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EVALUATION OF SENSOR-BASED CONDITION MONITORING METHODS AS IN-PROCESS TOOL WEAR AND BREAKAGE INDICES – CASE STUDY: DRILLING

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Summary

Today, effective unmanned machining operations and automated manufacturing are unthinkable without tool condition monitoring (TCM). Undoubtedly, the implementation of an adaptable, reliable TCM and its successful employment in industry, emerge as major instigations over the recent years. In this work, a sensor-based approach was deployed for the in-process monitoring and detection of tool wear and breakage in drilling. In particular, four widely reported indirect methods for tool wear monitoring, i.e. vibration signals together with thermal signatures, spindle motor and feed motor current measurements were obtained during numerous drillings, under fixed conditions. The acquired raw data was, then, processed both statistically and in the frequency domain, in order to distinguish the meaningful information. The study of the latter is influential in identifying the trend of specific signals toward tool wear mechanism. The efficiency of this information as a tool wear and/or breakage index is the feature that determines the effectiveness and reliability of a potential indirect TCM approach based on a multisensor integration. The paper concludes with a discussion of both advantages and limitations of this effort, stressing the necessity to develop simple, fast condition monitoring methods which are, generally, less likely to fail.

Key words: tool condition monitoring, vibration signals, thermal signatures, spindle motor current, tool wear, statistical analysis, frequency domain analysis.

1. INTRODUCTION

Manufacturing community is always striving to reduce operating costs while trying to improve product quality and meeting or exceeding customer satisfaction [1]. Focusing on the former intent, production cost reduction is achieved nowadays by using higher cutting speeds and by reducing human resources. As a consequence, over the years, the manufacturing environment has undergone dramatic changes, moving from the stage of conventional machinery to fully automated machining systems. Towards this advance, the oldest and most common "fix it when it breaks" strategy is clearly being replaced by "intelligent" condition monitoring (CM) systems. These systems monitor directly or indirectly the machining conditions utilizing vision-based techniques or sensor-based signals, in order to provide diagnostic/prognostic indices for hard and soft faults; soft faults develop progressively with time creating a gradual degradation of the tool, while, on the other hand, hard faults take place instantaneously causing an abrupt cutoff of the operation (Figure 1). In other words, soft faults lead to a predictable situation, an attribute that makes them appropriate for CM, while hard faults are generally unpredictable and ineligible for this area of research. Consequently, the former type of fault can be used for prediction, while the latter is easier for diagnosis [2].

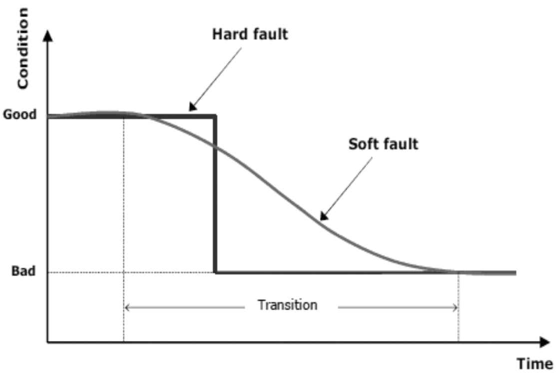

Figure 1: Hard and soft faults, Courtesy of [2]

Specific pivotal components of a machining system, such as the tool, are often related with either soft or hard faults in the form of tool wear and/or breakage. Wear is a loss of material at the cutting lips of drill bit due to physical interaction between the cutting tool and workpiece material [3]. Abrasion, adhesion, diffusion and fatigue are the basic mechanisms that cause wear in cutting tools. Tool wear in drilling is a progressive procedure but it occurs at an accelerated rate once a drill becomes dull. During this procedure, the cutting forces increase, temperature of tool rises, drill point deformation and immediate loss of sharp edges occur. After a certain limit, tool wear can cause catastrophic and sudden failure of the tool without any warning that causes considerable damage to the workpiece and even to the machine tool. This scenario can be illustrated in Figure 2 by classifying the wear stages as initial wear, slight wear (regular stage of wear), moderate wear (micro breakage stage of wear), severe wear (fast wear stage) and worn-out (or tool breakage) in terms of tool life [4].

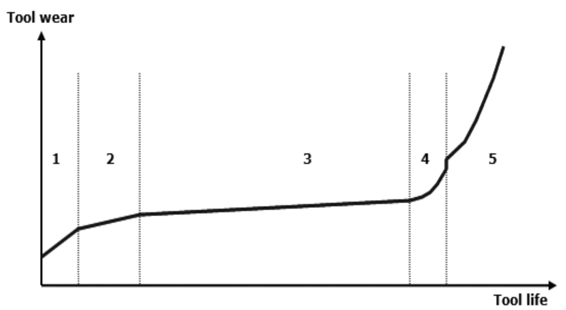

Figure 2: Tool wear evolution: (1) initial wear, (2) slight wear, (3) moderate wear, (4) severe wear and (5) worn-out

In drilling, which is a widely used machining process and represents approximately 40% of all cutting operations performed in industry, the failure of a common twist drill occurs by one of two modes; fracture or chipping and excessive wear. Experiments performed by Thangaraj and Wright [5] indicated that, under normal cutting conditions, failure due to fracture was observed with small size drills (≤ 3 mm diameter), while excessive wear was the dominant failure mode with large size drills (> 3 mm diameter), within a typical drill diameter size range of 1 to 20 mm.

