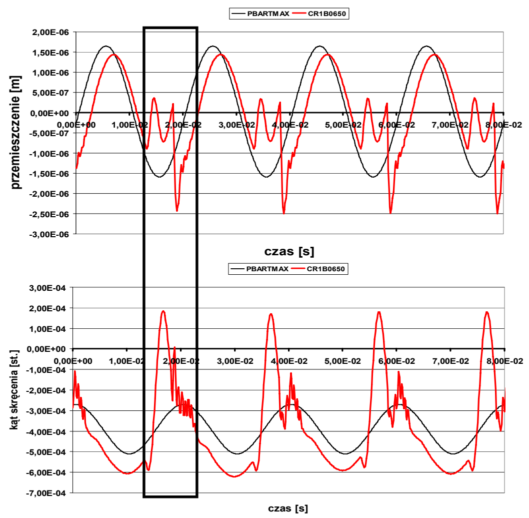


Fig. 10. The frame points the unsettled movement in axial (upper diagram) and torsional directions (lower diagrm) vibrations in bearing No.6 testifying coupling causd by crack. PBARTMAX – machine without defect, CR1B0650 – crack case No.1 (CR1), α_P=90^O, W_P=0.65

It also have to be pointed the crack causes coupled vibrations. Fig. 10 shows time histories of axial and torsional vibrations of bearing No.6 (journal vibrations). Correlation between axial and torsional vibrations (fig. 9) testifies some kind of coupling and identifies crack presence rather clearly.

4. CLOSING REMARKS

At the Institute for Mechanical Engineering Problems NASU a technique of determination of residual non-elastic deformations and residual displacements in shaft couplings by marks distributed along the shaft line at torsional strains is developed and validated experimentally. Experimental investigations have shown that for the turbo-set T250/300-240 the twisting angle changes proportionally the power variation on the turbo-set shaft with the ratio of 10 angular minutes per 100 MW.

Finally, investigations carried out, informational-diagnosing data collected during a number of years of turbo-sets vibration state analysis and diagnosing system operation and a technique of dangerous damages determination permit to obtain initial data for operative warning on dangerous faults propagation and for expert system of increased vibrations reasons determination that represents the next step of the described diagnosing systems development.

REFERENCES

[1] Б. Т. Рунов.: *Исследование и устранение вибрации паровых турбоагрегатов*– М.: Энергоиздат, 1982.– 351 с.

[2] Н. Г. Шульженко, В. П. Билетченко, А. М. Ганжа: *Влияние расцентровки опоры на колебания и устойчивость валопровода* Вестн. ХГПУ. Динамика и прочность машин. Харьков, 1999. Вып. 53. С. 70–71.

[3] Н. Г. Шульженко, А. М. Ганжа, Ю. Г. Ефремов: *Спектральные характеристики вибропереме-щений валопровода при просадке опоры и раскрытии полумуфт* Пробл. машиностроения. 2000. 3, № 1–2. С. 77–82.

[4] Н. Г. Шульженко, Г. Б. Овчарова: *Влияние излома упругой оси ротора с поперечной трещиной на его вибрационные характеристики* Пробл. прочности. 1997. № 4. С. 82–89.

[5] Н. Г. Шульженко, Ю. С.: Воробьев *Численный анализ колебаний системы турбоагрегат-фундамент-основание* Киев: Наук. думка, 1991.– 232 с.

[6] А. С. Гольдин *Вибрация роторных машин* М.: Машиностроение, 2000.– 344 с.

[7] Н. Г. Шульженко, В. П. Билетченко, Л. Д. Метелев, В. И. Цибулько, Ю. Г. Ефремов, А. А. Беспрозванный, Н. И. Вова *Аппаратное обеспечение системы непрерывного вибромониторинга роторных агрегатов* Энергетика и электрификация. 2000. № 7(204). С. 35–38.

[8] Н. Г. Шульженко, Л. Д. Метелев, В. И. Цыбулько, А. И. Чугреев, Ю. Н. Гуров, Ю. Г. Ефремов: *Помехоустойчивые измерители вибрации. Вибрация машин: измерение, снижение защита*: Материалы 2-й Междунар. науч.-техн. конф. Донецк: ДонНТУ, 2004. С. 35–39.

[9] Н. Г. Шульженко, Л. Д. Метелев, В. И. Цыбулько, Ю. Г. Ефремов: *Помехоусто-йчивые измерители вибрации и их применение в динамике машин. Вибрации в технике и технологиях*. 2005. № 2(40). С. 104–107.

[10] N. G. Shulzhenko and Yu. G. Efremov: *Influence of operational modes of a powerful turboset on its vibrational state*/ Transactions of the Institute of fluid-flow Machinery: Selected papers from the International Conference on Turbines of Large Output. Gdańsk, 2003. P. 147–153.

[11] Н. Г. Шульженко, Ю. Г. Ефремов: *Разработка методики автоматизированной оценки влияния режимных факторов на вибрационное состояние турбоагрегата* Пробл. прочности. 2004. № 1. С. 147–156.

[12] Н. Г. Шульженко, Ю. Г. Ефремов, А. М. Ганжа: *Идентификация стержневых моделей валопроводов по данным экспериментальных исследований* Пробл. машиностроения. 2002. № 4. С. 67–71.

[13] М. Г. Шульженко, Л. Д. Мєтєльов, Ю. Г. Єфремов, В. Й. Цибулько: *Технології діагностування вібраційного стану багатоопорних роторних агрегатів* Автоматизація виробничих процесів у машинобудуванні та приладобудуванні. – Львів: Нац. техн. ун-т "Львівська політехніка", 2006. № 40. С. 296–305.

[14] Н. Г. Шульженко, Л. Д. Метелев, Ю. Г. Ефремов, В. И. Цыбулько: *Обеспечение надежности и ресурса энергетических турбоагрегатов использованием системы диагностики вибраций и предупреждения нештатных ситуаций*/ Энергетика и электрификация. 2004. № 5. С. 41 – 43.

[15] Н. Г. Шульженко, Л. Д. Метелев, Ю. Г. Ефремов, В. И. Цыбулько: *Анализ и диагностирование вибрационного состояния мощных турбоагрегатов* Енергетика та електрифікація. 2006. № 11. С. 30–38.

[16] Н. Г. Шульженко, Л. Д. Метелев, В. И. Цыбулько, Ю. Г. Ефремов: *Методика определения параметров крутильных деформаций роторов турбоагрегатов* Датчики и системы. 2004. № 1. 30–31.

[17] М. Г. Шульженко, Л. Д. Мєтєльов, В. Й. Цибулько, Ю. Г: Єфремов *Оцінка крутильних деформацій роторів агрегатів* Вібрації в техниці та технологіях.– Вінниця. 2006. № 1(43). С. 149–151.

[18] Haas G.: *Großchäden durch Turbinen-oder Generator-läufer, enstanden in Bereich bis zur Schlenderdrehzahl* Der Maschinen Schaden. 1977. 50, № 6. P. 195–204.

[19] B. Grabowski, O. Mahrenholtz: *Theoretical and experimental investigating of shaft vibrations in Turbo machinery excited by cracks* Energia Electrica. 1982. 59, № 10. P. 507–514.

[20] Kicinski J.: *Rotor Dynamics* The IFFM Pub-lisher, Gdansk 2006.

[21] Knott J. F.: *Fundamentals of fracture mechanics*, Butterworths, London 1973.

[22] Ostachowicz W. M., Krawczuk M.: *Coupled torsional and bending vibrations of a rotor with an open crack.* Archive of Applied Mechanics, 62 (1992), pp.191-201.

GIGACYCLE FATIGUE AT HIGH-FREQUENCY LOADING

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Summary

In this work there are information about an experimental high-frequency testing apparatus and specimens enable to determine the fatigue properties in the ultra-high-cycles region (gigacycle fatigue) and the rates of long fatigue cracks growth in near-threshold areas. The selected characteristic examples about fatigue resistance of various structural materials are presented. The results are utilizable in the field of material engineering and threshold states of material.

Keywords: gigacycle fatigue, high-frequency loading, structural materials.

1. INTRODUCTION

At the actual operation, the components and construction are mainly loaded by repeating loading that could lead to the ultimate state, fatigue fracture in the final consequence. If it is assumed that the structural material will be repeatedly cyclically loaded in the operation, then it will be necessary to determine very complex fatigue characteristics for the given operation conditions [1]. To determine the fatigue characteristics there is usually realized the determination using normal frequencies, in the range from f ≈ 10 Hz to f ≈ 200 Hz, that is very time demanding and expensive. This statement emphasizes the fact, that fatigue fractures occur even after billion cycles and more [2, 3] and the stated, conventional criteria [4] do not fulfill the requirements for the safety and evaluation of components and constructions lifetime. Bathias, G. [5], Sakai, T. et all [6], Masuda, C. et al. [7], Naito, T. et al. [8], Bathias, G. and Bonis, J. [9], Asami, K. and Hironaga, M. [10], Bokůvka, O. and Nový, F. et al. [11-14] stated f. e. the decreasing of the fatigue characteristics, dependence stress amplitude (σ_a) vs. number of cycles (N) beyond conventional limit of cycles ($10^6 < N < 10^7$ cycles) in structural materials. Recently, the material research has been oriented on the questions of the verification of fatigue properties in the gigacycle regimes of loading ($10^7 < N < 10^{11}$ cycles); there have been developed the new testing apparatus, methods and techniques with the aim to achieve the experimental data in the ultra-high-cycles region, there are monitored the rates of the long fatigue cracks growth in near-threshold areas to $da/dN = 10^{-12} \div 10^{-13}$ m.cycle^{-1} [1, 3, 5, 15-18]. One of the possible directions is the application of experimental methods of high-frequency cyclic loading (f ≈ 20 kHz) to determination of the fatigue properties in structural materials. These experimental methods are progressive without question, with a wide future application, they are very time and economically effective [15-19].

2. TESTING APPARATUS AND SPECIMENS

The unique experimental testing apparatus of acoustic fatigue KAUP-ZU, KAUP-LM-ZU (at the working centres of the paper authors) enable to determine these fatigue characteristics – dynamic modulus of elasticity E_D, fatigue lifetime $\sigma_a = f(N)$ in the region from $N = 10^4$ to $N = 10^{11}$ cycles of loading, rate of long fatigue crack growing in dependence on stress intensity factor amplitude ($(da/dN = f(K_a))$, threshold values K_{ath} at $da/dN = 10^{-12} \div 10^{-13}$ m.cycle^{-1}. The applied high-frequency cyclic loading (frequency ≈ 20 kHz) has usually sinus character, fully reversed push-pull loading with the stress ratio R = -1 and the temperatures usually T = 20 ± 10 °C [15-18]. The testing apparatus KAUP-ZU is in Fig. 1.

The tested specimens with the shape and the general parameters are in Fig. 2 and Fig. 3. These specimens were proved successfully to investigating the fatigue lifetime $\sigma_a = f(N)$ on the testing apparatus KAUP-ZU and the testing apparatus KAUP-LM-ZU to investigate the long fatigue cracks growth rate in the dependence of the factor stress intensity amplitude ($(da/dN = f(K_a))$ incl. the threshold value K_{ath} [15-18]. To fulfill the resonance conditions the specimen with their parameters including cross-sections, by the given testing structural material and its acoustic properties, must suit to certain conditions [20]. For the entry experiment planning it is important to consider the initial parameters, diameter D = 12 mm, length L ≈ 80 mm in the case of specimen (Fig. 2) and diameter D = 16 mm, length L ≈ 80 mm in the case of specimen (Fig. 3).

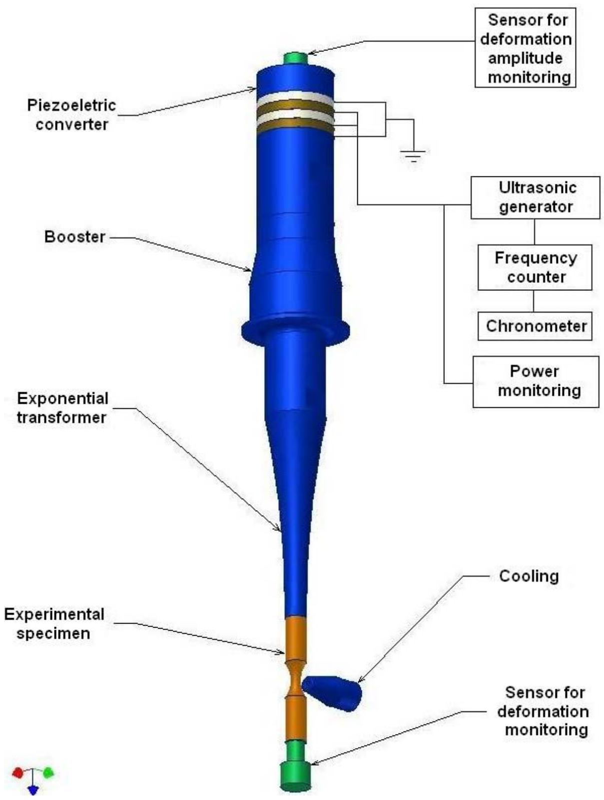

Fig. 1. The testing apparatus KAUP-ZU

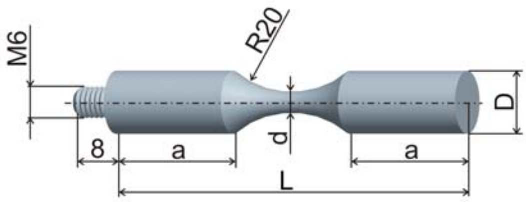

Fig. 2. The shape and general parameters of the specimens to determine $\sigma_a = f(N)$

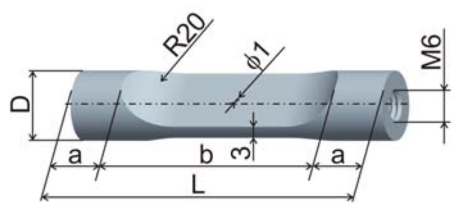

Fig. 3. The shape and general parameters of the specimens to determine $da/dN = f(K_a)$ and K_{ath}

3. APPLICATIONS

In the coarse of more than 30-years there were solved the tasks related with the methods and processes by high-frequency cyclic loading applications [15-18, 21-26] and in the last 10-years an interest is especially dedicated to gigacycle regimes of loading. The fatigue lifetime of various structural materials (steels incl. biomaterials, austempered ductile irons, Mg and Al alloys, brasses, …) respecting the external and internal influences was experimentally obtained [11-14, 27-30]. Selected characteristic examples from the ultra-high-cycles region and long fatigue crack growth rate are presented bellow (see Fig. 4 - Fig. 8).

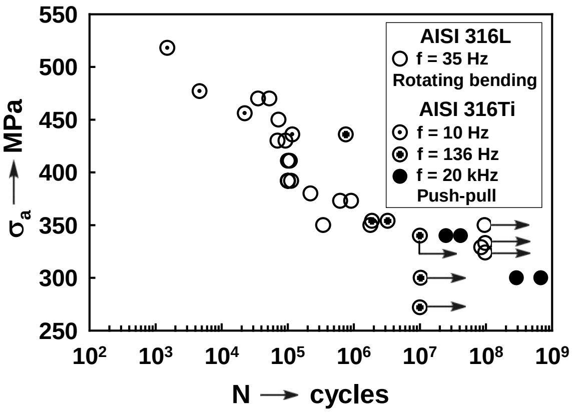

Fig. 4. Fatigue lifetime of AISI 316L and AISI 316Ti austenitic stainless steel

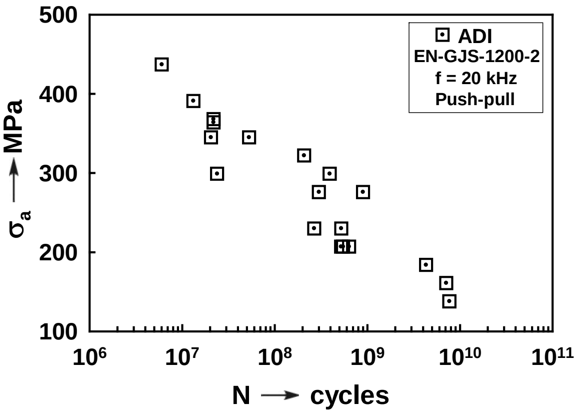

Fig. 5. Fatigue lifetime of EN-GJS-1200-2 ADI (Austempered Ductile Iron)

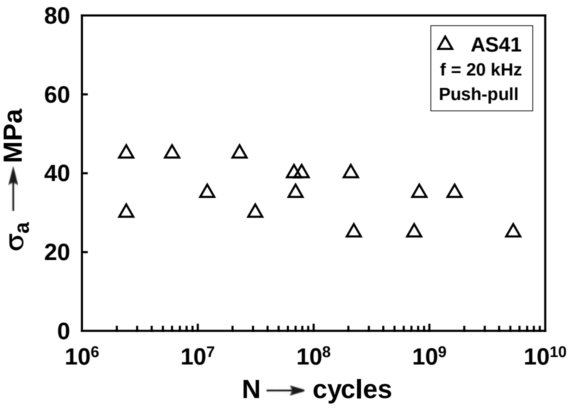

Fig. 6. Fatigue lifetime of AS 41 Mg-alloy

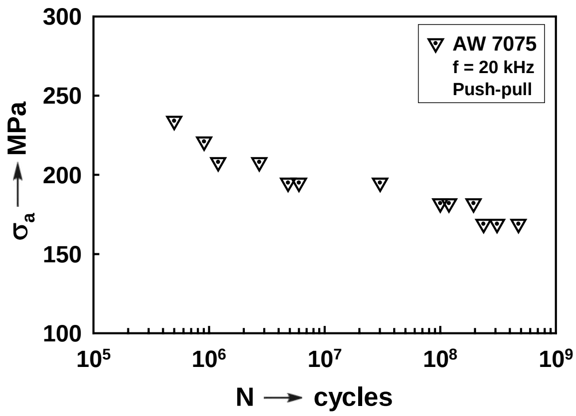

Fig. 7. Fatigue lifetime of AW 7075 Al-alloy

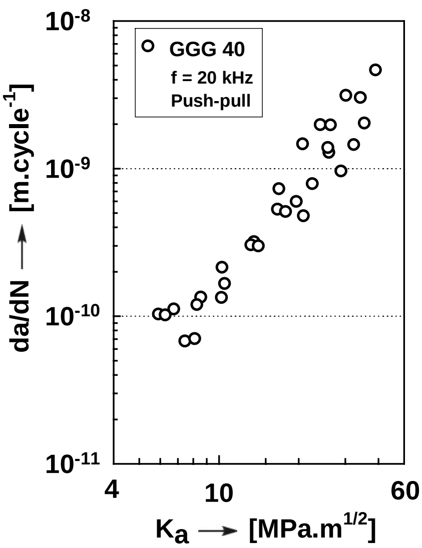

Fig. 8. Fatigue crack growth rate in nodular cast iron

4. CONCLUSION

The application of high-frequency cyclic loading (f ≈ 20 kHz) for the obtaining of fatigue characteristics in the ultra-high-cycles region and long fatigue crack growth in near-threshold areas is characteristic with the significant time, energy and work saving, the results are utilizable in the field of material engineering and threshold states of structural materials.

Acknowledgements

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BIBLIOGRAPHY

[1] Skočovský P. Bokůvka O., Konečná R., Tillová E.: *Náuka o materiáli pre odbory strojnícke*, EDIS ŽU, Žilina, 2006 (in Slovak).

[2] Marines I., Bin X., Bathias C.: International Journal of fatigue, Vol. 25, 2003, p. 1101.

[3] Bathias C.: Fat. Fract. Engng. Mater. Struct, Vol. 22, 1999, p. 559.

[4] Wőhler A. Z.: Bauw., 8, 642, 1858; 10, 583, 1860; 13, 233, 1863; 16, 67, 1866; 20, 74, 1870; Engineering, 11,199, 1871.

[5] Bathias C., Paris P. C.: *Gigacycle Fatigue in Mechanical Practice*, M. Dekker, New York, 2005.

[6] Sakai T. et al.: In Proc. 7th Int. Fatigue Congress, FATIGUE 99, Beijing, China, June, 1999, p. 573.

[7] Masuda C. et al.: Trans. JSME, Vol. 52A, 1986, p. 847.

[8] Naito T. et al.: Metal. Trans., Vol. 15A, 1984, p. 1431.

[9] Bathias C., Bonis J.: Fracture from Defects, Vol. 1, 1998, p. 321.

[10] Asami K., Hironaga M.: J. Soc. Mat. Sci., Japan, Vol. 43, 1994, p. 12.

[11] Kunz L., Lukáš P., Svoboda M., Bokůvka O.: *Materials Engineering*, Vol. 12, No. 3, 2005, p. 2.

[12] Bokůvka O., Nový F., Činčala M., Kunz L.: *Acta Mechanicca Slovaca*, Vol. 10, No. 1, 2006, p. 53 (in Slovak).

[13] Bokůvka O., Nový F., Činčala M., Chalupová M.: *Materials Engineering*, Vol. 14, No. 2, 2007, p. 1.

[14] Nový F., Činčala M., Kopas P., Bokůvka O.: *Materials Science and Engineering*, Vol. 462, No. 1-2, 2007, p. 189.

[15] Puškár A., Bokůvka O., Palček P., Meško J.: Strojírenství, 37, 9, 1987, p. 507 (in Slovak).

[16] Puškár A., Bokůvka O., Nicoletto G., Palček P.: Berichte und Informationen, Dresden, Germany, No. 1, 1997, p. 63.

[17] Puškár A.: Vyskofrekvenčná únava materiálov, EDIS Žilina, 1997, p. 322 (in Slovak).

[18] Puškár A., Bokůvka O., Nicolleto G., Palček P.: Strojniški Vestnik, Journal of. Mech. Engn., Ljubljana, Slovenia, Vol. 42, No. 11-12, 1996, p. 351.

[19] Mayer H.: Kovové materiály, 36, 23, 1998, p. 213.

[20] Salama K., Lamerand R. K.: In Proc. Ultrasonic Fatigue, *The Met. Soc. of AIME*, New York, 1982, p. 109.

[21] Bokůvka O., Puškár A., Nicoletto G.: In. Proc. 8th Danubia – *Adria Symposium, Experimental Methods in Solid Mechanics*, Gődőllő, Hungary, October, l99l, p. 36.

[22] Růžičková M., Bokůvka O., Palček P., Nicoletto G.: *Materiálové inžinierstvo*, č. 15, 6, 1999, p. 19 (in Slovak).

[23] Nicoletto G., Bokůvka O., Palček P., Růžičková M.: Materiálové inžinierstvo č. 18, 6, 1999, p. 9 (in Slovak).
[24] Bokůvka O., Nicoletto G.: In. Proc. 8th Int. Col. *Construction Materials, their Evoluation and Application in the Field of Transportation*, Žilina, SR, September, l99l, p. 88.
[25] Nicoletto G., Bokůvka O.: In. Proc. *Degradácia vlastností konštrukčných materiálov únavou*, Podjavorník, SR, November, l99l, p. 127.
[26] Janoušek M., Bokůvka O., Palček P. Nicoletto G.: In. Proc. Letná škola únavy materiálov 94, Rajecké Teplice, SR, September, l994, p. 158 (in Slovak).
[27] Bokůvka O., Nový F., Kunz L., Lukáš P.: In Proc. Životnost materiálů a konstrukcí 2006, ÚFM AV ČR Brno, CZ, 2006, p. 15 (in Slovak).
[28] Bokůvka O., Nový F., Činčala M., Bojanowicz P.: Berichte und Informationen, Dresden, Germany, No. 2, 2006, p. 11.
[29] Nový F., Bokůvka O., Kopas P., Chalupová M.: In. Proc. Improvement of Quality Regarding Processes and Materials 2007, Warszawa, PL, 2007, p. 71.
[30] Nový F., Bokůvka O., Chalupová M.: Materials Engineering, Vol. 15, No. 2a, 2008, p. 79.

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INFLUENCE OF NON-LINEAR ELEMENTS AS A SYMPTOM OF CHANGES IN TECHNICAL OBJECTS CONDITIONS[1]

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Summary

The processes of propagation of vibroacoustic energy can be modeled for use in technical condition assessment focusing only on their linear part; however, the model description will get closer to the real state if the non-linear elements are taken into account. Change of vibroacoustic signal, resulting from the ways of propagation of vibroacoustic energy having been modified as a direct result of a damage or wearing processes in technical object can be visible first of all in the amplitude spectrum.

It is confirmed by the results of model analysis compared to the results of studies of actual objects with modified parameters that non-linearity of a system is very important while considering and evaluating the technical state. It seems that the influence of non-linear elements reflected by spectral differences of vibroacoustic signal can be taken as a symptom of changes in the object's condition.

Key words: vibroacoustic signal; identification; vehicle.

EFEKTY ODDZIAŁYWANIA ELEMENTÓW NIELINIOWYCH JAKO SYMPTOM ZMIANY STANU

Streszczenie

Modelowanie procesów rozprzestrzeniania energii wibroakustycznej na potrzeby oceny stanu technicznego może ograniczać się do rozważenia części liniowej, niemniej lepsze przybliżenie opisu modelowego do rzeczywistości osiągnąć można z uwzględnieniem elementów nieliniowych. Zmiana sygnału wibroakustycznego będąca rezultatem modyfikacji dróg propagacji energii wibroakustycznej bezpośrednio spowodowanej uszkodzeniem bądź zużyciem eksploatacyjnym obiektu technicznego jest w szczególności dostrzegalna na widmie amplitudowym.

Rezultaty analiz modelowych zestawione z wynikami badań obiektów rzeczywistych o modyfikowanych parametrach potwierdzają znaczenie nieliniowości układu w rozważaniach dotyczących oceny stanu technicznego. Zasadna wydaje się teza, że odzwierciedlenie oddziaływania elementów nieliniowych różnicami widm sygnału wibroakustycznego może być traktowane jako symptom zmiany stanu.

Słowa kluczowe: sygnał wibroakustyczny, identyfikacja, pojazd.

1. INTRODUCTION

Considering real properties of technical objects, many simplifying assumptions have to be made. Modeling systems consisting of many interconnected continuous structures influencing each other seems unrealistic, same as obtaining accurate analytical solutions for such complex tasks. What can be done therefore is to apply simplified models, directed to the analysed phenomena and supported by empirical studies of real technical objects [1].

Studying real objects is extremely important for verifying intended properties of prototypical constructions. It is also impossible to optimize exploitation processes only on the ground of numerical simulations, passing over painstaking and expensive experimental studies. One of the main reasons is the non-linear phenomena present at almost every stage and usually impossible to be described in a very accurate way, nor to be accurately solved.

The classic approach to the problems of non-linear phenomena analysis consists in solving systems of one (maximum a few) degree of freedom, as well as in qualitative research. Developments in numeric technology have also allowed more extended application of approximate methods. However, it seems that the results useful in practice can be mainly obtained by compromise matching complexity of the model and the costs of empirical studies. The identification has proved to be

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a particularly useful tool, allowing for non-linear effects to be taken into account in considering a linear model.

2. BASES FOR IDENTIFICATION

The algorithms elaborated for evaluation of objects condition often use description based on the dynamic model. In general case it is the matrix equation of form:

$$\mathbf{M}\ddot{x}+\mathbf{C}\dot{x}+\mathbf{K}x=\mathbf{P}(t) \qquad (1)$$

where x symbolizes the generalized co-ordinate; **M** is the matrix of generalized masses; **C** – damping matrix; **K** – rigidity matrix; $\mathbf{P}(t)$ is the extortion vector. In practice, the matrix equation quoted above can be replaced with a system of differential equations solved in form of the function:

$$\mathrm{X}_i = f(t, m_1 \ldots m_n, k_1 \ldots k_n, c_1 \ldots c_n) \qquad (2)$$

If in the time moment t the measured value of the co-ordinate is $\mathbf{X}_{mi}(t)$, while the equation (2) result is $\mathbf{X}_i(t)$, then the error of model can be defined by the following relationship:

$$\mathrm{X}_{mi}(t) - \mathrm{X}_i(t) = \Delta\mathrm{X}(t) \qquad (3)$$

Parametrical identification consists in choosing the correction coefficients in all the equations of form (2) resulting in the minimum possible error of model description:

$$\left(\bigwedge_{t\in T} \mathrm{X}_{mi}(t) - \mathrm{X}_i(t, m_i, k_i, c_i) \to \min. \right) \Rightarrow m_i, k_i, c_i \qquad (4)$$

Obviously, one equation of form (2) and one point in the observation space allow for definition of only one parameter in identification process.

An important information carrier in the process of evaluation of condition of a technical object is vibroacoustic signal produced as a result of the processes carried out by its particular elements and units. Damages and wearing effects modify propagation paths of vibroacoustic energy and the process should be translated into changes in the signal registered by a receiver. If we assume that the receiver is registering the signal y*(t)* resulting from the system's response to the input x*(t)*, then in the frequency domain the Fourier transform of received output signal Y(*f*) will have the following form [2]:

$$\mathrm{Y}(f) = \mathrm{X}(f)\cdot \mathrm{H}(f)\cdot \Phi^*(f)\cdot \Psi^*(f) \qquad (5)$$

$\mathbf{X}(f)$ is the Fourier transform of input; $\mathbf{H}(f)$ is the transmittance of propagation path; $\mathbf{\Psi^*}(f)$ – exterior disturbances (noise). This description allows for identification of the element $\mathbf{\Phi^*}(f)$ representing non-linear influences in order to estimate its value. Considering the linear phenomena its value equals one.

Taking into account characteristics of the processes under scrutiny, as well as substantial absolute differences in analysed numeric values, the relationship (5) can be submitted to double-sided operator transformation and take the logarithmic form, being used all the time for analyzing decreases of levels [3]:

$$\mathrm{L}(f) = \mathrm{L_s}(f) + \Delta\mathrm{L_h}(f) + \Delta\Phi^*(f) + \Delta\Psi^*(f) \qquad (6)$$

In this relationship $\mathbf{L}(f)$ means the level of output signal; $\mathbf{L_s}(f)$ – the level of input signal; $\Delta\mathbf{L_h}(f)$ reflects the decreasing/increasing level as a consequence of system transmittance; $\Delta\mathbf{\Psi^*}(f)$ represents the description error, or the change resulting from random disturbances. The change of level at the output, provoked by the non-linear disturbances has been denoted as $\Delta\mathbf{\Phi^*}(f)$. The influence of these effects in dynamic system on the form of output signal, analysed as summing up of the levels has been shown in diagram in the Figure 1.

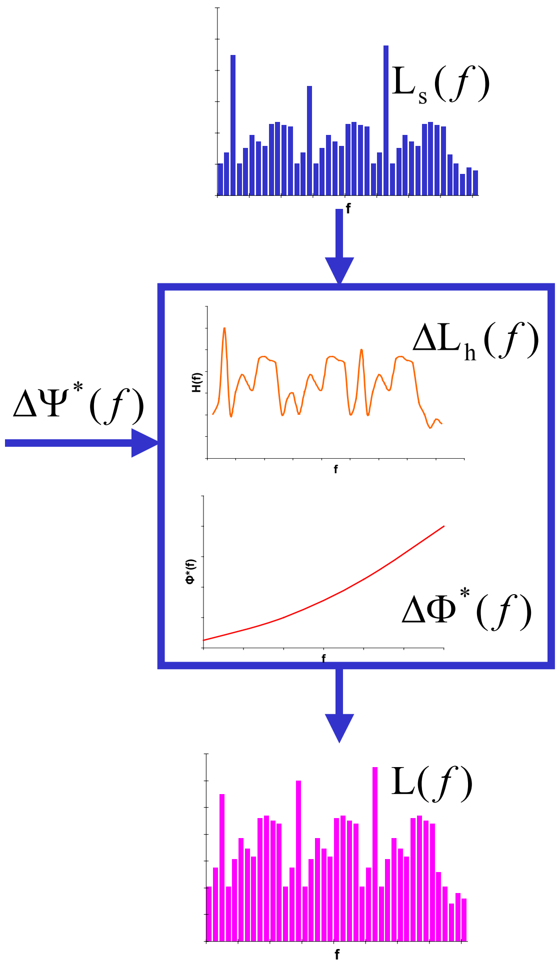

Fig. 1. Influence of the effects in dynamic system on the form of output signal

Identification in the frequency domain can be brought to definition of the correction vector $\mathbf{\Delta}(f)$ and the operator $\mathbf{\Phi}$ the product of which expresses the error of model for specific frequencies:

$$\Phi \cdot \Delta(f) = \mathrm{Y}_{i_m}(f) - \mathrm{Y}_i(f) \qquad (7)$$

The correction coefficient **Φ** and the correction vector are selected in such a way as to minimize the errors of model in the given frequency range:

$$\left(\bigwedge_{f \in F} \mathrm{Y}_{mi}(f) - \mathrm{Y}_i(f) \to \min. \right) \Rightarrow \Phi, \Delta(f) \quad (8)$$

$\mathbf{Y}_{mi}(f)$ is the solution for a model of actual frequency f, while $\mathbf{Y}_i(f)$ means the value of this particular component of real signal.

3. THE RESULTS OF EXPERIMENT

It is generally known that the acoustic signal of a vehicle carries a lot of information concerning its technical condition. Isolating in the spectrum of noise in the cabin the effects triggered by the elements of non-linear characteristics, modifying the propagation of vibroacoustic energy, does not seem a very difficult task either.

A diagnostic experiment with an electricity powered vehicle consisted of recording vibrations of the power unit and noise in the cabin of the vehicle in motion. The object was tested in two different states: with the power unit fixed directly to the supporting structure, and fixed with the elements of non-linear flexibility characteristics.

The analysis was based on the relationship (6), stressing the basic inputs generated by the most important units: the electric engine, the toothed gear and the chain transmission. The approach is justified by the form of amplitude spectrum of level of acoustic pressure in the cabin: what is dominating there it is the stripes (in the Figure 2 marked with circles) of components of frequencies resulting from work of the units.

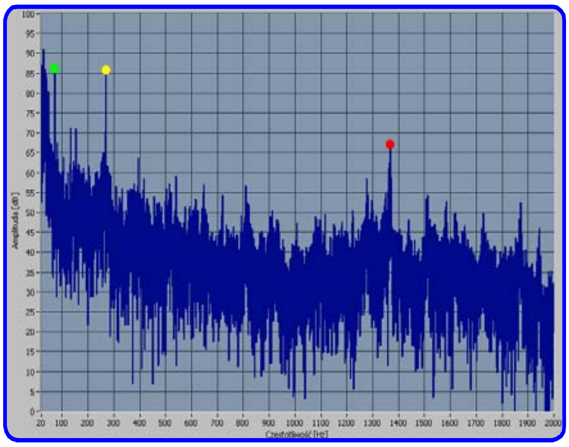

Fig. 2. Spectrum of noise in the cabin

Level of acoustic pressure in the vehicle cabin taken as the response of system to the vibrations of power unit (the amplitude spectrum of level of accelerations has been shown in the Figure 3) can be used in determining transmittance (understood as level increase/ decrease) for particular components.

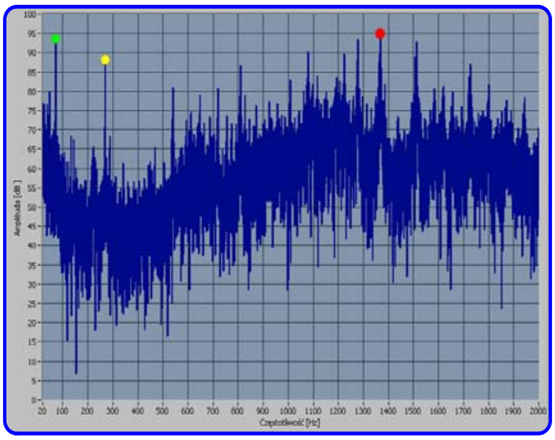

Fig. 3. Spectrum of acceleration of vibrations in the power unit

However, it seems that the procedure just described does not fully do for forecasting the form of outcome signal after the object's condition has changed, if the change is related to elements of non-linear characteristics. Smaller non-linearity can be decomposed into components of linear characteristics, and as a result particular input components can be replaced with vectors of co-ordinates p_i submitted to transmittances of linear character $\mathbf{H}_{i_{lin}}$ [3]. The resultant is therefore the result of summing the linear components up:

$$\mathrm{Y}(f) = \sum p_i \, \mathrm{H}_{i_{lin}} \quad (7)$$

Because of technical realities approximate description of systems with non-linear effects consisting in summing the linear components up results in many cases in solutions differing from reality, while the identification of model gives plausible results only within the area directly adjacent to the real object used in the identification process. Then, the components resulting from non-linear transmittance of the system can be easily shown in the spectrum [4].

These remarks let us to the conclusion that the influence of non-linear elements resulting in changes of spectrum of vibroacoustic signal can be taken as symptoms of changes in conditions of a technical object. It has been confirmed by the experimental studies of an electricity powered vehicle when condition of the object was changed by replacing the metal mounting sleeve of power unit with metal-rubber elements of non-linear flexibility characteristics.

The result of modification is illustrated by the spectrum of level of acoustic pressure in the cabin represented in the Figure 4. Decreasing level of amplitudes of the main input components can be forecasted by applying the relationship (6), taking damping properties of rubber-metal elements expressed by the decreasing level $\Delta\mathbf{L}_h(f)$ resulting from the system transmittance.

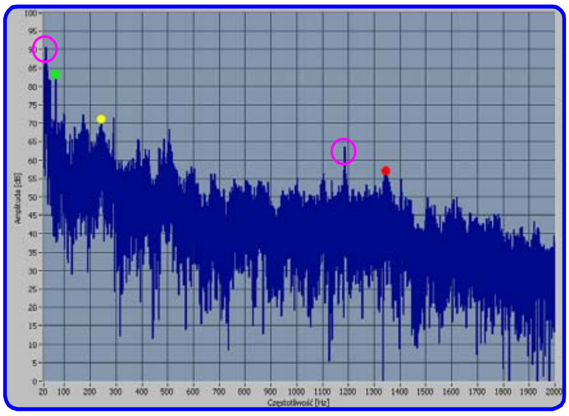

Fig. 4. Spectrum of noise in the cabin: state with elements of non-linear characteristics

Interpretation of relatively high level of components of the spectrum marked with circles results the most difficult task. The fact that the low frequency sounds are not being damped can be an indication that this particular area cannot be considered as a systemic response to the input by working power mechanisms but rather to some exterior disturbances $\Delta\Phi^*(f)$. High level of amplitude of components exceeding 1200 Hz is resulting from non-linear flexibility characteristics of rubber-metal sleeves used for alternating the object's condition. These spectrum characteristics result from influence of non-linear elements and can be taken as a symptom suggesting changes in condition of technical object.

4. CONCLUSION

The above remarks are part of broader study on methodology of using the information contained in vibroacoustic signal for monitoring vehicles condition, as well as in environmental noise management. The analysed object – prototype electricity powered vehicle – was chosen because of its ecological qualities that make us strongly consider future development of this group of individual transport means.

Due to the fact that non-linearity affects the majority of real processes we cannot omit it while considering evaluation of objects condition. Vibroacoustic signal treated as information carrier reaches the receiver in form of a resultant shaped also by non-linear elements. However, if a deep, detailed analysis of their role is usually not possible, the way they affect the system can be quite easily determined. The effects of non-linear elements visible in the spectrum of vibroacoustic signal reflect changes in condition of a technical object.

REFERENCES

[1] Dąbrowski Z.: *Modeling and identification of nonlinear system for technical diagnostics*. The 8th International Congress on Sound and Vibration, Hong Kong, China, 2001, pp. 1083÷1090.
[2] Dąbrowski Z., Radkowski S., Dziurdź J., Dybała J., Mączak J., Tomaszek S.: *Kształtowanie właściwości wibroakustycznych elementów i zespołów maszyn (uwagi metodyczne)*. Warszawa 2000 (ISBN 83-912190-4-6).
[3] Klekot G.: *Ocena wpływu elementów nieliniowych na propagację energii wibroakustycznej*. Przegląd Mechaniczny, nr 11/07 Warszawa 2007, 30÷32.
[4] Dąbrowski Z., Dziurdź J., Klekot G.: *Studies On Propagation Of Vibroacoustic Energy And Its Influence On Structure Vibration In A Large-Size Object*. Archives Of Acoustics 32, 2, 203 – 212 (2007).
[5] Klekot G.: *Selected Diagnostic Aspects Of Propagation Of Vibroacoustic Energy*. Diagnostyka, Vol. 4(44)/2007, str. 53-56.

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MATHEMATICAL MODELING OF NONSTATIONARY PROCESSES IN ENGINE AGGREGATES OF MUD PUMPS

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Summary

The mathematical model of dynamic processes in the engine aggregate of the mud pump with the operating friction clutch is offered. Inconstancy of reduced moment of inertia of crank mechanism of the pump and also interrelation of electromagnetic effects in asynchronous engine with non-linear oscillations of mechanical system are taken into account. The integration of system of the differential equations of movement of pump is realized by numerical methods.

Keywords: mud pumps, engine aggregates, nonstationary processes, mathematical modeling.

1. THE ANALYSIS OF RESEARCHESAND PROBLEM DEFINITION

The pumping aggregate of a drilling rig is one of primary elements of circulating system. Effectiveness of lifting of drilled solids depends on reliability of its functioning. Uninterrupted feed of flush fluid into borehole is important requirement for system functioning, because the temporary stopping of feed can cause heavy failure - sticking of drilling string as a result of a settling of slime and heavy fractions of a mud. It causes necessity of a raise of a technical level of mud pumps and their driving systems.

The drive of mud pump is realized by explosion engine or the electric engine through operating friction clutch, belting and tooth gear. With the purpose of definition of loads and prediction of fastness and durability of elements of drive appears a problem of execution of comprehensive analysis of nonstationary operating modes of a pumping aggregate. The theory of mud pumps is stated in transactions [2, 3, 7].

General methodology of modeling of electroconductive systems is enough completely stated in transactions [1, 6], examples of mathematical modeling of electromechanical systems which include asynchronous engine, reducing gear and operating mechanism – in transactions [5, 8]. In monograph [4] is offered method of calculation of nonstationary processes in engine aggregates of mud pumps, which one is grounded on combined integration of differential equations of movement, which are composed taking into account inconstancy of reduced moment of inertia of crank mechanisms of the pump, and equations of electromagnetic processes in asynchronous engine.

In this paper is offered mathematical model of dynamic processes in a pumping aggregate with any amount of pistons and with the operating friction clutch, which is composed taking into account inconstancy of reduced moment of inertia of crank mechanisms of the pump and continuity of interrelation of mechanical and electromagnetic oscillating appearances.

2. THE DIFFERENTIAL EQUATIONS OF MOVEMENT OF PUMPING AGGREGATE

The mechanical system of pumping aggregate, which consists of asynchronous engine, air clutch, belting, reducing gear and piston pump, is schematically represented on fig. 1.

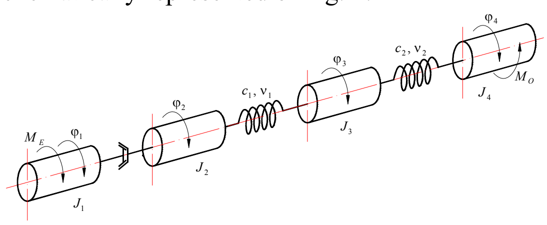

Fig. 1. The computation scheme of mechanical system of pumping aggregate

There are such designations on the scheme: J_1 – the reduced moment of inertia of rotor of the electric engine with driving part of air clutch; J_2 – the reduced moment of inertia of driven part of air clutch with shaft and with driving pulley of belting; J_3 – the reduced moment of inertia of transmission shaft with pinion and with driven pulley of belting; J_4 – the reduced moment of inertia of crank mechanism of the pump; c_1 – the reduced rigidity of V-belts; ν_1 – the reduced damping coefficient of V-belts; c_2 – the reduced rigidity of reducing gear; ν_2 – the reduced damping coefficient of reducing gear; M_E – the reduced electromagnetic moment of engine; M_O – the moment of forces of resistance to movement which acts on mainshaft of pump; φ_1, φ_2, φ_3, φ_4 – reduced angular coordinates. Inertial and elastic-dissipative characteristics we result in to the mainshaft of the pump.

The equation of movement of elements of aggregate we compose under the scheme of the equation of Lagrange of the second sort

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_j}\right)-\frac{\partial T}{\partial q_j}+\frac{\partial \Pi}{\partial q_j}+\frac{\partial \Phi}{\partial \dot{q}_j}=Q_j \quad (j=1,4), \quad (1)$$

де where T and Π – kinetic and potential energies of mechanical system; Φ – dissipation function of the Rayleigh; Q_j – the generalized force; q_j – the generalized coordinate; t – time.

Accepting for generalized coordinates such magnitudes

$$q_1=\varphi_1; \quad q_2=\varphi_2; \quad q_3=\varphi_3; \quad q_4=\varphi_4, \quad (2)$$

kinetic energy of system we give in such form

$$T=\frac{J_1\omega_1^{\,2}}{2}+\frac{J_2\omega_2^{\,2}}{2}+\frac{J_3\omega_3^{\,2}}{2}+\frac{J_4\omega_4^{\,2}}{2}, \quad (3)$$

where ω_1, ω_2, ω_3, ω_4 – reduced to mainshaft the angular velocity of rotor of the electric motor, angular velocity of the half-coupling, which is coupled to driving pulley of belting, angular velocity of the high-speed shaft of the reducer, which is connected to driven pulley of belting, and real angular velocity of mainshaft of the pump,

$$\frac{d\varphi_1}{dt}=\omega_1, \frac{d\varphi_2}{dt}=\omega_2, \frac{d\varphi_3}{dt}=\omega_3, \frac{d\varphi_4}{dt}=\omega_4. \quad (4)$$

Potential energy and dissipation function of the Rayleigh, taking into account (2) and (4), we give in such view

$$\Pi=\frac{c_1(\varphi_2-\varphi_3)^2}{2}+\frac{c_2(\varphi_3-\varphi_4)^2}{2};$$

$$\Phi=\frac{\nu_1(\omega_2-\omega_3)^2}{2}+\frac{\nu_2(\omega_3-\omega_4)^2}{2}. \quad (5)$$

For operating mode, when there is slippage in air clutch, finding derivatives from (3) and (5) and substituting them in the equations of Lagrange of the second sort (1), we gain the equations of movement in such form

$$J_1\frac{d\omega_1}{dt}=M_{E з}-M_T;$$

$$J_2\frac{d\omega_2}{dt}=M_T-c_1(\varphi_2-\varphi_3)-\nu_1(\omega_2-\omega_3);$$

$$J_3\frac{d\omega_3}{dt}=c_1(\varphi_2-\varphi_3)+\nu_1(\omega_2-\omega_3)-$$
$$-c_2(\varphi_3-\varphi_4)-\nu_2(\omega_3-\omega_4);$$

$$J_4\frac{d\omega_4}{dt}=-\frac{1}{2}\frac{\partial J_4}{\partial \varphi_4}\omega_4^{\,2}+$$
$$+c_2(\varphi_3-\varphi_4)+\nu_2(\omega_3-\omega_4)-M_O, \quad (6)$$

where M_T – reduced to mainshaft the friction torque in air clutch, which varies according such law:

$$M_T=\alpha_t\cdot t, \quad \text{as} \quad t<t_r;$$

$$M_T=\alpha_t\cdot t_r, \quad \text{as} \quad t\ge t_r,$$

here t_r – a time of filling up of clutch; α_t – coefficient determined by dependence

$$\alpha_t=\frac{M_{T0}}{t_r},$$

where M_{TO} – maximal torque of friction in clutch.

The reduced moment of engine is receivable by formula

$$M_E=M_{E0}\cdot u, \quad (7)$$

where M_{EO} – real electromagnetic torque of engine; u – drive ratio.

If the slippage in operative air clutch is absent, elements with moments of inertia J_1 and J_2 realize combined movement. The equation of movement of system is receivable by substitution of expressions (3) and (5) in relation (1) provided that $\varphi_1=\varphi_2$,

$$\omega_1=\omega_2; \quad \varphi_1=\varphi_1(t_1)+\varphi_2(t)-\varphi_2(t_1);$$

$$(J_1+J_2)\frac{d\omega_2}{dt}=M_E-c_1(\varphi_2-\varphi_3)-\nu_1(\omega_2-\omega_3);$$

$$J_3\frac{d\omega_3}{dt}=c_1(\varphi_2-\varphi_3)+\nu_1(\omega_2-\omega_3)-$$
$$-c_2(\varphi_3-\varphi_4)-\nu_2(\omega_3-\omega_4);$$

$$J_4\frac{d\omega_4}{dt}=-\frac{1}{2}\frac{\partial J_4}{\partial \varphi_4}\omega_4^{\,2}+$$
$$+c_2(\varphi_3-\varphi_4)+\nu_2(\omega_3-\omega_4)-M_O. \quad (8)$$

Conversion from mode of movement with slippage to mode without slippage happens, if such demands are fulfilled

$$\omega_2=\omega_1 \text{ i } M_E-J_1\frac{d\omega_1}{dt}\le M_T. \quad (9)$$

If during system's movement without slippage in operative clutch in some instant the condition, which is expressed by second relation (9), is violated, then mode of movement again begins, that is accompanied by slippage.

During numeric integration of differential equations (4), (6) and (8) it is necessary to define at every step the derivative of the function J_4 regarding coordinate φ_4 and also the electromagnetic moment of engine M_E.

The reduced moment of inertia of pump's mechanism, which includes n crank mechanisms, we give in such form [5]:

$$J_{3B}(\varphi)=\sum_{i=1}^{n}\left[J_{S1}+m_1a_1^{\,2}+m_2u_i\frac{l_1^{\,2}(\cos\varphi_i)^2}{h_i}+\right.$$
$$\left.+J_{S2}\frac{l_1^{\,2}(\cos\varphi_i)^2}{h_i}+m_3\left(-l_1\left(\sin\varphi_i+\frac{l_1\sin 2\varphi_i}{2\sqrt{h_i}}\right)\right)^2\right], \quad (11)$$

where

$$h_i = l_2^{\ 2} - l_1^{\ 2}(\sin\varphi_i)^2,$$

$$u_i = \frac{h_i}{(\cos\varphi_i)^2} + a_2^{\ 2} - 2a_2\frac{h_i}{l_2} + 2a_2\frac{l_1\cdot(\sin\varphi_i)^2\cdot\sqrt{h_i}}{\cos\varphi_i\cdot l_2};$$

where φ_i (i = 1, 2, …, n) – angular coordinate of the driving element of crank mechanism – the crank; m_1, m_2, m_3 – masses, accordingly, of crank, of crank mechanism and of piston; J_{S1} i J_{S2} – central moments of inertia of crank and of connecting rod; l_1 and l_2 – linear dimensions of elements; a_1 – distance from center of mass of crank to its rotation axis; a_2 – distance from center of mass of connecting rod to its axis of joint with crank.