Generally, tool wear influences the quality of the surface finish and the dimensions of the parts that are manufactured, whereas tool failure is a major cause of unplanned interruption in a machining environment. Particularly, for modern machine tools, 20% of the downtime is ascribed to tool failure, resulting in reduced productivity and economic losses [6]. Hence, the reason for acquiring the drill wear state information is to enhance the predictive capability to allow the machine operator to schedule tool change or regrind just in time to avoid underuse or overuse of tools, prevent shutdown of machines due to damage and minimize scrap or rework [1].

Yet, both tool wear and tool breakage are still unsolved primary problems in metal cutting processes, though a considerable amount of research has been done in the literature [3]. Many researchers have looked for variable ways to detect tool wear and, consequently, prevent a tool breakage, but a highly general and reliable on-line tool wear measurement technique has to be developed. Due to the high complexity of drill wear and breakage mechanisms, both mathematical models and numerical methods generally fail to provide a precise description of the relevant dynamics of drilling. As a consequence, the "safe" way to implement a system able to predict and diagnose drill wear and breakage lies upon on-line tool condition monitoring (TCM).

In principle, there are two possible TCM approaches, i.e. direct and indirect methods. Direct tool wear estimation systems are able to measure directly the tool wear via tool images, computer vision, etc. which means that these methods actually measure tool wear as such. Moreover, their application is simple and the reliability is high. However, the automated application of a direct tool wear estimation system is not feasible because the detection system should be able to detect the wear zone and measure it, requiring that either the tool be removed from the machine after a certain period of time or a measuring device be installed on the machine. Consequently, any of these practices would cause downtime and production loss, rendering direct methods either economically or technically inadequate. On the other hand, instead of wear, indirect monitoring methods measure something else, i.e. a parameter, which must be a function of wear [7]. Commonly used parameters in indirect methods are cutting forces, vibration, acoustic emission, current, power and temperature. The main advantage of indirect methods is that they are applied online. Unfortunately, these methods present limited reliability and design complexity due to the unpredictable impact of the wear process to the measured signal. Moreover, the sensor cost is generally high [2].

2. EXPERIMENTS

2.1 Experimental background

This experimental work deals with the use of four common indirect TCM methods in an attempt to evaluate their validity as in-process tool wear and/or breakage indices, during standard drilling processes. Specifically, vibration signals, thermal signatures, spindle motor and feed motor current measurements are obtained and, then, processed in order to extract the meaningful information from the raw data and assess the proclivity of the above parameters toward drilling tool wear.

Vibration is a widely used parameter in indirect TCM. It is logical to expect vibration measurements to react to tool wear; if in a dynamic system such as the machine tool the cutting forces increase, the dynamic response will also increase [8]. Vibration signatures are suggested as reliable, robust and applicable for TCM, in addition to the fact that vibration monitoring techniques present ease of implementation; no modifications to the machine tool or the workpiece are required. Furthermore, vibration signals can be acquired by fewer, easily replaceable and very cost-effective peripheral instruments in contrast to acoustic emissions (AE) for instance. Last but not least, such signals have the quick response time needed to indicate changes for on-line monitoring [9]. Unfortunately, vibration monitoring relates to several limitations. Besides their sensitivity to tool wear, vibrations are highly influenced by the workpiece material, cutting conditions, machine tool structure and machining noise that occurs under real industrial environments.

In the reported literature, tool temperature [10, 11], feed motor current and spindle motor current [12-24] are also widespread parameters for TCM and appear to be potential indices of drill wear. In the same manner as vibration, spindle motor and feed motor current can be related to the dynamics of drilling process, reflecting the amount of power used in the machining process. Although vibration and cutting force sensors are located close to monitored tool, offering hence more representative measurements, it is much easier to acquire the current of the spindle or the feed motor, to monitor the tool condition in a simple, but quite valid, way. In contrast, temperature-based TCM, involving infrared or fiber-optic pyrometers and infrared thermography imagers, is a major challenge due to numerous practical difficulties involved in cutting processes.

2.2 Experimental set-up

Figure 3 presents schematically the experimental setup of this work. As mentioned, vibration, spindle motor current and tool temperature signals were obtained during drilling operations conducted on Yang SMV-1000, a three-axis computer numerical controlled (CNC) vertical-type machining center.

The vibration signals were obtained from Kistler 8702/B25M1, single-axis K-shear accelerometer, mounted on the workpiece longitudinally to the drilling direction, i.e. the Z-axis. The accelerometer has a measuring range of ± 25 g, with a sensitivity of 200 mV/g (± 5%), while its frequency response band ranges from 1 to 8000 Hz. Referring to the spindle motor and the feed motor drives, the related current signals were obtained with two self-powered AC current transducers, LEM type AK 50 C10, with galvanic isolation between the primary (high power) and secondary circuits (electronic circuit). The transducers have a primary nominal input current up to 50 A and give an analogue output signal in the range of 0-10 V DC, with an accuracy of ± 1% and response time < 100 ms. Moreover, non-contact tool temperature measurements were performed with the use of Eurotron's IRtec series Rayomatic 10, a compact digital infrared (IR) temperature transmitter (IR pyrometer) mounted onto the tool bracket, at a distance of d=10 cm from the drill point, with an angle of $\theta=30^o$ from the drill axis. The measuring temperature range of the specific transmitter is from 0 to 600 ^oC, while it offers accuracy of ± 1% rdg and repeatability of ± 0.5% rdg, with a target-to-distance ratio of 25:1. The transmitter was calibrated measuring the known temperature of a specific heat source. Finally, the data from the above four sensors was recorded to a PC, with a sampling rate of 8 KHz, using a National Instruments Cdaq-9172 data acquisition unit and National Instruments LabVIEW software.

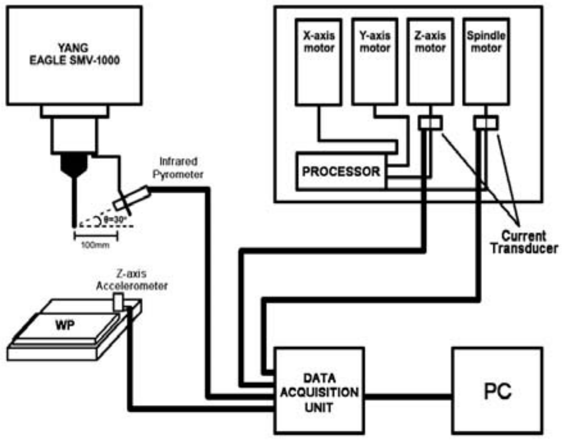

Figure 3: The experimental set-up

The experiments included drilling operations performed by a HSS-Co5% twist drill of 10 mm diameter, under dry conditions, to a number of reinforced C-70 steel workpieces (length=170mm, width=170mm, height= 20mm). Totally 109 bottom holes, of depth=15mm, drilled per each workpiece (Figure 4). The drilling path started from the 1A hole, continued to 1B, 1C and so on, finishing the first line (No. 1) of the workpiece. The process was continuing to the next lines (2 to 11), until the last hole 11K (Figure 5).

The whole process was provided with the use of Missler TopSolid, CAD/CAM software. The selected optimum drilling conditions were S=600 RPM regarding the spindle speed and F=100 mm/min for the feed rate. The duration for a drill was 9 seconds, and for the whole workpiece was estimated around 1800 seconds. The latter includes the "dead" –or rapid movement– time between each drill. One of the aims of this study was to intentionally hasten the drill wear by performing certain drilling operations, in specific workpieces, with "false" conditions (S=800 RPM, F=110 mm/min) between the "normal" sets of drillings, in order to investigate the impact of drill aging, and consequently drill wear, to the monitored parameters. For this scope, exactly after the drilling of hole 11K of the second workpiece, i.e. hole 218, the above "false" cutting conditions were applied for the operation of a whole workpiece; the experiment, then, continued under the aforementioned optimum conditions.

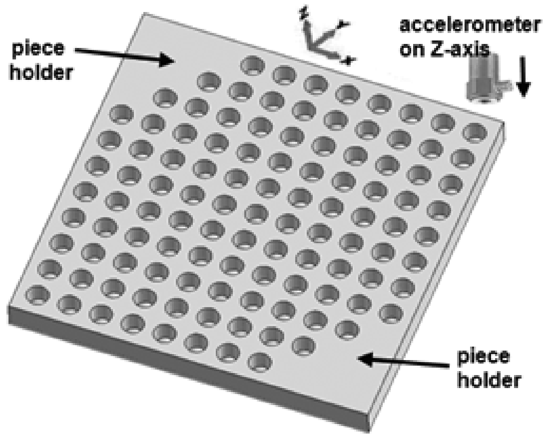

Figure 4: 3-D view of the workpiece model

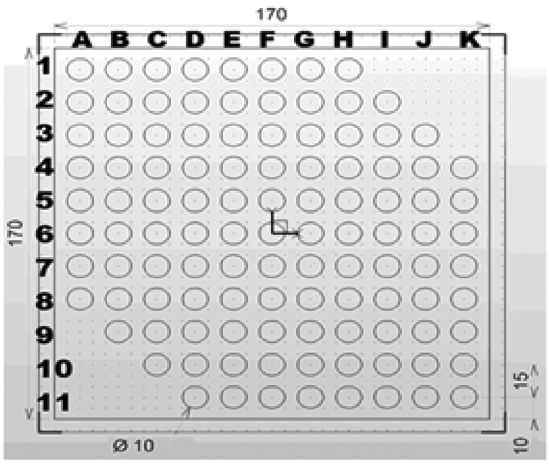

Figure 5: Top view of the workpiece model

3. RESULTS AND DISCUSSION

The previously described cutting conditions and drill aging strategy resulted to a quite significant deterioration of the tool's performance, evident even from the third operated workpiece (WP 3) and, finally, lead to a worn-out state due to which the tool failed and stopped any further drilling on the fourth workpiece (WP 4), after 367 drilled holes.