Turn's angles of driving elements of pump φ_i (i = 1, 2, ..., n) are linked with turn's angle of mainshaft of pump φ by such relations:

– for a simplex pump $\varphi_1 = \varphi$;

– for a 2-cylinder single direct-action pump $\varphi_1 = \varphi, \quad \varphi_2 = \varphi + \pi$;

– for a 2-cylinder bidirectional pump $\varphi_1 = \varphi, \quad \varphi_2 = \varphi + \pi/2$;

– for a 3-cylinder single direct-action pump $\varphi_1 = \varphi, \quad \varphi_2 = \varphi + 2\pi/3, \quad \varphi_3 = \varphi + 4\pi/4$.

Derivative $dJ_{3B}/d\varphi$ is receivable as sum of derivatives p_i from expression (11), and it depends on amount n of crank mechanisms of the pump and shift of turn's angles of driving elements of these mechanisms

$$\frac{dJ_{3B}}{d\varphi} = \sum_{i=1}^{n} p_i .$$

The moment of forces of useful resistance of mainshaft is receivable according to [5] by formula

$$M_O = \sum_{i=1}^{n} M_{Oi}, \tag{12}$$

where M_{Oi} – moment of forces of useful resistance, which is created by fluid pressure on i-th piston,

$$M_{Oi} = P_i l_1 \Theta_i, \tag{13}$$

where P_i – force of piston pressure, Θ_i – trigonometric function of turn's angle of crank.

For a bidirectional pump P_i is receivable by formula

$$P_i = -pF_n, \text{ if } v_i>0; \quad P_i = 0, \text{ if } v_i=0;$$

$$P_i = p(F_n - F_ш), \text{ if } v_i<0,$$

where F_n and $F_ш$ – cross-sectional areas of piston and rod, p – fluid pressure on piston; v_i – piston's speed

$$v_i = -\omega_2 l_1 \Theta_i . \tag{14}$$

Trigonometric function of turn's angle of crank Θ_i, which figures in associations (13), (14), has view

$$\Theta_i = \sin\varphi_i + \frac{\sin\varphi_i\cos\varphi_i}{\sqrt{\left(\frac{l_2}{l_1}\right)^2 - (\sin\varphi_i)^2}} .$$

Real electromagnetic torque of engine M_{E0} is receivable by equations of electromagnetic processes in asynchronous engine.

3. EQUATIONS OF ELECTROMAGNETIC PROCESSES IN ASYNCHRONOUS ENGINE

The differential equations of electromagnetic transients in an induction motor, tacking into account filling of magnetic conductor, are represented in such form [6]:

$$\frac{di_S}{dt} = A_S(u + \Omega_S\Psi_S - R_S i_S) + B_S(\Omega_R\Psi_R - R_R i_R);$$

$$\frac{di_R}{dt} = A_R(\Omega_R\Psi_R - R_R i_R) + B_R(u_S + \Omega_S\Psi_S - R_S i_S), \tag{15}$$

where i_S, i_R i u_S – matrixes-columns of currents and voltages; A_S, B_S, A_R, B_R – matrixes of links; Ω_S, Ω_R – matrixes of rotation frequencies; Ψ_S, Ψ_R – matrixes-columns of magnetic linkages. R_s, R_r – pure resistances of windings.

The index s specifies an inhering of magnitude to a stator winding, and r - to a rotor winding.

Matrixes-columns i_s, i_r and u_s are determined by means of dependences

$$i_j(j = S,\ R) = \mathrm{col}\,(i_{jx}, i_{jy}); \quad u_S = \mathrm{col}\,(U_m, 0),$$

where i_{jx}, i_{jy} – projections of currents to axes of coordinates x, y; U_m – a peak voltage of a network.

Square matrixes A_S, B_S, A_R, B_R are determined by dependences

$$A_S = \alpha_S(1 - \alpha_S G); \quad B_S = -\alpha_S\alpha_R G;$$

$$A_R = \alpha_R(1 - \alpha_R G); \quad B_R = B_S,$$

where:

$$G = \frac{1}{i_m^{\ 2}}\begin{bmatrix} Ri_x^{\ 2} + Ti_y^{\ 2} & (R-T)i_x i_y \\ (R-T)i_x i_y & Ti_x^{\ 2} + Ri_y^{\ 2} \end{bmatrix},$$

$$R = \frac{1}{\rho + \alpha_S + \alpha_R}; \quad T = \frac{1}{\tau + \alpha_S + \alpha_R}.$$

Here i_m, i_x, i_y – a current of magnetization and its components along x,y-*axes*; τ, ρ – the magnitudes determined on a curve of magnetization, representing dependence of working magnetic linkage Ψ_m on a current of magnetization; α_s, α_r – magnitudes, inverse to inductances of diffusing of stator windings and a rotor.

Matrixes of rotation frequencies:

$$\Omega_S = \begin{bmatrix} 0 & \omega_0 \\ -\omega_0 & 0 \end{bmatrix}; \quad \Omega_R = \begin{bmatrix} 0 & \omega_0 - \omega_R \\ \omega_R - \omega_0 & 0 \end{bmatrix},$$

where ω_0 and ω_r – synchronous angular velocity of the motor and angular velocity of the rotor, expressed in electric radians per second. Magnitudes ω_0 and ω_R have values

$$\omega_0 = 314\ ;\ \omega_R = \omega_1 \cdot u \cdot p_0\ ,$$

for second step:

$$\omega_R = \omega_2 \cdot u \cdot p_0\ ,$$

where u – drive ratio; p_0 – amount of pairs magnetic-poles.

Matrixes-columns of full magnetic linkages of stator windings and rotor look like:

$$\Psi_S = \frac{1}{\alpha_S} i_S + \frac{1}{\tau} i; \quad \Psi_R = \frac{1}{\alpha_R} i_R + \frac{1}{\tau} i,$$

where

$$i = \mathrm{col}\,(i_x, i_y).$$

Magnitudes

$$i_x = i_{Sx} + i_{Rx}\ ; \quad i_y = i_{Sy} + i_{Ry}\ ; \quad i_m = \sqrt{{i_x}^2 + {i_y}^2}\ .$$

Magnitudes τ and ρ are determined by dependences

$$\tau = \frac{i_m}{\psi_m}; \qquad \rho = \frac{di_m}{d\psi_m}.$$

The electromagnetic moment of the motor is discovered by formula

$$M_E = M_{E0} \cdot u = \frac{3}{2} \cdot u \cdot p_0 \frac{1}{\tau}\left(i_{Rx} i_{Sy} - i_{Ry} i_{Sx}\right).$$

If movement with slippage – $\omega_R = \omega_1 \cdot u$; if movement without slippage – $\omega_R = \omega_2 \cdot u$.

4. EXAMPLE OF CALCULATION

Let's consider the engine aggregate of mud pump У8-6М equipped by asynchronous engine АКЗ-15-41-8Б. As the reduced moment of inertia of moving parts of the pump is great, for launching the aggregate apply operative air clutch. At first operative clutch unlocks for pumping aggregate's activating and idle engine firing is carried out. The further acceleration of system occurs by gradual turning on the clutch. The moment of forces of useful resistance is receivable by formula (12). Engine's characteristic: amplitude of voltage U_m=4,9 kV; active resistances of phases of stator and rotor r_S=0,38 Ω, r_R=0,318 Ω; parasitic inductances $L_S=1{,}048 \cdot 10^{-2}$ H, $L_R=1{,}112 \cdot 10^{-2}$ H; operative inductance L_m=0,505 H; Amount of pairs magnetic-poles p_0=4; rotor's moment of inertia J_1=55 kg·m^2. Mud pump У8-6М is piston-like, 2-cylinder bidirectional pump and consists of driving and hydraulic parts, which are mounted on one frame. Angle between driving elements pump's crank mechanisms is 90° ($\varphi_1=\varphi$, $\varphi_2=\varphi+\pi/2$). Masses of elements: m_1=1000 kg, m_2=800 kg, m_3=420 kg; geometrical dimensions of elements: l_1 =0,2 m, a_1=0,13 m, l_2=0,85 m, a_2=0,25 m; central moments of inertia of crank and rod, accordingly, J_{S1}=42 kg·m^2, J_{S2}= 137 kg·m^2.

Initial conditions of integration of differential equations (4), (6), (15) for phase of acceleration of the pump by turning on operative clutch are such:

$$\omega_1(0) = 78{,}5\ ;\ \omega_2(0) = 0\ ;\ \omega_3(0) = 0\ ;\ \omega_4(0) = 0\ ;$$

$$\varphi_1(0) = 0\ ;\ \varphi_2(0) = 0\ ;\ \varphi_3(0) = 0\ ;\ \varphi_4(0) = 0\ ;$$

$$i_{Sx}(t) = 0{,}071\ ;\ i_{Sy}(t) = -30{,}27\ ;$$

$$i_{Rx}(t) = 6{,}777 \cdot 10^{-6}\ ;\ i_{Ry}(t) = 5{,}441 \cdot 10^{-6}\ .$$

Given here values of currents and angular velocity of rotor are gained after calculation of idle engine firing before steady mode.

As a result of combined numeric integration of differential equations of movement of mechanical system (4), (6) or (4), (8) and the equations, which present electromagnetic appearances in asynchronous engine (15), we gain temporal dependences of magnitudes ω_1, ω_2, ω_3, ω_4, of electromagnetic moment M_E, and also of torque M_{1c} and M_{2c} in elastic elements of aggregate, which are defined by dependences:

$$M_{1c} = c_1(\varphi_2 - \varphi_3) + \nu_1(\omega_2 - \omega_3)\ ;$$

$$M_{2c} = c_2(\varphi_3 - \varphi_4) + \nu_2(\omega_3 - \omega_4)\ .$$

Graphs, which are represented on fig. 2, illustrate temporal changing of angular velocity of rotor of the electric motor (*a*) and driving pulley of belting (*b*). As we can see, the rotor of the drive goes into the steady mode during acceleration of the pump, which is loaded by useful resistance, during incomplete three seconds. The time, during which angular velocities ω_1 and ω_2 are equalizing, essentially depends on the law of changing of friction torque in clutch M_T. Insignificantly oscillations of angular velocities of elements of mechanical system are caused by cyclic functioning of pumping aggregate. With increasing loading on pistons the amplitude of these oscillations essentially increases.

The curve, which is represented on fig. 3. (a), illustrates temporal changing of the electromagnetic moment of engine АКЗ-15-41-8Б during beginning of turning on air clutch before intromission of system in steady mode.

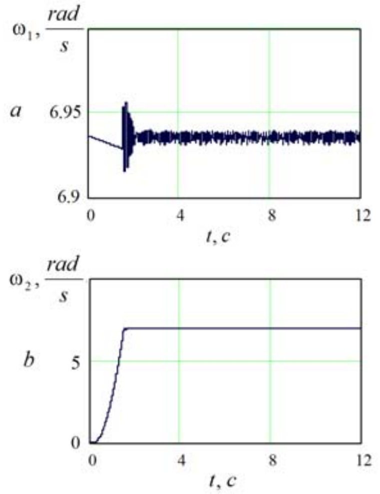

Fig. 2. Calculated dependences of angular velocity of rotor of the electric motor (a) and angular velocity of the half-coupling, which is coupled to driving pulley of belting (b)

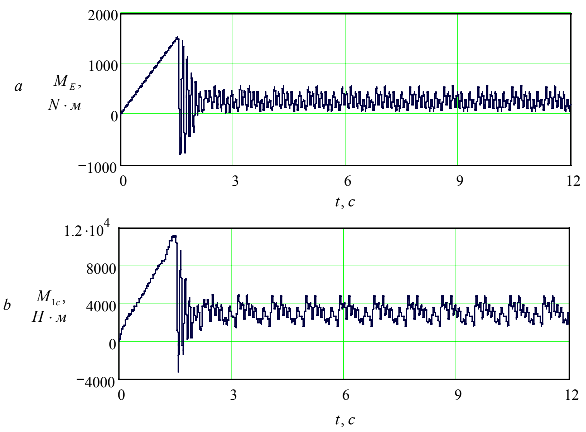

Fig. 3. Graphs of changing of electromagnetic moment of engine (a) and moment in belting (b) during gradual activation air clutch.

Curve, which is represented on fig. 3. (b), illustrates temporal dependences of torques in elastic elements of mechanism, that is in belting and tooth gear. Intensive oscillations of torques are caused by cyclic changing of load on piston and also great inertia of its elements.

SUMMARY

1. Created mathematical model enables to ensure necessary exactitude of strength analysis and prediction of resource of elements of pumping aggregate. By rational sampling of operating mode of drive system is possible considerably to decrease dynamic loads of its elements and to increase at the expense of it reliability of the engine aggregate.
2. The gained results allow to define rational performance of air clutch, namely, a friction torque in clutch M_T and fill-up time of clutch by air, which ensure enough acceleration of the aggregate under condition of limitation of loads of elements of the pump and its drive.

REFERENCES

[1] Вейц В. Л., Вербовой А. Ф., Кочура А. Е. *Динамика управляемого електро-механического привода с асинхронными двигателями.* Киев. Вища школа, 1988. 295 с.
[2] Ильский А. П., Миронов Ю. В., Черно-быльский А. Г. *Расчет и конструирование бурового оборудования.* – М. Недра, 1985. – 452 с.
[3] Николич А. С. *Поршневые буровые насосы.* Москва. Недра, 1973. 276 с.
[4] Харченко Е. В. *Динамические процессы буровых установок.* Львов. Свит, 1991. 176 с.
[5] Харченко Є. В., Ковальчук Р. А. *Розрахунок нестаціонарних процесів у насосному агрегаті бурової установки. Динаміка, міцність та проектування машин і приладів: Вісник Національного університету* «Львівська політехніка» № 539. Львів. Видавництво Національного університету «Львівська політехніка», 2005. С. 103–110.
[6] Чабан В. Й. *Методы анализа електро-механических систем.* Львов: Вища школа, 1985. 189 с.
[7] Юртаев В. Г. *Динамика буровых установок.* Москва. Недра, 1987. 155 с.
[8] Mudrik I. *Measurement of dynamic properties of machine aggregate with variable parameters and asynchronous motor.* J. Theor. and Appl. Mech. 1992. 23, № 1. P. 40–41.

DOPPLER'S EFFECT AS DIAGNOSTIC INFORMATION IN THE ACOUSTIC SIGNAL

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Summary

The paper presents a new concept of a diagnostic system supported by a model as well as relevant, for this concept, possibility of analyzing the acoustic signals coming from a moving vehicle and registered by a byside diagnostic station.

Keywords: modelling, result of Doppler Effect, resampling, beat effect, histeresis.

EFEKT DOPPLERA JAKO ŹRÓDŁO INFORMACJI DIAGNOSTYCZNEJ
W SYGNALE AKUSTYCZNYM

Streszczenie

W pracy przedstawiono nową koncepcję systemu diagnostycznemu wspartego modelowo oraz odpowiednią dla tej koncepcji możliwość analizy sygnału akustycznego pochodzącej od poruszającego się pojazdu a rejestrowanego przez przytorową stację diagnostyczną.

Słowa kluczowe: modelowanie, efekt zjawiska Dopplera, przepróbkowania, zjawisko dudnienia, histereza.

1. INTRODUCTION

Operation of technical objects is associated with occurrence of numerous physical phenomena caused by the operation of the object itself as well as by the environment in which a given object operates. The result of these interactions is the degradation of individual parts of devices, which leads to subsequent states of wear and tear until destruction. While being guided by these simple relations one applies, in a planned manner, Preventive Maintenance which consists of regular inspections and replacement of the parts which are subject to wear. As has been proven by research, such an approach leads to a situation where e.g. 34% of rolling bearings are dismantled too early. This simple analysis fails to account for failures or accelerated wear and tear caused by overload during the machines operation, its improper use or occurrence of extreme environmental impact, leading to accelerated wear or even sudden failure. The reasons of all these undesirable effects is the lack of assessment of the actual technical condition, which is indispensable especially in those cases when the technical object may have influence on human health or life. The constant awareness increases the importance of technical diagnosis while driving the development of Condition Based Maintenance. Numerous activities and analyses, both of the object and the signal received from it, must be performed in order to enable such an analysis. In order to carry out the analysis of operation of a system capable of such an evaluation, one first needs to collect the information on the object with the use of sensors (receptors). We obtain a certain signal which is a function in time of some physical quantity. Such information must then be processed into a set of features (parameters, symptoms) whose values serve as the basis for describing the condition of diagnosed objects. Then one still needs to define the relationships between the condition of the objects and the diagnostic parameters, that is the classification rules. From mathematical point of view it is mapping of the space of parameters to the space of states. Based on the supplied diagnostic parameters the classifier determines the class to which the examined object belongs. Due to certain arbitrary nature of the response of the classification system, this response is called the decision [1]. However for such a diagnostic system to operate one needs to solve a serious problem, that is extraction and selection of relevant diagnostic parameters which would be useful enough so as to enable performance of the diagnosis of an object's condition on their basis. The awareness of the problem of the need for constructing comprehensive diagnostic systems leads to the emergence of more and more advanced concepts. Despite this, unforeseen, tragic catastrophes continue to happen:

Catastrophes of machines:

- 1988, Aloha, B-737, multi-site damage, one casualty;
- 3.06.1998, derailing of a train in Eschede, 101 dead, 300 injured.

Catastrophes related to construction structures:

- 14.02.2004, Transvaal swimming pool with glass, concrete and metal dome, 28 dead, 110 injued;
- 17.03.2005, collapse of the roof in Leroy-Merlin hypermarket in Gdańsk;
- 28.01.2006, collapse of the roof of Katowice International Trade Fair building, 65 dead, 170 injured.

As we can see catastrophes happened both in the past and nowadays when technical diagnosis is much more advanced. Thus there is need for continuous development of this field, mainly to ensure safety of use of technical objects/facilities by people. The goals also include achievement of the following economic benefits:

- Increasing the reliability, security and readiness of machines;
- Reducing the cost of maintaining the fleet of machines, improvement of material management by tapping on the material reserves, reducing failures, downtimes and loss;
- Improvement of electrical power management, reducing the strain on the natural environment by reducing the emission of harmful materials as well reducing the generation of vibration and noise.

Below please find one of the concepts of the structure and functioning of a diagnostic system which could serve our purpose while monitoring any technical object throughout its operating life.

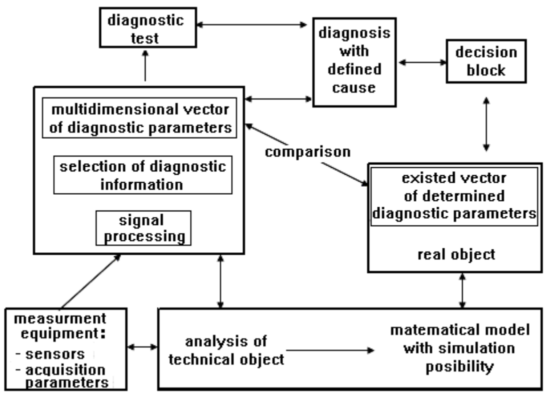


Fig. 1. State-of-the-art concept of the diagnostic system for any technical object.

The main difference when comparing to the structure and principles of operation of a classical diagnostic system involves introduction and use of a mathematical-and-physical model of the examined object during the entire diagnosis. Based on the analysis of the technical object and the physical phenomena associated with it, we create the preliminary structure of the diagnostic system. The functions of designated physical values are subjected to processing. The diagnostic information is subject to selection and comparison to the simulations in mathematical-and-physical model. During the entire period of object monitoring, the multi-dimensional vector of diagnostic parameters is compared against the actual parameters of the device, the vector of specific parameters, and it is also tested when new, earlier unknown conditions and behavior appear. The diagnosis, along with justification, is proposed and then a decision is made as regards the use of the object. All the information on the operation of the system is stored and thanks to this, as new events occur, the knowledge about diagnosis of an object or a certain groups of objects, which is fully contained in the mathematical model, is enriched and strives towards full learning of the occurring phenomena and the associated threats.

2. ANALYSIS AND PROCESSING

Even in the case of the most sophisticated diagnostic system, the evaluation of the technical condition on the basis of the signal reflecting the change of certain physical quantities generated by the object is generally not an easy task. This is so mainly due to the fact that the diagnostic information contained in the signal can have varied form (vibroacoustic signal contains not only the information on the dynamic forces associated with the object but also the information on the condition of structure which intermediates in carrying the signal from the source to the measuring point) while the richness of the information carried is an obstacle to its direct use and to making the comparison with the calculated multi-dimensional vector of diagnostic parameters which result from the mathematical-and-physical model of the object. For such an assumed comparison to make sense, one needs to account for the differences between the actual and the model processes which never fully reflect the reality. Transfer between the "two worlds" is realized through advanced methods of signal analysis and processing.

There are numerous techniques which process the signal to the form in which the diagnostic information is visible and close to the information assumed by the model in the extent which enables construction of the proper vector of diagnostic parameters. The present progress and advancement of technical objects as well as stringent requirements for diagnostic systems have enforced development and use of signal processing techniques which will be able to deal with complex systems of mixing and interaction of signals which make up the global run of physical quantities received by the receiver. As Fig. 2 presents, each subsequent source signal si(k), which represents a signal coming from various interworking parts of the machine, has its own propagation path and is disturbed by additive noise.

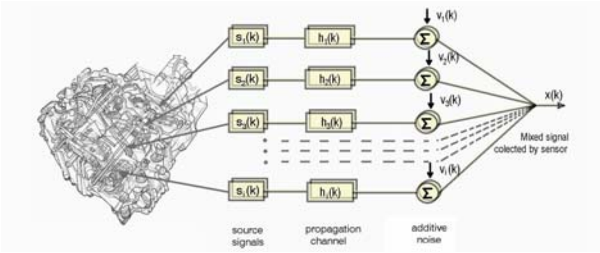


Fig. 2. Model of registration of a signal generated by a complex technical object [2].

Due to this a signal registered by a single sensor will be a composition of various sources and noises with various delays [2]. Let us consider a practical example when we want to separate a signal belonging to an operating bearing. In this case it is nearly always required that the real signal of the bearing is identified among the noise and vibration generated by other components which can be either in a good or bad technical condition. As long as all other components of the signal are so small that the bearing signal is dominant, the diagnostic parameters can be implemented without any fear. Otherwise this will lead to false values of calculated diagnostic parameters, which as a result will lead to false analysis. The presented issue is the main dilemma which has to be considered before we decide to apply a defined method of signal processing for a specific technical object.

To recapitulate, the task of detection of defects in technical objects, while relying on the analysis of the signal generated by the diagnosed object, entails the need for solving numerous problems. This in particular concerns the following issues [3, 4]:

- separation of the useful vibroacoustic signal from the noise;
- selection of relevant diagnostic parameters;
- formulation of diagnostic relations.

Analysis of the above issues calls for adopting a relevant mathematical-and-physical model of emergence of certain characteristic phenomena observed in the analyzed signal. Quick detection of model counterparts will enable avoidance of the situation when the advanced stage of a defect, which is detected late, offers not much time for taking corrective actions. Immediate repairs are necessary often and as a result the object has to be shut down regardless of the economic impact (the probability of the failure becomes too big). Early detection of the defect (in the initial stage of defect formation) allows for performing the repairs of the device in the most favorable moment from the point of view of minimization of losses and prevention of failure. If relevant methods are applied to analyze the registered processing of signals, then the detection of early stages of defect development by a diagnostic system becomes possible.

The form of the registered signal depends to a great extent on the transmittance of the propagation path of individual signals from their sources to the measuring point as well as on various types of interference, and it can be very complicated in the general case. Additional difficulty results from changes in the signal caused by varied level of load on the technical object [4] or varied environmental conditions. State-of-the-art techniques of signal analysis and processing should account for all of the above listed aspects in order to extract the informational features of the signal so as to be able to create, on their basis, the non-distorted, multidimensional vector of diagnostic parameters.

3. BYSIDE DIAGNOSTIC STATION

Along with the development of science and new cognitive tools, contemporary diagnostics sets increasingly difficult challenges for itself. One of the more interesting challenges is the diagnosis of moving vehicles, e.g. trains [5]. Diagnosis would be performed from a stationary wayside station and its purpose would be to analyze each vehicle traveling on the tracks. The main task would be to detect the information on the technical condition of the rolling systems of passing trains, and in particular to detect the early stages of defect formation. Additional stimulus for building such wayside systems includes the extensive consequences and the associated, enormous loss that a catastrophe of such a mean of transport could bring as well as the requirements of the users regarding operational availability, reliability and safety.

Assuming that diagnostically useful information is available from an acoustic signal emitted by a passing rail vehicle, one could propose a method of diagnosing defect development by means of stationary diagnostic equipment. The task that has to be solved first is to develop a mathematical model of physical phenomena, while accounting for the Doppler's effect in particular, as this phenomenon will occur for sure as the train will be a moving source of sounds vs. the receiver. As the basis for the analyses needed to construct the model, one should assume that the low-energy components of the signal are transmitted by the machine's structure from the measurement source located on its body as a result of modulation of a relevant carrier function. Particular attention should be paid to the phenomena of amplitude-and-phase modulation of a signal and occurrence of non-linear effects. Since the measured actual signal will contain both, the part generated by the diagnosed kinematic pair as well as additional components transmitted by the structure of the diagnosed object to the measurement point, hence the problem which needs to be solved is the issue of separation of diagnostically useful information contained in the non-linear part of the signal. The solution of this task will in fact depend on the results of search for diagnostically useful information contained in the non-linear part of the signal. The solution of this task will in fact depend on the results of the search for a set of diagnostic parameters which in a sufficient degree will be able to define the changes of the properties of the diagnosed object and which will be characterized by relevant resistance to noise. Finding such a vector of diagnostic parameters can be possible following an in-depth physical analysis of all the phenomena accompanying the assumed situation of an object's diagnosis, as well as by confronting the relevantly processed actual signals and signals simulated with the use of the developed model.

Based on the to-date theoretical considerations, we can create the certain necessary assumptions and create a model of the method of conducting the measurement by so-designed wayside monitoring station:

a) The source of signal will be moving with a permanent speed along a straight line,
b) The signal will be registered by a microphone, located at some distance from the path of the moving object**,**
c) Signal measurement will be conducted continuously, for various consstant speeds of the vehicle.

The diagram of such a diagnostic station could look like in Fig. 3:

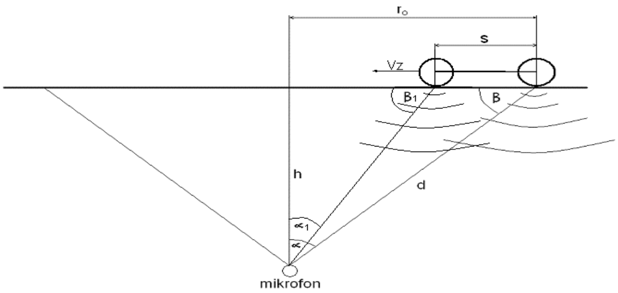


Fig. 3. Diagram of a measuring system.

It is of course most important that the created model reflects the reality and the main physical phenomena connected with it as precisely as possible. The result of the work on such a model is a mathematical expression which accounts for the main phenomena leading to distortion of the signal generated by a moving source:

$$y = \frac{ModA}{\sqrt{h^2 + (h \cdot tg\alpha - V_z \cdot t)^2}} \cdot \cos(2 \cdot \pi \cdot f_0 \cdot \frac{1}{1 - \frac{V_z}{V \cdot \sqrt{1 + \frac{temp_{pow}}{273}}} \cdot \frac{h \cdot tg\alpha - V_z \cdot t}{\sqrt{h^2 + (h \cdot tg\alpha - V_z \cdot t)^2}}} \cdot t + ModF)$$

$$\text{gdzie: } ModF = \frac{m \cdot \sin(2 \cdot \pi \cdot f_2 \cdot t)}{1 - \frac{V_z}{V} \cdot \frac{h \cdot tg\alpha - V_z \cdot t}{\sqrt{h^2 + (h \cdot tg\alpha - V_z \cdot t)^2}}}$$

$$ModA = A_0 \cdot (1 + M \cdot \cos(2 \cdot \pi \cdot f_1 \cdot t))$$

which accounts for the following physical phenomena:

- amplitude and frequency modulation;
- Doppler effect;
- acoustical pressure which is inversely proportional to the distance from the source of sound;
- change of the velocity of the acoustic wave propagation depending on temperature.

Analyses of model situations have demonstrated that the element of key importance is the occurrence of signal distortion by Doppler's effect which in line with its essence, and depending on the speed of signal source, will change the actual carrier frequency of the signal, like in the below example in Fig. 4.

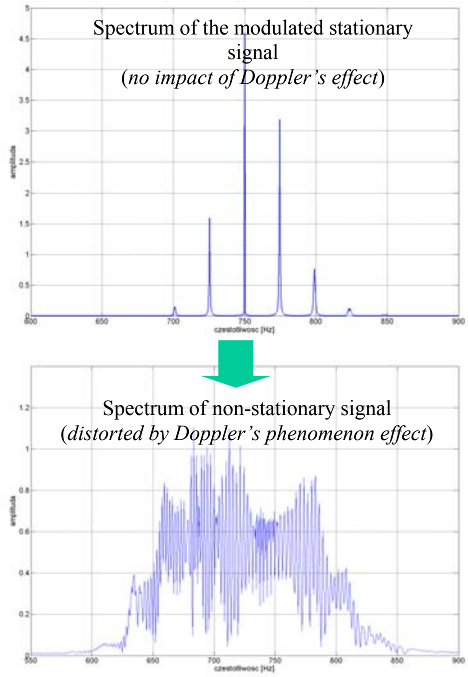


Fig. 4. Impact of the Doppler's phenomenon effect.

Further processing in terms of search for diagnostic information in a signal coming from the model led to distinction of three cases for which specific analysis should be assumed.:

I – Optimization of parameters to omit the Doppler's phenomenon effect
II- Separation and numerical elimination of Doppler's phenomenon effect
III – Analysis and use of Doppler's phenomenon

In the first case we will use the already proven claim that in a stationary diagnostic station the main disturbance for a moving object will be the effect of "non-stationarity" associated with the occurrence of the Doppler's phenomenon. The analysis of the created model has enabled us to note that in the case of certain assumptions as well as relevant parameters of the measurement, there exists the chance of minimizing the distortion caused by the Doppler's effect. Fig. 5, 6.

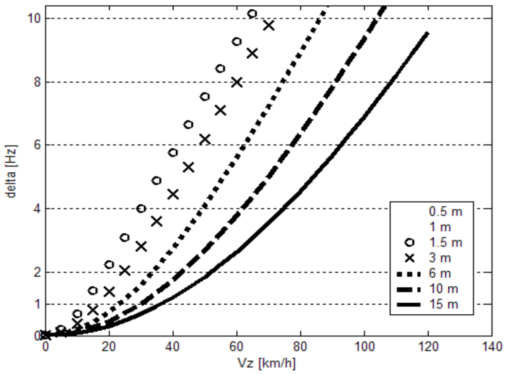


Fig. 5. Influence of Doppler's phenomenon effect in the function of speed of the drive for various distances between the microphone and the track.

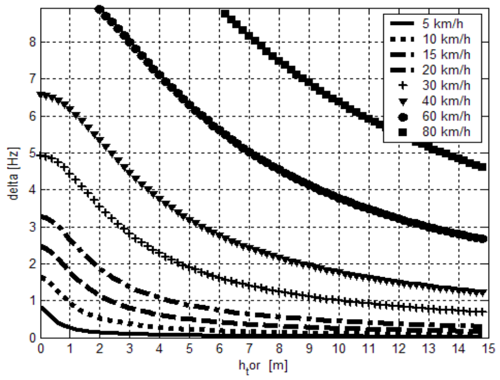


Fig. 6. Impact of the Doppler's phenomenon effect depending on the distance of the microphone from the track for various speeds of the vehicle.

The above graphs show that the relevant manipulation with such parameters as the object's speed and the distance between the microphone and the track we are able to control the delta value [Hz], representing the size of the disturbance caused by Doppler's phenomenon effect. Adoption of a relevantly small distortion will enable further analysis and signal processing to a form on the basis of which it will become possible to build the relevant diagnostic measures.

Another case assumes that due certain reasons, e.g. due to the required high speeds, it is impossible to disregard the impact of the Doppler's effect. In addition, there appears the problem of separation of signals coming from relevant driving systems, which may occur for some types of rail vehicles. Although the first problem calls for use of signal processing method in order to reduce the Doppler's effect, in the second case we can formulate relevant conditions for which separation and further analysis can be appropriate.

While taking a complex signal that has been obtained and that has been generated during the run of the railway car's truck, we are unable, based on the amplitude-and-time run, to separate the parts of the signal belonging to one or the other wheel. Let us remember however that the wheels moving in respect of the receiver, introduce the disturbance of carrier frequency to the signal. At any moment in time, as the car passes, a different value of the basic frequency is recorded. Such a change can be observed in Fig. 7:

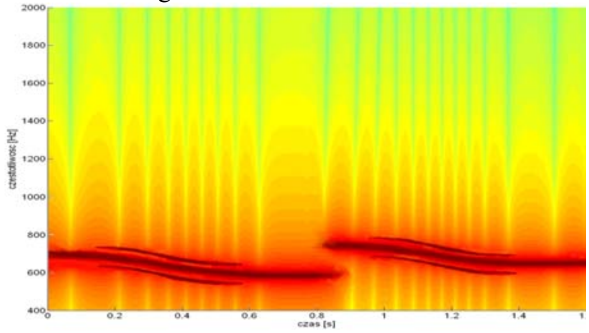


Fig. 7. Signal coming from two moving sources.

We have obtained the run of frequency change in time and at the same time the change of the value of amplitude, which is shown by the spectrum of colors in the spectrogram. For a relevant velocity of the source, when there is big scope of the change of the signal's frequency value caused by the Doppler's phenomenon, we are able to isolate the values of the frequencies belonging to individual signal sources. Apart from the signal's carrier frequency, we also note less distinct changes of modulating frequencies. Summing up, the main conditions which have to be fulfilled, in order to perform the separation properly, look as follows:

$$f_0 \cdot \min f_{dop} \neq f_1 \cdot \max f_{dop}$$

where: f_{dop} - the coefficient resulting from Doppler's phenomenon.

When the condition is fulfilled (like in the figure), then by using the time axis we can use the time ranges corresponding to respective signal sources.

Let us go further in our considerations and let us look at the practical sense of such a procedure. From the spectrogram let us choose the range/interval of $\Delta t = 0.2$ seconds (from $t = 0.3[s]$ to $t = 0.5[s]$), which corresponds to the signal generated by the first source. The velocity of the signal's source was $V_z = 11\left[\frac{m}{s}\right]$ in the analyzed case. Thus the distance that the source traveled during Δt equals:

$$s = V_z \cdot \Delta t = 2.2[m]$$

If the examined object was a wheel of a train with diameter of 0.92 m (a 424 W EVANS freight car), then diagnosing its diameter and the bearing would only be possible once it makes one full turn. The path traveled when one full turn is made by the wheel is equal to the wheel's perimeter, that is $s_{kola} = 2.89[m]$.

The calculated parameter defines the minimum wheel track of the truck which enables conducting the analysis of its technical condition. Assuming that the condition has been fulfilled, let us conduct further analysis . Let us note that s_{kola} is too big for the wheel to make the full turn during the selected time interval Δt. The conclusion from this is that the source must move at bigger speed in order to achieve this. This in turn leads to a situation where the frequency change, caused by Doppler's effect, will occur in a shorter time interval. Ultimately the time interval may turn out too small to be able to isolate a signal's sample with $\Delta t = 0.2$ [s]. The situation calls for finding the so-called "golden mean", that is to obtain the compatibility of selected parameters whose values can be obtained through subsequent trials.

If we are able to reach a single source of signal in which we look for diagnostic information, then we can start dealing with reduction of the Doppler's phenomenon effect which effectively hinders the diagnostic interpretation of the signal. It seems appropriate at this point to use the dynamic re-sampling of the signal [6], which should theoretically deal with the frequency disturbance.

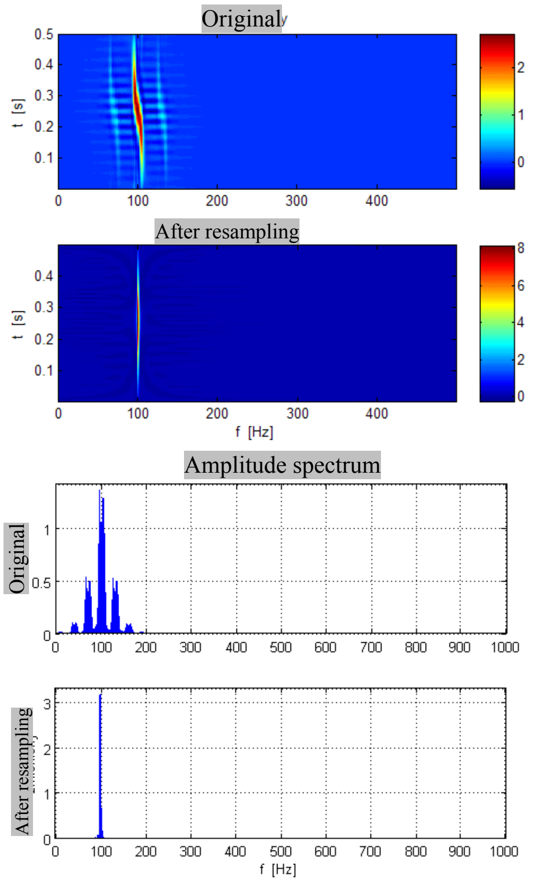


Fig. 8. Illustration of operation of dynamic signal resampling**.**

The simulation was performed for source velocity of 80 kph, distance of the microphone from the track of 2 m while the signal's carrier frequency was 100 Hz. As we can see in Fig. 8, the disturbed carrier frequency of the signal along with modulating frequencies has been reduced to the original carrier frequency. The procedure of dynamic resampling worked, however the module of automatic search for frequency changes, which was contained in it, caused destruction of the diagnostic information which modulating frequencies could carry. While using the model that we have developed, we can simulate the conditions of the experiment and obtain a realistic picture in the extent in which the model describes the phenomenon and the course of changes caused by the Doppler's effect phenomenon. This way we obtain the below curve, Fig. 9:

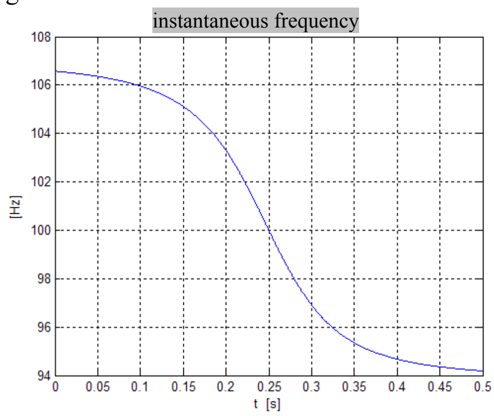


Fig. 9. Model course of change frequency caused by the Doppler's effect phenomenon.

By introducing the apriori knowledge to the dynamic resampling method, which was used earlier, we can expect that the processed signal will not only contain the distortions caused by the Doppler's phenomenon effect but that also the information contained in the modulating frequencies will be visible.

The obtained, modified signal (Fig. 10) does not demonstate the features of a non-stationary signal associated with motion of the signal's source versus the receiver and can be successfully subjected to further analysis while diagnostic measures can be constructed on its basis. In the described analysis we saw how the model of a signal, which is to be subjected to analysis, protected us from unaware removal of diagnostic information from the signal, as well as how it enabled us to introduce corrections to the method of dynamic resampling so that it worked correctly in our specific case of signal disturbance by the Doppler's phenomenon effect.

Another concept, which emerged during analysis of the model of the considered physical phenomena associated with the wayside diagnostic station, was not an attempt to escape from the Doppler's phenomenon effect, but search for valuable, from diagnostic point of view, information in this effect.

Let us note that by controlling the measuring parameters we are able to influence, at our discretion, and to change the course of change of frequency caused by the Doppler's phenomenon, Fig. 11.

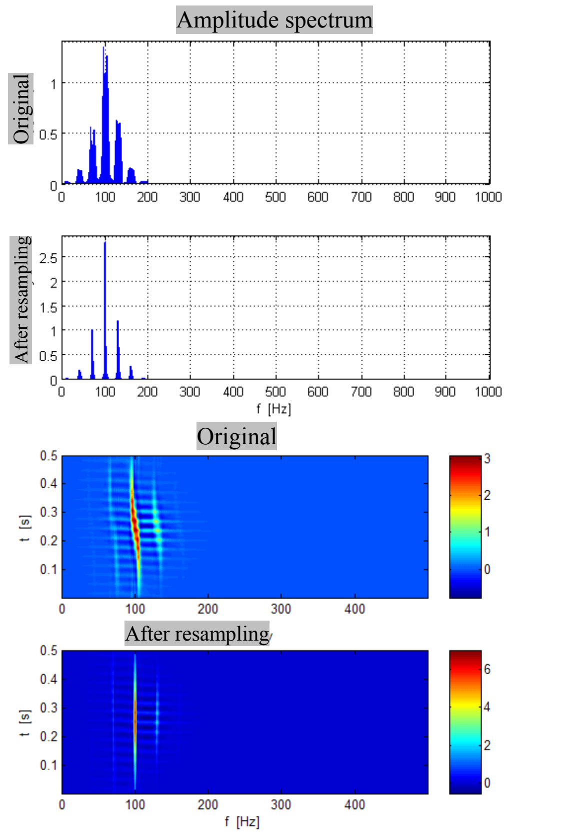


Fig. 10. Illustration of the operation of dynamic signal resampling method after introducing the apriori knowledge on the Doppler's phenomenon.

While analyzing the above graphs, one can see that the distortions of signal frequency by the Doppler's effect can be very rapid (a steeper curve) and assume higher values but they can also last longer, be milder and achieve smaller values.

Let us remember that while referring to the reality we need to take into account the fact that the registered signal will contain the data coming from two or more consecutive sources. Such a situation will occur e.g. for the passing trucks of a railway car. We know that separation of the registered signal into components, coming from individual sources, is not always possible. That is why let us add complexity to our model so that it simulates a moving pair of signal sources, separated from each other by a defined distance, and in addition let us use two, separated from each other by a relevant distant, microphones for registering the signals. Such a situation will roughly correspond to the moving railway car truck. While assuming the following parameters for performing the measurement:

Source velocity – 50 km/h
Distance from the microphone to the track – 2 m
Carrier frequency – f1=f2= 100 Hz
Distance between signal sources – 1.8 m
Distance between the microphones – 6 m
we will accordingly obtain the signals and frequency runs accounting for the Doppler's phenomenon effect from subsequent microphones, Fig. 12.

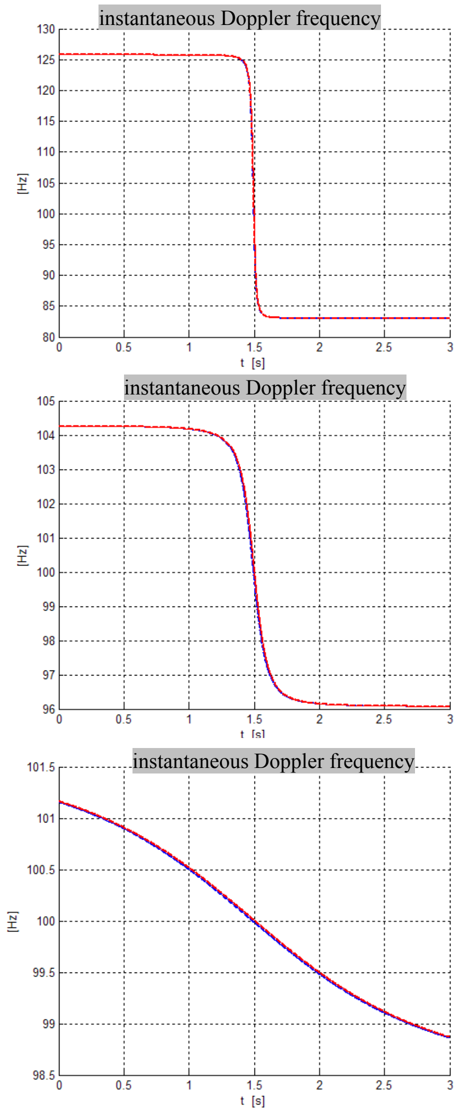


Fig. 11. Model change of the course of the frequency caused by the Doppler's phenomenon effect, depending on the measuring parameters selected.

Having at our disposal the situation modeled in such a way, we can observe the emerging shape of hysteresis created by the curves of carrier frequency changes for two sources. Hysteresis plays a major role in physics, taking into account the possibility of describing quite specific physical phenomena as well as the practical use of physical relationships associated with it. In our case we can influence the shape of the hysteresis by selecting the measurement parmeters and conditions. Model simulations demonstrated the physical phenomenon called dumping when the relative distance between signal sources increases, which is synonymous with increasing the area of the artificially generated hysteresis. Below we performed the simulation of signals (Fig. 13) for the following data:

Source velocity – 50 km/h
Distance from the microphone to the track – 2 m
Carrier frequency – f1=f2= 100 Hz
Distance between signal sources – 10.8 m
Distance between the microphones – 6 m

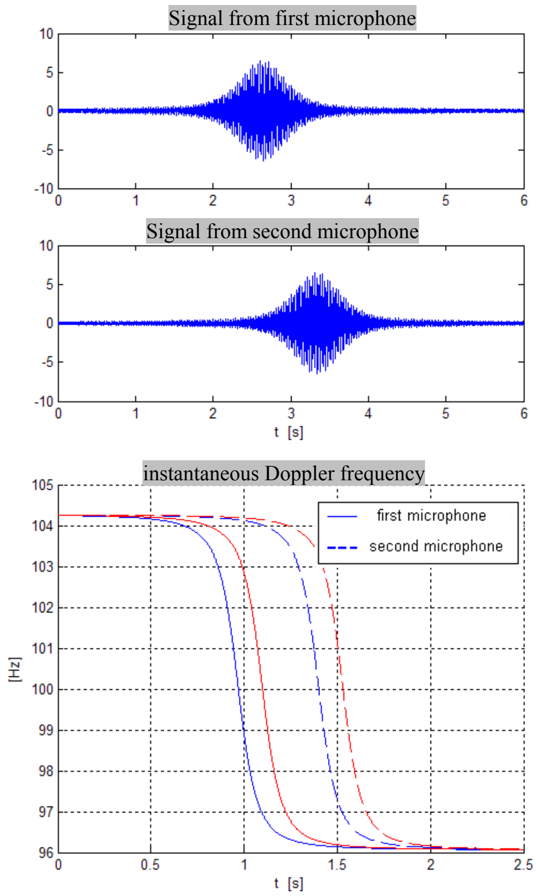


Fig. 12. Simulation of frequency changes for two moving sources.

This specific phenomenon, which has been generated, is characterized by the relationship concerning the frequency of interfering signals:

$$f_{dudnienia} = |f_1 - f_2|$$

In order to confirm the phenomenon that emerged, we examined the envelopes of interfering waves.

The frequency of around 8Hz is clearly visible which in accordance with signal disturbance model (Fig. 14) can be linked to the occurrence of the Doppler's effect phenomenon for two signal sources. The additional low-frequency component, which occurred in the spectrum of the amplitude-modulating signal, is associated with the change of acoustic pressure depending on the distance between the source of sound and the microphone.

The phenomenon of beat effect was generated by us by extending the shape of the hysteresis coming from two moving sources of signal, which is synonymous with the time of delay between signals. The impact of this delay is significant from the point of view of the ability to identify the phenomenon, which is presented in Fig. 3.15.

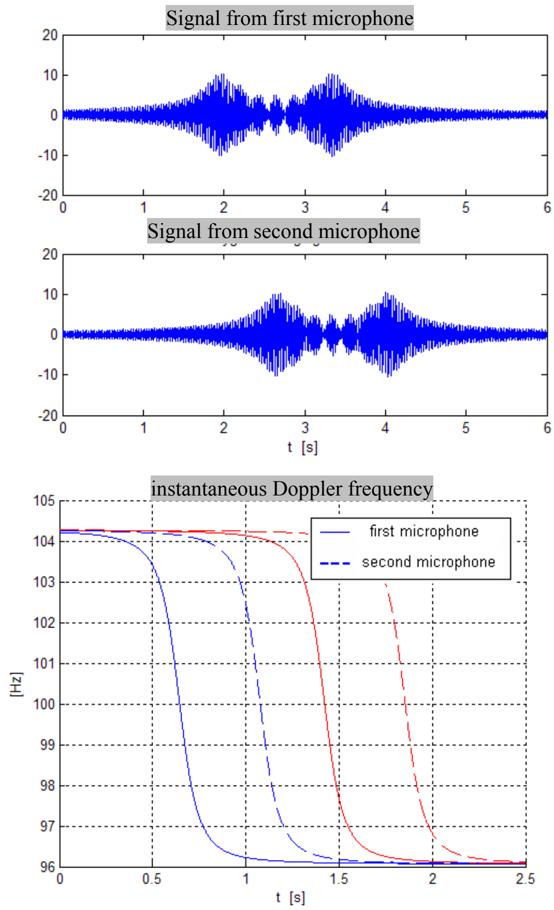


Fig. 13. Simulation of frequency changes for two moving sources for increased distance between them.

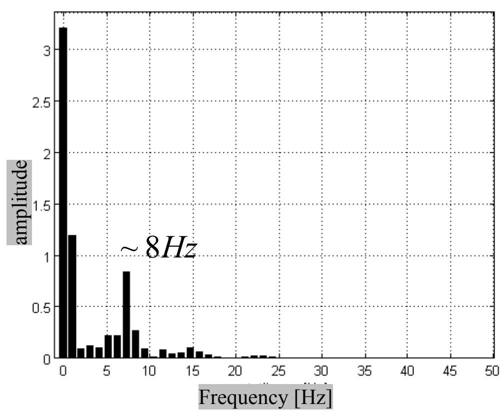


Fig. 14. Spectrum of the amplitude-modulating signal.

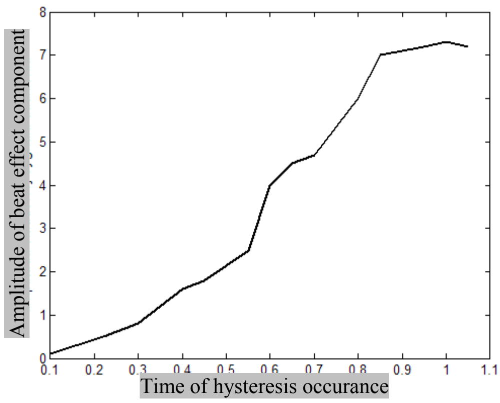


Fig. 15. Influence of duration of hysteresis on the possibility of identifying the frequency of the beat effect.

Longer duration of occurrence of "hysteresis" will enable better distinction of the frequency of beat effect among the components of the analyzed signal.

By correctly identifying the beat effect frequency, we can reach the information on the scope of change of the frequency, introduced by the Doppler's effect, which can be used, among others, foyr estimating the speeds of moving objects. What is also essential is the fact that damping effect occurred only in in the area where hysteresis occurs. This demonstrates that sources frequencies are identical, which we will see below.

So far the modeled signals described an idealized situation where the carrier frequencies of two sources were identical. In reality they will differ and the essential difference will be indicative of the relative difference in the nature of operation of the two systems. In the case of the truck of a railway car, this can be caused by different diameters of the truck's wheels. Let us look at the results of simulation (Fig.16) for the following parameters:

Source speed – 50 km/h

Distance from the microphone to the track – 2 m

Carrier frequency – $f_1 = 105Hz, f_2 = 100Hz$

Distance between microphones – 6 m

We observe the beat effect for two, different values of relative distance between the sources. In addition the scope of its impact covers the whole range of the registered signal. In this case the dumping frequency points to the existence of differences between carrier frequencies of the sources, which is the evidence of a different nature, kinematic and dynamic nature of the individual driving systems. Further detailed analysis can decide whether this could be the information about emerging or developing defects of the object.

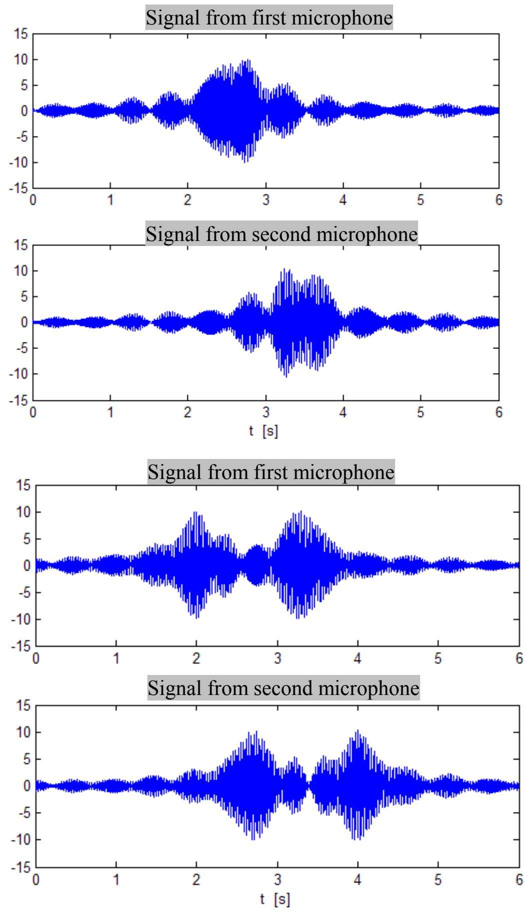


Fig. 16. Simulation of signals for two moving sources with a similar carrier frequency.

Such situation (Fig. 16) is more complex compared to the model with two moving sources with identical carrier frequency, since it has a bigger number of interfering signals. As a result, we will for sure obtain a signal which will be responsible for the occurrence of the beat effect due to the difference between the carrier frequencies of source signals:

$$y_1 = A_D \cdot \cos\frac{1}{2}(\omega_1 + \omega_2)t$$

where: $A_D = 2A \cdot \cos\frac{1}{2}(\omega_1 - \omega_2)t$

The frequency of occurrence of maximum value of amplitude $\pm 2A$ is the dumping frequency. This frequency is two times higher than $\frac{1}{2}(\omega_1 - \omega_2)$ since the maximum value of dumping occurs both for $\cos\frac{1}{2}(\omega_1 - \omega_2)t = 1$, and for $\cos\frac{1}{2}(\omega_1 - \omega_2)t = -1$. Thus, dumping frequency is: $\omega_D = (\omega_1 - \omega_2)$.

When analyzing a signal for small distance between the sources (1.8m), it is the calculated damping frequency that should be distinctly visible in the spectrum of amplitude-modulating signal. Let us subject the model signal to demodulation in order to reach the frequency (Fig. 17).

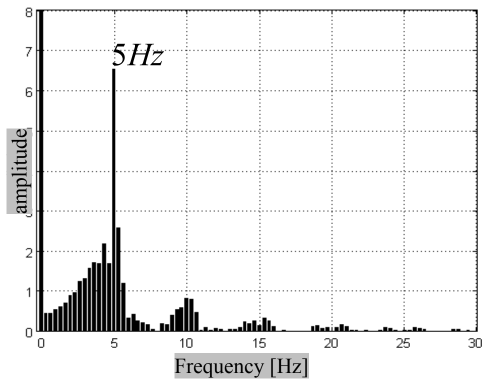


Fig. 17. Spectrum of amplitude-modulating signal.

The obtained spectrum confirmed our theoretical considerations. Let us now analyze the case when the relative distance between the sources increases in such an extent so that a beat effect phenomenon becomes possible, which is caused by the Doppler's effect phenomenon (relatively broad hysteresis of frequency disturbance caused by the Doppler's effect). The formula for the interfering signals within the area of artificially caused hysteresis will look as follows:

$$y_2 = A_{DD} \cdot \cos\frac{1}{2}(\omega_3 + \omega_4)t$$

where: $A_{DD} = 2A \cdot \cos\frac{1}{2}(\omega_3 - \omega_4)t$

Apart from another dumping frequency which has emerged $\omega_{DD} = (\omega_3 - \omega_4)$, one should remember that in the case of dumping phenomenon it is the carrier frequency of individual signals (components) that changes and equals to the arithmetical average of the source frequencies. Taking this phenomenon into account we discover another interference whose result will be dumping with frequency of:

$$\omega = \frac{(\omega_1 + \omega_2)}{2} - \frac{(\omega_3 + \omega_4)}{2}.$$

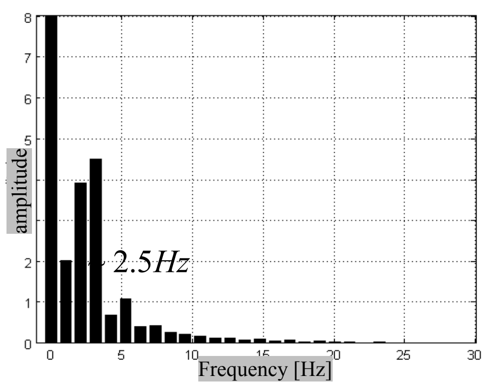
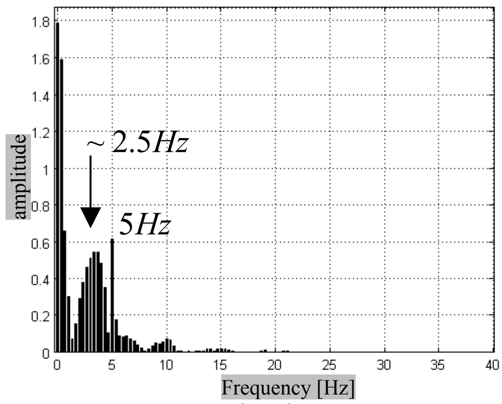


Fig. 18. Spectrum of amplitude-modulating signal.

While analyzing the amplitude spectrum for a time signal, which includes the phenomenon of occurrence of a hysteresis which disturbs the frequency, we can isolate the beat effect which was calculated earlier and which equals to the difference of average frequencies of dumping signals (Fig. 18). When the whole time run is subjected to the analysis, then we will see, in the amplitude modulating spectrum, the trace of this frequency as well as the dumping frequency which results from various frequencies of source signals.

Fig. 19. Spectrum of the amplitude-modulating



signal.

While continuing the analsysis of the model used, we can note the possibility of exploiting the fact that registration is done with the use of two microphones. Even when the hysteresis area is not big enough to observe the beat effect caused by the effect of Doppler's phenomenon for two moving sources, we can still bring it about while exploiting the fact of the difference of signal frequency while approaching and moving away from the signal. We can cause it, while making use of the difference in terms of a signal when coming closer or moving away from the source of signal, Fig. 20:

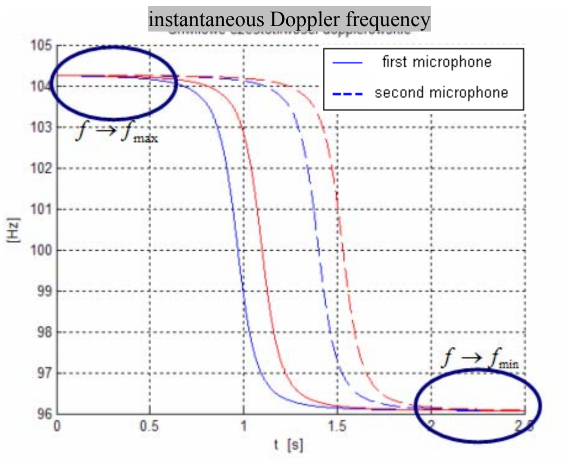


Fig. 20. Illustration of the possibility of capturing the maximum difference between the frequencies, as caused by the Doppler's phenomenon.

This way, while manipulating with the set of microphones, it becomes possible to combine with each other the signals while approaching and while moving away, which should trigger sufficient condition for causing the dumping phenomena (Fig. 21), providing us with the information on the frequencies distorted by the Doppler's effect phenomenon.

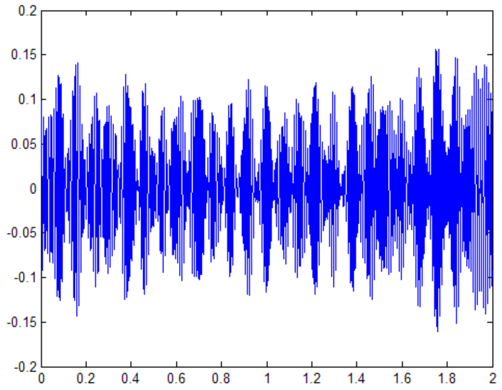


Fig. 21. Simulation of the damping phenomenon while using a model with two moving signal sources registered by two relevantly removed microphones.

All the up-to-date analyses of the beat effect concerned changes of the carrier frequencies of signals and can be also extended to include the analysis of the modulating frequencies (dumping caused by signals with similar modulating frequencies). The frequencies of modulating signals differ usually from the carrier frequencies of signals and that is why one should not expect the occurrence of the damping effect between them but a doubt emerges whether the observed dumping phenomenon, for the signals' carrier frequencies, could disturb the identification of the modulating frequency. Let us perform the simulation of two moving sources, of which one is amplitude-modulated (depth of modulation = 0.2; modulating signal frequency = 5Hz) while at the same time relevant conditions occurred for stimulating the damping phenomenon through Doppler's phenomenon. The envelope of such a signal was subjected to spectral analysis (Fig. 22)

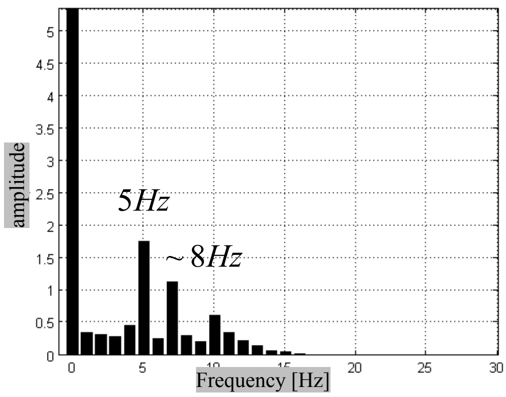


Fig. 22. Identification of amplitude modulation frequency.

Apart from the identified dumping frequency of $\sim 8Hz$, it is also the modulating frequency of 5Hz that is visible. Thus dumping will not interfere with the interpretation of the frequency of modulating signals which could appear in real-life signals in moving objects.

4. CONCLUSIONS

As we have demonstrated, the model can be used for proper selection of the conditions and methods of measurement as well as diagnostic parameters already at the stage of designing the entire diagnostic system. It is also later, at the moment of functioning of such a system that the model should continue to be updated in order to be able to meet the new measurement states and conditions as they appear during the operation. We have also demonstrated that there are several possibilities in the approach to diagnosis of objects in motion while using a stationary monitoring station, even in spite of the disturbance caused by the Doppler's effect.

BIBLIOGRAPHY

[1] Sobczak W., Malina W.: *Metody selekcji informacj*i (*Methods of information selection*). Wydawnictwa Naukowo-Techniczne, Warszawa, 1978

[2] Jacek Dybała, Jędrzej Mączak, Stanisław Radkowski: „*Wykorzystanie sygnału wibroakustycznego w analizie ryzyka technicznego*"; monograficzna seria wydawnicza ("*Use of vibroacoustic signals in technical risk analysis*;" a monographic publishing series: Biblioteka Problemów Eksploatacji, Warszawa-Radom 2006

[3] Jacek Dybała, Szymon Gontarz, Stanisław Radkowski, "*The pattern recognition in analysis of vibroacoustic signal*", Materiały konferencyjne ICSV13, Wiedeń 2006.

[4] Szymon Gontarz, Peter Tse and Xiaojuan Wang, "*Enhanced eigenvector algorithm for recovering multiple sources of vibration signals in machine fault diagnosis*", Mechanical Systems and Signal Processing 21 (2007) 2794–2813.

[5] Jacek Dybała, Szymon Gontarz, Stanisław Radkowski, "*Use of information embedded in vibroacoustic signal to crack evolution tracking of gear failure*", Materiały konferencyjne WCEMA 2007, Harogate 2007.

[6] Gałęzia A., Gontarz Sz.: referat pt.: „*Redukcja efektu zjawiska Dopplera dla potrzeb stacjonarnego stanowiska diagnostycznego*". VIII Seminarium Naukowe Studentów i Młodych Inżynierów Mechaników 2005 (*Reduction of the Doppler's phenomenon effect for the needs of a stationary diagnostic station*. 7th Scientific Seminar of Students and Young Mechanical Engineers, 2005)

[7] Jacek Dybała, *Use of task–oriented dynamic resampling in reduction of signal non–stationarity*. Diagnostyka 4(48)/2008. str.25-30.

USE OF THE GPS RECEIVERS FOR DATA SYNCHRONIZATION IN DISTRIBUTED SIGNAL ACQUISITION SYSTEMS

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Summary

The issues of synchronization of vibroacoustic measurements taken with the use of multiple mobile signal acquisition units were discussed in the paper. The problems existing with synchronization of DAQ measurement cards placed in different acquisition units were described and solutions allowing card synchronization using GPS signals were proposed. Described solutions were tested in the field measurements of the moving railway cars and simultaneously the stationary measurements taken next to the railway track.

Keywords: GPS, sound and vibration measurements, measurement synchronization, distributed signal acquisition systems.

WYKORZYSTANIE ODBIORNIKÓW GPS DO SYNCHRONIZACJI DANYCH W ROZPROSZONYCH SYSTEMACH REJESTRACJI SYGNAŁÓW

Streszczenie

W pracy omówiono zagadnienia związane z synchronizacją pomiarów wibroakustycznych wykonywanych za pomocą wielu mobilnych układów akwizycji sygnałów. Przedstawiono problemy występujące przy synchronizacji kart pomiarowych umieszczonych w różnych układach pomiarowych i zaproponowano rozwiązania pozwalające na synchronizację tych kart za pomocą odbiorników GPS. Zaproponowane rozwiązania zostały przetestowane w warunkach poligonowych podczas jednoczesnych pomiarów na poruszających się pociągach oraz pomiarów przytorowych.

Słowa kluczowe: GPS, pomiary hałasu i drgań, synchronizacja pomiarów, rozproszone systemy rejestracji sygnałów.

1. INTRODUCTION

In the measurement practise we are frequently forced to synchronize measurements taken simultaneously in separate distant places. Such systems are called distributed signal acquisition systems. An example of such measurements is the signal acquisition system built for the needs of acquiring signals needed for the development and testing of a pass-by railway monitoring station. For this purpose vibroacoustic signals from the moving railway car were recorded simultaneously on the stationary ground data acquisition station and on a mobile station carried on the moving railway car. The noise and vibrations signals from both stations were recorded and then analysed in laboratory for detection and removal of disturbances introduced in moving signal source by Doppler Effect [1, 2].

If we would like the time signals to be compared point by point we need the recorded data to be exactly timestamped. Speaking more precisely depending on the acceptable time difference between the beginnings of the measurements, the need to synchronize measuring cards sample clocks as well as depending on the distance between the measuring computers and thus the possibility of exchanging information between them, various configurations of the measuring equipment and synchronization methods could be used. In this paper several possible methods of synchronization of the measuring gear will be discussed with special focus taken on the possibility of the use of the GPS signal for this purpose. The methods described were implemented and tested in practice during field measurements using National Instruments data acquisition hardware and programmed with LabVIEW. The tests took place on in Żmigród on a CNTK railway test track. The testing equipment consists of two independent NI/PXI-8186 controllers equipped with NI/PXI-4472B data acquisition cards and two Garmin 18LVC GPS receivers used for synchronisation purposes.

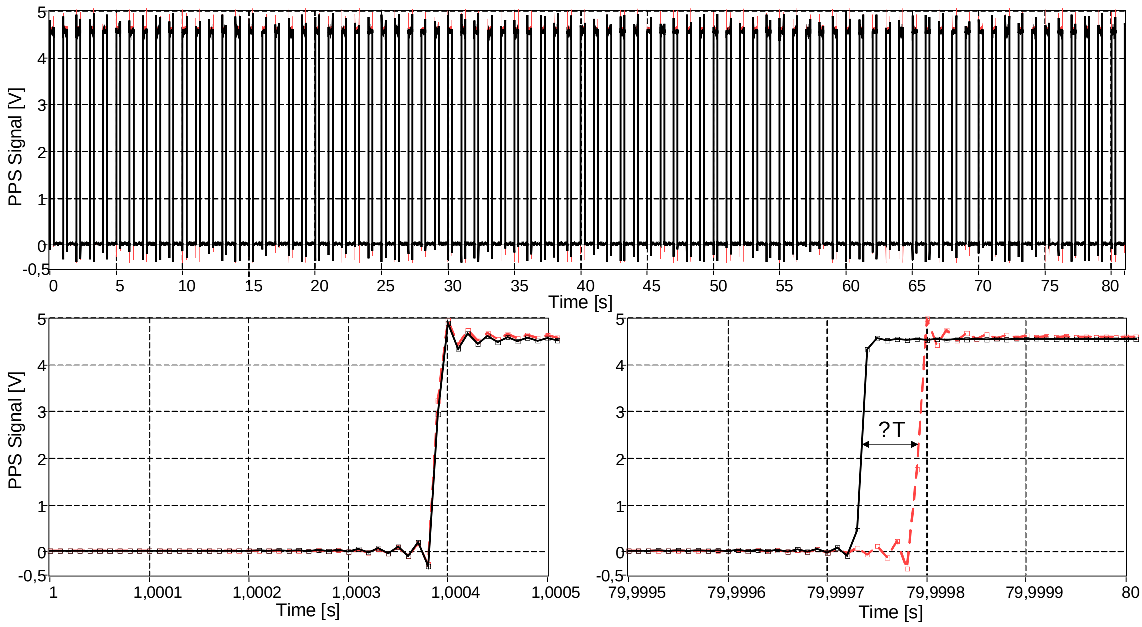

Fig. 1. Rectangular pulse acquired simultaneously with the use of two DAQ cards on separate units.

2. MEASUREMENTS SYNCHRONIZATION PROBLEMS IN DISTRIBUTED DATA ACQUISITION SYSTEMS

Proper synchronization of the signal recordings is very important if the correlation between time waveforms not their spectral representations should be analysed. For example if we would like to remove a Doppler Effect from the recorded signal of a moving source and would like to compare the results with data captured on a stationary system we need not only to align the beginnings of the recordings (starting points) but also align the sampling frequencies of the data acquisition (DAQ) cards.

In this paper we will not be dealing with inter channels synchronisation problems (i.e. multiplexed and non multiplexed cards) but rather focused on synchronisation problems of different, unconnected with themselves data acquisition units in a distributed signal acquisition system.

The first more common synchronization problem existing when synchronizing multiple units in distributed signal acquisition system is the simultaneous triggering of the DAQ cards i.e. selecting the moment of acquisition beginning. Usually it requires a physical (i.e. electric) connection of the cards and is possible only in case of relatively small distances between acquisitions units counted rather in meters. Other possibilities are to trigger the acquisition units using internet connection [3] or WI-FI signal or to start the measurements according to the specified time. Unfortunately, sending trigger signal over asynchronous lines except for small distances [3] introduces usually unknown delay hard to estimate and precision of the latter is very bad unless a computer clocks are radio synchronized and the precise timing of data acquisition is known.

Another problem usually not taken into account while creating data acquisition systems is the synchronization of the card oscillators. Crystal oscillators are implemented in any of the data acquisition cards and are the frequency base for generating sampling frequency of data acquisition (sample frequency). Although this oscillators are very precisely made their frequencies differs slightly introducing small differences in sampling frequency even in the cards of the same type. If the acquisition cards are in the same DAQ unit usually there is a possibility to chose one oscillator (clock) a as a basic for generation of sampling signals and exporting its signal programmatically or physically across the unit. For separate data acquisition units placed close to each other only hardware method of clock signal exporting is possible.

Usually the differences between clock frequencies are very small but even for the same type of cards if the signal is long enough the difference could disturb the synchronization between the signals recorded with use of different DAQ cards. An example of the rectangular pulses recorded on two independent NI/PXI-4472B DAQ cards placed in different, not connected with each other, chassis shows this problem (Fig. 1). On the upper diagram eighty seconds of 1Hz rectangular pulse sampled with 100kHz are visible. As was shown on bottom left diagram both signals were perfectly, to the single sample, aligned in the beginning (first acquired pulse). After next 78 seconds the rising edge of one of the signals is shifted $\Delta T=6$ points from the other signal. Additionally it is visible that the recorded frequencies of both signals are looks a little bit faster then 1Hz what is caused by clocks slower than documented. This frequency drift although very small could disrupt in some times, especially for very long recordings, the common analysis of recorded waveforms.

3. METHODS OF SOLVING MEASUREMENTS SYNCHRONIZATION PROBLEMS

As was mentioned above the two most common synchronization problems described could be easily resolved if the data acquisition units are in the same chassis or placed close to each other in such a distance that they could be connected with wires transmitted electric signals (clock). In other cases especially if the distance between units is too long for wiring or one or both DAQ units are placed on a moving platform we are limited to wireless communication between units or we could use GPS signal as a source of synchronization signals.

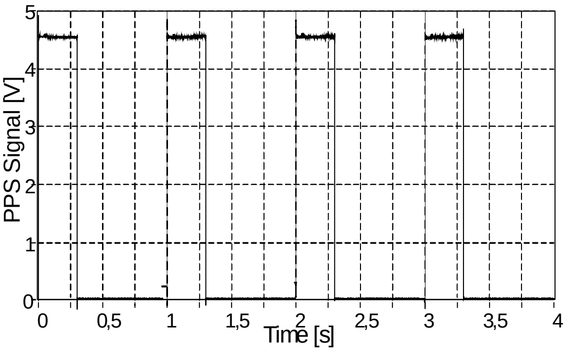

Fig. 2. PPS signal received from Garmin 18LVC GPS receiver.

3.1. GPS signal as a source of DAQ cards synchronization signals

GPS receivers could be used not only as a source of current position and precise time but also as a source of series of rectangular pulses that could be used for synchronising data acquisition cards. To do this the GPS receiver should be able to pass the Pulse Per Second (PPS) or Inter-Regional Instrumentation Group IRIG-B signal to its output. Both signals are of the TTL level. PPS signal is a rectangular pulse of duration of exactly 1 second (Fig. 2) with accuracy depending of the receiver electronics (for example for Garmin receiver 18LVC accuracy is ±1µs). On the other hand IRIG-B signal [4] contains BCD-coded information about the current time and date (Fig. 3). Usually IRIG-B signal is used for precise global timebase applications so the receivers are rather expensive and their usage is limited to standalone applications. On the other side the PPS signal does not contain timing information and as such should be accompanied with time data transmitted from the receiver over RS-232 interface.

PPS signal is usually available on OEM GPS receivers that supports serial RS-232 protocol and is not available on receivers with USB connections. One example of such receiver is Garmin GPS 18LVC shown on Fig. 3. It's extremely low cost (~70USD) makes it available for applications where the cost is crucial. The unit requires 60mA @ 5V power source that is usually available in the DAQ card connectors and has unconnected wires that could be connected to the computer's RS-232 interface (Data wires) and the DAQ card trigger line (Measurement Pulse Output wire) in TTL standard. The accuracy of PPS signal is 1µs [5] good enough for typical vibroacoustic signal recordings. Trough the receiver's serial interface NMEA-183 text informations could be transmitted from the receiver to the recording computer with alphanumeric informations about current time, positions and signal quality. The transmitted NMEA sentences follows immediately rising edge of PPS signal, so the latter could be used for triggering RS-232 reading. An example of $GPRMC (Recommended Minimum Specific GPS Data) sentence is shown below:
$GPRMC,091138,A,5128.1126,N,01651.5431,E,000.0,167.8,240707,003.0,E*73

This sentence contains current time (9:11:38), position (51°28'1126"N, 16°51'5431"E), speed in knots and course over ground (0, 0.0) and date (24-07-2007).

Fig. 3. Garmin 18LVC GPS receiver [5].

3.2. Triggering DAQ card with PPS signal

Practical realization of triggering the DAQ card acquisition with PPS signal at the specified time moment usually requires the use of additional digital counter card for triggering serial interface reading with this signal. The analogue acquisition is then started on the next rising edge of PPS signal (next second) after reading and checking specified time from the $PGRMC NMEA-183 sentence. The flowchart of data acquisition triggered with pulse per second GPS signal for each of the computers is shown on Fig. 4.

As was shown above (Fig. 1) waveforms acquired simultaneously on different acquisition units differ slightly from each other because of different sampling frequencies of DAQ cards. Fortunately the drift of the clock frequencies is constant in time and easy to compensate assuming that the precise PPS signal will be recorded together with other signals. In that case the recorded signals could be resampled taking as a base time distance between first and last rising edges of the PPS signal. The resampling coefficients of clock waveforms would be (Fig. 5):

$$R_1 = \frac{T}{T - dT_1} \quad R_2 = \frac{T}{T + dT_2}$$

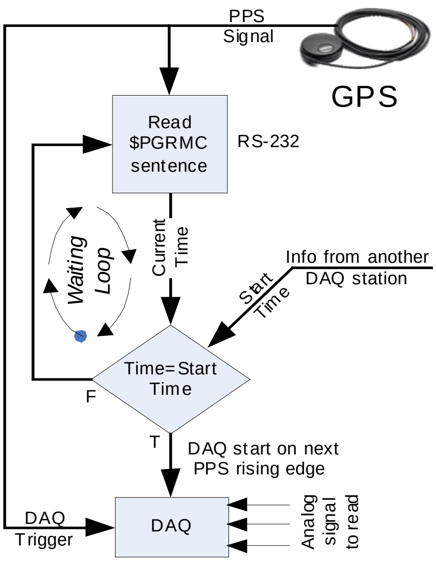

Fig. 4. Flowchart of data acquisition with PPS signal triggering.

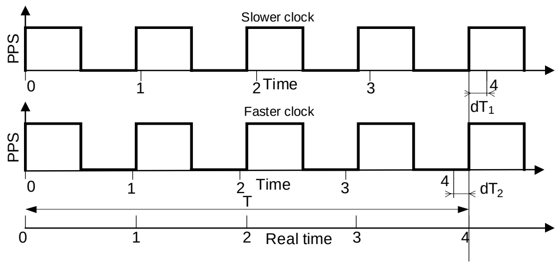

Fig. 5. Calculation of resampling coefficients using recorded PPS signal.

3.3. Online compensation of DAQ card clock frequency errors with PPS signal

The PPS signal could be directly used for online correction of clock oscillators in DAQ cards. There are at least two methods of doing this using National Instruments hardware on PXI platform.

First method [6] uses specially designed counter card NI/PXI-6608 as a source of clock for the DAQ card. This card has very stable clock oscillator capable of slightly changing its frequency according to the Pulse Per Second signal of the GPS receiver. The generated clock signal should then be exported to the DAQ card. During the measurement each rising edge of PPS signal introduces slight correction to the 6608 clock frequency so the timing of the DAQ card is very accurate (~300ns excluding GPS accuracy).

Another method requires use of FPGA (field-programmable gate array) acquisition card as a source of a sample clock for separate DAQ card. FPGA cards are extremely fast, capable of perform single loop in 25ns – 40Mhz. They could be used for generating sample clock of required frequency and in the same time for calculating time distance between consecutive PPS pulses. The frequency of the thus generated sample clock will be corrected in the last generated clock impulse but as this correction is very small it will not introduce any disturbances in the recorded signal.

4. SUMMARY

GPS signal allows synchronization of measurements taken by independent, unconstrained data acquisition units distributed on unlimited area. The proposed method is very cheap but powerful. In the simplest form, if used in the field measurement, the starting time of measurements on different units could be defined with use of conventional voice media or automatically over WI-FI network.
Results of the GPS synchronized measurements and their analysis were presented somewhere in this issue.

Author would like to thank to the National Instrument Poland team for their support in this (and not only) work.

REFERENCES

[1] Gałęzia A., Gontarz S.: *Reduction of Doppler Effect for the stationary pass-by diagnostic test stand.* VIII Seminarium Naukowe Studentów I Młodych Inżynierów Mechaników. Gdańsk 7-8.04.2005, p. 101-106 (in polish).
[2] Gałęzia A., Radkowski S.: *Reduction of Doppler Effect in vibroacoustic signal-a survey.* XXXI Ogólnopolskie Seminarium Diagnostyka Maszyn, Węgierska Górka 06.03-11.03.2006, p. 53 (in polish).
[3] DATAQ Instruments: *Synchronized and Distributed High Speed Data Acquisition.* http://www.dataq.com
[4] Timing Committee Telecommunications and Timing Group Range Commanders Council: *Irig Serial Time Code Formats.* http://irigb.com/pdf/wp-irig-200-98.pdf, Secretariat Range Commanders Council U.S. Army White Sands Missile Range, New Mexico 88002-5110
[5] GPS 18 Technical Specifications. Garmin Int., Inc. 1200 E. 151st Street Olathe, KS 66062 USA.
[6] Tutorial: *Synchronizing and Correlating Measurements to a Global Timebase with GPS.* National Instruments. 2006. http://zone.ni.com/devzone/cda/tut/p/id/4202

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DIAGNOSTICS OF NEW GENERATION DIESEL ENGINES

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Summary

The article describes the innovative conceptions of diagnoses of injectors in diesel engines with Common Rail system. What is more, the new features of acoustic emission of injectors are described. The correct as well as incorrect oscillograph course of acoustic emission are shown.

Some chosen data from the report of the world-wide known leader in the area of the production of the injector systems in the diesel engines as well as some numbers selected from the one of the biggest national services has bead discussed. The analyses as well as the reasons for the need to start the additional research of the direct injector systems in the diesel engines are described.

Keywords: Common Rail, Unit Pump System/Pumpen-Leitung-Düse, diagnostics of injectors, acoustic emission signature.

DIAGNOSTYKA NOWEJ GENERACJI SILNIKÓW O ZAPŁONIE SAMOCZYNNYM

Streszczenie

W pracy opisano wybrane przypadki uszkodzeń nowej generacji silników o zapłonie samoczynnym (ZS). Zaprezentowano skutki uszkodzeń oraz omówiono przyczyny ich powstawania. Przedstawiono również zapobiegawczą innowacyjną technikę diagnozowania stanu układu wtryskowego silników z systemem Common Rail (CR) oraz UPS/PLD będącą wynikiem wieloletnich badań interdyscyplinarnego zespołu badawczego. Przedstawiono zestaw nowych cech emisji akustycznej dla prawidłowo działających i uszkodzonych wtryskiwaczy.

Zamieszczono wybrane dane raportu światowego lidera w dziedzinie produkcji systemów wtryskowych silników o zapłonie samoczynnym oraz wybrane elementy statystyki jednego z większych serwisów międzynarodowych sieci serwisowych Autodistribution International oraz Bosch Car Service. Przedstawiono analizę i umotywowano konieczność podjęcia dodatkowych badań przez ośrodki naukowo-badawcze w zakresie diagnostyki układów wtryskowych silników o zapłonie samoczynnym z bezpośrednim wtryskiem paliwa.

Słowa kluczowe: Common Rail, UPS/PLD, diagnostyka wtryskiwaczy, emisja akustyczna.

1. INTRODUCTION

The development of new technologies used in injection systems of self-ignition engines caused a dynamic growth of their participation in the market of cars produced which use such motive units all over the world.

While such units prevail in lorries, when one takes into consideration motor-cars and light trucks whose permissible total weight is below 6 tons a rapid growth of its market participation since 2000 can be observed (details, Fig. 1).

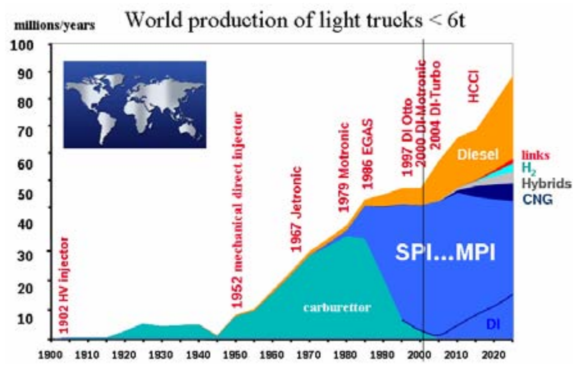

Fig. 1. World production of light trucks of permissible total weight below 6 tones [source: Bosch]

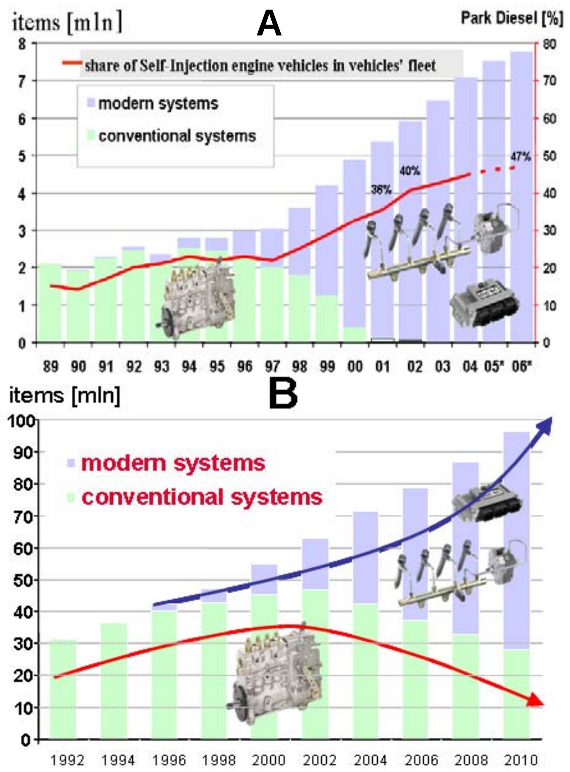

Fig. 2. Self-injection engines in the means of transport: A – production of self-injection vehicles in Western Europe, B – fleet of vehicles with self-injection engines in Europe [source: Bosch]

According to the data of world leader of diesel systems production – BOSH company, its income coming from the sell of Common Rail injectors for motor-cars in 2005 was estimated at € 36 million, for lorries it was estimated at € 10 million, and the sell of complete injectors was estimated at € 31 million. The overall income is € 77 million which is about 40% of total income for the spare parts of the injection systems and sensors to self-injection engines at this time. The total amount includes the earlier mentioned injectors, in-line pumps, distributor pumps, HR CR pumps, heater plugs and sensors.

According to the statistics based on the actual service repairs done in LOGIS Bosh Car Service and AD Service company in Radom between 2004 and 2007, the damages of injectors in Common Rail systems make up 62% of breakdowns of fuel systems[1]. Apart from the injectors the most commonly registered breakdowns of the system were: fuel pressure sensors in fuel dispensers and control valves of high pressure.

The above mentioned statistics results in the need of the development of the means of diagnosing of the injectors of self-injection engines and this is a question which needs introducing modern solutions by specialized research and development centres.

2. CHOSEN CASES OF BREAKDOWNS OF SELF-INJECTION ENGINES

In self-injection engines with Common Rail system the injection of the fuel takes place due to controlling of electromagnetic valve or piezoelectric servo of the injector by the *Electronic Diesel Control (EDC)* controller, which opens fuel channel of "leakages and steering dose" of the injector. Due to the pressures' difference between the steering chamber and the pressure chamber the atomizer needle raises and the fuel injection starts. Because of the fact that there can be fuel of poor quality on the market, the CR injectors often break down.

Those breakdowns can be divided into two groups according to the broken elements of the CR injector.

1. Breakdowns due to mechanical impurities of the steering chamber and its valve.
2. Breakdowns of nozzles' tips.

In the first situation when the impure fuel is into the port of the steering valve the valve has no possibility of closing the leakage despite the lack of controlling the valve by the EDC controller. Lower pressure of the fuel in the injector's steering chamber causes uncontrolled fuel injection, but the engine's computer will not register any fault in its memory. Moreover higher smokiness of exhaust gases can be noticed or, in extreme cases, there can be problems with starting the engine because of the leakage of the injector.

In the second case openings of the nozzle can be washed out erosively (Fig. 3A), they can lose its permeability and in the extreme case when a long-lasting overload of the engine occurs ,and ipso facto when there is high intensity of flow and a high portion of injection of the base fuel (motor-cars – $2.5x10^{-5}m^3/s$ ($50mm^3/2ms$), lorries up to $17.5x\ 10^{-5}m^3/s$ ($350mm^3/2ms$) nozzle wells can be torn apart (Fig. 3B). During high loading of the engine the speed of forcing through of the fuel can be as high as 555 m/s [l].

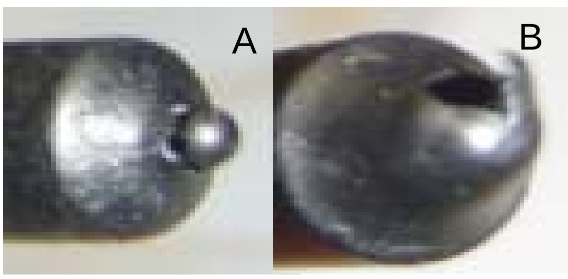

Fig. 3. Examples of breakdowns of CR injector's nozzles

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[1] 9872 motor-cars with Common Rail system were serviced, total amount of service problems with fuel system – 576, the amount of injectors breakdowns - 357

Such a type of a breakdown causes improper range of spout and the lack of proper nozzling of the fuel as well as improper shape, direction and division of the fuel in the can. Both types of breakdowns, after long-lasting period of application of the engine, can lead to its braking. The effect of such a situation can be seen in Fig. 4.

Fig. 4. Failure of the valve due to long-lasting exploitation with broken injectors

3. INNOVATIVE TEHNOLGY OF DIAGNOSING OF THE CONDITION OF THE INJECTION SYSTEM OF THE ENGINES WITH CR, UPS TECHNOLOGIES

The presented method of diagnosing has been developed as a target project [4] and has been successively modified. At present it is initiated in a few companies in Poland. It relies on the measure of acoustic emission (AE) whose source are moving elements of the engine. Measured signal is synchronously connected with its rotational speed. Piston-crank's system, valves and resonance effects create background noise, which occurs with low frequencies (<1000Hz). Searched emission signal is created due to spread of the wave of fuel pressure into injecting pipes because of minor changes of the fuel pressure after opening of the discharge jet (fuel injection) and the emission which happens after the phase change of fuel. The sensor registers waves deflected due to the closings of injectors, closings and openings of the injection pump. Strong signals coming from closures of inlet and outlet valves are also registered. The diagnostic signal is only a fraction of a percent of the total acoustic emission.

Due to the fact that there is no possibility of registering only of burst emission spectrum emitted by the injectors there is a need of employing not only a filter eliminating low frequencies but as well the one eliminating high frequencies (the division of given synchronous sources of acoustic emission in time) in the amplifier of AE signal as well as using the author's software with events' filter [4].

Parasitic frequencies attach to the diagnostic signal but they remain at a constant level for stabilized rotational speed of the engine. Diagnostic signal frequency is contained in the range 1 - 22 kHz for CR injectors which work properly and in the range 1-30 kHz for faulty ones described in point 2, according to type 1. Diagnostic parameters are: features of acoustic emission and additionally quality descriptors D_q calculated by the dedicated software. The descriptions of the researches, procedures, the technique of installation of the sensors and the elements of validation of the method have been earlier presented in the given literature [2, 3, 4, 5, 7, 9, 10, 11, 14].

3.1. System variables $EDC_{xy}C(P\ v\ U)_{vz}$

In Common Rail and UPS/CLD systems, depending of the working conditions of the engine and the *EDC* injection system version used the number of phases in the most up-to-date solutions used can reach five phases. Two initial injections, a principal injection and two postinjections. Their presence is not constant though. While at high engine revolution or loading and during engine brake central unit excludes one of the initial injections. A similar situation happens with the postinjections as it is only realized when the need of fining of the particular matter filter (Fig. 6) when the differential sensor registers pressures difference saved onto the map of controller. With the usage of piezoelectric injectors of new generation the possibility of steering of not only the number of injection phases but also of the time distance between them (Fig. 5) occurs thanks to the fact that piezoelectric valves are four times faster than electromagnetic ones [6].

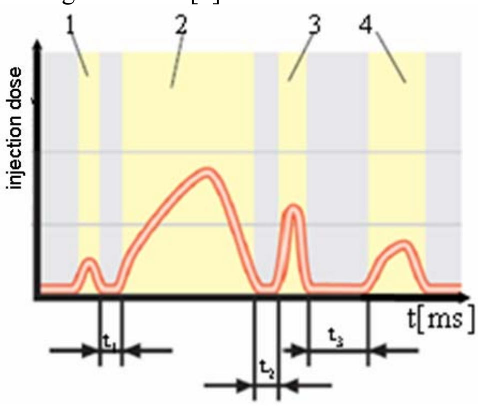

Fig. 5. Multi-phase fuel injector with piezoelectric servo. 1 – initial injection, 2 – principal injection, 3 – early postinjection, 4 – late postinjection, t_1, t_2, t_3 – regulated time interval between injections [6]

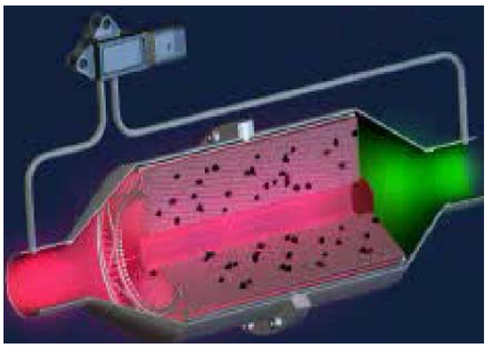

Fig. 6. Solid particles' filter with differential sensor of pressure and with occurring pressures' difference [source: Bosch]

That is why during the diagnosing with the usage of RMOG[2]2 tool a constant rotational speed of the engine should be kept in order to achieve a reference signal from the other injectors [12, 13].

There is, however, a theoretical possibility of the breakdown of all the injectors at the same time. Then the measure of the signal of steering injector should be done with the use of an oscilloscope to gain the needed value. The present steering of the injector must be reflected in the signal of the results' spectrum. The lack of such a reflection signals breakdown of the injector[3].

3.2. Acoustic emission features for properly working and broken down injectors

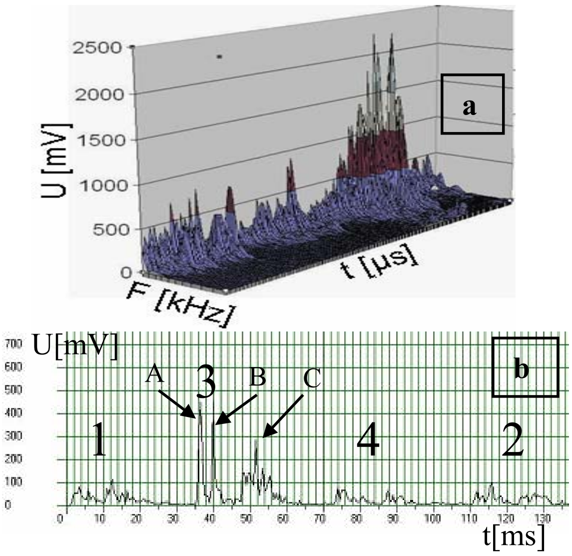

Fig. 7. Burst emission: a – three-dimensional projection, optimum for result's frequency (A, B – initial injection, C – principal injection), 1, 3, 4, 2 – sequence of fuel injection into an appropriate cylinder

For given solutions of the EDC system the optimum of the result's spectrum should be appointed experimentally (Fig. 7b) and which should be defined as the reflection of the expected value in the result's spectrum (in the result value). For a given optimum timing-frequency decomposition of the signal should be done (Fig. 8).

Acoustic emission data set can be analysed by the dedicated software with the aim of obtaining numeric values of the quality descriptor D_q and the signal power P_c. In the garage conditions the results after the decomposition are observed on the computer's screen and are additionally saved in non-transitory memory of the system. Acoustic emission features for properly working and broken down injectors have been shown in Fig. 8.

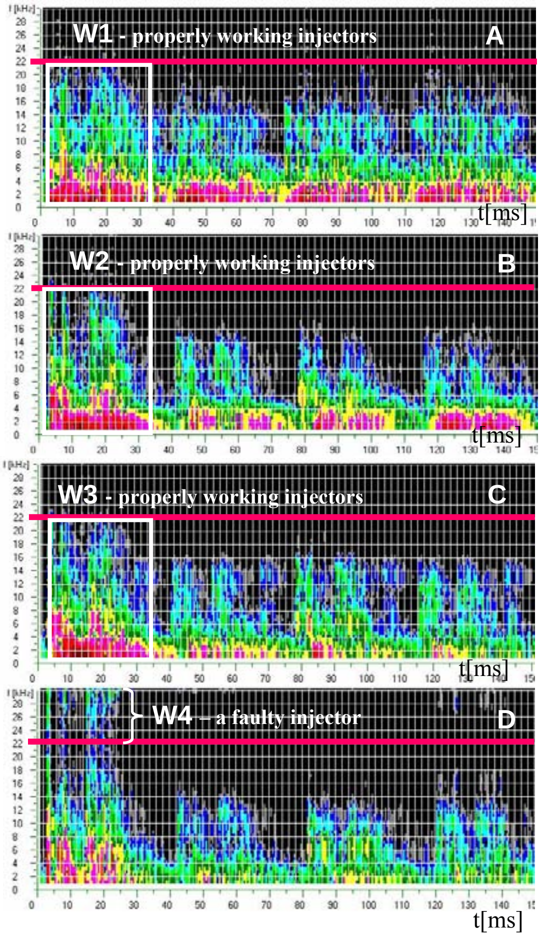

Fig. 8. A set of features of acoustic emission of Common Rail injectors. W1, W2, W3 – properly working injectors, W4 – a faulty injector

3. SUMMARY

According to statistic data and market information about the production of motor cars with self-injection engines in Western Europe in 2006 was estimated at 8 million which was over 47% of total production. At present a total amount of cars with self-injection engines in Europe is estimated at about 88 million cars and is expected to reach 97 million cars in 2010.

The share of new injection systems at the end of 2006 was 66% higher than the conventional systems and it is expected that in 2010 it will be over two times higher.

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2 The second edition of RMOG device. Its name comes from names of the device creators: **R**anachowski, **M**arczak, **O**lszowski, **G**uzik

3 Under a condition that the fuel pressure in the fuel container is correct. However, it is registered with the use of the sensor of high fuel pressure. Improper pressure is registered in the error memory of EDC controller and, in the case of any incompatibility a controller of heater plugs on the controllers' panel will light – in cars homologated after 2003 – MIL controller.

4. CONCLUSIONS

1. Statistics of breakdowns of the CR injectors indicated the need of subduing this system to preventive testing.
2. Due to the extensive growth of the market of vehicles with the new generation system the possibility of introducing preventive control testing into the compulsory duties of Vehicles' Control Stations.
3. Such an approach would create a need of examining all types of systems and introducing tables of reference for the quality descriptors' values.
4. Preventive testing would allow excluding from exploitation faulty working injectors, reduce the consumption of fuel as well as reduce the emission of harmful substations into the atmosphere.