Figure 6 presents the raw pattern of the obtained Z-axis vibration signals for the time period of specific drillings and the evolution of this raw data through the whole experimental process. As it can be seen in Figure 6, the acquired vibration signals can be characterized as consisting of short oscillatory transients of high, narrow band frequency, occurring randomly within the period required to drill one hole. With the progress of drill wear, the amplitude of these transients starts to increase. Immediately before breakage, these transients resemble those of a resonating system responding to some impulsive excitation in the cutting process at a frequency which is independent of cutting conditions such as feed or speed. By far, the majority of the vibration signals consist of frequency components related to the dynamics of the cutting system.

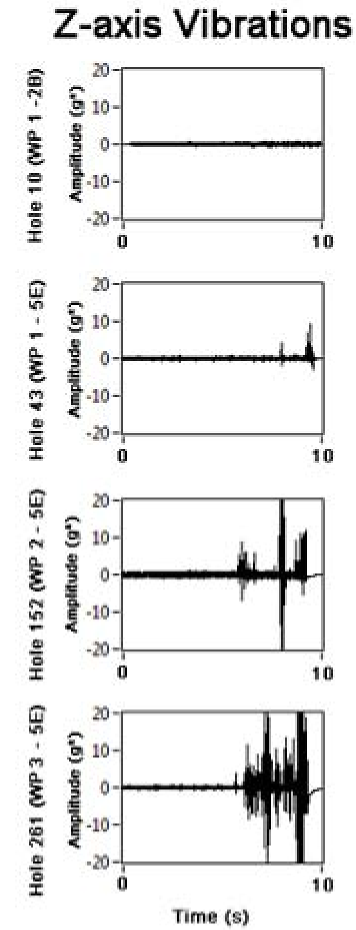

*Figure 6: Raw Z-axis vibration signals for the time period of specific drillings (*g=9.81 m/s^2)*

More specifically, there is an indicative "response" of the measured raw signal to the progressively evolving tool wear. The drilling of hole 2B of the first operated workpiece (WP 1), generated vibrations within the range of approximately ± 2 g, in a quite smooth signal pattern; a regular operation of a brand new tool is reflected to this steady-state stage. After 33 drillings, hole 43 gave a vibration signal similar to that of hole 2B of the same workpiece. However, this signal appears to be less smooth due to the presence of numerous spikes across its length, especially at its last part where some vibration spikes reach values near to 10 g. The respective hole 5E of the next operated workpiece (WP 2), i.e. hole 152, gave a vibration signal with a, certainly, rough second half part in which several spikes fluctuate around the region of 10 to 12 g. Moreover, approximately 8 seconds from the start of the specific drilling vibrations approach values near to 25 g, i.e. the measuring limits of the employed accelerometers. Even from this stage of the experiment, the pattern of the generated vibration signal reveals possible slight or moderate tool wear, a remark that can be affirmed observing the next vibration signal, regarding the drilling of hole 5E of the WP 3 (hole 261). Here, the roughness of the signal, in the last 5 seconds, became more intense and more characteristic of a possible severe wear state of the tool. The described dramatic change of the vibration pattern could be considered as a preliminary predictive index of excessive tool wear and, consequently, tool failure which occurred indeed, as mentioned, during a drilling on the next workpiece WP 4.

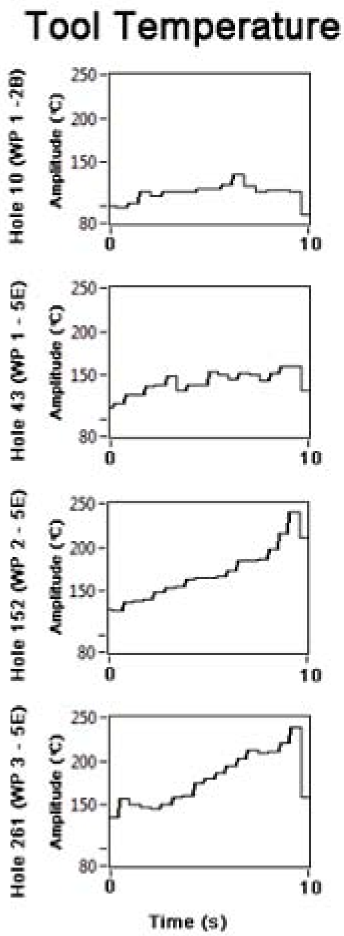

Figure 7: Raw temperature signatures for the time period of specific drillings

In the same way as vibration signals, thermal signatures, in Figure 7, appear to "react" to tool wear. When the tool is brand new (hole 10), its regular operation leaves a temperature offset that fluctuates between 80 and 130 °C. As the tool continues to drill, the overall temperature level of the signal increases, reaching to a maximum of 150 °C for hole 43 and 220-240 °C for holes 152 and 261. It should be noticed that, although the maximum temperatures for holes 152 and 261 seem to be practically equal, the overall level and the average value for hole 261 appears slightly increased in contrast to that of hole 152.