LITERATURE

[1] Robert Bosch GmbH. *Diesel-Speichereinspritzsystem Common Rail*. Fachwissen Kfz-Technik Dieselmotor-Management. Ausgabe 2004.
[2] Olszowski S., Marczak M., Guzik J., Ranachowski Z., Bejger A.: *Portable system for fault diagnostics of the fuel injectors of medium power maritime diesel engine with application of acoustic signal*. PSAE SCIENCE AND TECHNOLOGY PUBLICATION. The Archives of Automotive Engineering nr 3 '2005.
[3] Olszowski S., Marczak M., Guzik J., Ranachowski Z., Bejger A.: *Diagnostic of the fuel injectors of medium speed diesel engine with application of acoustic signal*. Transport. IX konferencja „Komputerowe systemy wspomagania nauki, przemysłu i transportu TRANSCOMP 2005. Str. 23-28.
[4] Guzik J., Olszowski S., Marczak M., Ranachowski Z., Wojtyniak M.: *Raport końcowy z realizacji projektu celowego nr ROW-II 039-2005, Nowa bezinwazyjna metoda diagnozowania stanu wtryskiwaczy zasilanych promieniowymi rozdzielaczowymi pompami wtryskowymi*. NOT Warszawa, LOGIS Radom '2005.
[5] Guzik J., Olszowski S., Marczak M, Ranachowski Z., Wojtyniak J.: *Investigation of acoustic emission signal generated in the friction pair lubricated width oils containing various lubricity additives*. Engineering transactions, 54, 2, 159-166, 2006.
[6] Olszowski S.: *Nowe metody diagnostyczne. Silniki wysokoprężne z bezpośrednim wtryskiem oleju napędowego ze sterowaniem EDC*. Akademia Techniki Samochodowej Autodistribution International. AD Polska, IV '2006.
[7] Marczak M.: *Walidacja bezinwazyjnej metody diagnozowania stanu wtryskiwaczy silników z bezpośrednim wtryskiem oleju napędowego*. Transport. IX konferencja „Komputerowe systemy wspomagania nauki, przemysłu i transportu TRANSCOMP 2005.
[8] Olszowski S. *Układ bezpośredniego wtrysku oleju napędowego Common Rail*. Materiały szkoleniowe. Biuro Ekspertyz Technicznych i Szkoleń, Radom '2007.
[9] Olszowski S. *Diagnostyka układów wtryskowych z bezpośrednim wtryskiem paliwa w silnikach wysokoprężnych*. Transport XXI wieku. Politechnika Warszawska '2007. Tom II, str. 69-75.
[10] Olszowski S. *Problemy diagnostyczne silników wysokoprężnych ze sterowaniem elektronicznym*. IV Konferencja Naukowo-Techniczna. LogiTrans. Szczyrk, kwiecień 2007. Prace naukowe „Transport" Nr 1/25/2007.
[11] Olszowski S., Marczak M.: *Acoustic Emission As The Best Way In Making Diagnosis Of The Diesel Engines*. Materiały XI Międzynarodowej Konferencji „Komputerowe Systemy Wspomagania Nauki, Przemysłu i Transportu", 2007, Politechnika Radomska, TransComp, vol. 2, str. 139-144.
[12] Olszowski S., Guzik J., Marczak M, Ranachowski Z.: *Akcelerometryczne badanie emisji akustycznej układu bezpośredniego wtrysku oleju napędowego przed i po czyszczeniu wtryskiwaczy bez ich demontażu*. X Międzynarodowa Konferencja „Komputerowe Systemy Wspomagania Nauki, Przemysłu i Transportu" TransComp. Zakopane 2006.
[13] Olszowski S.: *Badanie skuteczności regeneracji wtryskiwaczy silników z bezpośrednim wtryskiem oleju napędowego za pomocą nowej bezinwazyjnej metody diagnozowania z wykorzystaniem emisji akustycznej – etap 1*. Sprawozdanie z prowizorium nr 2463/46/P. Politechnika Radomska. Styczeń 2008.
[14] Olszowski S. *Innowacyjna technika diagnozowania wtryskiwaczy Common Rail*. Czasopismo Logistyka nr 2/2008, Poznań 2008.

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DIGITAL ORDER TRACKING ANALYSIS FOR ROTATING MACHINERY MONITORING. THEORY AND IMPLEMENTATION

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Summary

This paper presents a brief of properties and rules of digital order tracking analysis in diagnosis of rotary machines. The classical methods of order spectrum analysis are also provided. The main part of given paper is description of new approach of method for digital tracking analysis. The most important thing is a way of choosing samples for logical change of regular sampling in time domain by regular sampling in angle domain. The low-order filter based method is used. Presented paper shows design of such filter and the results of simulations and experiments. At the end short brief of expert systems idea for diagnosis of rotary machines was shown.

Keywords: digital order tracking analysis, vibrodiagnostic, real time.

CYFROWA RZĘDOWA ANALIZA ŚLEDZĄCA DO MONITORINGU MASZYN OBROTOWYCH. TEORIA I IMPLEMENTACJA

Streszczenie

W prezentowanej publikacji przedstawiono w skrócie zasady i cechy cyfrowej rzędowej analizy śledzącej w diagnostyce maszyn obrotowych. Wskazano, także klasyczne metody wyznaczania widma rzędowego. Zasadniczą częścią publikacji jest opis autorskiej metody prowadzenia cyfrowej analizy śledzącej. Najistotniejszą innowacją jest sposób wyznaczania próbek pozwalający na logiczną zmianę równomiernego próbkowania sygnału w dziedzinie czasu na równomierne próbkowanie w dziedzinie drogi kątowej. Metoda polega na zastosowaniu tzw. filtru niskich rzędów. W przedstawionej pracy opisano sposób projektowania takiego filtru oraz pokazano wyniki symulacji i eksperymentów. W zakończeniu przedstawiono krótko ideę systemu ekspertowego do diagnostyki maszyn wirujących, wykorzystującego opracowaną metodę.

Słowa kluczowe: cyfrowa analiza śledząca, wibrodiagnostyka, czas rzeczywisty.

1. VIBROACUSTIC SIGNALS AND REALTIME ANALYSYS

Vibroacoustic phenomenon (VP) in general are dynamic mechano-acoustic phenomenon [3, 7] which occurs with machines and moving devices or having elements in motion. Such phenomenons are vibration, air sound and material, pulsation of rounding machine work space [6, 4]. Projection of vibroacoustic phenomenons are vibroacoustic signals (VS) generated by any kind of electronics sensors.

In practice aspects of VS [7] the widest domain of appliance seems to be diagnostic, a specially during „on time" in real-time of work. The classical methods such as, signal decomposition using band filters, estimation of power spectrum density isn't acceptable diagnostic result in periods of unstable device work. It occurs when VP, so VS too, temporarily loose its stationary property. Such situation have place during speedup or breaking down of rotary machines eg. rotor, electric engine, plane and ships engines. In most of cases this stage of work isn't analyzed, because it's temporary and unstable state. However in causes, when we work with big objects, where run-up and run-down procedure is complicated, information of that period of work have very important practical meaning. It is early fault detection, so serious damage can be avoided.

Instability of signals is very big difficulty of measurement and analysis, so no one from classical time, amplitude or frequency characteristic will be useful. That shows spectrum map (fig. 1a), where placement of spectrum lines moves with every next measurement and not allows for correct estimation. The range of observed spectral component changes too. With the lowest rotations, all to the 8-th harmonic are visible but with the highest only to the 5-th harmonic. In this cases changing domain of analysis is demand [2, 13, 16], that the results have stable character and allows do analysis. Such possibility can be achieved using order domain versus frequency domain. In this approach observed signal (fig. 1b) can be analyzed in the same way like classic invariable picture of frequency spectrum. In order domain points on Y-axis presents x-time of current speed of rotary object so spectral lines of signal component (functions of rotary speed of engine) will be stationary.

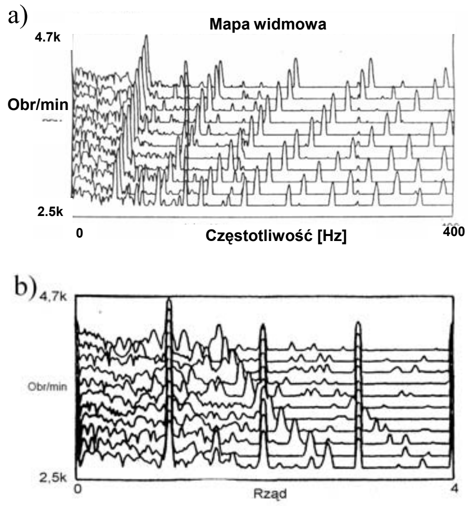

Fig. 1. Frequency spectrum of VS signal with increasing rotary speed and order spectrum of VS signal with increasing rotary speed

2. VIBROACOUSTIC SIGNALS ANALISYS MADE AS ORDER TRACKING ANALYSIS

The main work algorithm of measurement devices worked in order domain analysis are well known from publications [1, 2, 13], many companies like Hewlett-Packard, Bruel & Kjaer, Oros. The algorithm of work flow presents as follows:

a) measure and store the arrival times of each synchronizing tachometer pulse simultaneously (depending of spectrum resolution);
b) calculate the new points of digital resampling time on the base of different rotation models and store them;
c) interpolate the stored measurement data in some optimum manner to obtain new samples at the desired time points;
d) compute the spectrum in the order domain using FFT or any other transformation.

The hardest operation is reconstruction of signal amplitude in the angle movements corresponding the same time moments with precision allowed to achieve demand spectrum dynamic. In paper [13] of Hewlett-Packard company, for signal amplitude reconstruction the interpolation in time domain filter was used. The main defect of such approach is the same amplitude-frequency characteristic in every new collected point corresponding the same angle movements. In the machine speeding up situation threshold frequency should move into high frequency, and when the machine slowing down – into low frequency. Given property makes constant non-removable defect which limits dynamic of the method. For signal amplitude reconstruction the specialists from Bruel & Kjaer company applying different [1, 2] solution: decimation and interpolation with partial multiplicity. That approach decimation factor must be change with non-stationary frequency of engine rotary, but there is problem with setting of current, demanded value of decimation factor which depends on dynamic of specific machine.

In the next chapter the algorithm of spectrum order determination with angle domain filtering usage was described, that eliminates problems in presented methods.

3. SPECTRUM TRACKING ANALYSIS BASED ON DIGITAL LOW ORDER FILTER

Digital order tracking analysis is very important in case of diagnosis of big rotating machines. Disadvantages of traditional methods implicated number of their improvements [12, 10]. The key moments in algorithms that computes order spectrum are how to calculate time points on equal angular movements and how to approximate rotation speed in this points. In presented method [11, 10] linear acceleration rotation speed model and low order filter are used.

3.1. Calculation of new digital resampling time points

In presented work one's assumed that the reference shaft is constantly accelerating during three successive phase marks. Denominate T_j time between i and $i+1$ phase marks and T_{j+1} between $i+1$ and $i+2$ phase marks and using lows describing rotating movements one's get:

$$t_i = -\frac{T_{j+1}^2 + T_j^2}{2(T_j - T_{j+1})} \pm \sqrt{\left(\frac{T_{j+1}^2 + T_j^2}{2(T_j - T_{j+1})}\right)^2 + \frac{i}{N}\frac{(T_{j+1} + T_j)T_j T_{j+1}}{T_j - T_{j+1}}} \quad (1)$$

where N – number of resampling points, i – current time point (in equation (1) before square root is chosen „-" if acceleration is negative, otherwise is „+").

3.2. Amplitude interpolation at the desired time point

Amplitude interpolation can be made using digital filter of low orders (LOF – Low Order Filter). On fig. 2a time changes of rotation speed are shown. On fig. 2b one's see data collected with constant discretization frequency (Ts=const.) and two time moments t_j i t_k, where amplitude should be resampled. To achieve this, rotation angle in points 1 to 5 and 11 to 16 are calculated. Then, central point of filter impulse response is set on interpolated time moment. Resampled value is equal to sum of the next signal points stored with constant sampling rate weighted with impulse response of LOF. The impulse response of LOF in angle domain is symmetric and has constant width (fig. 2c), but in time domain varies tracking rotation speed (fig. 2b). Resampling algorithm is as follow: 1). To calculate a revolution angle for t_j resampled point from beginning of a revolution j on the base of the linear model of object rotation. It should be noticed that the central point of impulse response of LOF is in a resampled point:

$$\varphi_{tj} = \omega_{oj} t_j + \varepsilon t_j^2 / 2, \tag{2}$$

where: ω_{0j} – is initial angular rotation velocity of j revolution, ε - acceleration.

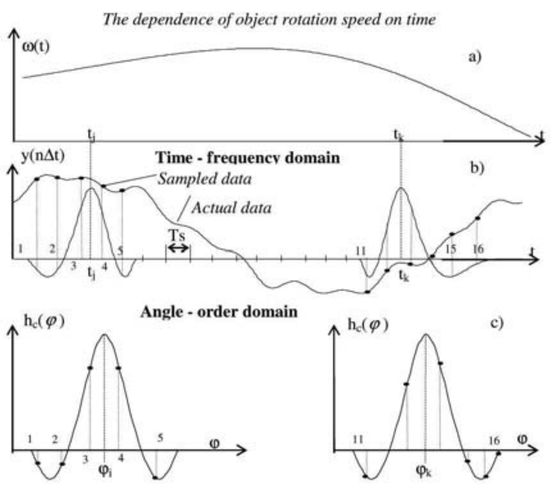

Fig. 2. Resampling amplitude method by the interpolation digital filter.

2. To calculate a current angle from beginning of *j-th* revolution for the nearest points stored with constant sampling time period to the resampled point on the base of the linear model of object rotation.

$$\varphi(nT_S) = \omega_{0j} nT_S + \varepsilon \frac{(nT_S)^2}{2}, \tag{3}$$

where T_S – discretization period. If the *n-th* point concerns to the previous *(j-1)-th* revolution, then:

$$\varphi(nT_S) = -2\pi + \omega_{0j-1} nT_S + \varepsilon \frac{(nT_S)^2}{2} \tag{4}$$

In addition to check up the angular distance from the resampled point up to some *i-th* nearest point stored with constant sampling time period, whether the angular distance is no more than half of length of the impulse response. The length of the impulse response of LOF is

$$\varphi_h = \frac{2\pi\left(N_h - 1\right)}{N \cdot L},$$

where N_h – number of points in impulse response, N – number of resampled points, L – number of phase markers. Now then it should be:

$$-\frac{\pi(N_h - 1)}{N \cdot L} \le \varphi(nT_S) - \varphi_{t_i} \le \frac{\pi(N_h - 1)}{N \cdot L} \tag{5}$$

3). To calculate according expression (1) the value of the impulse response of LOF with angle defined on the step #2 for the signal points stored with constant sampling frequency.

$$\varphi_{t_i}(nT_S) = \frac{N \cdot L}{N_h}\left(\frac{\pi(N_h - 1)}{N \cdot L} - \varphi_{t_i} + \varphi(nT_S)\right) \tag{6}$$

4). To calculate resampled y_{ti} of a signal in *i-th* point as a sum input signal points stored with constant sampling frequency weighted with impulse response:

$$y_{t_i} = \frac{\sum_n h_{t_i}(nT_S) x(nT_S)}{\sum_n h_{t_i}(nT_S)} \tag{7}$$

where $x(nT_S)$ – input signal. The summation in (7) is conducted for all of *n*, for which the inequality (5) is executed. The given division of the resampled signal amplitude on a size equal to sum of impulse response points is necessary to take account of the change of the impulse response length of LOW in time domain.

In presented resampling method low pass order filter with constant impulse response in angle domain is used. This fact eliminates methodological errors present in other methods. Additional advantage is that in further calculations only important part of spectrum is considered. As were shown, cut-off frequency in magnitude response in frequency domain of the LOF automatically tracks rotation speed changes.

4. SYNTHESIS OF LOW ORDER FILTER

The requests, which the LOF should satisfy are as follow:

1). The cut-off order of a filter should be selected from the required maximum order. In the generally case the normalized cut-off order of a LOF can be selected as: $p_C = 2p_{max}/(N \cdot L)$, where p_{max} – maximum order in signal spectrum, $N \cdot L$ – total number of resampled points.

2). The request to pass-band ripple of order response characteristics is selected according to a required dynamic range of the analyzer, as generally during revolution the acceleration of object rotation can be not to constant, then the passband ripple of order response will be perceived as a noise, which to reduce will be impossible without knowledge of the law of the acceleration change. For a required dynamic range D_T, [dB], the passband ripple is estimated by the following expressions:

$$\delta_1 = \pm 20 \cdot \lg(1 - 10^{-D_T/20})$$

$$\delta_1 = \pm 100\% \cdot 10^{-D_T/20}$$

For example, for a required dynamic range 70 dB will have $\delta_1 = \pm 0{,}032\%$ or $\delta_1 = \pm 0{,}003$ dB. Also the stop-band ripple of a order response should be selected not bigger than significance DT.

3). The ratio between pass-band, stop-band and transition band should be selected according to minimum to possible impulse response points number, as this number determines computing complexity of the resampling amplitude algorithm.

Thus, the problem of a low order filter synthesis is formulated as: Let on the set of orders $E_l \in (-L, L)$, the function is given *B(l)* and the order of transfer function *H(l)* of a nonrecursive filter (FIR) $H(l) = \sum_{k=0}^{N_h-1} h_k \exp(-jkl)$. Where *l* - current order.

It is required to find the vector $\mathbf{h}^* = [h_0, h_1, ..., h_{N_h}]^T$ such, that

$$\min_{\mathbf{h}} \max_{l \in L} \left| B(l) - \sum_{k=0}^{N_h-1} h_k \exp(-jkl) \right| = \max_{l \in L} \left| B(l) - \sum_{k=0}^{N_h-1} h_k^* \exp(-jkl) \right| = \delta^*$$

otherwise

$$\max_{l \in L} \left| B(l) - \sum_{k=0}^{N_h-1} h_k \exp(-jkl) \right| \Rightarrow \max_{\mathbf{h}} = \delta^*$$

The set E consists of the pass-band and stop-band of the desired filter. Thus, we have got the Chebyshev approximation problem. To solve for the filter parameters, we can use the Remez [8] exchange algorithm. The continuous impulse response of the LOF is determined according to the trigonometrical interpolation method [11]:

$$h(\varphi) = \frac{a_0}{2} + \sum_{l=1}^{\frac{N_h-1}{2}} \left[a_l \cos\left(2\pi l \frac{\varphi}{\vartheta_d N_h}\right) + b_l \sin\left(2\pi l \frac{\varphi}{\vartheta_d N_h}\right) \right] \quad (8)$$

where $\vartheta_d = 2\pi/(N \cdot L)$ – sampling period (angle), N_h – number of points of impulse response, ϑ_d - continuous angle ($0 < \vartheta_d < \vartheta_d N_h$),

$$a_l = \frac{2}{N_h} \sum_{q=0}^{N_h-1} h_q \cos\left(2\pi l \frac{q}{N_h}\right), \quad (9)$$

$$b_l = \frac{2}{N_h} \sum_{q=0}^{N_h-1} h_q \sin\left(2\pi l \frac{q}{N_h}\right) \quad (10)$$

where h_q - q-th point of the LOF impulse response.

On fig.3a – 3c impulse responses of the LOF in time domain are shown. The parameters are: ω_0=0, ε=200 rad/sec^2, N_h=33, T=10^{-3}s_c for N=64 points. On figures following labels are used: n –number of point, h1, h32 i h64 – accordingly impulse response in time domain for 1-th, 32-th and 64-th resampling point on the second rotation revolution. From fig. 3 it is visible that by machine run-up, impulse response in time domain is non-symmetric and its length (measured by number of points) decreases.

The magnitude characteristic of the LOF in the frequency domain for the given example is shown on the fig. 3d. The line 1 corresponds to the first resampled point, the line 2 - 32-th, and the line 3 - 64-th resampled points for equal transitions on the second revolution respectively. From fig. 3d it is visible, that LOF has a magnitude response in frequency domain with tunable cut-off frequency, and this frequency displaces in high-frequency area owing to run-up of object. Therefore, the offered filter realizes automatic tracking for the change of the object rotation velocity in the correspondence with the required model of the object rotation velocity.

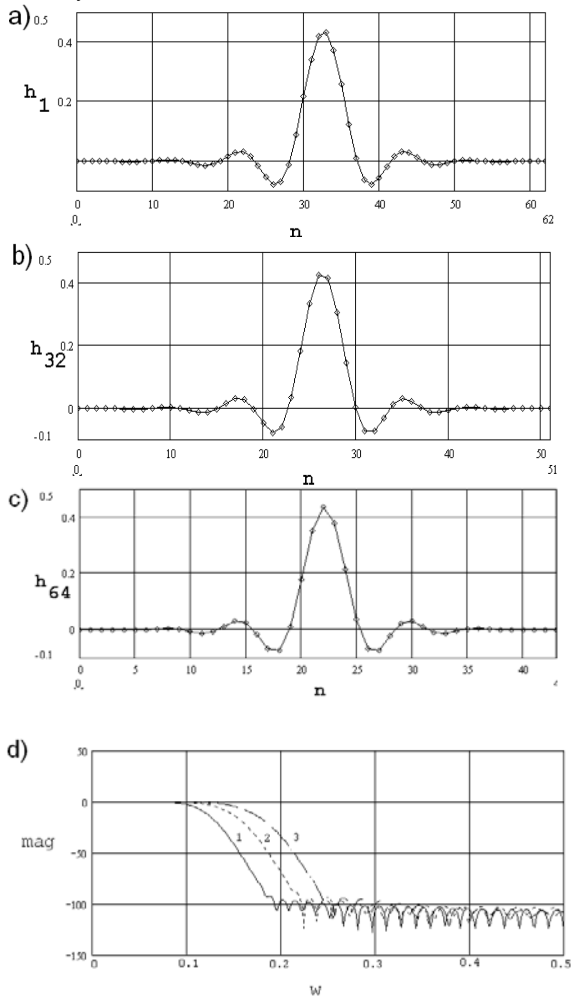

Fig. 3. a) Impulse response on the 1-st resampling point, b) on the 32-th point, c) on the 64-th point, d) magnitude response of the LOF in frequency domain.

5. SIMULATION AND TESTS

Algorithm of the developed spectral tracking analysis consist of following stages:

1. To measure some adjacent time intervals between phase markers on the object rotor. Number of intervals is find from expression *(L*N)/2 = Pmax*, where *Pmax* – maximum order required in spectral map. If spectral resolution *1/k* is needed, it is necessary to collect data throughout *k+1* revolutions.
2. To calculate time moments on equal angle movements of the rotor of the object.
3. To resample amplitude in time moments from stage 2.
4. To calculate spectral map using FFT algorithm. With purpose of a illustration of method work the simulation modeling of process of a unstable rotation is performed. Linear and sine wave are chosen as the law of time variation of object rotation speed. It includes run-up and run-down

stages of object. The following signal was used as the simulation signal:

$$x(t) = \sin[\varphi(t)] + 0{,}25\sin[10\varphi(t)],$$

where:

$\varphi(t) = \omega t + \varepsilon t^2/2$ - by linear changes,

$\varphi(t) = \omega_c t - \frac{a}{b}\cos(at) + \frac{a}{b}$ - by sinusoidal changes (a, b – signal parameters, ω_c – stationary rotation speed).

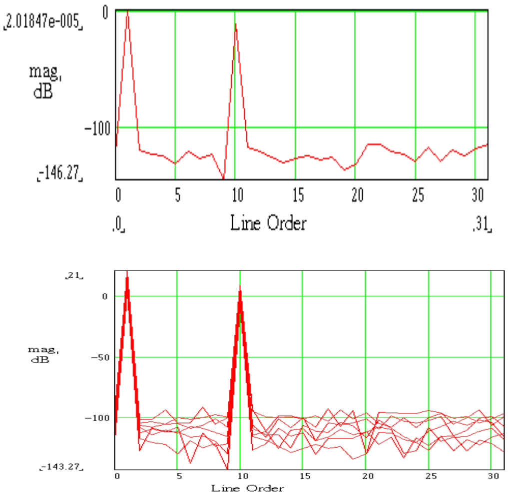

Fig. 4. The spectral map in order domain by linear velocity changes for one revolution (upper fig.) and for six revolutions (lower fig.).

Some simulation results are shown on fig. 4 and fig. 5. The simulation experiments depict that proposed method provides stable spectral line despite of velocity changes even by non-linear case.

By non-linear rotation speed changes spectrum noise component increases because of differences between modeled and real rotation speed.

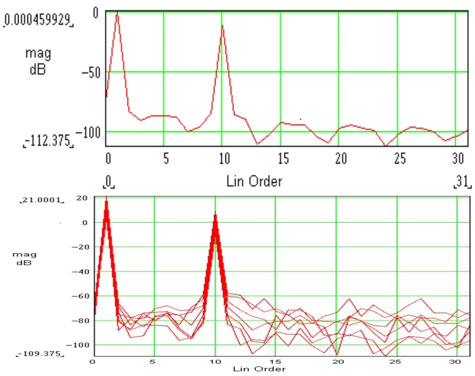

Fig. 5. The spectral map in order domain by sinusoidal velocity changes for one revolution (upper fig.) and for six revolutions (lower fig.).

For checking of the method it was also made a test of an asynchronous electric engine in the stage of start-up and some time later in the stage of rated load. The range of generated frequencies was closed to vibrations of symmetrical engine with 24 slots of stator. The testing results are shown on the fig. 6.

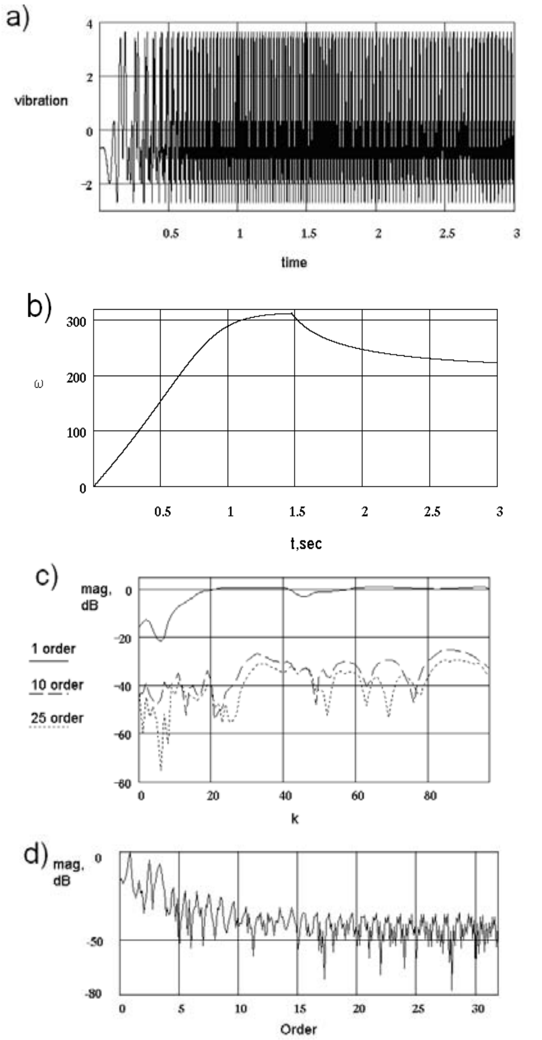

Fig. 6. a) The vibration signal of an electric engine, b) the dependence of object rotation speed, c) the dependence of the 1-th, 10-th and 25-th order amplitude upon number of revolution, d) spectral map in order domain.

6. EXPERT SYSTEM

Proposed method gives possibility of diagnosis rotary machines at instable environment.

Supplementing proposed approach by spectral analysis, there is possible to create automated diagnosis system [12] inclusive all cycle of rotary machines work. During the research the idea of such system was developed. The decision mechanism based on fuzzy-logic methods. The system is implemented in an objectoriented language C++. The object-oriented approach is used because it provides a rich structure for describing frames. The fuzzy reasoning algorithm and knowledge representation in this system are based on the results of the paper [9]. Each hypothesis is expressed as a frame, witch is organised as a hierarchy through a system of superlinks and sub-links. The rules about a hypothesis are attached in the associated frame. There are two kinds of rules. One is used for diagnosis, the other is for meta-knowledge. A grammar in Backus-Naur Form (BNF) for the rules are given below:

Rule:= rule-name IF [conditio] then conclusion cf(f) [rel(f)]
Condition:= fullpremise {relation fullpremise}
Fullpremis:= [sign] premise [weight(f)]
Relation := AND/OR/ADD/REL
sign:=NOT
conclusion:=[sign]premis/rule-name1 {rule-name}
premise:= string/(numeric-variable relation-op value)/string IS string-val)
numeric-variable:=string
relation-op:=>/</=
value:=decimal number
string-val:=string
f[-1,+1]
rule-name:=rule-name1/rule-name2
rule-name1:=r+digital number
rule-name2:=M+digital number
** bold letters denote keywords*

The rule is formulated in a class with the data and operations encapsulated in the rule class. The data include rule name, rule type, certainty, conjunction, conclusion, related factor and a premise list for the variable number of premises. The operations about the rules are written as methods. They include **getNumberofPremise()**, which will get the number of premises in a rule; **getnthPremise()** which will get the content of the *n*th premise; and so on. The definition of the diagnostic rule class is presented in the following view:

class: DiagRule
suoperclass: Rule
data:
ruleName:
ruleType: RULE_DIAG
pemiseList:
certainty:
preRelation:
relatedFact:
conclusion:
methods:
virtual readData()
getNumberofPremise()
genthPremise()
rulename()
ruletype()
certainty()
prerelation()
releatedfact()
conclusion()

A premise is also expressed as a class. It includes premise type, attribute name, relation between premises, weight for the premise and attribute value such as *increase*, *small*, *0.12* and so forth. An instantiation of the premise class is executed as follows:

class: Numeri premie
super-class: premie
premie-type: pre-num
attribute-name: the thickness of LVwall
relation: ADD
weight: 0.3
attribute-value: incrase
function: match()
certainty: 0.7

Each premise object may have its own **match** method to calculate the degree of match between the premise and findings. The certainty fact for a premise is calculated by the algorithm and filled in the certainty slot during the run time. In the system, the frames, rules and even premises are all expressed as classes. During the reasoning process, they are instantiated into objects. This objects will be created and deleted dynamically. The fuzzy reasoning algorithm is used to calculate an uncertainty measure for the conclusion.

7. CONCLUSION

Developed method of digital tracking analysis for monitoring industry machines working in runup and run-down phases and during big frequency instability, eliminates methodology inaccuracy caused by applying polynomial interpolation or interpolation filter in frequency domain. The filter works in order domain has constant order of cut-off (similarly frequency threshold) and choose only that part of order spectrum which is important for the next processing. Impulse response of the given filter is function of rotation angle and constant in this domain. After transformation of given characteristics into domains, time and frequency appropriately, the shape of them changes together with rotary speed change. In the case of frequency characteristic the cut-off frequency automatically fits to changes of speed of rotary machine rotations. In the case of impulse response the progress and the count of non zero points changes. The changes character depends on established model of rotary speed changes. Applying proposed method and appropriated parameters of interpolating filter (Low Pass Filter) the spectrum dynamics more than 100 dB can be achieved (polynomial interpolation or interpolation with frequency domain filter gave dynamics about 70-80 dB). Computation complexity is a defect of proposed method. It can be resolved using efficient microprocessors DSP or distributed arithmetic technology.

REFERENCES

[1] Broch J. T.: *Mechanical Vibration and Shock Measurement*. Bruel and Kjaer, Kopenhaga, 1980.
[2] Bruel & Kjaer: *Order Tracking Analysis.Technical Review*, Nr 2, Denmark 1995

[3] Cempel C.: *Wibroakustyczna diagnostyka maszyn*. WNT, Warszawa, 1989.
[4] Cempel C.*: Vibroacustic Condition Monitoring*. Hornwood E, Chichester-New York, 1991.
[5] Engel Z.: *Ochrona _środowiska przed drganiami i hałasem*, WNT, Warszawa, 2001.
[6] Engel Z., Stryczniewicz L: *Vibroacoustic Modelling of Machines*. Bulletin of Polish Academy of State, Warszawa 2001, s. 379-393.
[7] Engel Z.,Cempel Cz: *Vibroacoustic and its Place in Science*, Bulletin of The Polish Academy of Sciences, Warszawa 2001, Vol. 49, no.2.
[8] Omieljanowicz M., Piotrowski A.: *Synteza cyfrowych filtrów w analizatorach wibroakustycznych czasu rzeczywistego w postaci kaskady identycznych ogniw niskiego rzędu*. XXXV Międzyuczelniana Konferencja Metrologów, 8-11 wrzesień 2003, Kraków, s. 147-152.
[9] Kenneth Ong, Qiu-He Wang: *A generalised fuzzy reasoning algorithm for an object-oriented expert system tool. Expert Systems*, August 1995, Vol. 12, No. 3, pp. 199-207
[10] Petrovsky A., Stankevich A.: *Order Extraction as Order Waveform Based on The Digital Tracking Filter of Low Orders*. Structures-Waves-Biomedical Engineering, Polskie Towarzystwo Akustyczne, Kraków 2001, Polska, Vol.10, No. 1 s. 61-72.
[11] Petrowski A., Stankevich A.,. Balunowski J.: *The Order Tracking Front-end Algorithms in the Rotating Machine Monitoring Systems Based on the New Digital Low Order Filtering*. Sixth International Congress on Sound and Vibration, 5-8 July 1999, Denmark, s. 2985-2992.
[12] Piotrowski A., Stankiewicz A., Balunowski J., Sołbut A.: *Diagnostic Symptoms Forming in the Rotating Machine Monitoring Based on the Order Tracking Analysis*. II International Congress of Technical Diagnostics, 19-22 September 2000, Warszawa, na CD.
[13] Potter R.: *A New Order Tracking Method for Rotating Machinery*. Sound and Vibration, September 1990, s. 30-33.

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APPLICATION OF THE WAVELET TRANSFORM IN SI ENGINE VALVE FAULT DIAGNOSTIS

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Summary

In this paper, the wavelet transform of vibration acceleration signals which were acquired from the cylinder head in two different states of valve train were analyzed.

The valve works under two different conditions: the normal condition and the gasleakage fault conditions. The gasleakage fault was simulated by producing a 3 mm long crack on the cap of the exhaust valve. The sampling frequency was 25 kHz and during data acquisition process, the rotating speed of the engine was kept at a constant rpm and at run up condition.

A engine valve is opened by a camshaft and pushed back to its seat by a valve spring. Problems with valve mechanism can cause a change to the transient vibration produced during opening and closing.

The vibration signals collected from engine block are complicated the features of the signals in different fault condition often overlap together with each other.

The vibration signals from cylinder head are typically non-stationary and transient, which are usually analyzed with non-stationary signals analysis methods, such a time frequency analysis (STFT, WVD), wavelet analysis (DWT, CWT) and wavelet packet analysis (WPT).

In wavelet analysis, the signals are processed at different scales or resolutions. Wavelet analysis is one effective tool for signal processing and feature extraction. In this paper the time–energy density analysis approach based on wavelet transform is proposed.

Keywords: wavelet transform, valve fault, diagnostics.

ZASTOSOWANIE ANALIZY FALKOWEJ W DIAGNOZOWANIU USZKODZEŃ ZAWORÓW SILNIKA SPALINOWEGO ZI

Streszczenie

W artykule przedstawiono wyniki analizy falkowej sygnałów przyspieszeń drgań zarejestrowanych na głowicy silnika ZI z symulowanymi uszkodzeniami zaworów. Badania przeprowadzono na silniku sprawnym oraz na silniku z uszkodzonym zaworem wylotowym pierwszego cylindra. Uszkodzenie zaworu wylotowego, powodującego nieszczelność cylindra symulowano poprzez poprzeczne nacięcie grzybka zaworu o długości około 3 mm. Sygnał przyspieszeń drgań rejestrowano z częstotliwością próbkowania 25 kHz, podczas badań silnik pracował ze stałą i zmienną prędkością obrotową. Praca układu rozrządu wywołuje zaburzenia impulsowe, które są widoczne w sygnale przyspieszeń drgań. Drgania mierzone na bloku mają złożony charakter ze względu na nakładanie się sygnałów pochodzących od różnych źródeł. Sygnał przyspieszeń drgań kadłuba i głowicy jest niestacjonarny i do jego analizy stosuje się metody przetwarzania sygnałów w dziedzinie czasu i częstotliwości, tj. STFT, WV, oraz analizę falkową (CWT, DWT) i pakiety analizy falkowej (WPT). W analizie falkowej sygnał jest przetwarzany ze zmienną rozdzielczością w dziedzinie skali i czasu. Z badań wynika, że jest ona skutecznym narzędziem służącym do budowy zbioru cech diagnostycznych. W artykule przedstawiono wpływ uszkodzeń zaworu na rozkład energii sygnału drganiowego na płaszczyźnie czas–skala.

Słowa kluczowe: analiza falkowa, uszkodzenia zaworów, diagnostyka drganiowa.

1. INTRODUCTION

At present, time-frequency methods are commonly used for examining vibroacoustic processes (V.A.). In V.A. diagnostics, they are particularly useful for filtering disturbance, detecting pulse components induced by faults and finding significant features of the diagnostic signal. An important issue in vibroacoustic studies is a correct interpretation of complex signals by applying more and more proficient methods of their processing. The main tasks in diagnostics include separation of a useful vibroacoustic signal and selection of characteristic, damage-sensitive features of the processed signal. The VA signal generated by individual kinematic pairs and combustion engine tooling are most frequently nonstationary due to the occurrence of nonlinear phenomena induced, inter alia, by clearance or nonlinearity of elastic components’ characteristics. Frequency characteristics of signals essentially depend on transmittance of the propagation route of component signals from their source to the measuring point. The signal is usually measured by convolution and superposition of many signals and noises.

The paper presents the results of studies aimed at determining the effect of exhaust valve damage on the vibration energy distribution in the time-scale and time-frequency plane. The timing gear system is one of the principal components of the combustion engine. The operational and breakdown wear of such components as the camshaft, pushers, levers and valve springs, as well as valves themselves, has a significant influence on the work of the engine, its performance and reliability. Leakage of exhaust valves affects the engine power to a lesser degree, while the main problem here is a rapid increase of their wear intensity as a result of combustion gas blow-by, which very often leads to a complete damage of valve heads, caused by their burn-out.

For this reason, it is essential to search for effective methods of processing vibroacoustic signals, sensitive to valve damage in its initial stage.

2. TIME-SCALE SIGNAL ANALYSIS

A simultaneous analysis of the time and frequency related properties of signals by means of a wavelet transform is more and more frequently used in diagnosing combustion engines [6, 7, 8].

The continuous wavelet transform of a finite energy function, $x(t) \in L^2(R)$, is defined as follows:

$$W_x(a,b) = \langle x(t), \psi_{a,b}(t) \rangle = |a|^{-\frac{1}{2}} \int_{-\infty}^{+\infty} x(t) \psi \frac{(t-b)}{a} dt \quad (1)$$

$$a,\ b \in R,\ a \neq 0$$

An inverse transform of the transformation $W_x(a,b)$ takes the following form:

$$x(t) = \frac{1}{C_\psi} \int_{-\infty}^{+\infty} W_x(a,b) \psi_{a,b}(t) \frac{da\,db}{a^2} \quad (2)$$

Based on the definition, the function $\psi(t) \in L^2(R)$ is an acceptable elementary wavelet, if:

$$C_\psi = \int_0^\infty \frac{|\Psi(\omega)|^2}{\omega} d\omega < \infty \quad (3)$$

where $\Psi(\omega)$ is the Fourier transform of the function $\psi(t)$.

The wavelet transform is a transformation which retains energy following the dependence:

$$\int_{-\infty}^{\infty} |x(t)|^2 dt = \frac{1}{C_\psi} \int_{-\infty}^{\infty} \int_{-\infty}^{+\infty} |W_x(a,b)|^2 \frac{da\,db}{a^2} \quad (4)$$

In accordance with the above formula, $\frac{|W_x(a,b)|^2}{C_\psi a^2}$ can be treated as power density of the function in a, b plane. The equation (4) can be formulated as follows:

$$\int_{-\infty}^{\infty} |x(t)|^2 dt = \frac{1}{C_\psi} \int_{-\infty}^{+\infty} a^{-2} E(a) db \quad (5)$$

$$E(a) = \int_R |W_x(a,b)|^2 db \quad (6)$$

$E(a)$ is referred to as the wavelet power spectrum of a signal.

Wavelet coefficients $W_x(a,b)$ are the function of scale a and shift b. A change of the scale is tantamount to wavelet compression or stretch $\psi_{a,b}$. The coefficients $W_x(a,b)$ are the measure of signal’s $x(t)$ correlation with the wavelet $\psi_{a,b}(t)$: for narrow wavelets (small a), they represent the content of high-frequency components, and for wide wavelets (big a), of low-frequency components. The above-mentioned properties of wavelet analysis make it more and more popular in diagnosing combustion engines, where non-stationary signals with impulse components are processed. The current studies show that the wavelet power spectrum determined for a selected range of crankshaft rotation can be successfully used for the detection of combustion anomalies and clearance in the piston/cylinder system.

3. RESEARCH OBJECT AND TESTING PROCEDURE

The object of tests was a 1.3 dm^3 engine of a Ford Fiesta personal car. The tests were conducted on a Bosch chassis test bench FLA203. The tests were conducted on a fully operational engine and on an engine with a damaged exhaust valve of the first cylinder. Damage of the exhaust valve causing cylinder’s leakage was stimulated through a lateral notch, ca. 3 mm in length, of the valve head. During the tests, accelerations of the valve head vibration were recorded and rotational speed of the crankshaft. The frequency of sampling the vibration signals and rotational speed was 25 kHz. The tests were conducted for different rotational speeds and loads.

The main purpose of the study was to determine the effect of the simulated local fatigue crack of the exhaust valve of the first cylinder on the characteristics on the time-frequency and time-scale plane.

4. RESEARCH RESULTS

The distribution of wavelet coefficients for one working cycle of an undamaged engine during idle run is presented in Fig. 1, and for an engine with a damaged exhaust valve, in Fig. 2.

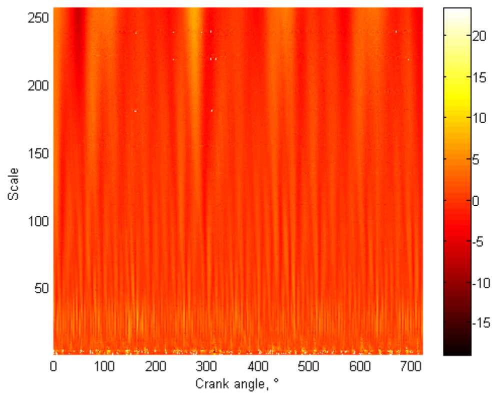


Fig. 1. Distribution of wavelet coefficients for the undamaged engine (wavelet CWT db4)

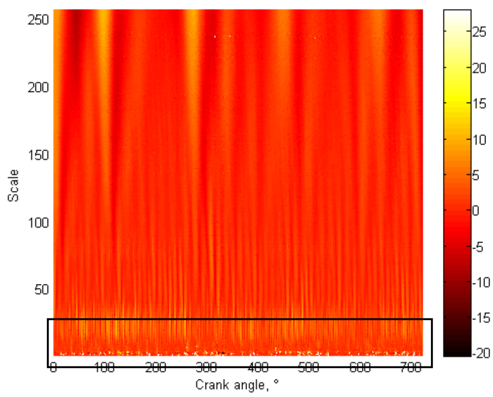


Fig. 2. Distribution of wavelet coefficients for the engine with a damaged valve (wavelet CWT db4)

Based on the above-demonstrated results, it can be assumed that the damage to the exhaust valve induced significant changes of the wavelet coefficient values, especially within the range of low scale values which correspond to high frequencies.

On the basis of dependence (6), the effect of the simulated damage of the exhaust valve on the distribution of vibration signal energy was determined as a function of scale, by determining the wavelet power spectrum *E(a)* (Fig. 3).

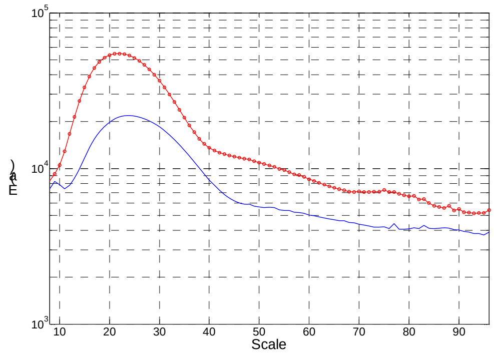


Fig. 3. Wavelet power spectrum E(a)

Based on the wavelet power spectrum, it can be affirmed that damage induces an increase in signal power for all scale coefficients. The damage also induced a shift of the spectrum maximum towards lower scale values (higher frequencies). Figure 4 presents the change of total signal energy, caused by the damage.

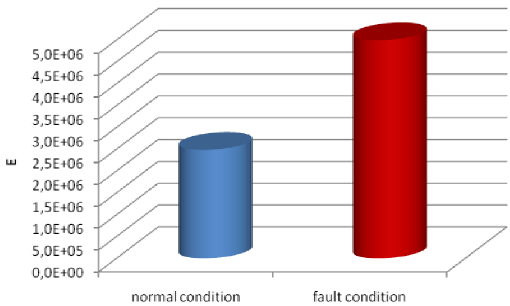


Fig. 4. Total signal energy determined for one working cycle of the engine

Figs. 5 and 6 show the time courses of vibration accelerations and their decomposition into low- and high-frequency constituents, performed with use of wavelet filtration, for a fully operational engine and an engine with a damaged valve, respectively.

The presented vibration accelerations were recorded during the engine's work under load at a travelling speed of 100 km/h, simulated on a test bench.

The results of time and frequency analysis, performed with use of Wigner – Ville transforms, corroborate, for both cases presented, the fact of the vibration energy shift towards higher frequencies (above 8 kHz). Based on the WV decompositions presented, it is possible to observe changes of the instantaneous value of vibration signal energy during the engine's working cycle. Time and frequency decomposition of the vibration acceleration signal allows detecting nonstationarity as a function of the crankshaft rotation angle and the vibration spectrum structures.

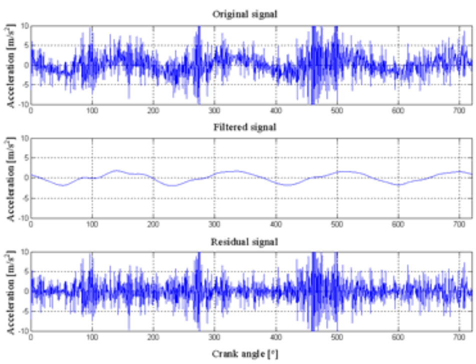


Fig. 5. Courses of vibration acceleration signals of an engine head with undamaged valves

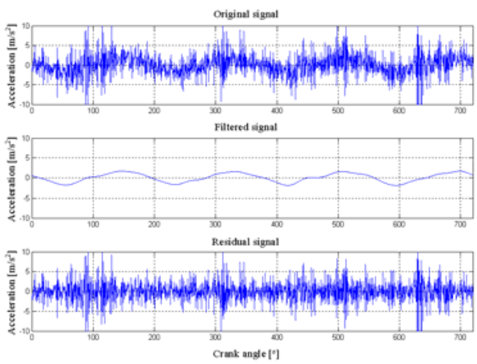
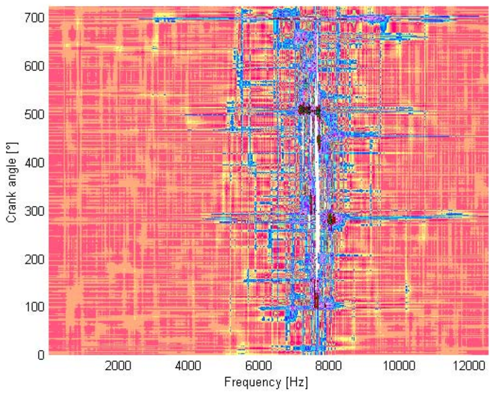


Fig. 6. Courses of vibration acceleration signals of an engine head with a damaged exhaust valve

a)



b)

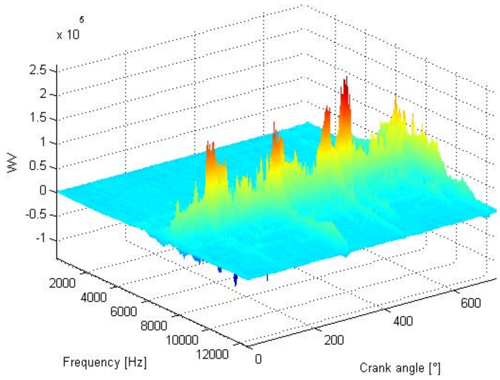
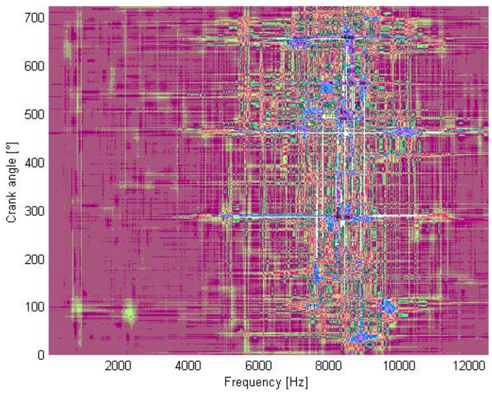


Fig. 7. Wigner-Ville distribution of vibration accelerations of an engine with undamaged valves

a)



b)

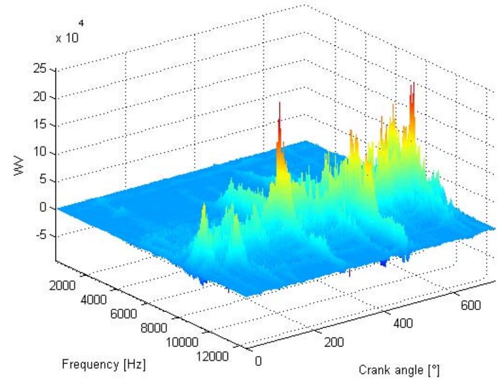


Fig. 8. Wigner-Ville distribution of vibration accelerations of an engine with a damaged valve

Based on the test results, it can be affirmed that the simulated damage to the valve caused stimulated the engine block to vibrate in a wider frequency band (Figs 7 and 8).

5. CONCLUSIONS

In the case of an engine working with a damaged exhaust valve, the maximum values of wavelet power spectra obtained on the basis of CWT move towards higher frequencies (lower scale), compared to the spectra obtained for an engine with no damage. This phenomenon is confirmed also by WV distributions.

The phenomenon can be used for constructing simple measures useful for an evaluation of the condition of engine valves.

The methods of analysing signals of head vibration accelerations, proposed by the authors, may be also useful for separating signal constituents induced by the combustion process and percussion phenomena connected with valves' operation.

REFERENCES

[1] Dąbrowski Z., Madej H.: *Masking mechanical damages in the modern control systems of combustion engines*. Journal of KONES, Vol. 13, No 3/2006

[2] Dąbrowski Z., Madej H.: *O użyteczności symptomów wibroakustycznych w nowoczesnej diagnostyce silników spalinowych*. Przegląd Mechaniczny nr 1 / 2007, s. 32-35

[3] Geveci M.: *An investigation of crankshaft oscillations for cylinder health diagnostics.* Mechanical Systems and Signal Processing 19 (2005) 1107–1134

[4] Isermann R.: *Diagnosis methods for electronic controlled vehicles*, Vehicle System Dynamics, Vol. 36, No. 2-3

[5] Janecki J., Gołąbek S.: *Zużycie części i zespołów pojazdów samochodowych*. Warszawa, WKiŁ 1984

[6] Madej H., Flekiewicz M., Wojnar G.: *Spatial-phase selection of diesel engine vibroacustic signal for piston slap diagnostic*. Journal of Kones. Powertrain and Transport vol. 14 no. 2 / 2007, s. 133-144

[7] Madej H., Flekiewicz M., Wojnar G.: *Zastosowanie ciągłej transformaty falkowej (cwt) do analizy drgań siników spalinowych*. Teka Komisji Motoryzacji PAN, zeszyt nr 33-34, Kraków, str. 259-267

[8] Yang W. X.: E*stablishment of the mathematical model for diagnosing the engine valve faults by genetic programming*. Journal of Sound and Vibration 293 (2006) 213–226.

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THE POSTUROGRAPH APPLICATION IN A DYSLEXIA DIAGNOSIS

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Summary

This paper shows the analysis of possibilities of center of mass projection tracking application in dyslexia diagnosis. The metrological, economical as well as constructional issues of computerized dynamic posturograph (CDP) are taken into consideration.

Keywords: posturograph, computerized dynamic posturography (CDP), dyslexia diagnosis.

KONCEPCJA ZASTOSOWANIA POSTUROGRAFU DO DIAGNOZOWANIA DYSLEKSJI

Streszczenie

W niniejszym artykule dokonano analizy możliwości wykorzystania przebiegu położenia rzutu środka ciężkości na płaszczyznę podstawy do diagnozowania dysleksji. Rozpatrzono aspekty metrologiczne konstrukcyjne i ekonomiczne zastosowania platform posturograficznych.

Słowa kluczowe: posturograf, komputerowa posturografia dynamiczna, diagnozowanie dysleksji.

1. INTRODUCTION

The majority of diagnostic examinations is based on reading and writing tests, therefore its application is restricted to children above 6-7 years old. Earlier dyslexia diagnosis gives children greater chances of normal development by the early start of therapy. The diagnosis is possible only basing on the aspects of child's behaviour. Medical and psychological researches show that dyslexia is indirectly connected to the occurrence of medulla deficiencies. Medulla is responsible for various cognitive and motor processes e.g. acquiring and mastering of new skills, coordination and keeping the body balance. It also plays an important role in a process of learning, detecting and correcting mistakes in motor processes. Medulla deficiencies are also attributed to development al dyslexia. Unbiased diagnostics tests of medulla deficiencies can be therefore helpful in dyslexia diagnosis. The electronic tests are useful in medicine to diagnose dyslexia in children in the pre-school age, they are also useful for legal purposes to verify dyslexia in students taking secondary school leaving exams.

One of the major methods that enables quality measurements of medulla functions quality is *Mirror Drawing test*, MD. The ways to automates the mirror droving test are described in [1] and [2]. The other method of assessment of quality of medulla functions is an analysis of motor coordination related to keeping body balance and analysis of the speed of acquiring of that skill. This test can be done by an electronic device that tracks the projection of the center of mass to the base plane – a posturograph.

2. REQUIREMENTS FOR A POSTUROGRAF

Posturograph should be able to provide the methods for doing various dyslexia diagnosing medulla deficiencies tests. For metrological requirement analysis the tests can be divided into: simple static, static with feedback and dynamic.

The realization of the described tests generates many requirements for parameters of the measurement set. But to generate precise construction requirements the target group of the patients should be also taken into consideration.

These are kids at the pre-school and primary school age, but secondary school students and adults can not be excluded. Therefore posturograph should enable conducting the tests on people weighting 20÷90 kg, and of height of 100÷190 cm and feet length of 18÷32 cm.

To sum up during the tests the frequencies of center of mass oscillations are expected to be no more than few Hz and expected amplitudes are up to 20 cm, expected force exerted on base plane is up to 90 kg. Moreover apart from measurement the techniques for data acquisition and processing need to be designed. The digital signals should be registered for further processing and for automatic diagnosis generation. Additional, but very import ant requirement is the low cost of the apparatus.

3. ANALYSIS OF CURRENT SOLUTIONS

Posturographs are manufactured for and applied in medicine and rehabilitation, most frequently In orthopaedic problems and for diagnosing and treating diseases that disrupt normal body balance keeping skills. The first to explore medical application of the posturograph in Poland was Institute of Measurement Systems and Automatics (currently Institute of Electronic Systems) MUT. Later there were few prototypes. Particularly interesting is the one designed by Military Institute of Aviation Medicine.

Currently broader is the offer of international companies, but software for currently available posturographs can not be used in dyslexia diagnosis. The NeuroCom USA products are used in rehabilitation of patients with dyslexia in the UK, but NeuroCom USA offers no diagnostic software.

Additional the prices of computerized dynamic posturograph sets start from 50.000 zł, what makes it practically impossible for psychologist to use it widely. Therefore it is necessary to design an economic version of posturograph that enables the dyslexia diagnosis.

4. CONCEPTION OF THE DIAGNOSTIC SYSTEM

It the dyslexia diagnosis designed posturograph various functional elements can be distinguished.

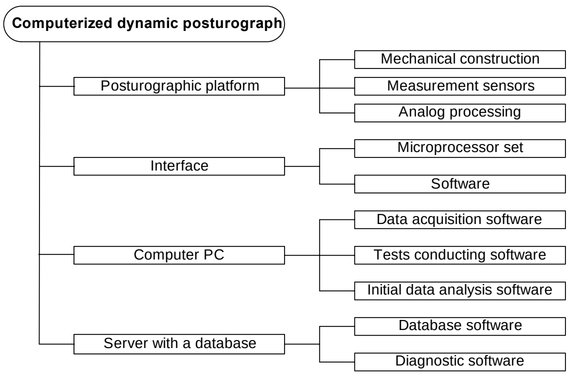

Fig. 1. Functional model of the diagnostics system with the posturographic platform.

The main functions of posturograph, the measurement sensors and analog processing units are: to change the force exerted on the base platform into voltage 0÷5 V and to provide the measurement range for the mass and center of mass position needed for performing these tests. The measurement errors should be below 0,5%, non-linearity of the characteristics below 0,1% time constant of reaction to the unit step below 0,1s.

Interface based on PIC microcontroller with analog – digital converter provides the solution for changing analog signals from the posturographic platform into Digital with frequency above 20 Hz and resolution above 12 bits

Moreover it is responsible for data transfer to the computer by the USC port. The personal computer has to be equipped with software that enables data acquisition by USB port, performing the tests, and introductory analysis of data for dyslexia symptoms. The data from all the tests are going to be send to the server, where the diagnostic software is going to be installed. Storing data on a one server would enable taking into consideration all the tests done by particular individual by diagnosis of the learning speed and abilities. This also provides the solution for investigating correlation with other tests e.g. MD tests, and using the classifiers and learning algorithms on the whole test base.

5. POSTUROGRAPHIC PLATFORM

The Basic models of posturographic platform are designed with three force sensors placed In the vertexes of a triangle or four placed in the vertexes of a rectangle. Platforms with three pivot points enable lower angles of departure from vertical position to be measured. Platforms with four points are prone to disturbance of measurement due to physical irregularities.

In the current project the three point posturographic platform is used but it has a rectangular shape as in figure 2.

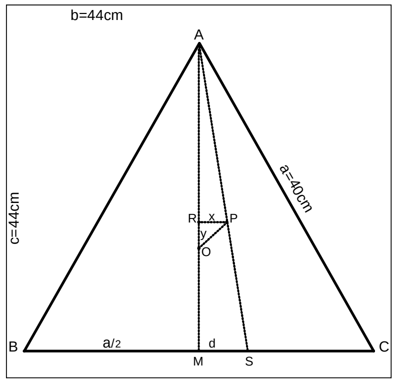

Fig. 2. The dimensions of posturographic platform.

The measurement sensors are placed In the vertexes of a equilateral triangle with edges of 40 cm length. It enables departure of the projection of the center of mass at least for a length of a radius of inscribed circle (r=11,55) cm in any direction from the middle of the platform and at most for the length of an circum circle R=23,09 cm in the direction of one of the sensors.

The most important is the range of the angle of departure from the vertical position of the posture of the examined individual. Assuming that the center of mass of human body is at height of around 60% of the height of the human, the range of measurement of angle of departure from vertical position α is:

$$\alpha = \arcsin\left(\frac{r}{0{,}6l}\right) \qquad (1)$$

where l – height of th examined person.

The ranges of angles measurable by platform with given lengths are : $\alpha \cong 5{,}9^0$ *for l*=190 cm, $\alpha \cong 10^0$ *for l*=111 cm. In case of children it is going to be sufficient.

In case of frequent exceeding of measurement range the next version of the platform is going to have greater measurement range of the angle of the departure from vertical position. It can be achieved by enlarging the dimensions but it also would decrease the resolution of the measurements.

To measure the force three measurement sensors, installed by Mensor company in the scales they produce were used. Their measurement range is 0÷60 kG, what enables conducting tests on people with weight up to120 kg in case of radius of angle of departure from vertical position r=11,55cm. In the case of using the platform only for testing children it is better to use measurement sensor with range up to 30 kg, which gives the measurement range of posturograph up to 60 kg. It could enable the greater resolution of the measurements.

The measurement sensors of the posturographic platform with the analog processing system generate the voltage proportional to the force exerted on the sensors described by:

$$u_x = u_0 - kF_x \tag{2}$$

where:
u_x – initial voltage for measurement sensor
u_0 – voltage for measurement sensor with $F_x=0$
F_x – the force exerted on the measurement sensor
k – proportionality constant

It is assumed that the proportionality constant k will be constant for all measurement sensors and it will be 1V/20kG and u_0 will be set before every series of measurements in the process of adjusting the measurement sensors.

6. INTERFACE

The initial voltages of theanalog parts of the platform are processed by microprocessor with 12 bit digital-analog converter. Because the range of voltage changes measured do not exceed 4096mV, the12 bit DC converter gives the resolution of 1mV in terms of force it is 20G for measurement sensors with range up to 60kG. The greater resolution would not significantly increase the accuracy of measurement because of the errors of the measurement sensors and other parts of the system.

The AD converter Has a frequency of 20 Hz. This frequency should be enough tracking the changes of the position of center of mass the tests. The dynamic characteristics of platform - the frequencies conducted by the mechanical system is going to be the subject of the research conducted in the near future.

The other functions of the microprocessor are: the data transmission by the USB port and storing In to the computer internal memory. The data transmission is conducted on –line by containing the measurement data from all three channels. It enables the visualization of the projection of the center of mass in the real time, what is necessary for conducting the tests that require feedback.

7. THE ASSUMPTION FOR DATA ACQUISITION AND VISUALIZATION

The function of PC computer is to enable the control of the testing process and the initial data analysis, therefore it should enable: patient's data input or the choice from previously registered data, the choice of test, adjusting the platform, the conversion of the initial voltages into the force and data storage in the file, the conversion of the force into the coordinates of the projection of the center of mass, on-line visualization of the projection of the center of mass, the automatic conductance of the chosen test with the option of control by the operator, the initial data processing that enables the assessment of correctness of the measurements done, the storage of patients' data and tests conducted on the server's database.

All these functions are performer by specialty designer computer program. to convert the voltages into the force this equation is used:

$$F_x = \frac{u_0 - u_x}{k} \tag{3}$$

After the conversion we obtain the sequence of data that represent the forces F_A, F_B and F_C exerted on measurement sensors A, B and C registered every 50ms. Then to visualize and analyze the results basing on the force values the position of the projection of the Center of mass In the classical X,Y coordinates with the middle in the point O is evaluated. The position of measurements sensors and the ex ample of the position of the center of mass is illustrated on the figure 2.

It can be assumed that the projection of the center of mass on the posturographic platform is represented by point P, which distance from point O can be expressed in terms of perpendicular components horizontal – x and vertical –y. Because forces were measured In point A, B and C, the functional dependencies between $x=f(F_A,F_B,F_C)$ and $y=f(F_A,F_B,F_C)$ need to be found.

Using the equalities of momentum in defined position of point P the relation between forces is described by:

$$F_B\left(\frac{a}{2}+d\right) = F_C\left(\frac{a}{2}-d\right) \tag{4}$$

and $$\left(F_B + F_C\right)\left(\frac{1}{3}h + y\right) = F_A\left(\frac{2}{3}h - y\right) \tag{5}$$

where: a –the length of the arm of equilateral triangle
d – the length of SM segment
h – the height of a equilateral triangle

Using the above equation the equation for the height of the equilateral triangle and the dependency:

$$\frac{d}{x} = \frac{h}{\frac{2}{3}h - y} \tag{6}$$

we obtain the equation for the vertical component:

$$y = a\frac{\sqrt{3}}{6}\frac{2F_A - F_B - F_C}{F_A + F_B + F_C} \qquad (7)$$

and the horizontal component

$$x = \frac{a}{2}\frac{F_C - F_B}{F_A + F_B + F_C} \qquad (8)$$

Additionally the mass of examined person is evaluated, what is the sum of the forces measured by three sensors:

$$m = F_A + F_B + F_C \qquad (9)$$

As a result of the measurements the position of the center of mass can be visualized in the real time or after the test is completed. The examples of characteristics are illustrated on figures 3, 4 and 5.

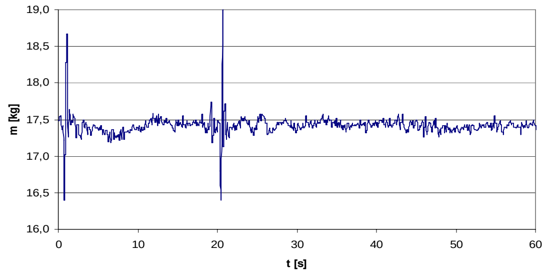

Fig. 3. The graph of the mass as a function of time

The other characteristics can be also drown including the characteristics done by computerize posturographic systems currently available on the market.

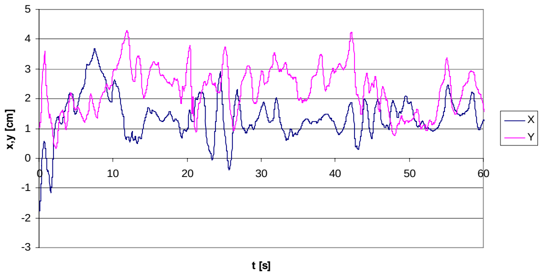

Fig. 4. The graph of X and Y coordinates as a function of time.

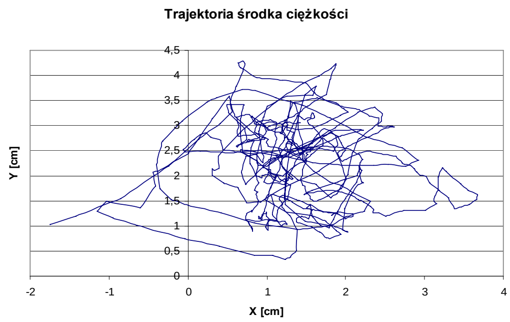

Fig. 5. The graph of the trajectory of the projection of the center of mass on the posturographic platform.

8. THE CONCEPT OF DIAGNOSTIC CONCLUSIONS

The analysis of the single test set can give the initial diagnosis, but the assessment of the speed of the acquiring of the body balance keeping skills can be done only basing on comparison of series of tests. To achieve this a database on the server should be created, where all the results should be stored. It would enable the design of the data analysis algorithms that recognize the dyslexia symptoms basing on maximally large data sample. Moreover it will be possible to evaluate the learning speed, what is one of the major symptoms of medulla deficiencies. basing on many test done by the same person.

The creation of the large database could also enable the large diagnostics analysis based on symptoms occurring in various kinds of electronic tests e.g. posturographic tests and MD tests. Central database would also enables comparison of tests done after few years and verification of the diagnosis basing on real condition of the patient.

As a result of current research the computerized dynamic posturograph has been designed and the prototype set including software has been made. It requires further examination and research on metrological aspects, data analysis and software.

However basing on current results it can be concluded that it gives satisfying results as a research tool and the production costs enable its wide usage. The next steps are further research and creation of database and diagnostics software.

REFERENCES:

[1] Olchowik W., Jenerowicz M., Modras G., Jaśkowski P.: *Badanie deficytów móżdżkowych za pomocą komputerowej wersji testu rysowania w odbiciu lustrzanym,* „Psychologia i medyczyna - wspólne obszary zainteresowań", Wizja Press&IT, Warszawa 2007; s. 103 – 108.

[2] Michalak K., Jaśkowski P.: *Predictability of posturographic signals: Influence of window width and embedding dimension.* Biocybernetics and Biomedical Engineering, 27/2007, 71-83.

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AN APPLICATION OF WAVLET TRANSFORM FOR NONLINEARITIES DETECTION

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Summary

In the paper an application of time – frequency technique for nonlinearities detection is presented. The wavelet transform is used to transform an impulse response of the system into time – scale domain. Ridge and skeleton definitions of wavelet transform for backbone curve estimation has been used. Statistical approach for ridge detection of wavelet transform has been applied. Estimation of dynamic characteristic of the system with use of envelope of signal response has been presented. Based on properties of wavelet transform possibility of use the method for nonlinearities detection has been shown. The method also make possible define the nature of this nonlinearities. MATLAB package is used as numerical tool for computation of wavelet transform and dynamical characteristics of the system. The algorithm has been tested on simulated data and data from test bed with dry friction.

Keywords: wavelt transform, nonlinear systems, backbone curve.

ZASTOSOWANIE TRANSFORMATY FALKOWEJ DO BADANIA WŁASNOŚCI DYNAMICZNYCH UKŁADÓW NIELINIOWYCH

Streszczenie

W artykule przedstawiono metodę detekcji nieliniowości układów dynamicznych opartą o reprezentację czasowo – częstotliwościową sygnału, bazującą n przekształceniu falkowym. Do określenia charakterystyk dynamicznych wykorzystano definicję grzbietu i szkieletu transformaty falkowej. Pozwoliło to na wyznaczenie funkcji obwiedni sygnału. Algorytm został zweryfikowany z użyciem pakietu MATLAB na danych symulacyjnych oraz pochodzących ze stanowiska laboratoryjnego.

Słowa kluczowe: transformata falkowa, układy nieliniowe, analiza modalna.

1. INTRODUCTION

Nonlinearities are effect which very often occur in mechanical systems. It can be caused by structural, geometrical and mechanical properties. Nonlinearities detection and define their properties its very important. Nonlinear systems – unlike linear systems – can behave in different way depending on excitation. Usually it works unpredictably, e.g. small change of initial conditions can lead to big changes in trajectory. Treatment this kind of mechanical system as linear can be reason of incorrect result of analysis. In the paper make an attempt use the wavelet transform for nonlinearities detection.

2. CONTINOUS WAVELET TRANSFORM

The wavelet analysis is a method of signal decomposition. As a result of the wavelet analysis, in contradiction to the Fourier transform, elementary signals – so called wavelets – are obtained. Wavelet curves are continuous, oscillated with various duration times and spectrums.

From the mathematical point of view, a wavelet transform of a signal *x(t)* can be defined as [3, 7]:

$$(W_g x)(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} x(t) g^*\left(\frac{t-b}{a}\right) dt \quad (1)$$

Using properties of wavelet transform [4], can be prove mathematically that his kind of time frequency analysis decoupling natural frequency contains in signal (fig. 1).

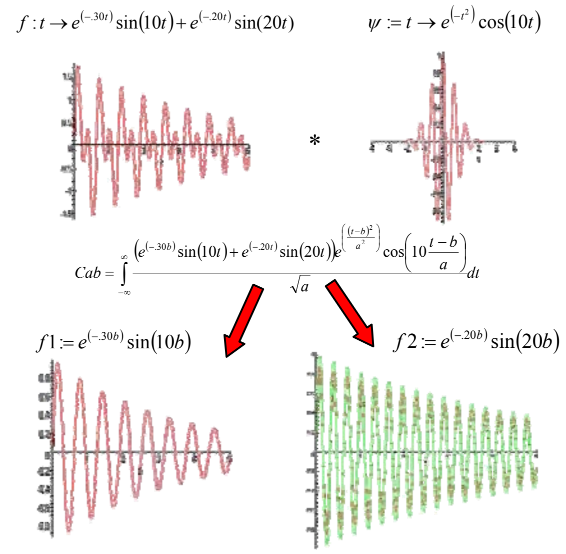
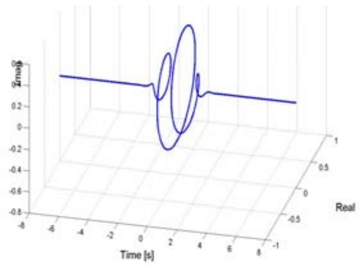


Fig. 1. Diagram of the analytical decoupling of natural frequencies.

The Morlet wavelet is one of the most widespread and most often used functions in the wavelet analysis. The Morlet wavelet is defined as:

$$g(t) = e^{j2\pi f_0 |t|} e^{-\frac{|t|^2}{2}} \tag{2}$$

a)



b)

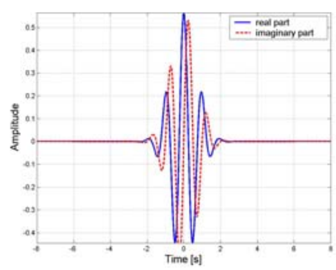


Fig. 2. Example of Morlet wavelet: a) in imaginary domain, b) real and imaginary part.

The rest of definitions and properties of wavelet transform can be found [2, 3, 4, 6].

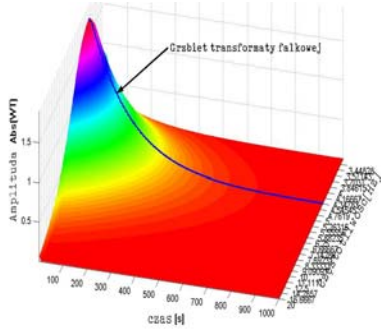
3. NONLINEARITIES DETECTION USING WAVELET TRANSFORM

The procedure of nonlinearities detection based on definitions of skeleton and ridge of wavelet transform. The ridge of wavelet $(W_g\, x)(a,\, b)$ of the signal *x(t)* is a set of points *f(a,b)* in wavelet transform domain, where phase $x(t)g_{(a,b)}(t)$ is stationary, that means that condition (3) is fulfilled:

$$t_0(a,b) = b\,, \tag{3}$$

where b - a translation (displacement) representing a region, a - a dilatation (expansion) or a scale parameter [3]. Skeleton of wavelet transform $(W_g x)(a,b)$ of signal *x(t)* is set of coefficients of wavelet transform calculated form ridge $(W_g x)(a_r(b),b)$, where a_r is a parameter of ridge scale [6]. Graphically, definition of ridge and skeleton of wavelet transform is shown on figure 3.

a)



b)

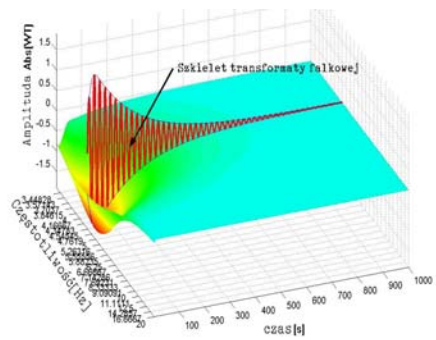


Fig. 3. a) Ridge of wavelet transform, b) Skeleton of wavelet transform.

Based on properties of wavelet transform presented above the algorithm of nonlinearities identification has been created. Diagram of the method is presented on figure 4.

In the first stage of the method matrix of coefficients of wavelet transform is calculated. This matrix can be interpreted as a energy distribution of the signal I time – frequency domain. Form this matrix ridge curve is estimated. Detection of ridge curve lead to estimation of skeleton of wavelet transform. Based on skeleton the envelope of given frequency component can be estimated.

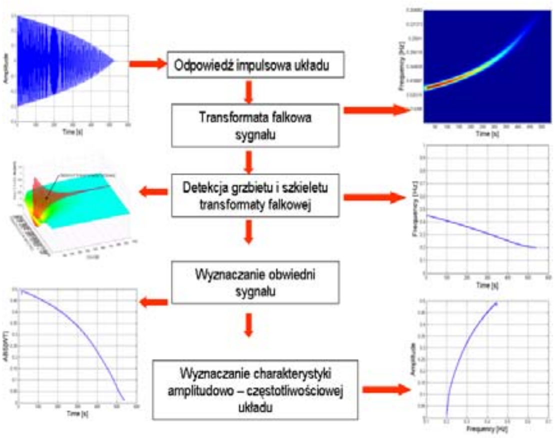


Fig. 4. Diagram of the nonlinearities identification with wavelet transform.

For the linear signals the envelope function can be written as:

$$A(t) = A_0 e^{-\xi\omega_n t} \tag{4}$$

And based on this the modal parameters of the system can be estimated. For nonlinear systems the envelope function will be depend on type of damping and stiffness nonlinearities. Using ridge and skeleton definition the characteristic call Backbone curve can be determined. This characteristic shows dependences between natural frequency function and envelope function of impulse response of the system. For linear systems backbone curve don't depend on envelope function and has constant value.

Using curve fitting method for estimated characteristics modal parameters of nonlinear systems can be estimated. Presented characteristic for linear and nonlinear systems are shown on fig. 5.

Main problem of this method is estimation of ridge curve of wavelet transform. Most often, method based on maximal values of wavelet coefficients for every section of matrix in time domain is used [2, 6]. This method can works properly only if signal to noise ratio has a big value. Otherwise it is possible to appear local maxima connected with noise. In this case result of analysis can be incorrect. For this reason the algorithm of detection ridge of wavelet transform based on statistical approach of scalograms. Base of this method is digitize of wavelet coefficients matrix and estimation of three dimensional histogram of this coefficients.

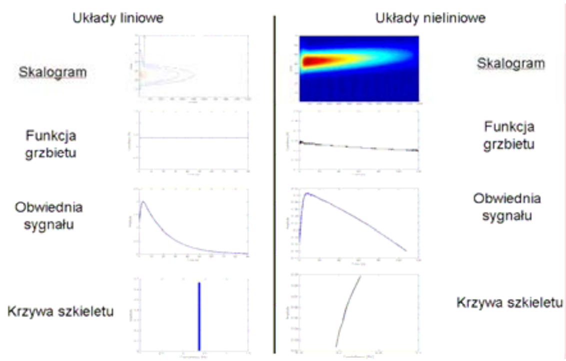


Fig. 5. Comparison of characteristics for linear and nonlinear systems.

This operation can eliminate effectively local maximums caused by noise. Comparison of results can be shown on figures 6, 7.

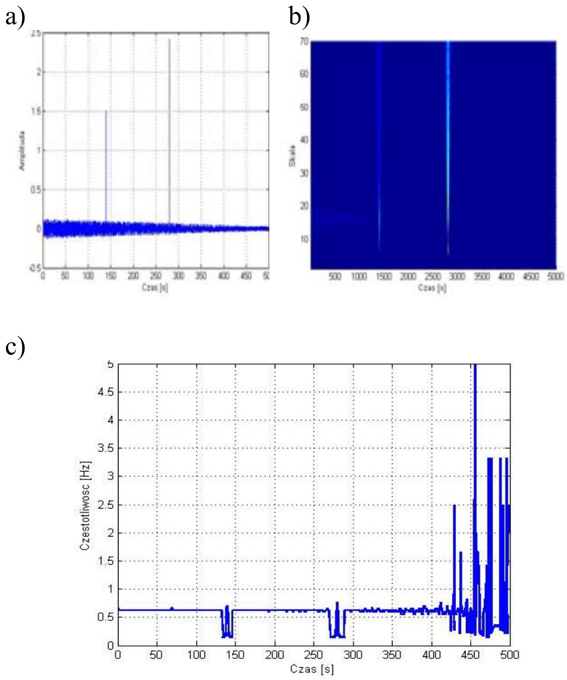
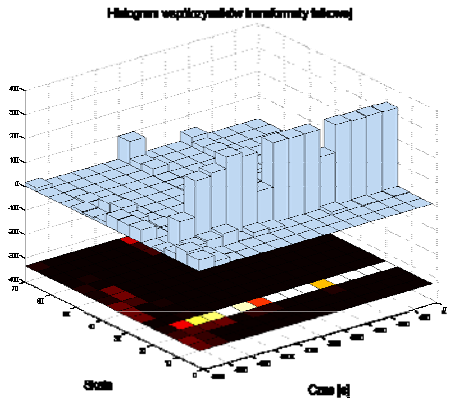


Fig. 6. a) Analyzed signal, b) Scalogram of the signal, c) Ridge curve obtained from scalogram ("maximum" approach).

a)



b)

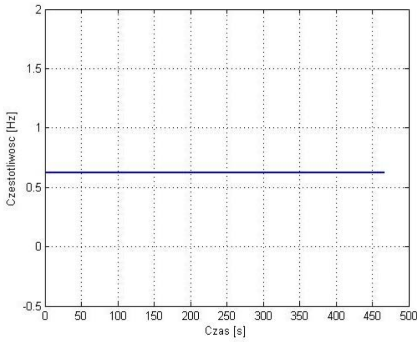


Fig .7. a) three – dimensional histogram of wavelet transform, b) Ridge curve obtained from scalogram ("statistical" approach).

Estimated ridge curve and envelope function for given natural frequency is possible to determine amplitude – frequency characteristic (Backbone curve). The backbone curve gives information about stiffness nonlinearities in the system. For impulse response envelope function gives information about types of damping in the system. Analytical function for different types of damping and stiffness can be found [1, 5].

4. NUMERICAL VERIFICATION

Numerical verification of proposed algorithms has been carried out. Response signal of nonlinear single degree of freedom system with dry friction and cubic stiffness has been described by formula:

$$\left(\frac{d^2}{dt^2}y(t)\right) + 0.001\ \text{signum}\left(\frac{d}{dt}y(t)\right) + 0.16\,\pi^2\, y(t) + 100\, y(t)^3 = 0$$

Additionally the signal has been disrupted by noise. Time history of the signal, scalogram and ridge curve are presented on figure 8.

In the next step the character of nonlinearities has been determined. It has been done by curve fitting method, using known dependences between envelope function and type of damping.

a) b) c) d)

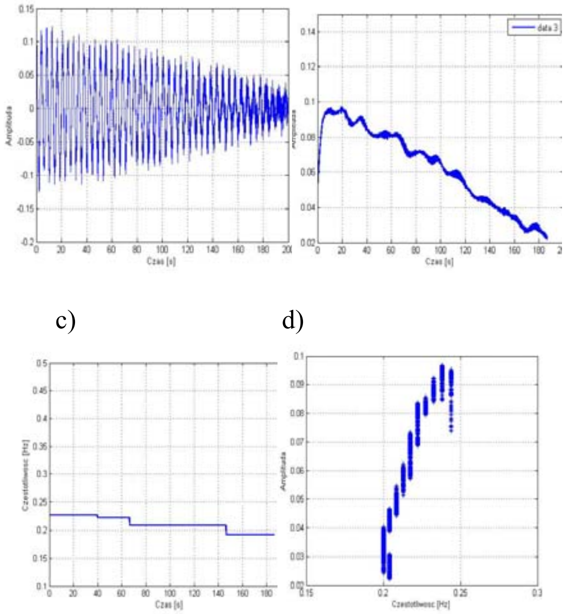


Fig. 8. a) Analyzed signal, b) envelope function, c) ridge curve, d) backbone curve.

As a criterion Root Mean Squares Error has been applied. Result of analysis compare in the table below.

Table 1. Modal parameters of the system

Parameter	Real value	Identifield value
ω [rad]	1,25	1,25
c [Ns/m]	0,001	0,00094
k1 [N/m]	1,57	1,57
k3 [N/m]	100	88,95

Table 2. Results (stiffness)

kx $\omega_n + \frac{k}{2\omega_n}$	kx^3 $\omega_n + \frac{3k}{8\omega_n}A^2$	kx^5 $\omega_n + \frac{5k}{16\omega_n}A^4$	kx^7 $\omega_n + \frac{35k}{128\omega_n}A^6$
	k3 = 88.95 RMSE: 0.00482	k3 = 1.446e+004 RMSE: 0.006138	k3 = 0.8419 RMSE: 0.02242

Table 3. Results (damping)

Quadratic friction $\dot{x}\lvert\dot{x}\rvert$	Dry friction $sigmum(\dot{x})$	Viscous damping ($c\dot{x}$)
f(x)=a(x+b) *a=9.777* *b=93.31* *RMSE:0.007325*	*f(x)=p1*x+p2* *p1=-0.0004333* *p2=0.09572* *RMSE:0.002665*	*f(x)=a*exp(b*x)* *a=0.101* *b=-0.006947* *RMSE:0.004987*

The last stage of the verification was analysis of test stand (fig. 9).

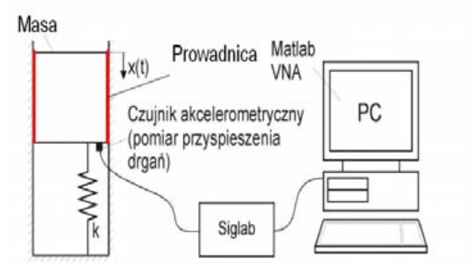


Fig. 9. Test stand

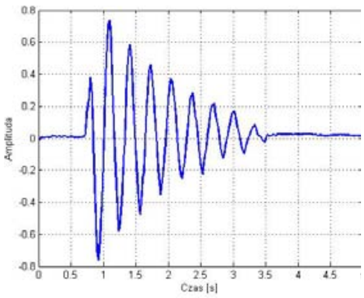


Fig.10. Impulse response of the system.

Using the method the characteristic of the system has been estimated (fig. 11).

a) b) c) d)

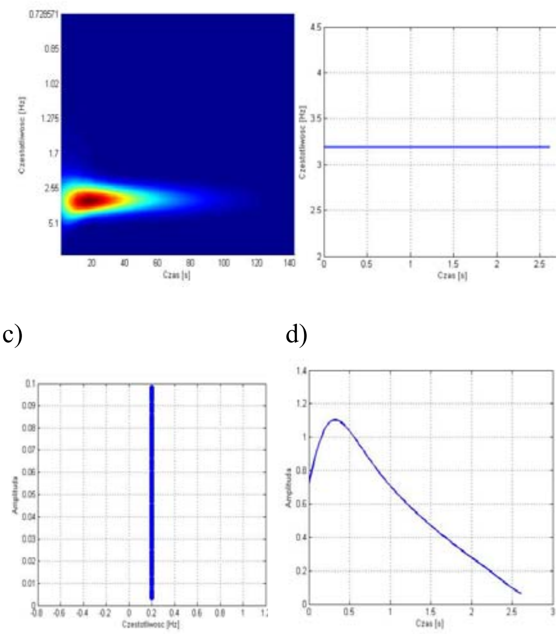


Fig. 11. a) Scalogram of the signal, b) Ridge curve, c) Backbone curve, d) Envelope.

Estimation of modal parameters has been carried out. Identified parameters has been used for creation an analytical model of the signal in order to method verification. Results has been presented in the table 4 and has been shown on the figure 12.

a) b)

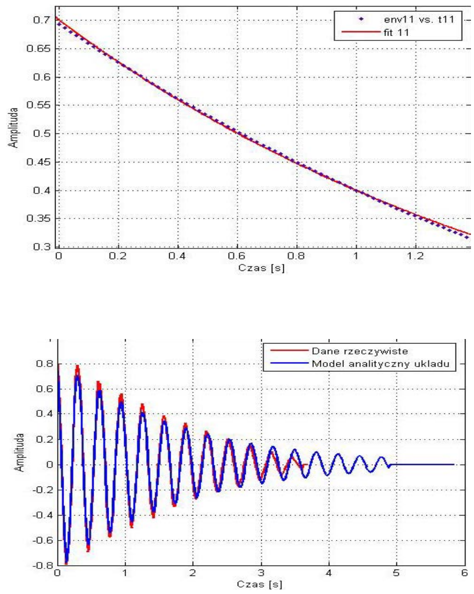


Fig. 12. a) Envelope of the signal, b) Comparison (model and signal).

Table 4. Identified parameters

Parameter	Real value	Identified value
ω[rad]	19.3	20.1
c[Ns/m] ($c\dot{x}$)	4,67	4,79
k[kN/m]	1,6	1,7

Assumed model was a linear model and result are correct only for initial part of the signal. The ending part of decay a differences between model and signal are visible. For this part of signal analysis with nonlinear model has been carried out. Result of estimation collected in the table 5 and show figures 13 and 14.

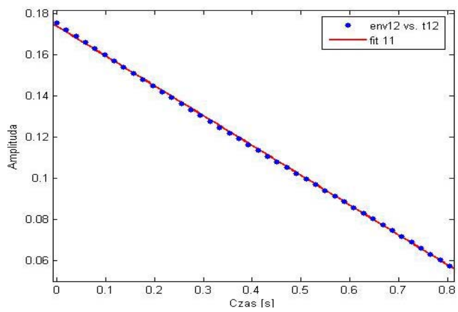


Fig. 13. Envelope of ending part of the signal.

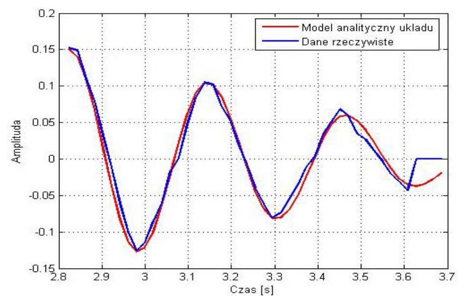


Fig. 14. Comparison (model and signal).

Table 4.5. Identified parameters

Parameter	Value
ω[rad]	20.1
c[Ns/m]($_{signum}(\dot{x})$)	18
k[kN/m]	1,7

5. CONCLUSIONS AN FURTHER WORKS

The numerical analysis confirmed that applying wavelet transform make possible to detect nonlinearities of the mechanical systems and can define character of this nonlinearities. The method of ridge curve detection allow to identify dominant frequency components in the signal for noised signals. The algorithm estimate correct values of modal parameters.

It is necessary to carry out consider for natural frequency decoupling for multi degree of freedom systems. The next stage of the researches should be creation a methods for nonlinear systems with operational excitation.

BIBLIOGRAPHY

[1]. Feldman M., Braun S.: *Analysis of typical nonlinear vibration system by using Hilbert transform*, Proceedings of 11th IMAC 1993, 799 – 805.

[2]. Joseph L., Ta Minh – Nghi: *A wavelet based approach for the identification of damping in non – linear oscillators,* International Journal of Mechanical Sciences 47 (205), 1262 – 1281.

[3]. Klepka A., Uhl T.: *Zastosowanie transformaty falkowej do wyznaczania współczynnika tłumienia konstrukcji*, VII Szkoła Analizy Modalnej Kraków 2002.

[4]. Klepka A, Uhl T.: *Zastosowanie transformaty falkowej do rozprzęgania postaci drgań oraz do wyznaczania współczynnika tłumienia,* Górnictwo odkrywkowe nr 2 – 3/2003, str. 61 – 64.

[5]. Nayfeh A. H.: *Perturbation method*, 1978, New York: John Wiley & Sons

[6]. Staszewski W. J.: *Identification of non – linear systems using Ridges and Skeletons of the Wavelet Transform*, Journal of Sound and Vibration 1998, 241(4), 639-658.

[7]. Uhl T, Klepka A.: *Application of wavelet transform for identification of modal parameters of nonstationary systems,* Journal of theoretical and applied mechanics 43,2, pp. 277 – 296, Warszawa 2005.

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DIAGNOSTICS OF ROLLING BEARINGS BY A QUASI-DYNAMIC METHOD

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Streszczenie

W pracy przedstawiono sposób identyfikacji stanu technicznego łożysk tocznych, metodą quasi-dynamiczną w której jako narzędzie badawcze zastosowano wahadła fizyczne. Dla prezentowanej metody wyróżniono cechy sygnału diagnostycznego umożliwiającego ocenę stanu technicznego łożyska tocznego na etapie naprawy. W artykule wskazano na współczynnik oporu ruchu łożyska jako uogólniony parametr diagnostyczny oraz na moc i moment tarcia jako miarę intensywności zużycia łożyska tocznego.

Słowa kluczowe: łożysko toczne, moc tarcia, moment tarcia, sygnał diagnostyczny.

DIAGNOSTYKI ŁOŻYSK TOCZNYCH METODĄ QUASI - DYNAMICZNĄ

Summary

This paper presents the technical state identification of rolling bearings by the quasi – dynamic method, where a physical pendulum was used as an investigative tool. For the presented method, the attributes of the diagnostic signal were distinguished. The attributes enable evaluation of the technical state of a rolling bearing over repairing. The coefficient of resistance to motion of a bearing was used as a generalized diagnostic parameter and power and moment of friction were used as a wear measure of a rolling bearing.

Keywords: rolling bearing, friction power, friction torque, diagnostic signal.

1. INTRODUCTION

Rolling bearings are those parts of machines which are among the most frequently replaced in the course of machine operation. Nearly 34% of rolling bearings are dismantled and scrapped prematurely due to a lack of proper assessment of their technical condition [4]. Such actions result mainly from the absence of available methods and diagnostic measures, intended for quick and reliable identification of the technical condition of rolling bearings in verification of systems and parts of technical facilities.

An economical approach to machine operation necessitates a reduction in the costs of maintenance and time of repair of technical facilities. At the same time, "environmental considerations" concerning recycling of faulty or worn products forces repair workshops and manufacturers to seek tools and diagnostic measures to identify the actual technical conditions of rolling bearings before taking a decision to replace or regenerate them.

Regeneration of rolling bearings is not a new idea; however, for various reasons it has not been widely applied yet due to the absence of a cost approach to overhaul or repair policy as regards technical facilities, but also the absence of awareness among company technical staff of the possibility of restoration of the rolling bearing potential in this manner.

The initial operational properties of a rolling bearing can be restored, at the expense of less time and money than for purchasing a new one. Depending on the scope of work, repairing a faulty bearing can save from 50 to 90% of the new one purchase cost [7]. The simplest manner of regeneration may consist in washing a bearing, filling it with new grease and installing new sealing. In the broadest approach: polishing (or grinding) of the balls and raceway, replacement of the bearing cage as well as grease and sealing.

Currently, the most commonly regenerated are rolling bearings with a pinhole diameter of ø76-203 mm. However, bearings of smaller diameters are also regenerated, especially if they are in greater numbers [7].

Though it has numerous advantages, regeneration of a faulty bearing is not always the best solution. For the proper application of the repair technology it is of key importance to determine if and when a bearing needs a repair. A visual inspection of a dismantled bearing is a common, and the only, criterion of qualification of a bearing for further operation or for scrapping.

In the author's opinion, the test procedure proposed in this paper, along with the test stand and distinguished features of a diagnostic signal which identify the technical condition of rolling bearing at the stage of repair, will allow for a quick and unambiguous decision as regards the future fate of an ordinary ball bearing.

2. METHODS OF IDENTIFICATION OF THE TECHNICAL CONDITION OF ROLLING BEARINGS AT THE MACHINE REPAIR STAGE

There are a number of techniques of identification of the technical condition of rolling bearings, with various level of advancement, which can be used to locate a failure in a bearing before it is permanently damaged. However, these are mainly diagnostic measures applied to identify technical facilities and bearing nodes as a whole, and are widely discussed in literature.

In accordance with the aim of the study, in its further part the author will focus on a diagnostic representation used to evaluate the technical condition of a bearing which has already been dismantled and whose technical condition is being verified.

The following diagnostic methods can be distinguished which are used to identify the technical condition of a rolling bearing at the stage of repair:

- a sensory method [8];
- identification of radial and axial clearance and misalignment of a bearing [6, 8, 10];
- physicochemical analysis of the grease which fills the bearing [3, 6, 8];
- measurement of the friction coefficient [2];
- the coasting method[1];

2.1. The limiting value of the diagnostic signal

The literature contains only scarce information on the limiting values of the features of diagnostic signals for rolling bearings intended for bearing verification at the stage of repair. These are mainly data related to geometric features rather than to the utility features, which carry more information about the technical condition of an examined bearing.

This approach to identification of the technical condition of rolling bearings is exemplified in [9]. The paper presents an extensive analysis of diagnostic signals of special rolling bearings and supports the conclusion that using bearing motion anti-torque as an indicator of the rolling bearing technical condition is justified. An increase in the anti-torque to the value typical of a new bearing, which is still wearing in, has been determined as the limiting value of the diagnostic signal [9]. The paper concludes that bearings have a "life curve" which has a shape of a bathtub curve and can be described by the moment of friction function $M_t=f(\tau)$ – Fig. 1.

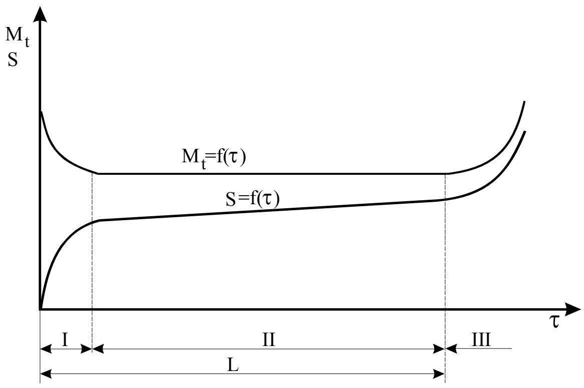

Fig. 1. The "life curve" of rolling bearings as a function of time. $M_t = f(\tau)$ – moment of friction at a constant rate of rotation, $S=f(\tau)$ – intensity of the wearing symptom, I –a stadium of digressive increase in the wearing symptom (wearing-in), II – established level or slight increase, III – progressive increase in the wearing symptom, L – operational durability of a hypothetical rolling bearing, (based on [9])

Another paper [1] shows the power of friction as a diagnostic symptom which is a measure of intensity of the wearing processes in the tribological nodes of a combustion engine. The power of friction is identified during an engine acceleration and coasting, and its measure is the mechanical efficiency and/or the product of the moment of friction and the crankshaft rate of rotation [1].

3. A METHOD OF IDENTIFICATION OF THE TECHNICAL CONDITION OF A ROLLING BEARING BY THE QUASI-DYNAMIC METHOD

The quasi-dynamic method of diagnosing the technical condition of rolling bearings is based on identification of the features of the oscillation of a physical pendulum (fig. 2) in which the pendulum rotates through the bearing which is being examined. The presented diagnostic method consists in identification of changes of the angular velocity of the pendulum, with the known amount of energy supplied to the pendulum in order to unbalance it. The angle of the first deflection α is adopted as the measure of the degree of unbalance.

Measurement of the features of diagnostic signals which are necessary to evaluate the technical condition of the bearing which is being examined is done only on the pendulum clockwise movement back to the state of balance. The measurement of the identified diagnostic parameters in one direction of the pendulum movement does not necessitate its static or dynamic balancing each time a bearing is replaced.

The presented method may be applied to check the technical condition of in-line rolling bearings, without sealing or grease. The examined bearing should have normal clearance (i.e. it should not exceed the limit clearance determined by the manufacturer) and its rings should not be misaligned. In other words, the bearing should have been verified organoleptically with a positive result.

The described method does not take into account the aerodynamic resistance of the pendulum or the mass of the examined bearing.

3.1. The mathematical model of a test stand

The proposed method uses a physical pendulum as a diagnostic tool. The pendulum body with the mounted bearing performs pendular movement (around point *O* Fig. 2), under its own weight (*mg*) as it is unbalanced and deflected by the angle of α.

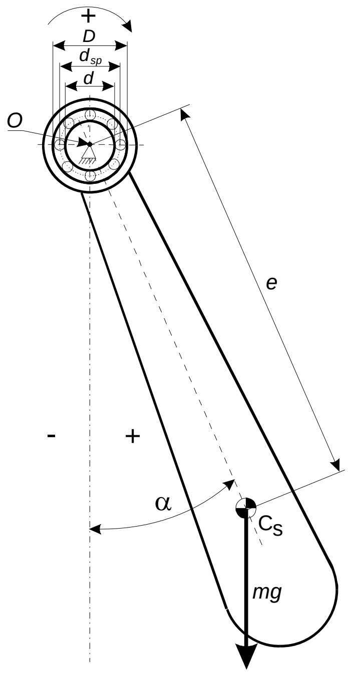

Fig. 2. A graphic model of a physical pendulum, α - first pendulum deflection angle; C_s – position of the pendulum geometric centre; *e* – distance from the pendulum centre of gravity to the centre of rotation *O*; *mg* – pendulum force of gravity; D, d_{sp} d – external, effective and internal diameter of the bearing, respectively

Oscillations (rotational vibrations) of an unbalanced physical pendulum result from the moments generated by the forces of gravity and inertia. The pendulum position is determined by angle α, and the pendulum equation has the following form:

$$I \cdot \ddot{\alpha} + C_w \cdot \dot{\alpha} = -mg \cdot e \cdot \sin\alpha \qquad (1)$$

where: I_o – mass moment of inertia of the pendulum in relation to the point of rotation *O*, C_w – coefficient of viscotic resistance of the bearing in its rotation (in relation to the point of rotation *O*), the other notations – as per Fig. 2.

Equation (*1*) is a non-linear differential equation for which no analytic solution exists. Only an approximate solution of equation (*3*) may be obtained, assuming that the angle of deflection α is small ($\sin\alpha \approx \alpha$).

3.2. Identification of the features of diagnostic signals in the quasi-dynamic method

The following features have been chosen for the evaluation of usability and quality of the diagnostic signal, identified at the lowest point of the pendulum, which transmits information about the technical condition of a bearing in the proposed method:

- duration of the oscillation of the test pendulum – T;
- the number of individual swings of a test pendulum – i, (the number of times when the test pendulum passes through its lowest point);
- coefficient of friction in the pendulum oscillations – μ_o (own study based on [5]), identified on the basis of individual swings of the pendulum i;
- coefficient of the viscotic resistance of the pendulum bearing in its rotation – C_w;
- moment of friction in the bearing – M_t;
- coefficient of rolling friction – f_t [5, 10] as a measure of the condition of surfaces of the elements that work together in a bearing;
- friction power – as a generalised mechanical efficiency of the bearing – W_t.