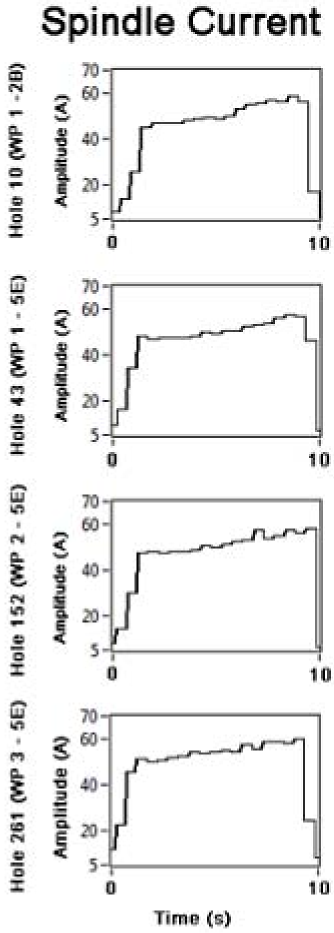

Figure 8: Raw spindle motor current signals for the time period of specific drillings

On the other hand, according to Figure 8, spindle motor current signal, in a raw form, may not be considered as legible tool wear index. Feed motor current showed a raw signal pattern similar to the spindle motor current's one and it is neglected in this analysis. It can be said that, both spindle motor and feed motor current do not "react" to tool wear as dynamically as other parameters, such as vibrations and tool temperature; the obtained raw signals from holes 10, 43, 152 and 269 have similar characteristics and any effort to interpret and correlate them in terms of tool wear is, at least, unreliable. Thus, for these two parameters, further analysis and signal processing are reckoned as necessary.

In order to configure a more in-depth view of the impact of tool wear to the measured parameters, statistical (time domain) and Fast Fourier Transforms (FFT) analyses (frequency domain) were performed. Statistical analysis of the acquired signals included the assessment of mean, average, maximum, variance, kurtosis and RMS values in each signal. Kurtosis and RMS performed significantly well as tool wear indicators but kurtosis proved to be unable to "notify" and obviate tool breakage. Hence, suggestively, Figure 9 shows the chart resulted from the RMS values of the obtained vibration signal and the related best fit curve, through the entire duration of operations to the first three workpieces, i.e. from hole 1 (WP 1 – 1A) to hole 327 (WP 3 – 11K). Both the obvious trend of the RMS values and, mostly, the best fit curve show the expected; vibration measurements react to drill wear, as it has been also noticed from Figure 6. The machine tool is a dynamic system and as the wear of the tool increases, cutting forces increase too and consequently the system's response will also increase. This "interaction" between the tool wear evolvement and vibrations, renders to an exponential curve, as shown in Figure 9.

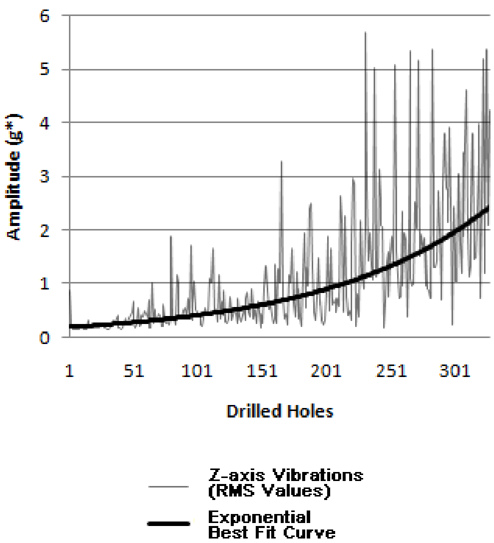

*Figure 9: RMS values of the obtained vibrations and the related best fit curve (*g=9.81 m/s²)*

The corresponding function of the exponential curve is giver from equation (1).

$$v = 0.186 \cdot e^{0.008 \cdot h} \qquad (1)$$

where v is the amplitude or the vibration value, in g (vertical acceleration), and h is the number of drilled holes which corresponds to tool use and, consequently, to tool wear. Experientially, in such cases, there is a threshold where the slope of the curve increases in a sensible way that reflect the worn-out state of the tool. For the current cutting conditions, workpiece material and tool structure this threshold is estimated between hole 327 and 340.

In the same way, Figure 10 shows the chart generated from the RMS values of the obtained tool temperature signal (tool thermal signature) and the related best fit curve, for the same duration as Figure 9. As the tool wear increases during the time and the process, the heat balance among the tool, the piece and the chip is unsettled and consequently the cutting edge temperature increases too. As with the RMS vibration values, here, RMS tool temperature values reveal the same substantial interaction between tool wear and tool temperature that is noticed in Figure 7 and can be described by a logarithmic approach, i.e. the best fit curve that corresponds to the function that is given by equation (2).

$$T = 12.45 \cdot \ln(h) + 96.17 \qquad (2)$$

where T is the amplitude or the tool temperature (in ^{o}C). The logarithmic form of the above best fit curve can be explained by the fact that, after a prompt increment to the tool's temperature value (transient state), its finite heat capacity decelerates the rise of the temperature within the tool material until a critical "breakdown" in which the tool glows and fails due to excessive wear and/or dissolving.