Table 1 shows the diagnostic signals and their features which have been selected for identification of the technical condition of rolling bearings at the stage of repair.

3.3. The test stand and equipment

The aim of the experiments was to identify the measures of features of the diagnostic signal and their utility in assessment of the technical condition of rolling bearings by a quasi-dynamic method.

The test stand used to identify changes of the angular velocity and to count individual swings of the bearing under test is shown in Fig. 3. The test stand consists of a base (1) and a test pendulum (2). The bearing which is being tested (3) is placed in the pendulum mounting and mounted in the self-centring holder of the test stand so as the inner raceway of the test stand is immobilised against its outer raceway. Changes of the angular velocity of the tested bearing loaded with the test pendulum (m=1.67 kg), are recorded with a CF-110 photo-optical sensor and a KSD-400 measuring analyser.

Following initial tests of the identified signal the observed value, a static processing of the observed value (the angular velocity of the tested system) was performed (the pendulum with the outer ring of the bearing). The analyses indicate that in the test conditions, the observed value is a stationary and repeatable signal.

Table 1. Diagnostic signals and their features which have been selected for identification of the technical condition of rolling bearings by the quasi-dynamic method

No.	Feature of the diagnostic signal	Notation	Equation
1	duration of the movement of the test pendulum	T [s]	-
2	number of swings of the pendulum	i [ ]	-
3	coefficient of friction in oscillations	μ_o [ ]	$\mu_o = \dfrac{720 \cdot mg \cdot e \cdot (1-\cos\alpha)}{\pi \cdot i \cdot \alpha \cdot m \cdot (D+d)}$
4	coefficient of the viscotic resistance of the pendulum	C_w [Nm/s]	$C_w = \dfrac{mg \cdot e \cdot \sin\alpha - I_o \cdot \varepsilon}{\omega}$
5	moment of friction	M_t [Nm]	$M_t = I_O \cdot \ddot{\alpha} = I_O \cdot \dfrac{\omega_1 - \omega_2}{\Delta t}$
6	coefficient of the rolling friction	f_t [m]	$f_t = \dfrac{M_t}{mg}$
7	friction power	W_t [Wat]	$W_t = M_t \cdot \dot{\alpha}$

Fig. 3. A view of the test stand for identification of the technical condition of a rolling bearing. 1 – base with a holder, 2 – test pendulum, 3 – tested bearing, 4 – photo-optical sensor, 5 – recording device KSD-400

4. THE TEST AND ITS RESULTS

Five brand-new 6305 single-row unsealed ball bearings, randomly chosen from a group of 30, were used in the experiment. The number of repetitions for each bearing was established as 5.

After the base was levelled and the pendulum with the bearing was mounted in the self-centring holder, changes in the angular velocity of the pendulum mount were recorded with a photo-optical velocity sensor and a signal recorder.

The test consisted in unbalancing the system by the angle α, and recording the time of passage between two markers situated on the pendulum mount. The markers situated on the pendulum mount facilitated the identification of the pendulum angular velocity at its lowest position, which corresponds to its highest angular velocity. Only times of passage from the right to left (clockwise) were identified for analysis.

The measurements and calculations yielded a range of diagrams of the identified diagnostic signal vs. time. Fig. 4 shows diagrams of the angular velocity vs. time (of the outer raceways) of two bearings with various technical conditions, recorded at the lowest point of the pendulum.

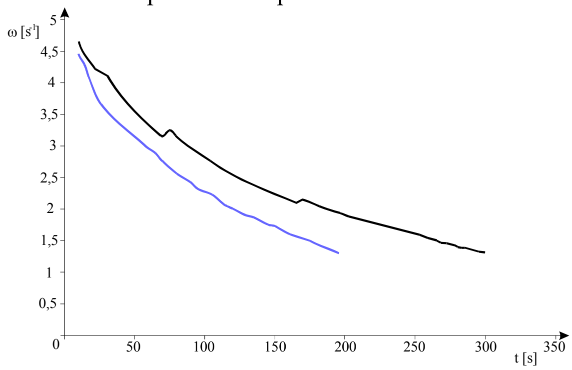

Fig. 4. Comparison of diagrams of the angular velocity vs. time for two 6305 bearings, differing in technical condition, recorded at the test stand

An example diagram of the angular velocity (ω) and acceleration (ε) of the pendulum mount vs. duration of the pendulum movement (t), number of individual swings (i) and the angle of pendulum deflection (α) at the lowest point is shown in Fig. 5.

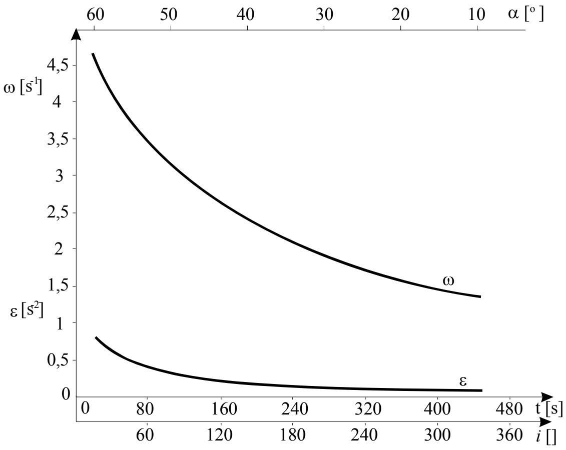

Fig. 5. Angular velocity and acceleration of the outer raceway of a 6305 bearing vs. time, number of swings and the angle of the first deflection angle

Fig. 6 shows an exemplary diagram of the power of friction W_t and the moment of friction M_t for the tested pendulum vs. time of the pendulum movement, identified at the lowest point.

The experiment performed at the test stand resulted in the values of diagnostic signal features for five tested bearings at the lowest point. The obtained values the diagnostic features are shown in Table 2.

The value of the friction coefficient in oscillations μ_o of the bearing under test is much higher than the value of the coefficient of friction, provided by the manufacturer. The coefficient for an unsealed rolling bearing manufactured by CX is equal to μ=0.0010÷0.0015 [6], while for bearings manufactured by SKF it is close to μ=0.0015 [8].

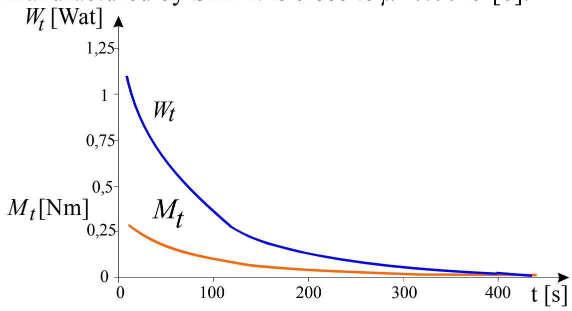

Fig. 6. Characteristic curve of the power of friction (W_t) and the moment of friction (M_t) of a 6305 bearing, identified at the lowest point of the test pendulum

The difference from the values obtained in the tests stems from the fact that the bearings under test were examined at the wearing-in stage, whereas the values given by manufacturers are for worn-in bearings, and the μ is identified at a different bearing load. Another factor which affects such relatively high coefficient values may be the fact that the coefficient of friction decreases with an increase in the angular velocity of the bearing raceway.
The experiment supports the conclusion that each of the selected features of the signal bears diagnostic information related to the technical condition of a rolling bearing in terms of its tribological node.

Table 2. The values of features of diagnostic signals of 6305 bearings, without grease (brand-new), manufactured by CX, obtained during the experiment

No.	**Feature of the diagnostic signal**	**Notation**	**Mean value**	**Standard deviation**
			for the tested group of bearings	
1	duration of the movement of the test pendulum	T [s]	454.6	2.88
2	number of swings of the pendulum	i [ ]	320.2	1.788
3	coefficient of friction in oscillations	μ_o [ ]	0.01218	0.00011
4	coefficient of the viscotic resistance of the pendulum	C_w [Nm/s]	0.063	0.00408
5	moment of friction	M_t [Nm]	0.278	0.01095
6	coefficient of the rolling friction	f_t [m]	0.0134	0.00612
7	friction power	W_t [Wat]	1.034	0.04560

According to the author, the coefficient of friction in oscillations is the most universal diagnostic feature of a rolling bearing; it may be referred to the value of the conventional coefficient of friction provided by manufacturers for brand-new bearings or compared to historical data obtained in experiments.

Identification of the moment of friction, coefficient of the rolling friction or the power of friction during a bearing use may be a measure of intensity of use in a bearing node.

5. SUMMARY AND CONCLUSIONS

The main problem faced in verification of dismantled systems, units and parts of machines is the identification of their actual technical condition. This is caused by a variety of restrictions resulting from the construction, test methods and mainly by a lack of knowledge of the nominal or limiting values for specific units or parts. Because of this, when the actual technical condition of a part is unknown, the part is scrapped rather than tested for its technical condition and remounted.

Rolling bearings are parts for which there are no satisfactory diagnostic tools or limiting values for determination of their technical condition at the stage of repair.

The tests and analyses conducted for this study have provided grounds for the following conclusions:

1. The coefficient of resistance for a bearing, which may be referred to the value of the conventional coefficient of friction, provided by manufacturers for a new bearing, or the value of such coefficient determined in an experiment for each of the three states of a bearing “life”, is the universal diagnostic feature of a rolling bearing.
2. The use of movement resistance as the moment of friction is justified; it may be practically applied for unsealed ball bearings.
3. Change of the power of friction, as compared to the nominal value, during the life of a bearing, identified in the course of a major overhaul or an emergency repair, is a measure of the intensity of the wearing processes in the tribological nodes of a bearing and may be useful in identification of its current technical condition.
4. The proposed diagnostic method of identification of the technical condition of a rolling bearing may be useful where the coasting method cannot be applied.
5. Further studies of the quasi-dynamic method will aim at interpretation of the presented features of the diagnostic signal as a function of bearing wear (the number of bearing rotations at its nominal load).

6. REFERENCE

[1] Bielawski P.: *Diagnozowanie maszyn z wykorzystaniem mocy tarcia*. Diagnostyka Nr 29/2003. s. 15÷20;

[2] Capanidis D., Czarny A.: *Stanowisko dydaktyczne do wyznaczania oporów ruchu łożysk stożkowych*. Zeszyty naukowe. Zeszyt Nr 8. Wydawnictwo AT-H, Bielsko Biała 2003, s. 135-140;

[3] Conyers J.: *Lekcja z uszkodzenia łożysk*a. Utrzymanie Ruchy, Marzec 2004;

[4] Dwojak J. Rzepiela M.: *Diagnostyka i obsługa techniczna łożysk tocznyc*h. Biuro Gamma. Warszawa 2003;

[5] Kowal A.: *Opory ruchu w mechanizmach maszyn górniczych*. Monografia. Wydawnictwo Politechniki Śląskiej. Gliwice 2003;

[6] Łożyska toczne. *Katalog produktów CX-LO/PL/2.01/07.2005*. Delta Marketing Sp.z o.o., 2005;

[7] Roger L. Oberweiser.: *Naprawa łożyska tocznego jako alternatywa jego wymiany*. Utrzymanie Ruchy, Maj 2004;

[8] SKF: P*oradnik obsługi technicznej łożysk. SKF*, Warszawa, 1994;

[9] Styp-Rekowski M.: *Diagnozowanie specjalnych łożysk tocznych*. Diagnostyka Nr 25/2001. s. 65÷71;

[10] Praca zbiorowa: *Mały Poradnik Mechaniczna*, WNT Warszawa, 1970.

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EVALUATION OF EXPLOITIVE CHARACTERISTICS BA1032 ALLOY AFTER TIG WELDING METHOD TREATMENT

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Summary

The aim of this study was to make the diagnosis of the operating conditions of aluminium bronze BA 1032. Current intensity was selected on an experimental way to assure of stable melting of the surface layer together with inserted components at small current intensity. The examined questions were: the influence of surface treatment of aluminium alloy onto structure by collected energy source; the geometric parameters of the surface melted by TIG welding method of bronze surface plated alloy ingredients by using different current parameters.

The results of this study indicate that the thermic exposure value, it means: the sort of concentrated energy source as well as its speed, as well as the sort of alloy additives have an influence on exploitation parameters of tested samples.

Keywords: Cu alloys, welding, using properties, aluminium bronze.

OCENA WŁAŚCIWOŚCI EKSPLOATACYJNYCH STOPU BA1032 PO OBRÓBCE SPAWALNICZĄ METODA TIG

Streszczenie

Celem pracy była diagnostyka właściwości eksploatacyjnych brązu aluminiowego BA1032. Próbki do badań pobierano z obszaru ustabilizowanego oddziaływaniem skupionego źródła ciepła (stała, ustabilizowana szerokość strefy wpływu ciepła). Natężenie prądu dobrano eksperymentalnie zapewniając stabilne przetopienie warstwy powierzchniowej wraz z wprowadzanymi składnikami przy realnie małym jego natężeniu.

Z analizy wyników badań wynika, że zarówno wartość ekspozycji cieplnej, tj. rodzaj zastosowanej energii źródła skupionego ciepła, prędkość jego przemieszczania jak i rodzaj dodatków stopowych wpływają na parametry eksploatacyjne obrobionych elementów.

Słowa kluczowe: stopy Cu, spawanie, właściwości użytkowe, brąz aluminiowy.

1. INTRODUCTION

Aluminium bronzes are one of the most important cooper alloys. They have the highest resistance characteristics and considerable corrosion resistance comparable to the other bronze alloys. Another notable attribute of aluminium bronzes is that they retain mechanical properties at the high temperature, and especially at the low temperature. Because of these properties they are commonly used in many technical applications.

Aluminium bronzes, which contain aluminium in an amount of 9.5 to 11%, are susceptible to hardening [2, 4, 6]. The β-Phase of Aluminium Bronzes – a solid-solution based on intermetallic phase Cu_3Al with electron-concentration of 3/2 – crystallizes in a regular space-centered lattice. During slow (equilibrium) cooling it decays into eutectoid mixture ($\alpha+\gamma_2$). When the cooling exceeds the critical value, this phase becomes over cooled and it changes into a martensitic transformation. Hard and abrasion resistant phase is formed as a result of this transformation. The transformation of aluminium bronzes can be realized by surface or volumetric treatment. The TIG welding method is perfect for surface processing [1, 3, 5].

Direct-current electrode negative (DECN) is used for treatment of all metals except aluminium. This method enables a stable work of welding arc. About 60% of total heat quantity is generated on the surface layer of a test object, a large part of the heat is utilized to a melting of native metal. About 10% of the heat is wasted on the radiation, and only 30% generates on electrode. It is possible without any difficulties to maintain an electrode temperature below its melting temperature (3370^0C). The end welding electrode has a conical shape to maintain the arc on it, what increases the work stability and facilitates the ability of an operator to maintain a constant arc length. Pure argon gas is generally used as a shield gas for the TIG welding method. As an inert gas it ensures a good protection for both direct and alternating current and it can be used for all sorts of materials.

2. PURPOSE AND METHOD OF THE INVESTIGATION

The purpose of this investigation was to determine the geometric parameters and modifications proceeded in the surface structure melted by TIG welding method of bronze BA1032 surface plated alloy ingredients by using different current parameters.

BA1032 aluminium bronze was tested. This alloy was chosen as the base material because of its specifics possibilities of heat treatment

In order to remove the surface oxides and ensure comparable surface roughness, the tested surface, before a treatment of concentrated energy source, was polished with the help of abrasive paper of granularity of 400 and washed with alcohol.

Next the samples were surface-treated by TIG welding method in a shield of inert gas (Argon).
The treatment was realized for every sample by one concentrated energy source passage. Constant linear velocity 4.7mm/s of electrode feed speed (of reversed polarity) was assured with respect to sample surface in a shield of technical argon.
The electrode feed speed was selected on an experimental way by taking up a criterion of optimizing heat energy utilization. During small electrode feed speed the concentrated energy source causes "keeping" metal under heat influence for too long time, and after crossed the fixed value of intensity causes melting metal with formation of characteristic crystalline cavity (with applicable source power, metal was melting and then was subject to thermic convection). During very high electrode feed speed, it was found that there are no significant differences in a treatment of concentrated energy source into sample, despite of changing the heat energy (current intensity) in analyzed scope.

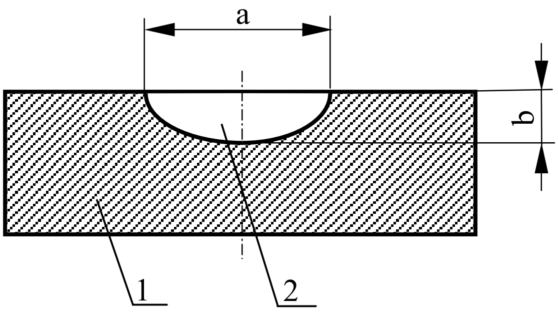

Fig. 1. Location scheme for measured parameters: 1 – tested sample, 2 – place treated by concentrated energy source

Test samples were taken from the stabilized area by the treatment of concentrated energy source (constant, stabilized width of heat-affected zone (HAZ)).

Current intensity was selected on an experimental way to assure of stable melting of the surface layer together with inserted components at small current intensity.

Geometric measurements were made on the automated test stand of image analysis MultiScan. Total width, depth of melted zone and heat-affected zone were measured. Measured parameters scheme is presented in Fig. 1.

Tab. 1. Treatment parameters

Tested point	Current Type	Current Intensity	Feed speed [mm/s]	Alloy additives
A	Direct	160	4.7	-
B	Direct	160	4.7	Al
C	Direct	160	4.7	40%Al + 60% Zr
D	Alternating	160	4.7	-
E	Alternating	160	4.7	Al
F	Alternating	160	4.7	40%Al + 60% Zr
G	Direct	100	2.3	42% $NaNO_3$ + 17% Mg + 6% Al + 35% Cr_2O_3
H	Direct	100	4.7	
I	Alternating	100	4.7	

3. RESULTS OF INVESTIGATION

A depth of melted zone for every tested point was presented in Fig. 2. The parameters were divided into two groups. 1st group; values for intensity of 160 A (dark colour of scheme), 2nd group; values for intensity of 100 A (light colour of scheme). For all tested points with a feed speed of 4,7 mm/s it was found that their melted zone is deeper after the treatment with alternative current than with direct current (compare points: A-D, B-E, C-F, H-I). Weld bead, without adding any alloy additives, was deeper than during using some. It can be explained by energy consumption needed to melt them down.

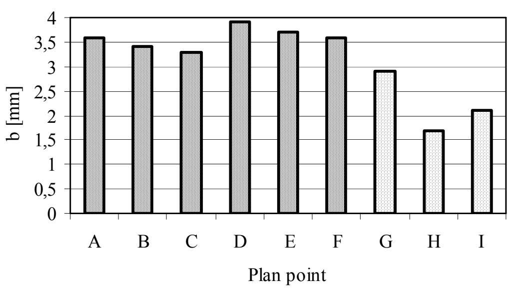

Fig. 2. Depth of melted zone for every tested point (Tab. 1)

Point G presents an alloy treated twice at small electrode feed speed. Evident increase of depth of weld bead was found. When observing metal and mixture reaction during treatment, it was noticed that in the central part of melted zone there are some movements reminding a boiling together with its thermic convection.

Width of melted zone for every tested point (a Fig. 1. was presented in Fig. 3. Width dimensions presented in Fig. 2 are similar to growth dimensions presented in Fig.3. Melted zone is wider after the treatment with alternative current than with direct current. After treatment without adding any alloy additives, wilder melted zone was obtained. While the alloy in the presence of mixtures was treated with intensity of 100 A, the width of weld bead differs not much from the dimension obtained during treatment of proper alloy additives with current intensity of 160 A. The width difference demonstrated (point G and H) is not as big as the depth of weld bead.

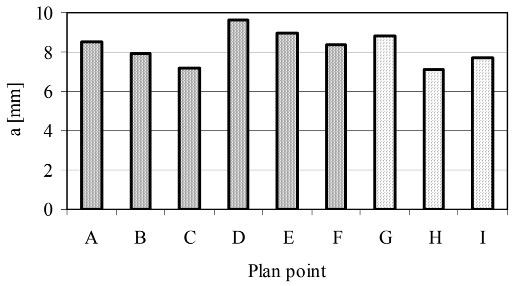

Fig. 3. Width of melted zone for every tested points (Tab. 1)

Comparison of proportion of width and depth changes was presented by quotient a/b (Fig. 1) in a Fig. 4. For direct and alternating current intensity of 160 A, the difference in groups (A-B-C and D-E-F) is insignificant. The proportional width changes of weld bead can be found. Differently quotient a/b can be found when using a mixture with exothermic effect. The highest ratio is in point H (Fig. 4). The highest difference of weld bead geometrical values (test conditions) was observed for direct current intensity of 100A and feed speed of 4.7 mm/s. During lower feed speed, quotient a/b decreases its value. For alternating current intensity, quotient a/b value oscillates between values of points G and H.

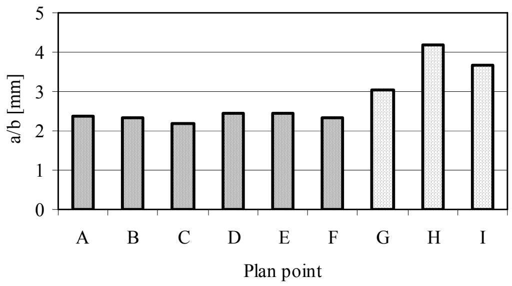

Fig. 4. Quotient width/depth of melted zone for every tested points (Tab. 1)

Structure of melted zones of alloy BA1032 for tested points was presented in Fig. 5-10. Fig. 5 presents a coarse-grained structure of test point G. Alloy structure of test point F crystallized with a finer grain (Fig. 6).

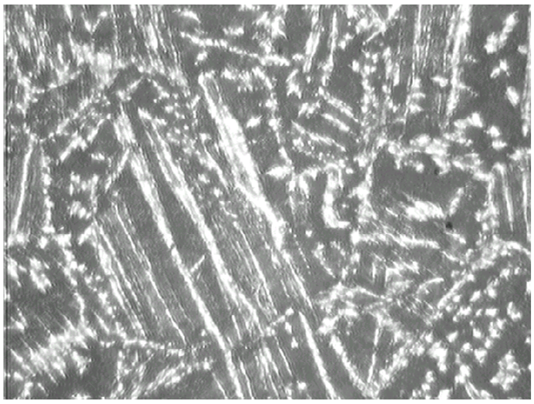

Fig. 5. BA1032 alloy structure, test point G, Magnification 230x. Etch Mi8Cu

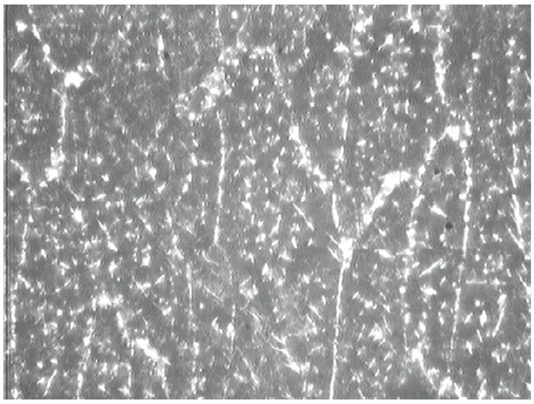

Fig. 6. BA1032 alloy structure, test point F. Magnification 230x. Etch Mi8Cu

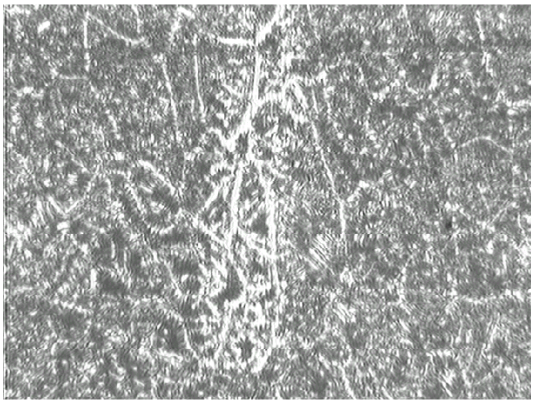

Fig. 7. BA1032 alloy structure, test point I. Magnification 120x. Etch Mi8Cu

Fig. 7 presents a transformation of structure into microstructure caused probably by convectional interaction of mixture components. Enlargement of a central part of this micro-zone was shown in Fig. 8. Fig. 5 shows an example of transformation, which probably was proceeded in the same grain boundary. The alloy was heated above a critical temperature, after it changed into liquid phase, but it hasn't enough time to stabilize and to crystallize with new gain. As a result a new quality of structure "with old grain" was formed. Enlargement of this structure was presented in Fig 10.

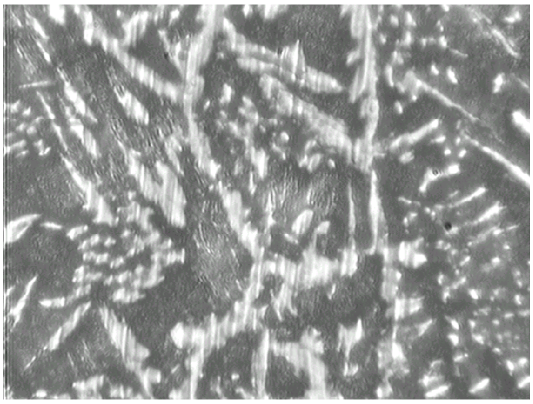

Fig. 8. BA1032 alloy structure, test point I. Magnification 470x. Etch Mi8Cu

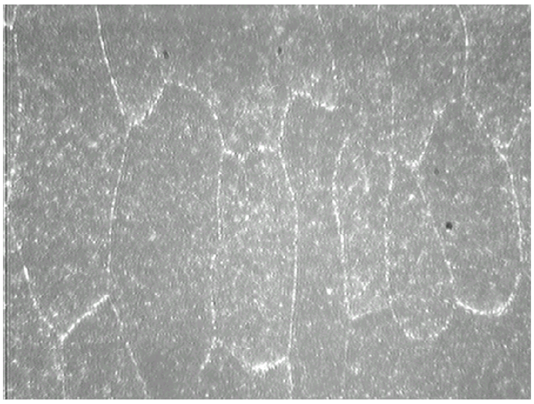

Fig. 9. BA1032 alloy structure, test point H. Magnification 230x. Etch Mi8Cu

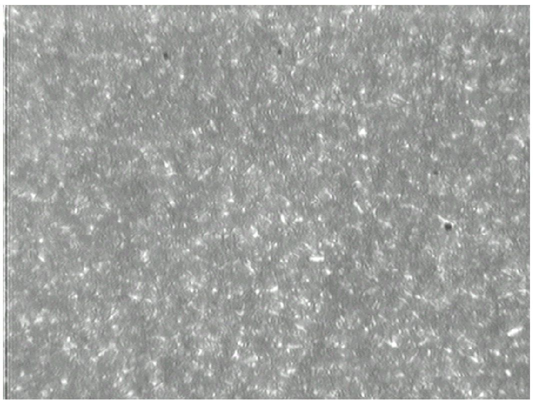

Fig. 10. BA1032 alloy structure, test point H. Magnification 470x. Etch Mi8Cu

4. STATEMENTS AND CONCLUSIONS

1. Use of alternating current to surface-treatment of BA1032 with alloy additives, causes the higher geometrical parameters of weld bead than use a direct one.
2. Treatment of BA1032 with mixtures creating exothermic effect, increases thermal efficiency of the process.
3. Quickly carrying away of heat causes reaction retention of alloy components moved into BA1032, which lead to form a micro-zones weld bead composed with part-reaction products.

LITERATURE

[1].Chodkowski Sz.: *Metalurgia metali nieżelaznych.* Wyd. Śląsk Katowice 1971.

[2].Lipiński T.: *Obróbka stopów Al-Cu skupionym źródłem energii*. Efekty eksploatacji systemów technicznych. Olsztyn 1999.

[3].Lipiński T.: *Wpływ obróbki cieplnej na budowę strukturalną stopu BA1032.* III Międzynarodowa Konferencja Naukowa Olsztyn 2000. "Rozwój Teorii i Technologii w Modernizacji Rolnictwa".

[4].Lipiński T.: *Wpływ natężenia prądu na parametry geometryczne ścieżki stopu BA 1032 po obróbce powierzchniowej metodą TIG*. Miesięcznik naukowo - techniczny Przegląd Mechaniczny nr 2'01.

[5].Napadłek W. i inni: *Podwyższanie twardości zaworów wylotowych silnika z wykorzystaniem nowoczesnych technologii*. III Ogólnopolska Konferencja Obróbka powierzchniowa. Częstochowa-Kule 1996.

[6].Opatny-Myśliwiec D, Myśliwiec M.: *Techniki wytwarzania*. Spawalnictwo. PWN Warszawa 1981.

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Mgr inż. **Anna WACH** zajmuje się badaniami materiałowymi.

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METHODOLOGY OF ACQUISITION OF KNOWLEDGE CONCERNING DIAGNOSTICS OF MACHINERY AND PROCESSES

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Summary

The paper deals with an outline of a methodology of acquisition of diagnostic knowledge concerning machinery and processes. The problem formulated in the paper concerns the possibility to develop a general methodology of acquiring knowledge of technical diagnostics. Two issues are discussed: methods of knowledge acquisition about machinery mainly considered as static objects, and methods of acquiring knowledge in the form of heuristic models of dynamic objects and processes. Methods developed in the author's research group are mainly dealt with. The paper concludes with future work envisaged.

Keywords: technical diagnostics, knowledge acquisition, heuristic models of processes.

METODYKA POZYSKIWANIA WIEDZY DOTYCZĄCEJ DIAGNOSTYKI MASZYN I PROCESÓW

Streszczenie

W artykule przedstawiono zarys metodyki pozyskiwania wiedzy diagnostycznej dotyczącej maszyn i procesów. Sformułowany problem badawczy dotyczy możliwości utworzenia i rozwoju ogólnej metodologii pozyskiwania wiedzy w zakresie diagnostyki technicznej. Omawiane są dwie grupy metod: pozyskiwania wiedzy o maszynach interpretowanych jako obiekty statyczne, a także pozyskiwania wiedzy w postaci heurystycznych modeli obiektów (dynamicznych) oraz procesów. Przedmiotem opisu SA w głównej mierze metody rozwijane w grupie badawczej, w której pracach uczestniczy autor. Artykuł zakończony jest próba określenia przyszłych prac dotyczących pozyskiwania wiedzy diagnostycznej.

Słowa kluczowe: diagnostyka techniczna, pozyskiwanie wiedzy, modele heurystyczne procesów.

1. INTRODUCTION

Recently technical diagnostics has been developed to the practical domain whose objects of interest are both machines and equipment, and processes the machines are involved in. Although many processes can be considered, such as process of degradation of elements, process of maintenance, and many others, the most broadly investigated type of processes corresponds to the operation of the object. It is worth emphasizing two main tasks of technical diagnostics, i.e. diagnostics of machinery, and diagnostics of processes, that at their very beginning have been developed by two different scientific societies: the former by mechanical engineers, while the latter by control engineers.

Let us consider for a while how these historical issues have influenced main paradigms of both the branches of technical diagnostics. The goal of technical diagnostics is to diagnose the given object (machine/process), i.e. to formulate a statement about the object's state or occurrence of possible faults. To this end, the subject of diagnosing, regardless of being human or automated unit, shall have access to sufficient knowledge. This knowledge may be represented in many ways. Process diagnostics mainly takes advantage of models, which represent either the behavior of machine (or its elements) operating properly, or the behavior of the machine in different faulty conditions. On the other hand, machinery diagnostics usually does not use any apparent model at all, therefore it is sometimes referred to as model-free diagnostics (or: *diagnostics with a hidden model*). However, knowledge represented mainly in declarative form, and more rarely in procedural one, is used in order to arrive at a conclusion about the state of the diagnosed object.

Technical diagnostics is a highly knowledge-intensive technical domain of both theoretic and applied character. To deal with diagnostic knowledge, methodology of Knowledge Engineering (KE) is being used. Methodology of KE:

- allows acquiring relevant knowledge and assessing chunks of knowledge in a very systematic way;
- allows taking advantage of enormous streams of data collected nowadays, which can carry relevant knowledge upon objects of diagnosing;
- allows managing knowledge by:
  - preserving it,
  - sharing and making it available to end-users;
- allows applying knowledge in an automated way.

The author has taken part in several projects that could be classified into both the branches mentioned above. He and his research group have been involved in different projects focused on knowledge acquisition for technical diagnostics. This paper briefly addresses several issues concerning methodology of knowledge acquisition for technical diagnostics, and is based upon the author's experience in the field. Limited volume of the paper does not allow to enumerate and describe many methods that have been developed in research centers interested in technical diagnostics. There are described mainly methods developed in the author's research group. Due to very limited space no applications are presented. However, some of them can be found in the bibliography cited thorough the paper.

2. PROBLEM FORMULATION

The problem to be solved may be formulated by means of the following fundamental questions:

1. Can comprehensive methodology of acquiring diagnostic knowledge be developed?
2. Is it possible to efficiently acquire knowledge from diverse knowledge sources?
3. Can chunks of knowledge collected from different sources be linked together allowing to create knowledge-based applications that would operate more efficiently?
4. Is it possible to develop tools supporting diagnosticians in acquiring and managing diagnostic knowledge?

To find answers to these questions, a comprehensive research has been initiated in mid-nineties of 20th century by the author and the research group collaborating with him. An exhaustive description of the results is contained in [3]. Some issues are addressed in the following sections.

Before entering discussion of the methodology it is worth paying some attention to static and dynamic objects of diagnosing. Static objects are described by means of models that are not (openly) dependent on time. Hence, any representation of knowledge about the object of diagnosing does not involve time variable at all. Conversely, dynamic objects are described by means of models that engage parameter(s) of time, either lifetime of the object, or dynamic time corresponding to the timescale where take place dynamic operations of the object, such as single revolution of the shaft of a rotating machine, and many others.

It is nature of diagnostic objects that *they are involved in processes* such as: usable processes, wear, service, repair, and many others. Understanding dynamics of objects and taking advantage of dynamic models allows better diagnosis. On the other hand, let us understand that static models, although they have been implied especially in machinery diagnostics since many years, allow less accurate and more approximate diagnoses. Therefore, more attention is paid thorough the paper to the elements of methodology, that allow acquiring dynamic models of processes. Furthermore, diagnostics with apparent model (or *model-based* one) is addressed instead of model-free diagnostics (or – better speaking – *diagnostics with hidden models*).

3. METHODS OF KNOWLEDGE ACQUISITION ABOUT MACHINERY

At the earlier stage of the author's research [1, 3] several methods concerning static knowledge have been developed and implemented, including methods of knowledge acquisition, methods and techniques of knowledge assessment and a scenario of knowledge acquisition process. In the following sections some groups of methods applied within the described research are briefly discussed.

3.1. Methods of Knowledge Acquisition

Methods of knowledge acquisition are strongly related to knowledge sources: human experts (who may take active or passive part into the knowledge acquisition process) and databases. The latter group may be further classified into supervised Machine Learning (ML) methods and unsupervised methods of Data Mining (DM) and Knowledge Discovery (KD).

Domain experts are very valuable sources of diagnostic knowledge and cannot be omitted through the whole process. Their role is especially important in the introductory phase of this process when a description of the domain is acquired. However, these methods are inefficient if we have to acquire great amount of knowledge counted e.g. in numbers of rules. Therefore ML and KD methods are even more and more frequently applied.

3.1.1. Methods of Knowledge Acquisition from Domain Experts

Two methods have been implemented: knowledge acquisition using paper forms and using an electronic form. They differ in range of required activity of a knowledge engineer.

The first method consists in that the expert elicits his/her own knowledge without participation of a knowledge engineer and represents it filling in cells in a special paper form. Then the forms have to be interpreted by the knowledge engineer who puts down respective records into the knowledge base. This method is suitable for the experts who are unfamiliar with modern software and hardware. However, the influence of the knowledge engineer on the final portion of knowledge is very crucial.

The second method depends on the use of some specialized software tool which the author called an electronic form [1, 3]. This application is a knowledge base editor, which allows reducing role of the knowledge engineer to integration and merging knowledge acquired from different experts and in many cases his/her activity is not required.

Both the methods have been implemented using supporting means [1, 3].

Apart from these classical methods of knowledge acquisition from domain experts, a new class of methods targeted at belief networks is rapidly developed, e.g. by W. Cholewa and his team [8]. Experts represent their knowledge in the form of a structure of the network, variables associated to nodes, topology of links, and tables of conditional probabilities associated with the nodes. There are also solutions where knowledge represented in the form of a belief network is acquired from classified examples provided by the knowledge engineer.

Another method that is worth mentioning is representation of knowledge in the form of fuzzy-neural networks (FNN, see [7]) where experts' knowledge is used for the domain description.

3.1.2. Methods of Knowledge Acquisition from Databases

Both supervised and unsupervised methods have been used extensively. Machine Learning (ML) methods that belong to the supervised ones can be used if a database containing previously classified examples is available. The whole process of knowledge acquisition may be carried out within a special diagnostic experiment, either numeric or active one. Several steps can be distinguished. Active diagnostic experiments require measurements of needed diagnostic signals. Realizations of signals are stored in the system's database. Features of diagnostic signals consist examples, each of them being represented by one record in the database. Fields in this record contain several values of conditional attributes and value(s) of at least one decision attribute(s) denoting the class(es) where the classified example belongs. Each example is considered as positive one for some concept that corresponds to some given technical state and as negative one (counterexample) for all other classes. Values of attributes are usually represented as qualitative ones, hence some kind of discretization of continuous variables is required.

To make the whole process computationally efficient a subset of relevant attributes should be selected. There are several methods of selection, e.g. based on minimal reducts using rough-sets approach, or statistical methods such as PCA. After that the database of examples is prepared for knowledge acquisition using supervised ML methods.

To acquire knowledge from databases of examples several very well-known ML methods can be applied, including induction of rules and decision trees, and many others.

Validation and assessment of acquired knowledge depends on the application of either special set of testing examples or some resampling technique and then calculation of classification errors. The very convenient and frequently used criterion concerns the overall empirical error rate. If the error rate obtained is unacceptable then the process may be repeated iteratively.

The author and J. M. Żytkow have also begun the research on applications of KD methods to machinery diagnostics [6]. The KD process included several steps. To discover qualitative (approximate) dependencies and estimate their strength, contingency tables were applied, which suggested very strong functional dependencies. However, obtained results were imprecise. Contingency tables are suitable for identification of approximate dependencies, that may be refined by finding equations. These equations correspond both to 'direct' knowledge and 'inverted' one, the latter being suitable for diagnostic concluding from the collected evidence (diagnostic symptoms).

3.2. Methods of Knowledge Assessment

Methods of assessment of knowledge acquired previously may be also divided into those applied by human experts and 'automatic' ones.

Expert-based methods consist in an assessment of either a single rule or the whole ruleset (which is rare because of many rules contained in a typical ruleset) with respect to its/their substantial correctness. A value of the belief degree is assigned to each individual rule being assessed. Only several qualitative (predefined) values of the belief degree [3] are used. Such activity of the human expert may be aided by a special tool.

'Automatic' methods of assessment of acquired knowledge depend on the application of either special set of testing examples or some resampling technique and then estimation of classification errors. To this end, the overall empirical error rate is often used, defined as the ratio of errors to the total number of testing examples. In case of uneven distribution of examples across previously specified classes, weighted overall empirical error rate defined by the author is used [3].

Moreover, hybrid couples of methods of knowledge acquisition and subsequent assessment of this knowledge base have been suggested [3]. There are two 'cross-like' possibilities: knowledge acquired from a domain expert may be verified using a set of testing examples, or knowledge acquired by ML methods may be assessed by human experts. The former pair is particularly interesting since it makes possible to assess quality of a dataset of examples using a set of generally acknowledged rules [3]. These rules may be acquired e.g. from very much experienced and widely recognized domain experts.

4. HEURISTIC MODELS OF DYNAMIC OBJECTS

Similarly to methods of knowledge acquisition about machinery, it is possible to acquire knowledge in the form of models either from experts, or from databases.

This is not the task for this paper to discuss possible kinds of models that are applied in process diagnostics. Very comprehensive descriptions of this methodology can be found in [7]. Nowadays physical and mathematical models are created by experts. They also develop logical and rule-based models of dynamic objects. A very efficient kind of models takes advantage of fuzzy neural networks, which are based on sets of rules created by experts.

A new approach to model identification consists in applying and/or developing methods of soft modeling whose application will allow automatic discovery of models in databases. In the author's opinion the task formulated above is very similar to the process of Knowledge Discovery in Databases.

Methods of heuristic modeling can be considered according to the general way of representing models, and to their application. Models can globally represent data in the form of multivariate time series collected from the object.

Carriers of the global heuristic models can be:

1. Neural and Fuzzy-Neural Networks representing relations between spaces of inputs/controls and delayed outputs, and the spacer of output(s); this application is similar to functional dependencies in the form of equations that allow calculation of output values [7];
2. Neural and Fuzzy-Neural Networks whose topology and coefficients tuned in result of training represent generalized knowledge about the process [5];
3. Functional dependencies in the form of equations that allow calculating numerical values of output(s) basing on values of inputs, controls and states, as well as values of previous outputs (for dynamic objects).

Multivariate time series can be also modeled in intervals using hypersurfaces (hyperplanes, multivariate splines etc.) whose dimension is equal to the dimension of the space of independent variables. For the data represented in such a way it is possibile to define an event as some determined pattern (regularity) in the database that is assigned some semantic meaning. The support of the event (time interval, on which the regularity holds) can in some cases reduce to a single point located at the time axis.

Furthermore, a historically the most early method of modeling dynamic processes has to be recalled, which is based on sequences of events that correspond to some discrete control actions and inputs as well as observed outputs. An example of such an event can be opening or closing a valve, switching on the supply, signaling warning or danger, adjustment of an element of the system and the others. In such sequences of events it is possible to identify characteristic sequences that allow detecting some faults.

Several methods are developed with the author's supervision and participation:

1. Modeling multivariate time series with the use of sequences of events (P. Tomasik);
2. Modeling one-dimensional courses of control variable by means of linguistic description (R. Szulim);
3. Discovering dependencies that describe operation of dynamic objects (D. Wachla);
4. Modeling dynamic processes with the use of neural networks and fuzzy-neural ones (P. Przystałka, R. Wyczółkowski, B. Wysogląd).

5. RECAPITULATION

The paper dealt with very brief description of the comprehensive methodology of knowledge acquisition about machinery and processes. The methods mentioned in the paper were developed and implemented in the author's research group. Since it is ever more widely believed that further development of technical diagnostics depends on application of efficient methods of knowledge acquisition, the problem addressed in the paper will become ever more and more attractive for many researchers. Other important issue that causes systematic development of this methodology is the growing possibility to collect data about machinery and processes. This data really carry very crucial information about the objects and processes to be diagnosed. Implementation of automated methods should boost creation of valuable applications that would help the personnel in operation of machinery and control of processes.

BIBLIOGRAPHY

[1] Moczulski W.: *Methodology of Diagnostic Knowledge Acquisition*. Bulletin of the Polish Academy of Sciences - Technical Sciences, vol. 49, No. 2, 2001, pp. 337-357.

[2] Moczulski W.: *Metody pozyskiwania wiedzy diagnostycznej*. [In:] [7], chap. 17

[3] Moczulski W.: *Diagnostyka techniczna. Metody pozyskiwania wiedzy*. Monografie, Wyd. Politechniki Śląskiej, Gliwice 2002.

[4] Moczulski W.: *Metodyka heurystycznego modelowania obiektów i procesów dynamicznych w diagnostyce i sterowaniu*. Diagnostyka Procesów Przemysłowych DPP'2005, PAR, 2005.

[5] Moczulski W.: *Odkrywanie wiedzy w bazach danych*. [In:] [9] chapter 23.

[6] W. Moczulski, J. M. Żytkow: *Automated Search for Knowledge on Machinery Diagnostics*, [In:] Kłopotek M., Michalewicz M., Raś Z.: Proceedings of the Workshop "Intelligent Information Systems" IIS'97 held in Zakopane,

194-203, Institute of Computer Science PAS, Warszawa 1997.
[7] Korbicz J., Kościelny J. M., Kowalczuk Z. i Cholewa W. (Ed.): *Diagnostyka Procesów. Modele, Metody Sztucznej Inteligencji, Zastosowania*. WNT, Warszawa 2002.
[8] Cholewa W., *Diagnostyczne modele obiektów*. [In:] [9] chapter 2.
[9] Kiciński J. (Ed.): *Modelowanie i diagnostyka oddziaływań mechanicznych, aerodynamicznych i magnetycznych w turbozespołach energetycznych*. IMP PAN, Gdańsk 2005.

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DIGITAL FILTERS PARAMETERS SELECTION FOR HARDWARE IMPLEMENTATION IN PROGRAMMABLE DEVICES

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Summary

This article regards hardware processing of diagnostic signals. It is solely devoted to the problem of bit-length accuracy of digital filter coefficients with the application of fixed-point numbers. This problem has not been properly studied before, since arithmetic operations bit-width is usually fixed, e.g. 32 bits for DSPs or microprocessors. For programmable devices arithmetic bit-length may be freely selected. This research provides guidelines for proper selection of filter-coefficient bit-length for a given filter-tap number and filter characteristics. Furthermore, different filter types are compared for the required minimum bit-length of coefficients.

Keywords: Digital filters, programmable devices, filter parameters.

DOBÓR PARAMETRÓW FILTRÓW CYFROWYCH DLA IMPLEMENTACJI SPRZĘTOWEJ NA UKŁADACH PROGRAMOWALNYCH

Streszczenie

Artykuł dotyczy sprzętowego przetwarzania sygnałów diagnostycznych. Poświęcono go problemowi dokładności zapisu współczynników filtrów cyfrowych na liczbach stałoprzecinkowych. Ze względu na brak literaturowych doniesień na ten temat, celem opracowania było przedstawienie sposobu doboru parametrów filtrów cyfrowych tak, by przy sprzętowej realizacji stałoprzecinkowej jak najefektywniej wykorzystać rząd filtru. W artykule przedstawiono analizy wymaganej dokładność zapisu współczynników dla spełnienia założonych kryteriów filtru. Porównano różne rodzaje filtrów pod względem minimalnej ilości bitów potrzebnych do zapisu ich współczynników.

Słowa kluczowe: filtry cyfrowe, układy programowalne, parametry filtrów

1. INTRODUCTION

Processing of vibroacoustic signals is crucial in contemporary diagnostics systems. In most cases those signals are recorded and processed in a digital form. An example of the device enabling recording and analyzing of diagnostic signal is Programmable Unit for Diagnostics - PUD [1]. It was designed on the basis of FPGA programmable systems (*Field Programmable Gate Array*), which enable hardware signal processing [4]. The PUD consists of a digital module and four independent analogue-digital modules.

The PUD is a real-time analyzer dedicated to processing of non-stationary signals which feature time-dependent frequency spectrum [7, 9]. One of the methods of their processing is Procedure of Linear Decimation (PLD) implemented on the PUD and implemented in hardware [3]. It involves processing of vibroacoustic signals recorded in variable operating conditions and enables conversion of those signals into a form relating to stabilized states.

The method involves down-sampling of significantly oversampled signal with the variable decimation ratio corresponding to the variations in operating cycle. In other words, it means selecting input samples in such a way that a constant sample number per rotation cycle is chosen [2].

2. PROBLEM AND SOLUTION

2.1. Research problem

The version of PUD being programmed is fitted with analogue-digital processors enabling to record a signal with sampling frequency of 500 kS/s necessary for the procedure of decimation with variable increment. Therefore the digital signal recorded by the unit is comprised within a frequency band up to 250 kHz. Such a high oversampling frequency is needed only in few cases, so it was necessary to reduce this frequency even down to 1kHz through the decimation with constant ratio. This process requires using low-pass filter in order to avoid aliasing.

Due to the great number of samples resulting from high sampling frequency and recording the signal simultaneously on several channels a hardware signal processing was applied in order to precipitate the execution of filtering operation. For this purpose in a FPGA system a dedicated module was designed. This module is designed in VHDL hardware description language and it enables to carry out filtration operation expeditiously [6, 4]. The module executes arithmetic operations on fixed-point numbers.

Therefore, the present research is devoted to the problem of recording the coefficients of digital filters on fixed-point numbers. The intention was to select digital-filter parameters in such a way, so that the available resources of FPGA were used efficiently assuming the fixed-point hardware implementation.

2.2. Conception of problem solving

The maximum frequency of the post-processed signal should be down to 1kHz as compared to 250 kHz of maximum input frequency. Therefore maximum decimation ratio of 250 is obtained. Two-stage filtration was selected as a solution of this problem, since transition from 250 kHz to 1kHz maximum frequency would require the application of filter of excellent parameters and high numbers of taps. That would entail great processor loading and long calculation time [5].

Consequently a recursive filter with a fixed cut-off frequency of 50 kHz was selected for the first stage of filtration, since it operates quickly and the processor is only slightly loaded [7, 8]. The second stage of filtration is done by a filter of finite pulse response because of its good parameters [1]. At this stage, there is a possibility that an user choose the cut-off frequency in the range of 1kHz through 50 kHz.

Two questions have arised owing to the necessity of recording filter coefficients on fixed-point numbers:

- how representation of filter coefficients on fixed-point numbers of limited bit-length affects filter characteristics,
- what is the minimum required bit-length of filter coefficients to satisfy the desired filter criteria.

The following criteria were assumed for filters:

- ripples in the passband lower than 1 dB,
- attenuation in the stopband not lower than 40 dB,
- transition region not greater than 20% of the cutoff frequency.

3. COEFFICIENTS ACCURACY

3.1. Recursive filters

The analyzed recursive filters were: Czebyszew type I and II, Butterworth and elliptical filter. The selected filters were analyzed for variable bit-length accuracy in the integer part and fraction part of their coefficients.

Below, on Fig. 1 and Fig. 2, the effect of changed accuracy of the integer part of coefficients on Czebyszew II, order eighth, filter characteristic are illustrated.

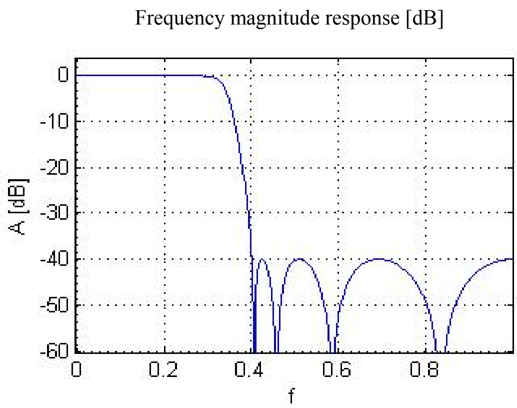

Fig. 1. Characteristics of Czebyszew II filter, of eighth order without changing the accuracy of coefficients' representation

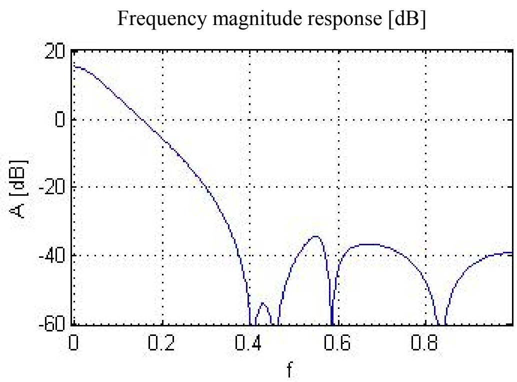

Fig. 2. Characteristics of Czebyszew II filter, of eighth order after changing accuracy of the integer part of coefficient B

As it can be noticed on the above charts, the reduction accuracy of integer part of B coefficients by as slight as one bit significantly affects filter characteristic. For other filter types, reduction in the accuracy of integer part of coefficients related to both input and output signal also significantly influences their characteristic. Therefore, in the process of coefficients representation on fixed-point numbers, the accuracy of the integer part of a coefficient cannot be changed.

In order to test the required coefficient accuracy of the fraction part, the analysis of filter characteristic was conducted on the same Czebyszew type II - order 8^{th} filter. It involved cutoff frequency change in the range of 0.1 through 0.9 (Nyquist frequency). The number of bits necessary for representing the fraction part of coefficients (the same bit number for A and B coefficients), was checked. The minimum bit-length was selected through decreasing accuracy of coefficients by 2 bits, starting from the bit number that does not change the accuracy, so that the filter satisfies the required criteria with minimum bit-length.

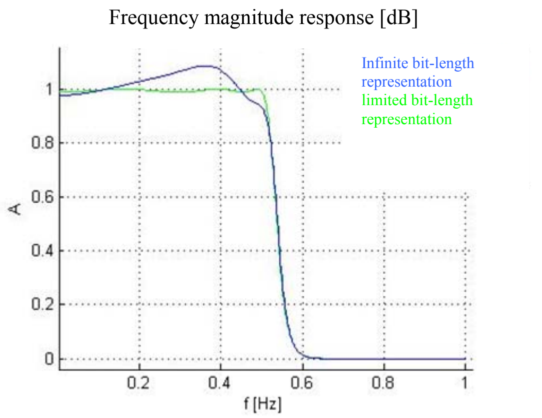

Fig. 3. Characteristics of Czebyszew II filter, of eighth order. Infinite accuracy and 6-bit fractional part representation.

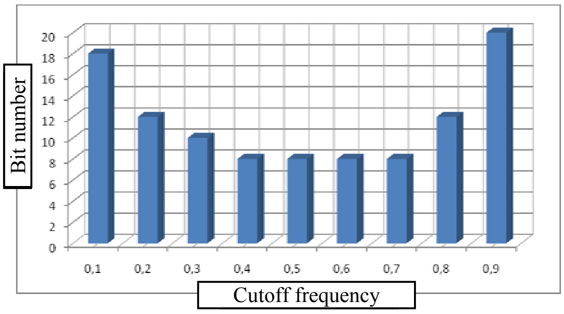

Fig. 4. Relation between the fraction of cutoff/ Nyquist frequency and minimum bit-number required for fraction part of coefficients of Czebyszew II filter (excluding the integer part of coefficients)

In the above analysis it can be observed that there is a certain correlation between coefficients accuracy and cut-off frequency of the filter. The lower the cutoff frequency (in comparison to the Nyquist frequency) the greater the required bits-length of the coefficients. And as the frequency converges towards the middle of the range (Nyquist/2), the bit-length decreases, reaching minimum value.

The next section of this research covers the analysis of minimum bit-length for filters of specified cut-off frequencies of 0.2, 0.1 0.05 and 0.001 of the Nyquist frequency.

The Fig. 5 illustrates the bit-length required for the integer and fraction parts of A and B coefficients in the specific filters. The filter order is selected so that the filter of a specific order satisfies the assumed criteria without changing recorded coefficient accuracy, starting from order 2. Maximum order considered in the calculations was 8.

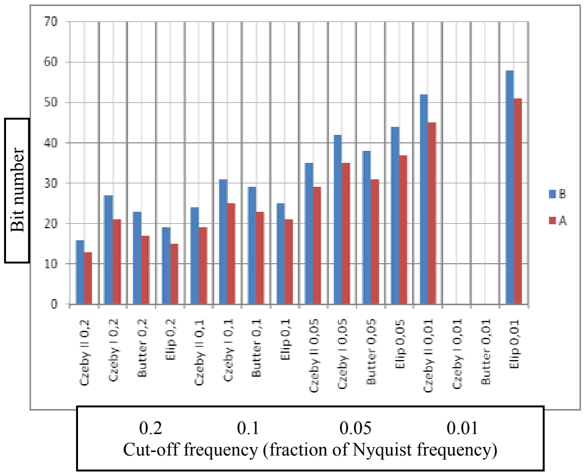

Fig. 5. Required minimum bit-length for coefficients corresponding with signal (A) and output one (B) for the analyzed filters in relation with the cutoff frequency.

Fig. 5 presents the assembled results obtained for the tested cutoff frequencies. It can be noted that the best results in terms of bit-length required for the fraction part of coefficients are obtained with Czebyszew type II filter. When the cutoff frequency is 0.01 Czebyszew type I and Butterworth filters do not meet the criteria owing to too wide transition region

4. CONCLUSIONS

This research contains the analysis of the effect of representation accuracy of coefficients on digital filter characteristic. Conclusions to be drawn from the conducted analyses are as follows:

- recording accuracy of the integer part of a coefficient cannot be reduced,
- the greater bit-length is required for the lower cutoff frequencies,
- in the analysis of the required coefficients bit-length at specific cutoff frequencies, the best results were provided by Czebyszew type II filters,
- it was not possible to reduce the cutoff frequency below 0.001 Nyquist frequency. Significant interference and noise appeared, apparently as a result of reduced bit-length in a program that was applied in analyses.

For hardware realization at the first stage of anti-aliasing filtration IIR Czebyszew type II, order 8th filter was chosen. It features a cutoff frequency of 0.2 Nyquist frequency. This selection was made due to the most favorable bit-length required for recording of filter coefficients (A-18 bits, B-20 bits) in the PUD device.

LITERATURE

[1] Jamro E., Adamczyk, A., Krzyworzeka, P., Cioch, W.: *Programowalne urządzenie diagnostyczne stanów niestacjonarnych pracujące w czasie rzeczywistym*, XXXIII Ogólnopolskie Sympozjum Diagnostyka Maszyn, Węgierska Górka, 8.-11.03. 2006 r.
[2] Krzyworzeka P., Cioch W., Jamro E.: *Dokładność przybliżonej analizy drgań maszyn w stanach niestacjonarnych*, Polskie Towarzystwo Diagnostyki Technicznej, Diagnostyka'4 (40)/2006.
[3] Krzyworzeka P., Cioch W., Jamro E.: Hardware abilities of Linear Decimation Procedure in practical applications. Journal of POLISH CIMAC, Diagnosis, Reliability and Safety, vol. 2, No 2, Gdańsk, 2007.
[4] Majewski J., Zbysiński P.: *Układy FPGA w Przykładach*, Wydawnictwo BTC, Wydanie I, Warszawa, 2007.
[5] Shehata S., Meiner J.: *Optymalization Technique for FIR and IIR Filter Design*, San Jose, California, US 2006/0218213 A1, Sep. 28,2006.
[6] Skahill K.: *Język VHDL Projektowanie Programowalnych Układów Logicznych*, Wydawnictwo Naukowo Techniczne, Wydanie II, Warszawa, 2004.
[7] Smith S. W.: *Cyfrowe Przetwarzanie Sygnałów: Praktyczny poradnik dla inżynierów i naukowców*, Wydawnictwo BTC, Wydanie I, Warszawa, 2007.
[8] Yamazaki T.: *IIR Digital Filter*, Kanagawa, Japan, United State Patent, Patent Number 4, 751,663, Jun. 14,1988.
[9] Zieliński T. P.: *Cyfrowe Przetwarzanie Sygnałów: od teorii do zastosowań*, Wydawnictwo Komunikacji i Łączności, Wydanie II, Warszawa, 2007.

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DIAGNOSTICS OF VESSEL POWER PLANTS

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Summary
In this paper, the problems of diagnostics of main propulsion marine engines are presented. Piston or turbine engines are used for main propulsion of vessel power plants. Diesel engine diagnostic systems of merchant vessel engines are discussed. Finally, description of diagnostic methods implemented in turbine and piston engines in Polish Navy ships are introduced.

Keywords: technical diagnostics, piston engines, gas turbine engines, vessel power plants.

DIAGNOSTYKA OKRĘTOWYCH SIŁOWNI SPALINOWYCH

Streszczenie
W referacie przedstawiono problematykę diagnozowania okrętowych silników napędu głównego. Silnikami tymi mogą być tłokowe lub turbinowe silniki spalinowe. Omówiono stosowane systemy diagnostyczne silników statków handlowych. Przedstawiono także opis metod diagnostycznych w zbudowanych systemach diagnozowania silników tłokowych i turbinowych okrętów Polskiej Marynarki Wojennej.

Słowa kluczowe: diagnostyka techniczna, tłokowe silniki spalinowe, turbinowe silniki spalinowe, siłownie okrętowe.

1. OPERATING CONDITIONS OF MARINE ENGINES

Marine internal combustion engines operate under specific conditions which have a considerable influence on their characteristics change and can cause their increased wear and even failure.

Marine engines run in constant rolling conditions. Although rolling does not directly affect the characteristic change it can cause systematic wear of engine components i.e. bearings.

Most components of control systems and ship engine safety systems are related to fuel system. These installations require high purity of fuel which can constitute a serious problem on board vessels due to the possibility of water getting into fuel. Polluted fuel can cause engine start up problems, deterioration of load changes and can prevent proper work of control systems because of the structure change in relation to particular elements of automatic systems.

Fuel contamination with water can occur in ship conditions and can cause the wear of bearing units, which can not be repaired on board vessels.

2. ENGINE TECHNICAL CONDITION IDENTIFICATION – PARAMATERS NUMBER REDUCTION

Type and number of technical parameters that require assessment without disassembling can affect diagnostic method and indirectly influence the costs of a diagnostic system. The most numerous are the engine construction parameters which are as follows:

– components dimensions in their wear areas;
– clearances;
– condition of working surfaces and their wear geometry;
– assembly and adjustment settings;
– cleanness of heat exchange surfaces and flow of working medium ducts;
– parameters characterizing static connections condition (bolts tension etc.).

The parameters that characterize the quality of lubricating oils, fuel, cooling water should be included in the set of engine technical condition parameters. Engine technical condition parameters with their graphic values and the frequency of overhauls and checks are given in operating manuals by the manufacturers. It appears that the number of engine technical condition parameters is about 50 only for one section of medium speed engine Sulzer type AL 20/24 for instance. If this number is multiplied by the number of cylinders and they are added to parameters characteristic for the whole engine, its machinery and systems – the total number will be enormous and as a result the task of technical condition evaluation without disassembly will practically be impossible. In marine engine diagnostics the evaluation without disassembly of most of these parameters is rejected and attention is paid to the most relevant parameters from the point of view of engine reliability, economical work and cost effective operation. Therefore each engine is divides into particular functional, trybological units [3].

One of the methods used for further limitation of the number of engine technical condition parameters is to determine the leading parameter considering the intensity of changes due to wear. For example it is possible to limit technical condition assessment to the upper compression ring in piston engine, which was adapted by Sulzer diagnostic system SIPWA.

In that case it was reasonably assumed that the wearing intensity of the remaining compression rings will be lower. However it is not always possible to determine a leading parameter or apply this method for other reasons.

Classical determination of engine technical condition is very often rejected and is related to symptomatic parameters of technical condition changes.

The change in reproduction level of technical condition evaluation requires proper testifying documents. Otherwise it will not be approved by ship owners, and especially be classification societies. However it not easy to achieve classification societies approval of a new diagnostic method and measurement system as a substitute for a traditional overhaul with disassembly.

3. DIAGNOSING PISTON ENGINES OF VESSELS MAIN PROPULSION PLANT

Marine engine is a complex technical object. For the purpose of diagnostics it is convenient to divide the engine into several units – subsystems such as: piston –crank assembly; working medium exchange system, fuel supply system, lubricating system, cooling system, starting up – reversing system; combustion chamber (Fig. 1).

The organization of the marine engine diagnostic process can usually come down to two stages, general diagnostics and damage location. The task of general diagnostics is to categorize the engine as one of the two states of being operable or inoperable. In case of an inoperable engine, the second diagnostic stage is to be carried out to define the reason of the ensuing situation [5]. Defining the reason is necessary to outline the range of service activities. Decomposing the engine into particular functional systems allows to determine and develop diagnostic methods in relation to particular engine systems.

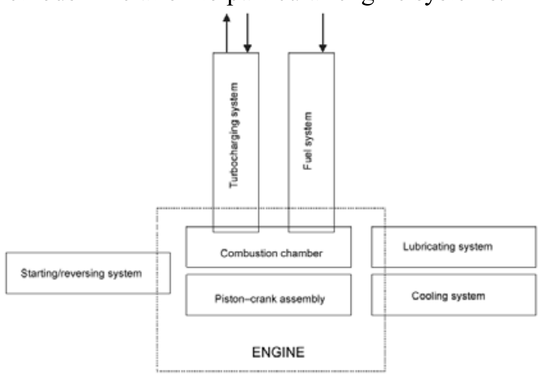

Fig. 1. Engine division into functional sub systems.

3.1. Examples of diagnosing marine piston engines

Contemporary engine diagnostic systems can be divided into two basic groups. The first one comprises systems offered by the greatest marine engines manufacturers such as MAN Diesel, Wartsilia and Mitsubishi. These are usually complex systems assisting marine engine room management. Apart from evaluating engine condition these systems are responsible for managing overhauls, service activities, and spare parts store [6]. The second group forms diagnostic systems created by the producers of measuring equipment and ship automation. It is dominated by the so called MIP (Mean Indicated Pressure) calculators that enable measuring pressure changes in a cylinder which in turn is the basis for defining parameters connected with the combustion process. They are often equipped with the ability to measure extra parameters such as injection pressure or supercharging air pressure and temperature. Besides the above mentioned MIP calculators, it is also possible to come across complex systems enabling the operation evaluation of piston-cylinder assembly or engine main bearings for instance.

The most representative and well known diagnostic systems in shipping are :

1. "Data Trend" system by Norcontrol [7], which on the basis of parametric method of diagnosing allows to evaluate the technical condition of piston-cylinder assembly, supercharging system, engine injection system as well as waste heat boiler.
2. CC-10 system by B&W [8] built for technical condition control of main propulsion system. The CC 10 system monitors:
   - cargo handling system;
   - piston-cylinder assembly;
   - injection system;
   - auxiliary mechanisms supporting the engine.
3. SEDS system by Sulzer [9] created to monitor and diagnose marine main propulsion engines. The system takes measurements of a dozen parameters and then enables quick access to their results as well as to the visualization of parameters measured.
4. Comos and DMTAS systems of MITSUBISHI [10, 11] service main propulsion engines and auxiliary engines. Parameters are measured systematically and are compared to their model values. The trend analysis of these parameters is also carried out.

So far the most popular in marine engine diagnostics have been the periodic run analyzers, called pressure analyzers ,electronic indicators or MIP (Mean Indicated Pressure) calculators. They are built as stationary or portable. Such devices are utilized for measurement, digital record and visualization of combustion pressure graph and fuel injection in the function of crankshaft rotation angle at established working conditions of a marine engine. The most important elements of this electronic indicator are : sensors for combustion pressure and fuel injection, the sensor of crankshaft position and piston top dead centre (TDC), as well as signal amplifiers, analogue to digital converters and microprocessor central unit (computer). A well known analyzer is MIP Calculator NK-100 produced by Autronica [12].

3.2. CoCoS system by MAN Diesel

CoCoS system belongs to the most complex contemporary systems for diagnosing marine engines.

It was designed as modular expert system whose aim was the complex management of engine operation. It is composed of the following modules:

- CoCoS-EDS (Engine Diagnostic System) – a subsystem for supporting diagnostics;
- CoCoS-SPC (Spare Parts Catalogue) – an electronic catalogue of spare parts;
- CoCoS-MPS (Maintenance Planning System) – a subsystem to support planning the repairs and service activities;
- CoCoS-SPO (Stock Handling and Spare Parts Ordering) – to support the process of managing the spare parts store.

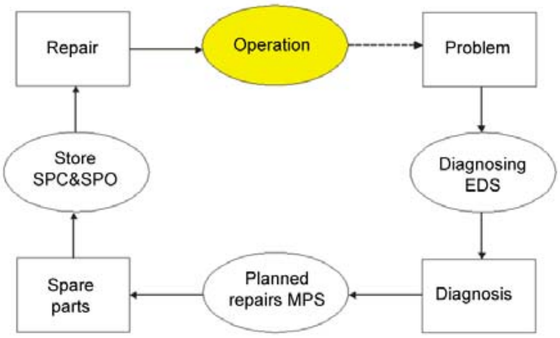

Fig. 2. CoCoS system configuration.

All modules of CoCoS system can cooperate by an application called CoCoS shell or they can work independently. The configuration of particular elements and their possibilities of cooperation was shown in Figure 2.

In case of a problem the diagnosis is performed by EDS module. The information of the engine condition is then used to plan service activities or repairs and to define required spare parts. With the help of SPC and SPO modules it is possible to check the stores or, alternatively, to order spare parts indispensable for carrying out repairs. The basis of system competence contains manufacturer's long experience gathered during design process, production and operation. EDS makes it possible to archive information and to monitor and analyze parameters recorded during operation. The diagnostics has been worked out on the basis of in-operational condition symptoms.

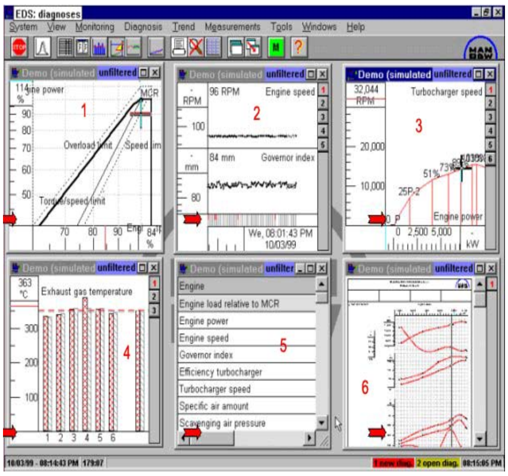

Fig. 3. Monitoring parameters In CoCoS-EDS module.

CoCoS system performs detection of engine damages such as filters wear and fouling but also detection of measuring sensors damages. CoCoS-EDS enables among other things , monitoring engine condition by measurement of working parameters and comparing them with model values. Figure 3 presents chosen possibilities of engine parameters analysis (1 – engine running area with current running point, 2 – engine speed and load factor time graph, 3 – turbocharger speed in the function of engine horse power, 4 – exhaust gases temperatures on particular cylinders, 5 – values of selected engine parameters, 6 – general engine characteristics).

4. DIAGNOSING NAVY VESSELS POWER PLANTS

Appropriate engine type application results from the power required for the propulsion and its dimensions, taking into account its reliability and its susceptibility to diagnosis. Piston engines used in naval vessels power plants work in multi-shaft and multi-engine systems. The engines are of compact design, with high thermal loads and high degree of automation. Due to such requirements these engines are generally built in V and "star" arrangements with the number of cylinders reaching 56 or even 112 in blocked systems. Utilization of three or four engines in propulsion plants considerably complicates the engine room and gives the crew high requirements in the operation process and simply demands the application of diagnostic systems.

4.1. Pressure and vibration curves analyzers

Up till now , the periodic runs analyzers have been commonly used in marine engines diagnostics. They are designed to measure combustion pressure graphs and to determine their basic parameters and usually serve to measure and define pressure changes in injection pipes. The most well known and commonly used pressure analyzer is the one produced by Autronica. The microcomputer analyzer of periodic graphs was also developed in the Institute of Ship Technical Operation at Gdynia Naval University (GNU) [4, 5].

Cpt Stanislaw Polanowski was the concept creator and the author of the methodology of piston engines diagnosing which was introduced on Polish Navy vessels.

These are devices designated to measure, visualize and digitally record combustion pressure changes, injection and vibration curves in the function of crankshaft rotation angle at established engine working conditions. For that purpose the analyzer was provided with three 12 bit (100kHz) channels of analogue to digital converters.

The software for the analyzers makes it possible to accept any measuring configuration of the above mentioned values, for example setting to measure vibrations curves in all channels. Therefore the analyzer is suitable for diagnosing both marine powerful engines and car engines.

Sampling is based on angle axis impulses of $0,1^{o}$OWK for n<1600 min^{-1} resolution. The runs are made average by the number of engine working cycles: 4, 16, 64 set by the operator.

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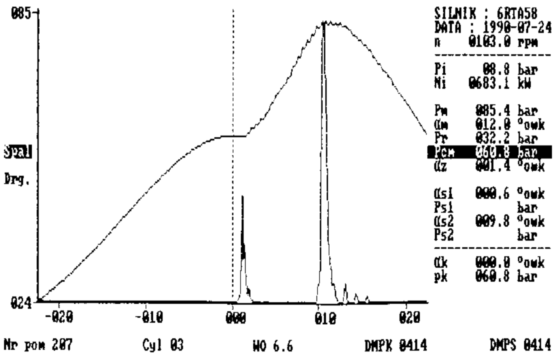

Fig. 5. Pressures recorded in cylinder and the vibrations curves with the use of GNU indicator.

The analyzer also performs the function of an automatic calculator of mean indicated pressure, the automatic gauge of basic parameters in a developed indicator graph and the engine speed meter.

Analyzers of this type apart from being utilized in piston engines diagnostics on navy vessels, were also applied in diagnosing engines on natural gas pumping. They were also installed on four merchant vessels built by Gdynia shipyard for a French ship owner.

5. DIAGNOSING MARINE TURBINE ENGINES

Marine turbine engine operation requires professional technical supervision. This requirement can not be fulfilled by crews on small vessels of our Navy. Therefore, taking into account the level of crews competence in operating modern vessels with turbine engines, a concept of supporting ship crews by creating "Basic diagnostic system for turbine engines" was put forward in 1985 [1, 2]. This system was designed to carry out periodic inspection of technical engine condition, and particularly in case of:

- annual overhaul;
- prolongation of the period between repairs;
- identification of abnormalities in engine running found out by the crew during operation.

The basic diagnostic system is able to assess the current engine condition and give forecast concerning its future operation in a complex way with the use of computer technology. Working out operating decision was based on proper preparation of operational parameters which were processed in a computer according to defined algorithms.

It was assumed that the diagnostic information for creating basic diagnostic system would be collected:

- systematically – form the ship operating documentation (engine log book);
- periodically – with the use of automatic recording device;
- periodically – by examining special parameters characterizing engine condition, i.e. endoscope inspection, recording start up process etc.;
- periodically – based on interviews and experts opinions.

The basic diagnostic system allowed to accomplish the following tasks:

a) detection of engine condition in danger of failure or catastrophe;
b) diagnosis of technical condition of measuring – inspection equipment;
c) carrying out current evaluation of engine characteristics , the level of its fouling and consequently determining the necessity of flow track flushing;
d) organizing engine operation data base for each engine and vessel and forecasting changes of engines technical conditions.

The system configuration is based on the experience of plane turbine engines operation where computer records, examinations methodology and data base constitute original development [2].

To complete all tasks that ensure proper turbine engine operation the diagnostic system is equipped with the following specialized devices:

a) vibrations measuring device;
b) station for checking oil for metallic particles;
c) engine parameter measurement computer set during start up and shut down;
d) engine parameter measurement computer set at constant running;
e) engine parameter measurement computer set in transient stages;
f) fast –changing signal analyzer;
g) endoscope;
h) laser gauge of shafts coaxiality evaluation;
i) testers for checking the indications regularity of measuring – inspection equipment and engine protections;
j) computer data base.

This diagnostic system was introduced on board Navy vessels and was used to diagnose all types of Navy turbine engines. The system was highly appraised by engine manufacturers due to considerable improvement of engine operation which was observed by engine condition evaluation during periodic overhauls at the manufacturer's. Over 20 years of system operation it was demonstrated that the concept adapted was correct and so novel that it has been used up till now with the same methodology.

6. SUMMARY

- The diagnosis of piston and turbine engines has been carried out on Polish Navy vessels since 1986 on the basis of the worked out methodology and diagnostic systems.
- At present there are several methods and systems for diagnosing engine technical condition that are being developed by both research centers and by producers of engines and measuring equipment.
- Contemporary marine piston engine diagnostic systems can be divided into two groups. The first one is made up by the co called calculators of mean indicated pressure (MIP Calculator). The second group comprises systems that additionally enable diagnosing the piston-rings-liner assembly.
- In spite of the obvious benefits of using piston engines diagnosing systems, their application on board vessels is still limited due to high costs and the lack of data related to real economic advantages of their utilization.

BIBLIOGRAPHY

[1] Charchalis A.: *Diagnozowanie okrętowych siłowni spalinowych.* Inżynieria Diagnostyki Technicznej. Żółtowski B., Cempel Cz. (red.), Instytut Technologii Eksploatacji PIB, cz. III, rozdz. 9, Radom 2004.
[2] Charchalis A *Nadzór eksploatacyjny siłowni z turbinowymi silnikami spalinowymi* Problemy Eksploatacji nr 4/2001.
[3] Charchalis A.: *System diagnostyczny okrętowych turbinowych silników spalinowych*. Przegląd Mechaniczny Warszawa 1993, nr 1 s. 4-5.
[4] Polanowski S.: *Diagnostyka techniczna okrętowych tłokowych silników spalinowych*. Zeszyty Naukowe AMW 1991 nr 3.
[5] Polanowski S *Studium metod analizy wykresów indykatorowych w aspekcie diagnostyki silników okrętowych* Zeszyty naukowe AMW nr 109A Gdynia 2007.
[6] Witkowski K.: *Stan diagnostyki technicznej okrętowych silników tłokowych*, Diagnostyka Vol. 34, 2005 r.
[7] Foyen A.: *Aspects of condition monitoring andmaintenance of machinery*. Norvegian Shiping News, 1977, No11C.
[8] Ostergard A., Fisher P.: *B&W condition check system CC-10 for 2-storke K-GF diesel engines.* Proceeding of 2-nd IFAC/IFIP Symposium, Washington 1976.
[9] Berle M.: *Diagnostic system for diesel engines*. Sulzer Technical Review, No 7, 1976.
[10] Chikao Furukawa, Takamasa Matsuo: *Condition monitoring &data loading system (Comos D2),* Bulletin of the Mar. Soc., Japan 1980.
[11] Rinichi Sagawa, Yonichi Nakamura: *Devolopment of new diagnosis and trend analysis system for marine diesel engine,* Bulletin of the Mar. Eng. Soc., Japan 1980, vol. 8.
[12] *MIP-Calculator NK-100*. Technical Information. Autronica.

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ZASTOSOWANIE SZTUCZNEJ INTELIGENCJI DO IDENTYFIKACJI TYPOWYCH USZKODZEŃ WTRYSKIWACZY SILNIKÓW OKRĘTOWYCH

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Streszczenie

W artykule przedstawiono możliwość wykorzystania sztucznej inteligencji do identyfikacji uszkodzeń wtryskiwaczy silników okrętowych. W tym celu zastosowano sieci neuronowe, pakiet analityczny wykorzystujący współczesną technologię.

Na podstawie symulowanych komputerowo, stopniowanych relacji cechy stanu technicznego wtryskiwaczy – przebieg ciśnienia w przestrzeni wtryskiwacza, poddano sieci neuronowe procesowi uczenia. Po procesie uczenia podjęto próbę rozpoznawania symulowanych różnych stanów technicznych zdatności i niezdatności z pojedynczymi i łącznymi uszkodzeniami.

Słowa kluczowe: silniki okrętowe, sieci neuronowe, identyfikacja uszkodzeń wtryskiwaczy.

THE APPLICATION OF ARTIFICIAL INTELLIGENCE TO IDENTIFICATION OF TYPICAL DAMAGES OF MARINE DIESEL ENGINES INJECTORS

Summary

In article have been presented of usability artificial intelligence to identification of damages of the marine diesel engines injectors. To his end have been application neural networks, analytic packet that utilized of present processes engineering.

On the base computer simulated, stopped relations features of technical state of injectors – course of pressure in injector in injector space, have been subjected the neural networks to learning process. Past learning process has been attempted recognition simulated of different technical up states and disability with single and total damages.

Keywords: marine diesel engines, neural networks, identification damages of injectors.

1. WSTĘP

Jednym z najbardziej zawodnych elementów silnika okrętowego jest wtryskiwacz, dlatego jest on szczególnie objęty diagnozowaniem [2, 6, 12]. Współczesne systemy diagnozujące oprócz diagnozy właściwej umożliwiają jeszcze prognozowanie i genezowanie [12]. Tak, więc oprócz lokalizacji uszkodzenia istotne jest zidentyfikowanie rodzaju uszkodzenia. Przez identyfikację elementów należy rozumieć przyporządkowanie im informacji o ich własnościach [1].

W pracy podjęto, zatem próbę identyfikacji uszkodzeń zawodnego wtryskiwacza na podstawie symulowanych komputerowo zmian jego stanu technicznego i wpływu na przebieg ciśnienia we wtryskiwaczu. Rozpoznawanie pojedynczych i łączonych wybranych zmian cech stanu technicznego podjęto z wykorzystaniem sztucznych sieci neuronowych.

2. DOTYCHCZASOWE METODY ROZPOZNAWANIA USZKODZEŃ

Identyfikacja występujących uszkodzeń możliwa jest między innymi przy wykorzystaniu teorii rozpoznawania obrazów [2, 8, 9, 10, 12]. Stosowane są probabilistyczne i deterministyczne metody rozpoznawania [10, 12].

W pracy [11] przedstawiono metodę diagnozowania spalinowego silnika okrętowego na podstawie odległości od wzorca z zastosowaniem metrycznych metod rozpoznawania.

Wykorzystano również sztuczne sieci neuronowe do diagnozowania obiektów technicznych [12 rozdz. 22] oraz diagnozowania sterowania silnika spalinowego [8]. Sztuczne sieci neuronowe zbudowane są z neuronów na wzór neuronów biologicznych [3]. Sztuczny neuron jest to przetwornik, w którym sygnały wejściowe są mnożone przez współczynniki wag. Następnie sygnały są sumowane i generowany jest sygnał wyjściowy w bloku sumowania.

Sztuczne sieci neuronowe wykorzystywano do diagnozowania wybranych niezdatności okrętowego silnika spalinowego [7] oraz do klasyfikacji stanu aparatury wtryskowej [2].

3. METODA I WYNIKI BADAŃ

3.1. Symulowane stany techniczne wtryskiwacza

W celu identyfikacji uszkodzeń potrzebna jest znajomość występujących rodzajów zużycia i uszkodzeń, którym one ulegają. Na rys. 1

przedstawiono elementy wtryskiwacza wraz z przyczynami ich zużycia bądź uszkodzenia.

Badania symulowane na modelach obiektów rzeczywistych nie tylko zmniejszają koszty badań eksperymentalnych, ale również pozwalają na analizowanie wyizolowanych uszkodzeń, co w rzeczywistości mogłoby napotkać na wiele trudności. W tej pracy ograniczono się jedynie do analizy wpływu następujących parametrów wtryskiwacza:

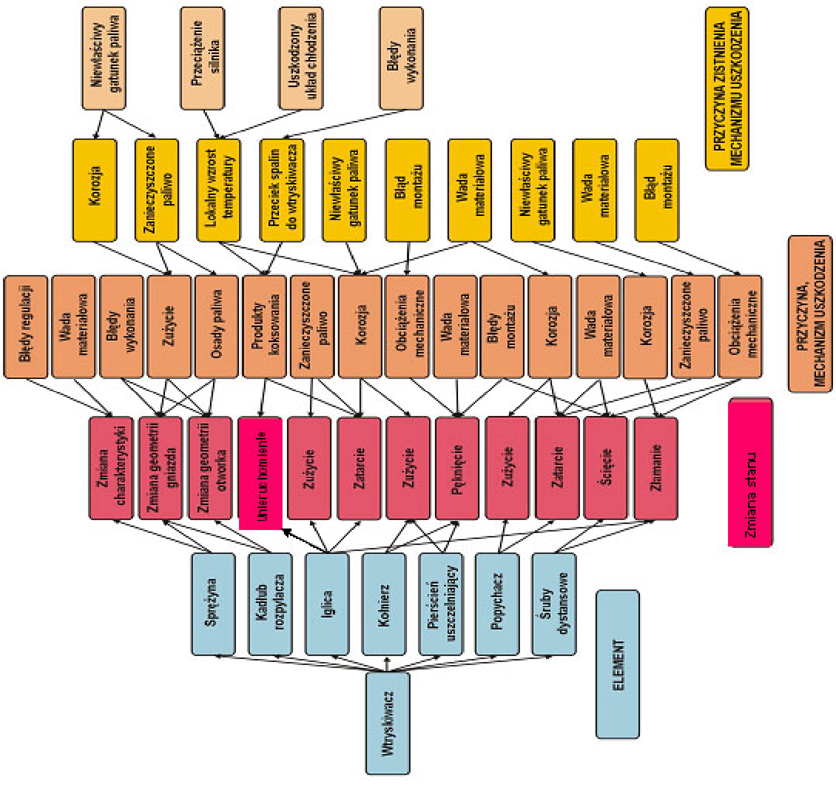
- zmiany ciśnienia otwarcia iglicy wtryskiwacza w zakresie 35÷41 MPa;
- zmiany liczby drożnych otworków w rozpylaczu;
- zmiany średnicy otworków rozpylających.

Symulacje zostały przeprowadzone dla silnika AL20 pracującego ze stałą prędkością obrotową n = 750 obr/min, przy maksymalnym wychyleniu listwy paliwowej. Symulacje te polegały na zmianie jednego parametru (cechy stanu), przy czym pozostałe dwie analizowane cechy stanu miały stałe, niezmienne wartości znajdujące się w polu tolerancji dla badanego modelu.

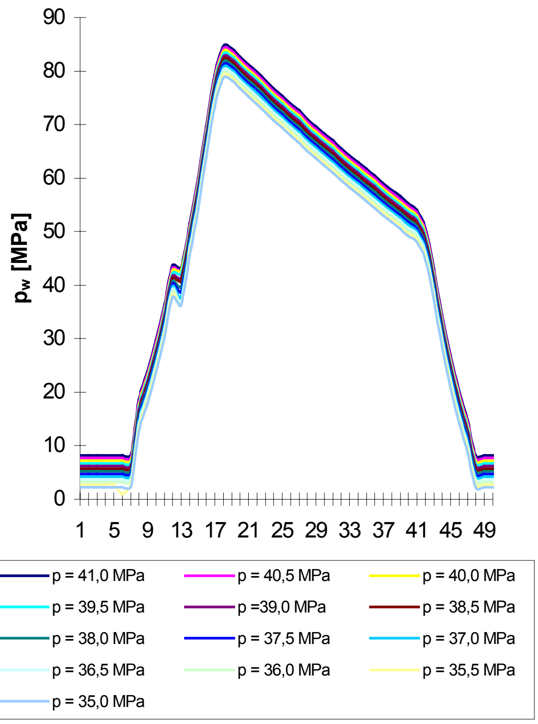
Zmiana ciśnienia otwarcia wtryskiwacza wpływa na cały przebieg procesu wtrysku. Im ciśnienie otwarcia jest wyższe, tym szybciej następuje wypływ paliwa, i tym większa jest wartość ciśnienia w przestrzeni wtryskiwacza. Z kolei spadek ciśnienia otwarcia powoduje późniejszy wtrysk paliwa do komory spalania, niższe ciśnienie procesu wtrysku wiąże się dodatkowo z gorszym rozpyleniem paliwa. Do stanu zdatności przypisano przebiegi o ciśnieniu otwarcia 40 MPa oraz 40,5 MPa (rys. 2).

3.2. Przygotowanie danych dla modelu sieci neuronowej

Właściwa interpretacja uszkodzeń wtryskiwacza przez model sztucznej sieci neuronowej uzależniona jest od umiejętności rozpoznawania przez nią charakterystycznych symptomów niezdatności. Utworzono w tym celu zestawy składające się z różnych wariantów pojedynczych zmian cech stanu, przy zachowaniu stałych w stanie zdatności pozostałych..



Rys. 1. Schemat postaci i przyczyn uszkodzeń elementów wtryskiwacza



Rys. 2. Wpływ ciśnienia otwarcia wtryskiwacza p na wartości przebiegu ciśnienia w przestrzeni wtryskiwacza p_w w zależności od kąta obrotu wału rozrządu α_w

Uwzględniono jednak także wpływ uszkodzeń łączonych. Ciśnienie we wtryskiwaczu zależne jest od następujących cech stanu i regulacyjnych:

$$p_w = f(p, i, d, N, n) \qquad (1)$$

gdzie:

p – wartość ciśnienia otwarcia wtryskiwacza;
i – liczba drożnych otworków;
d – wartość średnicy otworków rozpylacza;
N – nastawa paliwowa,
n – prędkość obrotowa wału korbowego.

Wartości regulacyjne utrzymano na stałym poziomie (N, n), a cechy stanu zmieniano. Przyjęto, że dla niezdatności wymienione cechy stanu przyjmują wartość „1", natomiast gdy mieszczą się one w polu tolerancji to przyjmują wartość „0". Przygotowano dwa zestawy uszkodzeń po 11 przebiegów ciśnienia paliwa przepływającego przez wtryskiwacz. Pierwszy zawierał jedynie pojedyncze uszkodzenia, tj. uwzględniał następujące cechy stanu:

– (0, 0, 0) – 11 różnych przebiegów ciśnienia w przestrzeni wtryskiwacza, w których wszystkie cechy stanu mieściły się w polu tolerancji;
– (1, 0, 0) – niewłaściwe ciśnienie otwarcia wtryskiwacza;
– (0, 1, 0) – liczba drożnych otworków mniejsza od 9;
– (0, 0, 1) – średnica otworków nie mieszcząca się w polu tolerancji.

Drugi zestaw składał się dodatkowo z łączonych postaci uszkodzeń, to znaczy swym zakresem obejmował również:

– (1, 1, 1) – niezdatność ze względu na niewłaściwe ciśnienie otwarcia wtryskiwacza, liczbę drożnych otworków oraz przekroczenie tolerancji średnic otworków rozpylających;
– (0, 1, 1) – niezdatność w wyniku zmiany liczby drożnych otworków oraz przekroczenia tolerancji średnic otworków rozpylacza;
– (1, 1, 0) – uszkodzenie spowodowane zmianą ciśnienia otwarcia wtryskiwacza oraz zmianą średnic otworków;
– (1, 0, 1) – uszkodzenie w wyniku przekroczenia tolerancji ciśnienia otwarcia wtryskiwacza, a także w wyniku zmiany liczby drożnych otworków rozpylacza.

Wartości przebiegu ciśnienia przepływającego paliwa w przestrzeni wtryskiwacza zostały obliczone dla każdego stopnia obrotu wału rozrządu w zakresie 1÷50°. Dla wszystkich wyróżnionych przypadków w tych badaniach obliczono je na podstawie zależności zawartych we wcześniejszej pacy autora [5].

Pierwszy zestaw składał się z 44 przebiegów, co dało 2200 wyników obliczeń. Drugi zestaw obejmujący nie tylko pojedyncze uszkodzenia, ale i łączone niezdatności, zawierał 8 różnych przypadków po 11 przebiegów dla wszystkich 50° obrotu wału krzywkowego, co dało w sumie 4400 wartości ciśnienia w przestrzeni wtryskiwacza.

Oba zestawy przypadków zostały dodatkowo podzielone na dwa zespoły składające się ze zbiorów:

– zbiór uczący (ZU) uwzględniający zmiany przebiegu ciśnienia w przestrzeni wtryskiwacza, w zależności od stanu technicznego modelu i przypisano je do konkretnych klas;
– zbiór walidacyjny (ZW), który miał za zadanie nie dopuścić do przeuczenia się sieci, służył również do monitorowania samego procesu uczenia sieci;
– zbiór testujący (ZT), składający się z przypadków nie ujętych w poprzednich zbiorach, ten z kolei miał na celu sprawdzenie skuteczności identyfikacji stanu technicznego przez sztuczną sieć neuronową.

3.3. Automatyczny projektant sieci

Neuronowe modele diagnozowania stanu technicznego wtryskiwacza zostały zbudowane przy użyciu automatycznego projektanta sieci programu *Statistica Sieci Neuronowe* (*Neural Networks*), rozbudowanego pakietu analitycznego do sieci neuronowych.

Wykorzystując automatycznego projektanta sieci przetestowano następujące typy sieci:

- liniowe – złożone z 2 warstw neuronów,
- probabilistyczne (Probabilistic Neural Networks – PNN),
- sieci o radialnych funkcjach bazowych (Radial Basis Functions – RBF),
- perceptron trójwarstwowy (Multilayer Perceptron MLP3),
- perceptron czterowarstwowy (MLP4).

Automatyczny projektant przetestował 100 różnych architektur sieci o różnorodnym stopniu złożoności, dla każdego z powyżej wymienionych typów sieci. Następnie spośród nich wybrał 5 (opcjonalnie), w których osiągnięto najlepsze wyniki. Analizie poddano oba zestawy przypadków. Wszystkie sieci zostały zbudowane pod kątem klasyfikacji, to znaczy, że zadaniami sieci było zakwalifikowanie badanych przypadków do wcześniej opisanych klas w rozdziale 3.2.

3.4. Wyniki badań

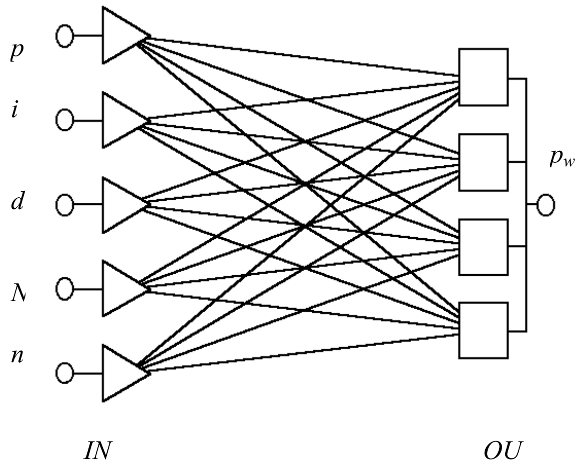
Dla każdego rodzaju wymienionych sieci wykonano 3 analizy przy pomocy automatycznego projektanta. Dla pierwszego zestawu uszkodzeń i sieci liniowych przykładowe wyniki obrazuje tabela 1. Program prezentował wyniki do 6 cyfr, które zaokrąglano do 3 lub 4 cyfr znaczących.

Najlepsze wyniki osiągnięto dla sieci nr 5: 5:5-4:1. Zapis ten oznacza 5 wykorzystanych sygnałów wejściowych (26÷30ºOWK) i jeden wyjściowy. Sieć składała się z 5 neuronów w pierwszej warstwie i czterech neuronów w warstwie wyjściowej (rys. 3.)

Analiza sieci probabilistycznych (PNN) wykazała, że najlepszą siecią okazała się sieć o 41 wejściach składająca się z 41 neuronów w warstwie wejściowej, 18 neuronów w warstwie ukrytej, oraz czterech neuronach w warstwie wyjściowej.

Dla sieci neuronowych o radialnych funkcjach bazowych (sieci RBF) uzyskano najlepsze wyniki dla sieci 3:3-2-4:1.

Najlepszą siecią z grupy sieci liniowych okazała się sieć 2:2-8:1, złożona z dwóch neuronów na wejściu (19 oraz 32ºOWK) oraz 8 neuronach na wyjściu.



Rys. 3. Sieć liniowa 5:5-4:1: *IN* – warstwa wejściowa, *OU* – warstwa wyjściowa; *p, i, d, N, n* – wymuszenia wejściowe, p_w – odpowiedź sieci

Dla sieci PNN najlepszą siecią jest sieć 12:12-43-8:1. Dla sieci RBF ukazano najlepsze wyniki osiągnęła się sieć 41:41-1-8:1, która posiadała na wejściu 41 neuronów, w warstwie ukrytej jeden oraz w wyjściowej 8.

Dla perceptronu trójwarstwowego najlepszą dla tego typu sieci była sieć złożona z 27 neuronów w warstwie wejściowej, 41 neuronów w warstwie ukrytej oraz ośmiu w wyjściowej 27:27-41-8:1.

Dla perceptronu czterowarstwowego najlepsze rezultaty z tego zbioru uzyskała sieć 31:31-41-41-8:1. Sieć ta składała się z 31 neuronów w warstwie wejściowej, dwóch warstw ukrytych po 41 neuronów każda, 8 neuronów w warstwie wyjściowej.

3.5. Analiza i interpretacja wyników badań

Jakość uczenia, walidacji oraz testowania mówi o liczbie poprawnie zaklasyfikowanych przypadków i wyrażana jest procentem dla właściwie zidentyfikowanych cech stanu (rozdz. 3.2)

Tabela 1. Wyniki badań dla sieci liniowych

L.p.	Typ	Jakość uczenia	Jakość walidacji	Jakość testowania	Błąd uczenia	Błąd walidacji	Błąd testowania
1	16:16-4:1	0,278	0,444	0,333	1,378	1,149	1,228
2	15:15-4:1	0,444	0,111	0,222	1,020	1,122	0,862
3	13:13-4:1	0,500	0,556	0,444	0,853	0,959	0,635
4	7:7-4:1	0,722	0,556	0,444	0,418	0,880	0,472
5	**5:5-4:1**	**0,444**	**0,778**	**0,444**	**0,414**	**0,350**	**0,486**

Przy podejmowaniu decyzji, której sieci użyć, zaleca się brać pod uwagę błąd walidacji. Błąd uczący nie określa zdolności sieci do poprawnej klasyfikacji w przypadku nowych danych (przebiegów), błąd testowy pomocny jest jedynie przy diagnozowaniu problemów związanych z uczeniem sieci. Jeżeli wartość błędu testowego odbiega mocno od błędu walidacji i uczenia to świadczyć może albo o nielosowym wymieszaniu zbiorów: uczącego, walidacyjnego, testującego, albo o zbyt małej liczbie przypadków. Właściwym do oceny skuteczności działania sieci był błąd walidacji oraz jakość walidacji, na podstawie tych wartości wybierano najlepsze sieci w rozdziale 3.4.

Do dalszej analizy obliczono średnią arytmetyczną S, dla jakości uczenia, walidacji, testowania, a także dla błędu uczenia, walidacji oraz testowania. Wyliczono go dla poszczególnych rodzajów sieci, na podstawie wzoru:

$$S = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad (2)$$

Następnie obliczono odchylenie standardowe wyrażone wzorem:

$$\sigma = \sqrt{\frac{1}{n-1}(x_n - S)^2} \qquad (3)$$

Współczynnik zmienności obliczono ze wzoru:

$$V = \frac{\sigma}{S} \qquad (4)$$

Wyliczone współczynniki zmienności pozwoliły na zobrazowanie rozrzutu wyników między testowanymi sieciami. Dla drugiego zestawu przedstawiono na rys. 4.

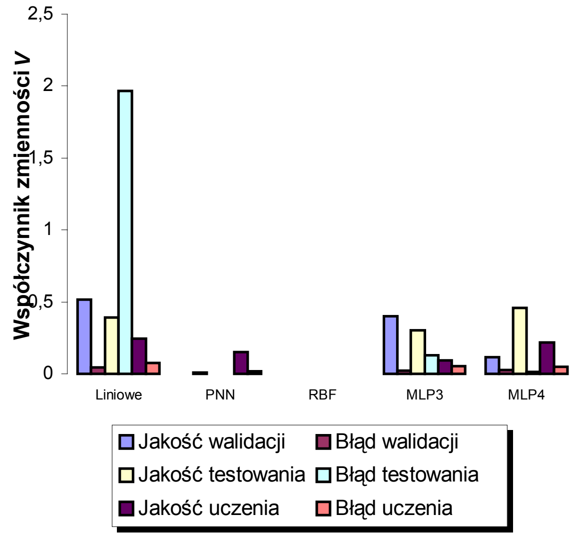
Dla pierwszego zestawu wariantów najmniejszy rozrzut błędów oraz jakości uzyskały sieci PNN, oraz MLP3. Największy natomiast rozrzut wykazały sieci liniowe, a także sieci MLP4.

Dla drugiego zestawu przypadków (rys. 5) rozrzut jakości oraz najmniejszy rozrzut błędów uzyskały sieci o radialnych funkcjach bazowych (RBF), następnie sieci probabilistyczne. Największy rozrzut wyników dotyczył sieci liniowych.

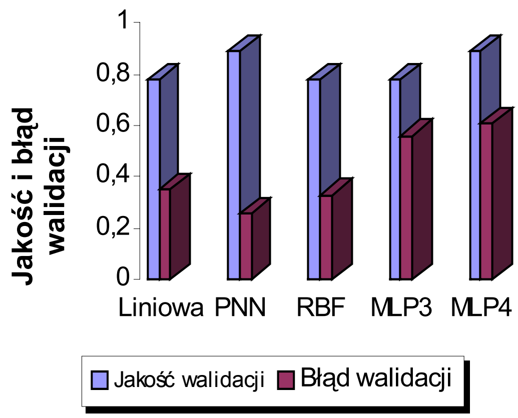
Sieci uzyskały zbliżoną umiejętność zaklasyfikowania cech stanu do właściwych typów, różniły się natomiast błędem walidacji. Największa różnica dotyczy tu sieci PNN oraz sieci MLP4.