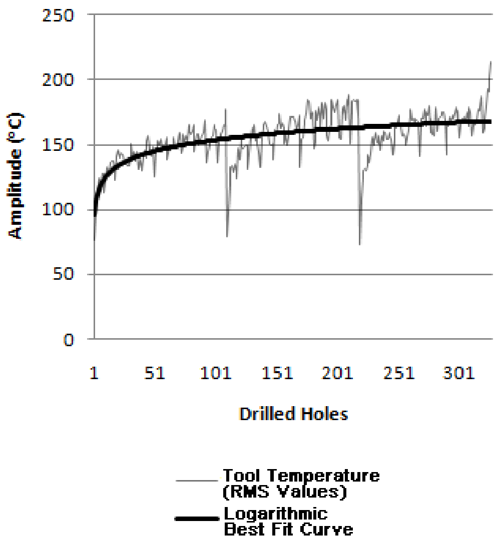

Figure 10: RMS values of the measured tool temperature and the related best fit curve

Figure 11 presents the chart resulted from the RMS values of the obtained spindle motor current signal and the related best fit curve, from drilled hole 1 to 327. There is a slight, but evident, trend of the RMS values of spindle motor current toward the number of drilled holes and, consequently the tool wear. This trend can be described by the linear best fit curve in the same figure and mathematically represented by equation (3).

$$I_s = 0.013 \cdot h + 46.5 \qquad (3)$$

where I_s is the amplitude or the spindle motor current (in A). This linear function reflects the slowly evolving increment to the spindle current's values as the tool passes from the initial wear state to moderate, severe and, finally excessive wear state (worn-out). In other words, when the cutting tool is almost new, it drills under optimum performance consuming the less possible spindle motor power/current. As the tool continues drilling, its cutting edge cannot perform in an optimum way and, therefore, the tool needs more power; as a result, the spindle motor current consumption increases progressively with the tool wear.

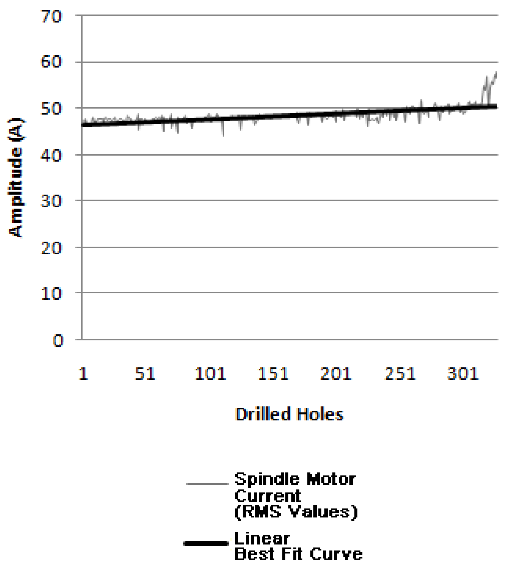

Figure 11: RMS values of the measured spindle motor and the related best fit curve

During the analysis of the obtained signals that were evaluated in this work, the feed motor current proved to be the less representative parameter for tool wear detection. As it has been already noticed, raw data showed that feed current presents an almost stable behaviour against progressive tool wear, a fact that is confirmed by the statistical analysis, in time domain, of this signal. Figure 12 shows the evolution of the RMS values of the obtained feed motor current signal and the related best fit curve, for the operation of the first three workpieces. It is clear that, the major part of these RMS values ranges from 1 to 3 A with several, but random, spikes across the entire signal, that reach values from 4 to 5 A. Similarly to the spindle motor current case, the best fit curve for the feed current is linear.

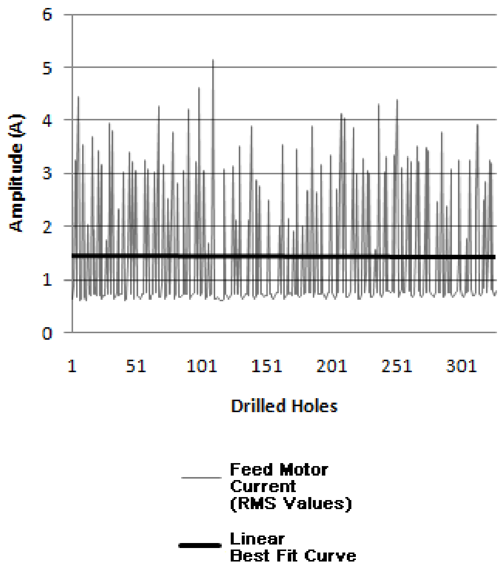

Figure 12: RMS values of the measured feed motor and the related best fit curve

However the feed motor current's amplitude curve of Figure 12 remains constantly to the value of approximately 1.5 A and, consequently, does not indicate any interaction between the tool wear and the feed motor current. The relative linear function is given by equation (4):

$$I_f = -7 \cdot 10^{-5} \cdot h + 1.44 \qquad (4)$$

where I_f is the amplitude or the feed motor current (in A). As for spindle motor current, the above best fit curve is described by a linear function, in the form of $y = a \cdot x + b$. In this case, the slope of the curve is $a = -7 \cdot 10^{-5}$ and, thus, it can be neglected resulting to a nearly constant feed motor current $I_f = 1.44$, independent from tool wear.

In addition to statistical analysis, Fast Fourier Transforms from time domain to frequency domain is also a widely reported signal processing technique, for such indirect methods of tool wear monitoring. FFT is an efficient algorithm to compute the discrete Fourier transform (DFT) and its inverse. In this work, FFT analysis was applied to the raw data of the obtained signals, using a 3rd order Chebyshev bandpass filter with cutoff frequency n_c=4 KHz. Figure 13 presents the results of this analysis to the signals of vibration for holes 10, 43, 152 and 261. The presented power spectral density (PSD) of each signal is in fact the square of the FFT (magnitude).