Najlepszą siecią dla klasyfikacji przypadków zestawu pierwszego okazała się sieć probabilistyczna (PNN), w której uzyskano największą skuteczność oraz najmniejszy błąd.

Sieć MLP4 uzyskała identyczną jakość walidacji, różniły się natomiast błędem, który był dla niej znaczny. Zbliżony błąd miały pozostałe sieci rzędu 0,31.



Rys. 4. Współczynnik zmienności dla jakości i błędów dla drugiego zestawu przypadków



Rys. 5. Jakość i błąd walidacji dla najlepszych sieci przy 4 cechach stanu

4. PODSUMOWANIE

Sieci neuronowe mogą być pomocne w identyfikacji typów uszkodzeń w diagnostyce wtryskiwaczy silników okrętowych. W badaniach przeanalizowano 5 rodzajów sieci (liniowe, PNN, RBF, MLP3, MLP4) o zróżnicowanej budowie i wybrano sieci, które uzyskały najlepsze wyniki.

Klasyfikacja pojedynczych uszkodzeń wypadła najlepiej (pierwszy zestaw przypadków), przodowała tu sieć typu probabilistycznego, która jednocześnie osiągnęła najmniejszy błąd walidacji. Sieci identyfikujące 8 cech stanu (drugi zestaw przypadków) nie uzyskały dobrych wyników. Przyczyną tego mogło być:

– zbyt mała liczba przypadków;
– nielosowe wymieszanie zbiorów: uczącego, walidacyjnego, testującego;
– podobne przebiegi ciśnienia wtrysku, dla niezdatności łączonych.

Wartości przebiegów ciśnienia w przestrzeni wtryskiwacza dla uszkodzeń łączonych dla niektórych niezdatności były zbliżone, powodem tego było zwiększenie średnic przy jednoczesnej zmianie liczby drożnych otworków, co dawało podobne sumaryczne pole przekroju dla paliwa wypływającego przez otworki rozpylacza. Sprawiło to, że między innymi takie przebiegi były błędnie klasyfikowane.

Do badania sieci pominięto wartości ciśnienia szczątkowego, bowiem nie może to być miarą określenia typu uszkodzenia, o ile w tej symulacji osiągało ono wartość stałą, to w rzeczywistości jest ono zmienne w czasie.

Do analizy wykorzystywano przebiegi czasowe ciśnienia w przestrzeni wtryskiwacza. Wyniki dla identyfikacji pojedynczych uszkodzeń (3 rodzajów) były satysfakcjonujące. Przodowała sieć typu probabilistycznego (PNN), która osiągnęła najmniejszy błąd walidacji przy najmniejszej jakości. Sieć identyfikująca 8 cech stanów, przy 7 typowych uszkodzeniach, to jednak dla łączonych typów były nie akceptowalne. Przyczyną był podobny wpływ na przebieg ciśnienia w przestrzeniach wtryskiwaczy przez różne zmieniane cechy stanu. Należałoby przeanalizować więcej przypadków do ostatecznego zweryfikowania przydatności sieci neuronowych w diagnozowaniu wtryskiwaczy silników okrętowych.

LITERATURA

[1] Czajgucki J. Z.: *Niezawodność spalinowych siłowni okrętowych*. WM, Gdańsk 1984, s. 30.

[2] Jankowski M., Kwidziński M.: *Zastosowanie sieci neuronowej do automatycznej klasyfikacji aparatury wtryskowej*. Kongres Diagnostyki Technicznej. Gdańsk 1996. s. 312–318.

[3] Korbicz J. i in., *Sztuczne sieci neuronowe*. Oficyna Wydawnicza PWN, Warszawa 1994.

[4] Monieta J.: *Identyfikacja typów uszkodzeń wtryskiwaczy silników okrętowych*. Diagnostyka'99, ATR Bydgoszcz, Borówno 1999, cz. 2, s. 119–123.

[5] Monieta J.: *Model funkcjonalny wtryskiwacza średnio-obrotowego silnika okrętowego*. Journal of KONES 2007 Powertrain and Transport 2007 Vol 14, No 3, s. 423–428.

[6] Monieta J. *Problemy jakości wytwarzania wtryskiwaczy silników okrętowych typu AL20/24. Marine Technology 2000*. Szczecin–Dziwnówek 2000, s. 211–217.

[7] Pawletko R.: *Wykorzystanie sieci neuronowej do diagnozowania wybranych niesprawności silnika okrętowego*. Diagnostyka 2002 vol. 27, s. 43–47.

[8] Sitnik L.: *Sieci neuronowe w sterowaniu silnikiem o zapłonie samoczynnym*. PTNSS Kongres – 2005. The Development of Combustion Engines. Szczyrk 2005, CD s. 1–15.

[9] Tadeusiewicz R.: *Sieci neuronowe jako wciąż jeszcze nie w pełni wykorzystane narzędzia diagnostyczne. II International Congres of Technical Diagnostics*, Warszawa 2000, s. 81–94.

[10] Witkowski K.: *Analiza możliwości zastosowania w diagnostyce okrętowych silników spalinowych wybranych metod rozpoznawania obrazów. Diagnostyka techniczna Urządzeń i systemów*. Diag'98. Wyższa Szkoła Morska w Szczecinie, Szczecin-Międzyzdroje 1998.

[11] Witkowski K., Włodarski J. K.: *Zastosowanie metody rozpoznawania obrazów w diagnozowaniu silników okrętowych*. Zagadnienia Eksploatacji Maszyn 1992 nr 4.

[12] Żółtowski B., Cempel C.: *Inżynieria diagnostyki maszyn*. Wyd. Biblioteka Problemów Eksploatacji, Warszawa, Bydgoszcz, Radom 2004.

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Mgr inż. **Tomasz CHOROMAŃSKI**, absolwent Akademii Morskiej w Szczecinie. W kręgu jego zainteresowań jest identyfikacja typów uszkodzeń w diagnostyce wtryskiwaczy silników okrętowych. Obecnie pełni funkcję oficera mechanika we flocie handlowej.

EDYTORY WIEDZY DLA DIAGNOSTYCZNEGO SYSTEMU DORADCZEGO DIADYN [1]

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Streszczenie

W referacie przedstawiono fragment systemu doradczego Diadyn. Diadyn to otwarty internetowy system doradczy. W systemie tym, do reprezentacji wiedzy zastosowano koncepcję stwierdzeń. Stwierdzenia są reprezentowane jako węzły w sieci stwierdzeń. W systemie Diadyn wiedza jest reprezentowana w postaci sieci stwierdzeń. Sam system Diadyn składa się z wielu modułów. Niektóre z nich są przeznaczone do zapisywania wiedzy. Inne służą do zapisywania objaśnień wyników przeprowadzonego wnioskowania. Do realizacji tych zadań przygotowano dwa moduły Dia_Wiki oraz Dia_Sta. Opis tych modułów przedstawiono w tym referacie.

Słowa kluczowe: diagnostyka, system doradczy, reprezentacja wiedzy.

KNOWLEDGE EDITORS FOR AN DIAGNOSTIC EXPERT SYSTEM DIADYN

Summary

In this paper a part of an expert system called Diadyn is presented. Diadyn is an open internet expert system. In this system the knowledge representation is based on statement concept. Statements are nodes in a statement network. Within Diadyn system the knowledge is represented by means of the statement network. The Diadyn consists of several modules. Some of them are built for coding the knowledge. The others are prepared for writing explanations of inference results. In order to perform this task, modules called Dia_Wiki and Dia_Sta are prepared. A description of this modules is presented in this paper.

Keywords: diagnostics, expert system, knowledge representation.

1. WSTĘP

Rozwój nowoczesnych maszyn i urządzeń oraz stawiane im wymagania dotyczące ich nieprzerwanej pracy spowodował rozwój dziedziny wiedzy nazywanej diagnostyką techniczną. Celem stosowania diagnostyki technicznej jest określenie stanu maszyn. Do określenia tego stanu stosowane różne metody i techniki. Jednak stopień skomplikowania współczesnych maszyn wymaga wspomagania tego procesu przez odpowiednie oprogramowanie. Do grupy ciekawych narzędzi wspomagających diagnostów w ich codziennej pracy zaliczyć możemy systemy doradcze. Systemy tego typu mają wspomagać diagnostów w ich codziennej pracy poprzez wykorzystanie zapisanej w nich wiedzy.

Do podstawowych elementów systemów doradczych możemy zaliczyć [4]:

- bazę wiedzy,
- bazę danych,
- układ wnioskujący,
- układ objaśniający.

Baza danych umożliwia gromadzenie danych, na podstawie których będzie możliwa ocena stanu technicznego maszyny. Baza wiedzy umożliwia zapisanie wiedzy specjalistów, która posłuży systemowi doradczemu do określenia stanu maszyny na podstawie danych zgromadzonych w bazie danych. Bazę wiedzy systemu doradczego należy wypełnić odpowiednio zapisaną wiedzą. Wiedzę w bazach wiedzy systemów doradczych można zapisywać w różny sposób. Można tutaj wyróżnić takie techniki reprezentacji wiedzy jak:

- techniki bazujące na bezpośrednim zastosowaniu logiki,
- tablice decyzyjne,
- zapis stwierdzeń,
- zapis reguł,
- sieci semantyczne i sieci stwierdzeń,
- obiekty abstrakcyjne,
- sieci neuronalne.

Aby móc wykorzystać zgromadzoną wiedzę i na podstawie zebranych danych o obiekcie określić jego stan, konieczne jest opracowanie odpowiedniego układu wnioskującego. Układ taki pozwoli na podstawie aktualnej wiedzy zapisanej w bazie wiedzy oraz zebranych danych określić aktualny stan techniczny maszyny. Bardzo ważną rzeczą jest uzasadnienie otrzymanej w ten sposób oceny stanu technicznego. Do tego celu

[1] Opisywany system opracowano w ramach projektu badawczego zamawianego pt. „Zintegrowany dynamiczny system oceny ryzyka, diagnostyki oraz sterowania dla obiektów i procesów technicznych (nr rej. PBZ-KBN-105/T10/2003)

wykorzystywany jest układ objaśniający systemu doradczego. W układzie objaśniającym, mogą znajdować się zarówno informacje związane z samym procesem wnioskowania diagnostycznego jak również wyjaśnienia dotyczące zebranych danych, badanego obiektu, czy ważniejszych pojęć używanych w opisie objaśnienia. Aby móc korzystać z samego systemu doradczego konieczne jest zapisanie w nim niezbędnej wiedzy oraz uzupełnienie systemu objaśniającego. Stąd pojawia się konieczność przygotowania odpowiednich narzędzi umożliwiających zarówno zapis wiedzy jak również przygotowanie systemu objaśnień.

2. SYSTEM DIADYN

System Diadyn [2, 3] został zaprojektowany jako otwarty internetowy system doradczy, umożliwiający zapisywanie wiedzy z różnych dziedzin. Zasada jego działania opiera się na pojęciu stwierdzenia [4, 5]. *Stwierdzeniem* nazywać będziemy informację o uznaniu wypowiedzi orzekającej o obserwowanych faktach lub reprezentujących określoną opinię [1]. Stwierdzenia można rozpatrywać jako rozwinięcie pojęcia *zdanie*. Pojęcie to stosowane jest w rachunku zdań. W odróżnieniu od zdań, w przypadku stwierdzeń mogą one dotyczyć wypowiedzi, o których nie możemy powiedzieć czy są prawdziwe czy fałszywe. Każde stwierdzenie posiada swoją treść oraz wartość. Treść stwierdzenia jest zdaniem oznajmującym. Natomiast wartość stwierdzenia jest liczbą z przedziału [0, 1] określającą stopień przekonania o prawdziwości danego stwierdzenia. Wartości stwierdzeń mogą być zadane lub wyznaczane przez układ wnioskowania systemu doradczego. Zadania realizowane przez system Diadyn, są realizowane przez wiele różnych modułów. W tym referacie zostanie opisany sposób działania dwóch z nich: moduły Dia_Wiki i Dia_Sta.

3. EDYTORY WIEDZY SYSTEMU DIADYN

Tak jak opisano to wcześniej podstawą do budowy bazy wiedzy w systemie Diadyn jest pojęcie stwierdzenia. Do zapisywania tych stwierdzeń przygotowano w tym systemie odpowiednie edytory. Praca z systemem Diadyn, dotycząca zapisywania wiedzy oraz przygotowania odpowiedniego systemu objaśnień składa się z dwóch etapów. W pierwszym etapie przygotowywane są zasoby obejmujące *stwierdzenia*, *hasła*, *słowniki* oraz *tematy*. Stwierdzenia stanowią podstawę budowy bazy wiedzy. Możne je łączyć w grupy nazywane słownikami. Do budowy systemu objaśnień wykorzystywane są hasła. Hasła mają podobne znaczenie jak informacje zapisywane w słownikach lub encyklopediach. Stanowią rozszerzony opis pojęć zastosowanych do definiowania stwierdzeń. Hasła mogą być łączone w tematy, przy czym tematem nazywany jest zbiór haseł opisujących zagadnienia o podobnej tematyce. W tym przypadku można mówić o analogi do rozdziałów w książkach. Pierwszy etap nazwano redagowaniem stwierdzeń, haseł i grupowanie ich odpowiednio w słowniki i tematy. Drugi etap obejmuje konstruowanie sieci stwierdzeń oraz definiowanie zadań umożliwiających przeprowadzenie procesu wnioskowania. Do przeprowadzenia tych działań w systemie przygotowano dwa moduły Dia_Wiki oraz Dia_Sta.

1.1. Redagowanie stwierdzeń

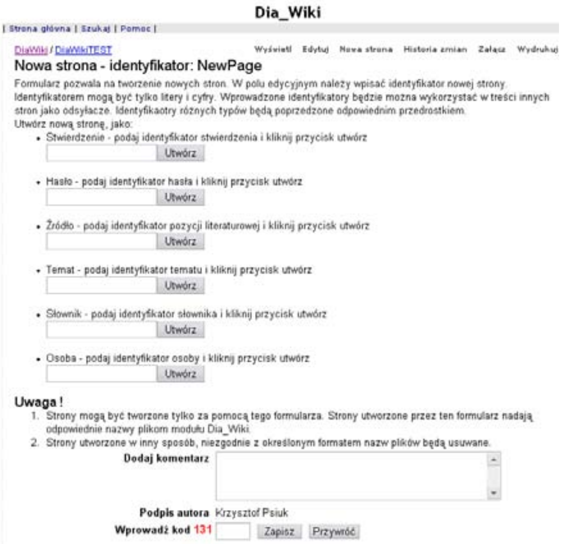
Redagowanie stwierdzeń odbywa się w specjalnym module, będącym częścią systemu Diadyn. Działanie tego modułu jest podobne do przygotowywania definicji w encyklopediach internetowych typu WikiWiki. Przykładem takiej encyklopedii jest Wikipedia. Moduł Dia_Wiki został opracowany na podstawie jednej z wielu implementacji systemów typu WikiWiki, bazującej na opracowaniu PmWiki [8]. Dla potrzeb zastosowania tego rozwiązania zostało ono zmodyfikowane i dostosowane do zadań związanych z zapisywaniem wiedzy w systemie Diadyn. Dla potrzeb tego systemu została dodana możliwość definiowania następujących zasobów:

- *stwierdzenie*,
- *słownik*,
- *hasło*,
- *temat*,
- *autor*,
- *pozycja literaturowa*.

Wymienione wyżej elementy tworzą zasoby systemu. Stwierdzenia i słowniki są elementami umożliwiającymi zapisywanie wiedzy i umożliwiają, w kolejnym etapie, konstruowanie sieci stwierdzeń. Pozostałe elementy służą do utworzenia systemu objaśnień. Do definiowania każdego z zasobów została przygotowana odpowiednia procedura. Definiowanie nowego zasobu rozpoczyna się od wyboru typu nowo definiowanego zasobu. Okno edycyjne pozwalające na definiowanie nowego zasobu pokazano na rys. 1. W oknie tym, znajdują się pola umożliwiające wybór typu zasobu. Utworzenie nowej definicji rozpoczyna się od wpisania identyfikatora nowego zasobu. Po wprowadzeniu indywidualnego identyfikatora, system automatycznie doda do niego przedrostek. Identyfikuje się w ten sposób typ zasobu. Przyjęto, że poszczególne typy zasobów będą miały różne przedrostki. Przyjęto, że:

- stwierdzenia będą miały przedrostek *Stw*,
- hasła będą miały przedrostek *Str*,
- słowniki mają mieć przedrostek *Slw*,
- tematy będą rozpoczynały się od liter *Tem*.

Takie założenie pozwala na późniejszą identyfikację zasobów w systemie, ale również ułatwia pracę użytkownikom, gdyż w trakcie edycji, identyfikator jest użytkownikowi prezentowany (np. rys. 2, rys. 3). Edycja samego zasobu odbywa się poprzez wpisywanie tekstu w odpowiednie pola, wykorzystując w tym celu zestaw poleceń dostępnych w systemach typu PmWiki. Zestaw takich komend można znaleźć np. w [8]. Elementami, które są konieczne do dalszych działań są stwierdzenia i słowniki stwierdzeń.



Rys. 1. Definiowanie nowego zasobu

Rys. 2. Edycja Stwierdzenia

Dlatego też konieczne jest utworzenie przynajmniej zasobów tego typu. Każdy z nich posiada swój tytuł oraz treść właściwą. Przyjęto, że tytuł jest jednocześnie treścią stwierdzenia. Dodatkowo można pod właściwą treścią stwierdzenia wprowadzić dodatkowy opis, informujący np. o autorze danego stwierdzenia (odwołanie do zasobu *autor*) oraz źródłach literaturowych na podstawie których dane stwierdzenie zostało opracowane (odsyłacz do zasobu *pozycja literaturowa*).

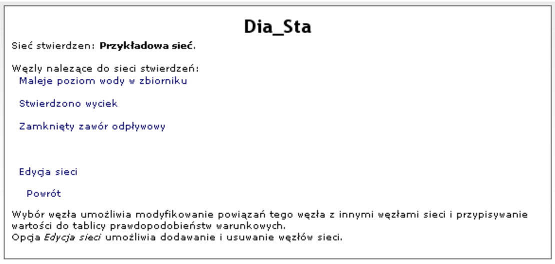
Podstawą do opracowania sieci stwierdzeń są słowniki. Słowniki grupują stwierdzenia w zbiór, będący podstawą do późniejszej budowy sieci stwierdzeń. Założono, że stwierdzenie może należeć do kilku słowników jednocześnie.

Rys. 3. Przykładowy Słownik Stwierdzeń

Dodatkowo oprócz stwierdzeń i słowników można definiować hasła i tematy. Wprowadzenie haseł umożliwia wyjaśnienie stosowanych przy definiowaniu stwierdzeń słów oraz zwrotów lub opisu zagadnień, których stwierdzenie może dotyczyć. Hasła o podobnej tematyce mogą być łączone w tematy, przy czym dane hasło może należeć jednocześnie do kilku tematów.

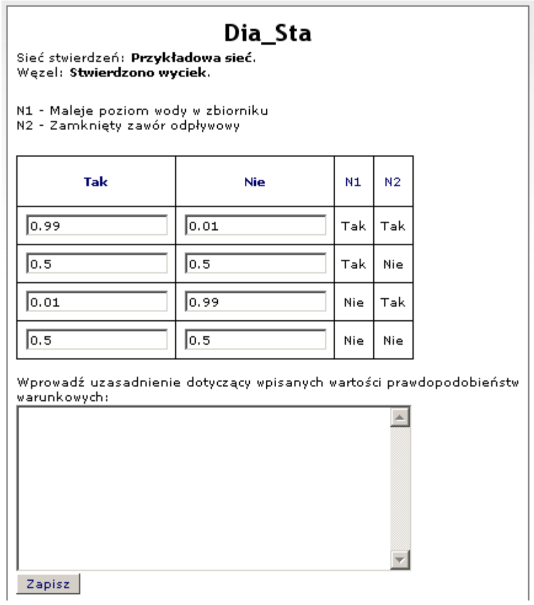
1.2. Konstruowanie i uruchamianie sieci stwierdzeń

Po utworzeniu koniecznych zasobów w postaci słowników stwierdzeń oraz tematów zawierających hasła, można przystąpić do projektowania sieci stwierdzeń. W tym celu korzystamy z modułu Dia_Sta. W module tym można wykonywać dwa rodzaje operacji: definiować lub edytować sieć stwierdzeń, oraz definiować lub edytować zadanie uruchamiające proces wnioskowania.



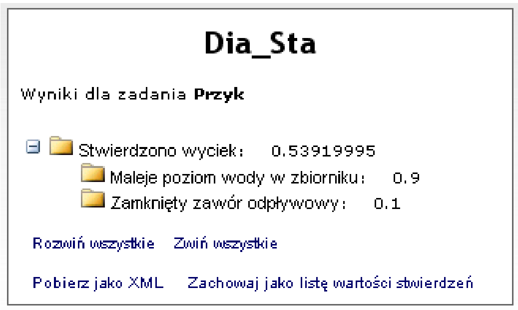
Rys. 4. Definicja przykładowej sieci

Definiowanie sieci stwierdzeń (rys. 4) rozpoczyna się od wyboru słownika, zawierającego stwierdzenia mające być węzłami sieci. Oczywiście nie wszystkie stwierdzenia należące do danego słownika muszą być wykorzystane do utworzenia nowej sieci. System umożliwia wybór tych stwierdzeń, które mają być użyte. Po wyborze słownika i stwierdzeń, konieczne jest określenie zależności pomiędzy węzłami danej sieci. Definiowanie zależności odbywa się w ten sposób, że dla wybranego stwierdzenia określa się stwierdzenia od których jest ono zależne. Poprzez powtórzenie takich operacja dla wszystkich stwierdzeń, można zdefiniować całą sieć stwierdzeń.



Rys. 5. Definiowanie prawdopodobieństw warunkowych dla węzła przykładowej sieci

Kolejnym krokiem jest zapisanie relacji pomiędzy poszczególnymi stwierdzeniami. Relacje zapisywane są przez określenie wartości tablicy prawdopodobieństw warunkowych dla każdego stwierdzenia. Przykład takiej tablicy pokazano na rys. 5. Liczba pól które należy w takiej tablicy wypełnić zależy od liczby węzłów, od których wartość danego stwierdzenia jest zależna. Po zdefiniowaniu całej sieci stwierdzeń, należy przystąpić do uruchomienia procesu wnioskowania.



Rys. 6. Przykładowe drzewo stwierdzeń

W tym celu należy zdefiniować zadanie, które ma wykonywać obliczenia dla nowo zdefiniowanej sieci. Przy definiowaniu zadania należy wskazać sieć stwierdzeń, zbiór wartości początkowych oraz drzewo stwierdzeń. Zbiór wartości początkowych zawiera początkowe wartości stwierdzeń. Przewidziano również możliwość wprowadzenia wartości nieznanej, co oznacza że nie możemy stwierdzić, czy dane stwierdzenie jest prawdziwe czy fałszywe.

Wyniki procesu wnioskowania prezentowane są w postaci drzewa stwierdzeń. Przykład drzewa stwierdzeń przedstawiono na rys. 6. Drzewa stwierdzeń zawiera te stwierdzenia, których wartości mają być prezentowane użytkownikowi systemu doradczego. Podobne rozwiązanie zastosowano np. w [6, 7]. Konstruktor sieci stwierdzeń sam decyduje o tym, czy wartości danego stwierdzenia mają być prezentowane. Może zdarzyć się tak, że niektóre stwierdzenia mają pełnić rolę stwierdzeń pomocniczych i ich wyznaczone wartości nie muszą być prezentowane użytkownikowi systemu doradczego.

Elementy drzewa stwierdzeń są elementami aktywnymi, i umożliwiają odwołanie się do zdefiniowanych wcześniej zasobów w postaci definicji stwierdzeń. Dzięki temu użytkownik ma możliwość uzyskać informację na temat wyników procesu wnioskowania, jego przebiegu oraz wspomóc się wiedzą udostępnioną w systemie objaśnień.

Wartości prezentowane w drzewie stwierdzeń określają stopień przekonania o prawdziwości danego stwierdzenia.

LITERATURA

[1] Korbicz J., Kościelny J. M., Kowalczuk Z., Cholewa W. (red) *Diagnostyka procesów. Modele. Metody sztucznej inteligencji. Zastosowania*. Warszawa, WNT, 2002.
[2] Cholewa W. (red) *Warsztaty DIADYN. Materiały seminaryjne*. Ustroń, KPKM, 2006.
[3] Cholewa W. (red.) *Warsztaty DIADYN'07. Materiały seminaryjne*. Gliwice, KPKM, 2007.
[4] Cholewa W., Pedrycz W. *Systemy doradcze*. Skrypt Pol. Śl. Gliwice 1987.
[5] Cholewa W. *Tablice ogłoszeń w diagnostycznych systemach doradczych*. Pomiary, Automatyka Sygnały 1998.
[6] Cholewa W., Psiuk K.: *Wizualizacja stanu złożonego obiektu technicznego*. Diagnostyka Procesów Przepływowych, Kazimierz Dolny, 1999, s.173-178.
[7] Psiuk K. *Obiektowe modele procesu propagacji stanów w układach maszyn*. Praca doktorska, Gliwice, 2001.
[8] *Dokumentacja systemu PmWiki*. http://www.pmwiki.org.

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ODWZOROWANIE PROCESU WTRYSKU PALIWA W SYGNALE DRGANIOWYM SILNIKA O ZAPŁONIE SAMOCZYNNYM

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Streszczenie
W artykule przedstawiono wyniki badań nad możliwością detekcji oraz stopniem odwzorowania procesu wtrysku paliwa w silniku o zapłonie samoczynnym. Przedstawiono genezą tematu i metodykę badań realizowanych na jednocylindrowym silniku badawczym. Wyniki badań laboratoryjnych zweryfikowano na wielocylindrowym silniku kolejowym. W podsumowaniu przedstawiono możliwości wykorzystania uzyskanych wyników badań do detekcji niesprawności wtryskiwacza paliwa silnika 2112SSF.

Słowa kluczowe: diagnostyka drganiowa, silnik spalinowy o ZS, wtrysk paliwa.

REPRESENTATION OF FUEL INJECTION PROCESS IN A VIBRATION SIGNAL OF A DIESEL ENGINE

Summary
The article presents some results of the research on possibilities of use a vibration signal of diesel engine in order to detect and describe a fuel injection process. This paper includes a genesis of this problem and a methodology of performed tests, which were executed on one-piston laboratory tests engine. Author presents also the verification results, executed on multi-pistons locomotive diesel engine. As a conclusion, the possibilities of implementation of this method are described, for example to perform an injector fault detection on the locomotive diesel engine.

Keywords: vibrodiagnostics, diesel engine, fuel injection.

1. ŹRÓDŁA SYGNAŁU DRGANIOWEGO W CYKLU PRACY SILNIKA SPALINOWEGO O ZAPŁONIE SAMOCZYNNYM

1.1. Cykl pracy silnika spalinowego

Silnik spalinowy jest maszyną cieplną o działaniu cyklicznym, zamieniającym energię chemiczną zawartą w paliwie na energię mechaniczną obracającego się wału korbowego. Bez względu na cechy konstrukcyjne silnika spalinowego podstawą jego funkcjonowania jest sekwencja procesów gwarantujących konwersję energii oraz zachowanie ciągłości pracy. W cyklu pracy musi dojść do pobrania powietrza do przestrzeni roboczej silnika, przygotowania ładunku palnego przez uformowanie palnej mieszaniny paliwa i powietrza, spalenia mieszanki w komorze spalania oraz wykorzystania sił gazodynamicznych spalin w procesie rozprężania gazów spalinowych.

Silnik o zapłonie samoczynnym jest silnikiem, w który spalanie ładunku w cylindrze jest inicjowane samoczynnie poprzez bardzo złożone mechanizmy fizyko-chemiczne. Ze względu na dużą dynamikę przebiegu poszczególnych procesów zachodzących podczas cyklu pracy silnika można wskazać na dynamiczne oddziaływania pomiędzy czynnikiem roboczym a poszczególnymi elementami konstrukcji. Efektem tych oddziaływań jest generowanie sygnału wibroakustycznego.

Zgodnie z klasyfikacją zaproponowaną przez Piętaka [8] dynamikę silnika spalinowego, a przez to i efekty dynamiczne w postaci drgań, można rozpatrywać w skali makro- i mikrozjawisk. W ujęciu ***makrodynamicznym*** zakłada się, że przepływ energii od silnika spalinowego do odbiornika ma charakter ciągły, stacjonarny i nie związany z jego cykliczną pracą [9]. W konsekwencji można wyprowadzać równania bilansu energetycznego silnika i budować modele diagnostyczne, jako procesora energii.

Mikrodynamika silnika jest związana z jego cykliczną pracą kolejnych cylindrów. Wytwarzają one moment obrotowy zmienny w czasie, o złożonym, pulsującym przebiegu. Jest on uwarunkowany przebiegiem ciśnień w cylindrach oraz działaniem sił bezwładności, a także dynamiką przepływów w układach zasilania (w paliwo i powietrze) i układzie dolotowym silnika.

Proponuje się przejście na jeszcze niższy poziom analizy pracy silnika spalinowego o ZS w aspekcie diagnostyki drganiowej – analiza poszczególnych procesów przetwarzania energii chemicznej i generowania sygnału drganiowego w cylindrze zachodzących podczas cyklu pracy. W takim ujęciu przytoczoną wcześniej klasyfikację rozważań o dynamice silnika spalinowego można rozszerzyć o ***dynamikę elementarnych procesów silnikowych*** opisującą, wyjaśniającą i analizującą charakter zjawisk zachodzących w komorze spalania w każdym cyklu pracy silnika spalinowego.

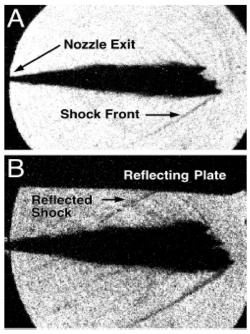
Kompleksową analizę poszczególnych zjawisk i mechanizmów generowania drgań w silniku spalinowym o ZS omówiono w pracach [10] natomiast poniższą pracę poświęcono kluczowemu procesowi jakim jest wtrysk paliwa i formowanie ładunku palnego w komorze spalania.

1.2. Wtrysk paliwa

Wtrysk paliwa do przestrzeni roboczej silnika o ZS jest złożonym procesem mającym na celu dostarczenie w odpowiednim momencie, odpowiednio odmierzonej dawki paliwa tak, aby ułatwić formowanie i samozapłon mieszaniny palnej. Niezależnie od rozwiązania konstrukcyjnego układu wtryskowego, jego poprawne funkcjonowanie silnie wpływa na własności użytkowe silnika (moc maksymalna, dynamika, cichobieżność) i ekologiczne (toksyczność spalin), a przede wszystkim ekonomię eksploatowania (zużycie paliwa) [11]. Charakteryzując źródła sygnałów drganiowych w układzie wtryskowym należy zaznaczyć, że ze względu na skomplikowany mechanizm rozpylania paliwa można podzielić je na źródła mechaniczne, hydrauliczne i aerodynamiczne. Jak wynika z przeprowadzonych badań jednym z dominujących źródeł wtryskiwacza, a przez to i całej głowicy silnika jest formowanie strugi i rozpylenie paliwa [1, 4]. Z punktu widzenia mechaniki płynów wtrysk paliwa to przepływ cieczy przez otwór ostrokrawędziowy, którego charakterystycznym wymiarem jest długość dużo mniejsza od 50D, gdzie D jest średnicą otworu rozpylacza [7]. Przepływ przez otwór ostrokrawędziowy charakteryzuje się przewężeniem (kontrakcja) strumienia, która występuje za przekrojem. Stanowi to źródło silnego zawirowania paliwa, a przy znacznych prędkościach wypływu paliwa (w literaturze wskazuje się prędkość rzędu 80-100 ms^{-1}) prowadzi do rozpadu strugi na skutek niestabilności statycznej. Niestabilność statyczna decyduje o przejściu z jednej formy rozpadu strugi w drugą, a kryterium stateczności pojedynczej kropli może być definiowane kryterialną liczba Webera [11]. Rozpad strugi na pojedyncze krople jest wykonany kosztem energii pulsacji paliwa w kierunku poprzecznym do osi cylindra. W literaturze spotyka się ściśle zdefiniowane pasmo częstotliwości, w którym skupiona jest większość energii pulsacji czynnika [10] jednakże nie odnaleziono opublikowanych wyników badań potwierdzających słuszność przytoczonych teorii dla warunków niestacjonarnego przepływu cieczy.

Najnowsze, publikowane badania nad procesem rozpylania paliwa wskazują na możliwość powstawania zjawiska kawitacji w rozpylaczu, co stanowi dodatkowe źródło drgań w układzie wtryskowym. Efektem wibroakustycznym takiego wspomagania rozpylania paliwa są wysokoczęstotliwościowe drgania o energii równej pracy rozprężania/sprężania par paliwa.

Dodatkowo badania wizualizacyjne dowiodły istnienia kolejnego źródła drgań, jakim jest fala uderzeniowa [6]. Zjawisko hipersoniczne było przypisane procesowi spalania ładunku i gwałtownym przyrostom ciśnienia w komorze spalania. Dopiero badania wizualizacyjne z wykorzystaniem fotografii rentgenowskiej wskazały na pierwszeństwo wtrysku nad spalaniem w kwestii powstawania fal uderzeniowych w cylindrze prezentowane na rys. 1.



Rys. 1. Wizualizacja fali uderzeniowej przy wtrysku paliwa z ciśnieniem 80MPa; [6] A – fala uderzeniowa przed czołem strugi paliwa, B – odbicie fali uderzeniowej od ścianki cylindra

Przedstawione rozważania na temat identyfikacji poszczególnych źródeł sygnału drganiowego stały się podstawą opracowania metodyki badań nad odwzorowaniem procesu wtrysku w sygnale drganiowym.

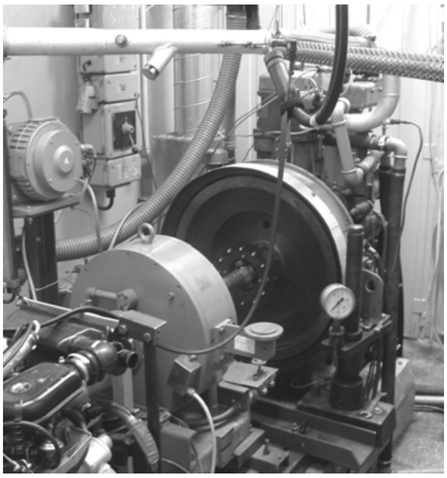
2. METODYKA I OBIEKT BADAŃ

Wtrysk i spalanie paliwa w silniku o ZS jest złożonym, wielofazowym procesem fizykochemicznym, który charakteryzuje się wysoką niestacjonarnością oraz składowymi wysoko częstotliwościowymi [11]. Dlatego też zdecydowano o wykonaniu badań rozpoznawczych, bazujących na pomiarze drgań głowicy jednocylindrowego silnika spalinowego o ZS i wtrysku bezpośrednim typu SB3.1.

Ze względu na nowatorski charakter badań wibroakustycznych oraz konieczność weryfikacji poprawności uzyskanych wyników postanowiono wykonać pomiary przyspieszeń drgań głowicy silnika o ZS w trakcie przeprowadzania rutynowych badań silnikowych. W związku z tym przystosowano stanowisko dynamometryczne silnika SB3.1 do badań wibroakustycznych. Widok silnika spalinowego na stanowisku badawczym przedstawiono na rys. 2.

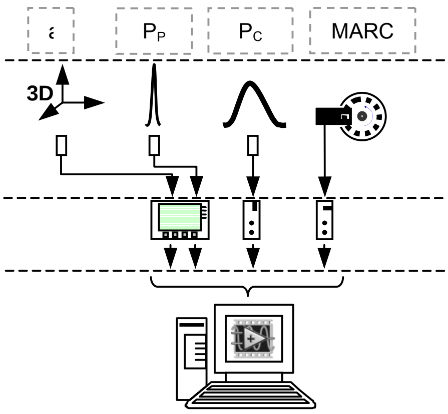
Badania zostały przeprowadzone w Laboratorium Silnikowym Instytutu Silników Spalinowych i Transportu Politechniki Poznańskiej. Stanowisko dynamometryczne pozwala na kontrole i rejestrację między innymi następujących parametrów:
– ciśnienie w przestrzenie nad tłokiem silnika,
– ciśnienie paliwa przed wtryskiwaczem,

– prędkość obrotowa i moment obrotowy na wale korbowym,
– jednostkowe bieżące zużycie paliwa,
– temperatura cieczy chłodzącej i spalin,
– skład spalin (kontrolnie).



Rys. 2. Widok silnika badawczego SB3.1 na stanowisku dynamometrycznym

Na potrzeby badań przystosowano stanowisko zostało zaadaptowanego do badań wibroakustycznych przez montaż przetworników drgań B&K typ 4391 ze wzmacniaczem ładunku B&K typ 2692 NEXUS firmy Brüel&Kjær. Poglądowy schemat toru pomiarowego zamieszczono na rysunku 3.

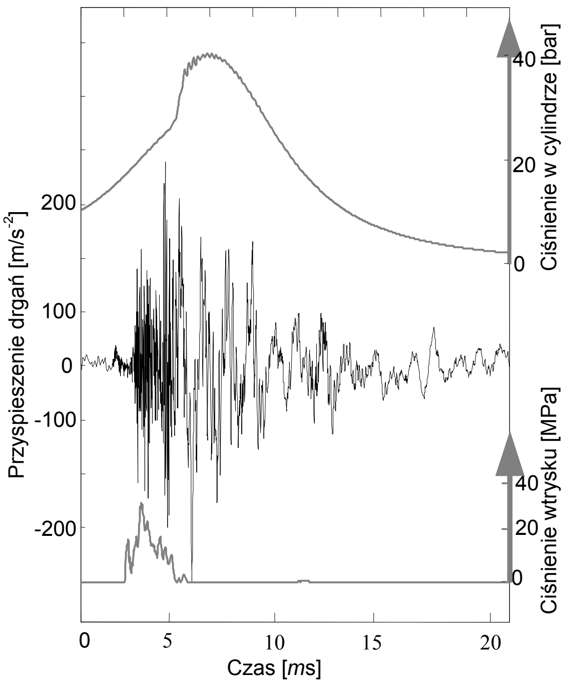


Rys. 3. Schemat toru pomiarowego: a – przyspieszenie drgań, P_P – ciśnienie paliwa P_C – ciśnienie w cylindrze, MARC – znacznik obrotu wału korbowego

Rejestracja dokonywana była z wykorzystaniem komputera PC wyposażonego w kartę analogowo-cyfrową do akwizycji sygnałów dynamicznych NI DAQ – 4472 firmy National Instruments. Sterowanie akwizycją, wizualizacja przebiegów sygnałów oraz ich bieżąca, częściowa analiza była realizowana z wykorzystaniem dedykowanego oprogramowania LabView® tej samej firmy. Szczegółowe analizy zarejestrowanych sygnałów przeprowadzono w środowisku Matlak® Ze względu na impulsowy charakter przebiegu obserwowanych zjawisk zdecydowano, że sygnały zostaną rejestrowane z szybkością 102400 próbek na sekundę. Pozwoliło to na akwizycję sygnału drganiowego w użytecznym paśmie częstotliwości 45 kHz. Jednocześnie zwraca się uwagę na wykorzystanie zjawiska mechanicznego autowzmocnienia sygnału w zakresie nieliniowości charakterystyki przetwornika drgań (naturalna częstotliwość rezonansowa dla użytych przetworników to f_N=52kHz). Technika ta pozwoliła dokładniej obserwować składowe wysokoczęstotliwościowe o niskiej energii, które są wynikiem procesów hydrodynamicznych (wtrysk paliwa) i fizykochemicznych (tworzenie ładunku palnego) występujących w czasie cyklu pracy silnika spalinowego. Poprawność przyjętej metody uzasadnia się przez rozpoznawczy charakterem badań prowadzonych w stałych warunkach.

3. WYNIKI BADAŃ

Przykładowy przebieg zarejestrowanych sygnałów drgań oraz pomocniczych sygnałów ciśnień przedstawiono na rysunku 4.

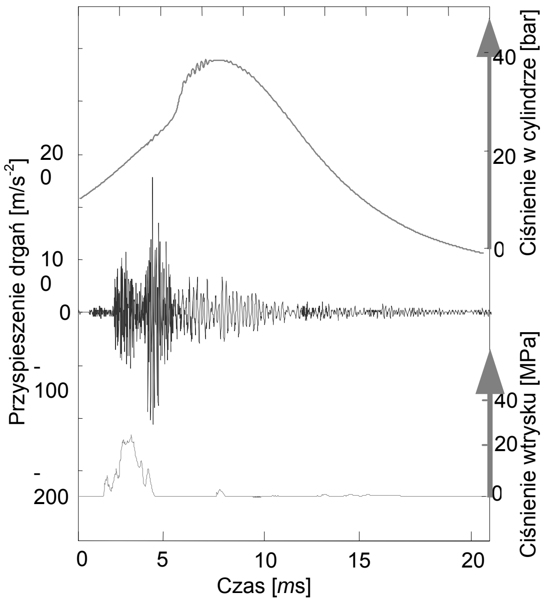


Rys. 4. Przebiegi czasowe drgań w paśmie 45 kHz oraz ciśnień: w cylindrze i paliwa przed wtryskiwaczem; n=1000 obr/min, Mo=20 N·m

Zarejestrowane sygnały poddano analizie w dziedzinie czasu i częstotliwości. Wykorzystując autorską metodę Operacyjnej Analizy Odpowiedzi Częstotliwościowej **OFRA** (**O***perational* **F***requency* **R***esponse* **A***nalysis*) [5] odseparowano drgania strukturalne od drgań generowanych przy wtrysku paliwa i tworzeniu ładunku palnego w cylindrze. Po przeprowadzeniu analizy sygnałów zarejestrowanych dla 48 sytuacji badawczych dokonano selekcji widmowej i filtracji sygnałów drgań głowicy silnika badawczego związanych z wtryskiem paliwa i tworzeniu ładunku palnego. Przykładowy wynik postprocessingu przedstawiono na rys. 5.

4. PODSUMOWANIE

Przedstawione badania potwierdziły wysoką przydatność sygnału drganiowego do oceny przebiegu procesów silnikowych. Istnieje możliwość identyfikacji elementarnych procesów silnikowych, tj. wtrysk paliwa, tworzenie ładunku z podziałem na fizyczny i fizykochemiczny rozpad strugi, agregację samozapłonu oraz spalanie i dopalanie ładunku w cylindrze.



Rys. 5. Przebiegi czasowe filtrowanego sygnału drgań w paśmie 1500÷4000 Hz oraz ciśnień: w cylindrze i paliwa przed wtryskiwaczem; n=1000 obr/min, Mo=0 N·m

Przeprowadzone badania i analizy pozwoliły na:
- potwierdzenie, że proces wtrysku paliwa i tworzenia ładunku palnego jest bardzo skomplikowanym i wielofazowym procesem fizykochemicznych, którego efekty drganiowe są silnie niestacjonarne,
- wskazanie możliwości wykorzystania efektu autowzmocnienia wysokoczęstotliwościowych sygnałów drganiowych,
- potwierdzenie przydatności metody OFRA do selekcji sygnałów drganiowych.

Uzyskane wyniki analiz posłużyły przygotowaniu eksperymentu na silniku kolejowy typu 2112SSF, których celem była weryfikacja przydatności metod i technik opracowanych dla silnika badawczego SB3.1 w eksploatacyjnych badaniach diagnostycznych lokomotyw spalinowych.

LITERATURA

[1] Czechyra B.: *Odwzorowanie procesów silnikowych w sygnale drganiowym silnika spalinowego o zapłonie samoczynnym.* Zeszyty Naukowe Politechniki Poznańskiej. Seria Maszyny Robocze i Transport, nr 59, Poznań 2005.

[2] Czechyra B.: *Operacyjna analiza odpowiedzi częstotliwościowej OFRA w ocenie procesów silnikowych.* Wybrane zagadnienia analizy modalnej konstrukcji mechanicznych – praca zb. pod red. T. Uhla, AGH, Kraków 2008.

[3] Czechyra B., Szymański G. M., Tomaszewski F.: *Ocena luzu zaworów silnika spalinowego w oparciu o parametry drgań – założenia metodyczne.* Silniki Spalinowe nr 1/2004 (118)49.

[4] Czechyra B., Szymański G. M., Tomaszewski F.: *Odwzorowanie procesu spalania w sygnale drganiowym tłokowego silnika spalinowego o zapłonie samoczynnym.* 3rd International Congress of Technical Diagnostics, Diagnostics' 2004, 6-9 September 2004, VOL. 30 tom 1 2004.

[5] Czechyra B., Tomaszewski F.: *OFRA – vibration signal selection method for fast diagnostics of diesel engine.* XXIII Symposium Vibrations In Physical Systems, Poznań – Będlewo 2008.

[6] MacPhee A. G. and others: *X-ray Imaging of Shock Waves Generated by High-Pressure Fuel Sprays.* Reports. Science, VOL 295/ Feb. 2002.

[7] Oleśkowicz-Popiel Cz.: *Osiowosymetryczny strumień swobodny i uderzający.* Seria: Rozprawy Politechniki Poznańskiej, nr 120, Wydawnictwo Politechniki Poznańskiej, Poznań 1981.

[8] Piętak A.: *Diagnozowanie silników o ZS na podstawie przebiegu procesu przejściowego.* Wydawnictwa Politechniki Poznańskiej Seria Rozprawy, nr 340, Poznań 1998.

[9] Rackmill C. I., Blumberg P. N., Becker D. A., Schuller R. R., Garvey D. C.: *A dynamic model of a locomotive diesel engine and electrohydraulic governor.* Journal of Engineering for Gas Turbines and Power, Transactions of the ASME, Vol. 110, No. 3, 1988.

[10] Tomaszewski F.: *Zastosowanie procesów wibroakustycznych do oceny stanu technicznego silnika spalinowego lokomotywy.* Rozprawa doktorska. Politechnika Poznańska Poznań 1987.

[11] Zabłocki M.: *Wtrysk i spalanie paliwa w silnikach wysokoprężnych.* Wydawnictwa Komunikacji i Łączności, Warszawa 1976.

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Tomasz BARSZCZ,
Piotr CZOP

Methodologies and Applications of Virtual Power Plant. New environment for power plant elements modeling

ITE Radom, 2007

The next few decades will be characterized by a significant increase in the number of distributed, smaller, flexible and cost-effective fully automated power supply units, including: wind, photo-voltaic, fuel cell, and biomass. However this trend is noticeable, currently and in the near future thermal power generation, including the coal and nuclear power plants, will have the central role to play in electric power supply. Therefore, research towards optimization and diagnostics of power generation units have very strong demand from industry. Nowadays, power plant performance is one of key factors for proper management of plant assets. Numerous methods are used to assess the technical state of supervised objects. In general, they are referred to as fault detection and identification (FDI) methods. Very successful approach is based on models, either based on analytical equations, either on parametric models obtained during the process of system identification. Since preparation of such models is laborious and requires integration of information from several heterogeneous sources, a new approach was proposed in the book by Tomasz Barszcz and Piotr Czop.

The book describes the Virtual Power Plant laboratory (VPP). The development of VPP was included in the project DIADYN as a practical laboratory, which would facilitate validation of various technologies developed within this and other projects. The VPP is the innovative work environment for technical state assessment of dynamic objects. In theory, it can be applied to any complex dynamic system. This versatility was achieved, because no assumptions from power generation were “hardcoded” in the VPP structure. This structure was general and flexible enough to allow large number of future extensions and applications.

The Virtual Power Plant is the group of computers, connected by a fast computer network. Main elements of VPP are: main data exchange library, SCADA database, SCADA user interface, specialized database with its interface and group of computers running a power unit model.

The book contains seven chapters. The first one is introduction, which shows importance of the subject and presents the outline of the book. The second chapter describes the architecture of VPP. All elements listed above are presented in details. The standards of communication, based on OPC, are presented. Important problem of synchronization of various elements is also presented. The third chapter presents details of the model of a power generation unit implemented in VPP. General structure of the model is presented first. Next, the model of the 200MW unit is described. Following components are described: coal mills, combustion, heater, boiler, steam turbine, condenser, deaerator, generator, dynamic state and unit controllers. Chapter 4 presents results of operation of the VPP in a few conditions, like steady state, power change and start up of the unit. Two examples of modeling of faults are also presented. Chapters 5 and 6 are detailed manuals for, respectively, installation with configuration and operation of the VPP. The final chapter contains summary and conclusions.

There are several interesting topics covered by the book. The development of VPP included development of powerful software infrastructure, predominantly for data handling and processing. The main data exchange point has capability to run and control all other software modules. It is possible to replay data acquired at the real plant, preprocess data and detect alarms. Additionally, VPP implements efficient real time database, which can store scalar and dynamic (i.e. vibration) values. There is a useful advanced user interface for researchers. Another DCS-like database and user interface provides users with the same environment as in the power plant, which is important in operators training. VPP is based on the OPC interface to support object oriented efficient interfacing. It also allows easy adding of new systems, when there is such a need.

The second most valuable result of the project was demonstration of idea feasibility by implementing the VPP to the real 200MW power plant unit in one of Polish power plants. The largest task was to configure the software systems (all the channels in Central Bus, screens in SCADA etc.) appropriately. All the tags and screens were prepared basing on the real configuration files. The most complex task, however, was the development of the model.

The VPP model may be run over wide range of operation conditions including transient and steady state operation, i.e. start phase (startup), idle mode, synchronization, load mode and coast down. VPPM has the structure composed of the components, which are essential in a power generation process. Several versions of the model were prepared. Some are optimized for accuracy and consume extensive time to run. Others are optimized for speed of execution and can run in the real time.

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