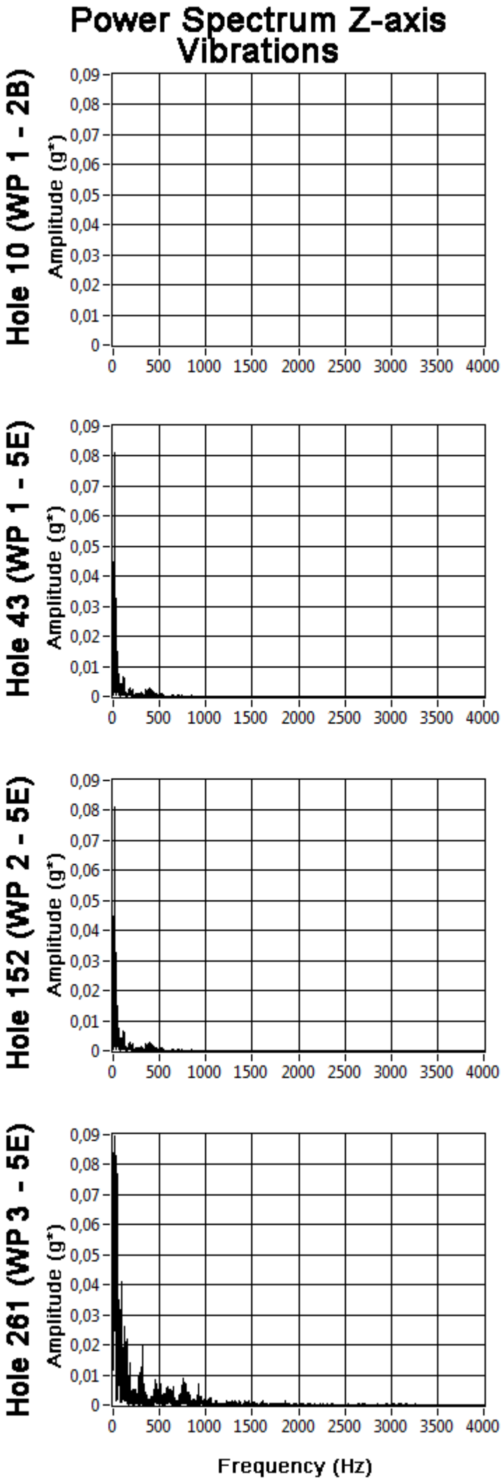

*Figure 13: FFT analysis of the obtained vibration signals (*g=9.81 m/s²)*

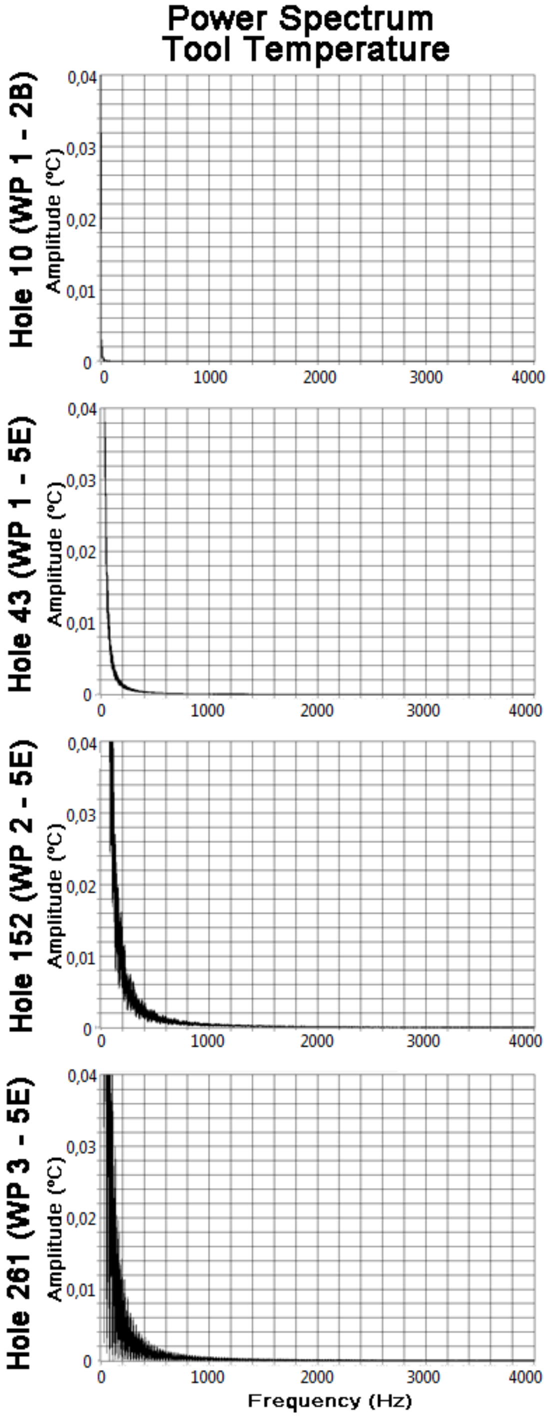

Figure 14: FFT analysis of the obtained tool temperature signatures

As other researchers have already mentioned [25], different combinations of cutting conditions result in different patterns and amounts of drill wear. The various drill wear patterns may change the resulting vibration signatures in the frequency domain. Therefore, it is important to investigate the effect of each type of wear on the vibration power spectra generated during drilling process. This is accomplished by performing "controlled" wear experiments. In the experiments of the current work, due to lack of "controlled" aging mechanism, mainly two types of wear were experimentally induced on the drill, and the resulting vibration and temperature spectra were evaluated. These types of wear are the outer corner wear and the flank wear according to Kanai and Kanda [26] classification. According to the same researchers, the dominant types of wear which result in drill failure and breakage are: chisel wear, outer corner wear, flank wear and margin wear.

Figure 13 indicates qualitively the increment of the vibration signal's power amplitude, in the frequency range of 1.0-2.5 KHz, gradually with the progress of wear. An almost identical trend is seen in the temperature related signal (Figure 14). In general, the vibration signals measured in the Z-axis direction are predominantly affected by corner wear and margin wear. Flank wear and chisel wear have similar, but lesser effects on the vibration spectra, as other researchers have mentioned [27]. The results show, undoubtedly, that both vibration and temperature spectra can be used to identify worn drills.

Figures 15 and 16 show, in an unambiguous way, the impact of tool wear to the tool edge's surface morphology. These images, obtained by a microscope lens, confirm the observed and previously discussed progressive tool wear that was indicated, mainly, by both vibration signals and tool temperature signatures and, secondly, by the spindle motor current measurements.

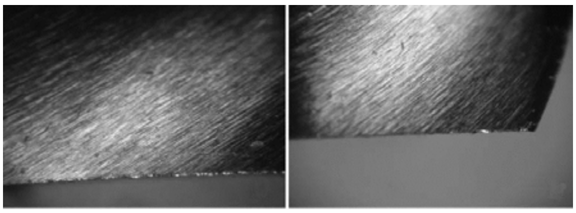

Figure 15: Microscope-based view of the performed tool's edge before the experiment

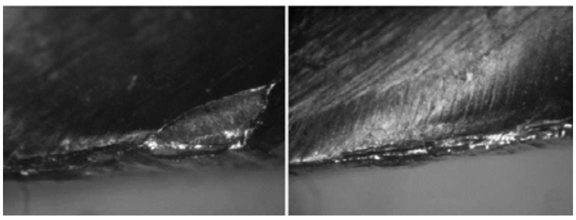

Figure 16: Microscope-based view of the performed tool's edge after 367 drills (excessive wear)

4. SUMMARY

The presented experimental study investigated the efficiency of vibration signals, tool temperature signatures, spindle motor current and feed motor current as in-process tool wear and/or breakage indices in drilling.

A brand new drilling tool was employed to perform several drills under selected "normal" and "false" conditions in order to achieve a significant level of wear. During these operations, an accelerometer, an IR temperature transmitter (infrared pyrometer) and two current transducers were used to obtain the generated signals of vibration, tool temperature and spindle/feed currents respectively. Statistical parameters in time domain, such as RMS, and FFT analysis in frequency domain were used to extract the meaningful information from the raw data.

The results of this work indicated a significant interaction between specific signals and the dynamics of the drilling process, i.e. the slowly evolving tool wear. Even from a quick view to the raw signals, vibrations and tool temperature prove their supremacy as quite reliable and robust tool wear prognostic indices. Further signal processing of these two parameters clearly confirms their reaction to tool wear, verifying Figure 2. Although, it can be said that, tool temperature acquisition was proved to be more suitable for implementation in a real industrial environment, in contrast to vibration monitoring techniques, which are strongly dependent on noise, cutting conditions and specific, only, tool wear types. With regard to spindle motor current, it was noticed that the acquired raw data was inadequate to indicate a clear correlation between this parameter and the tool wear. Nevertheless, statistical processing helped to extract a quite crescive curve reflecting a linear relation between spindle motor current and tool wear. On the other hand, feed motor current was found as contraindicative parameter in this study. Neither raw data analysis, statistical parameters nor FFT analysis showed that tool wear could induce the characteristics of feed motor current signal.

In conclusion, generally speaking, the simpler a TCM system is, the less likely it is to fail. Reliability was rated as being the most important concern by those actually using some form of TCM. Thus, it is obviously vital to minimize the complexity of any future TCM system [6]. Further ambition of the current research team is to:

- Develop practical vibration monitoring techniques which are sensitive to tool conditions but relatively insensitive to cutting conditions and sensor location.
- Assess the applicability of infrared thermography, with the use of portable thermal imagers, to tool temperature data acquisition.
- Prepare and implement several precise and "controlled" rapid tool aging strategies.
- Investigate same or similar sensor-based methods for in-process tool wear/breakage monitoring in other cutting operations, e.g. turning or milling.
- Enrich the presented monitoring system with a fuzzy logic and neural network based classification tool.

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A MULTI-BODY MODEL OF GEARS FOR SIMULATION OF VIBRATION SIGNALS FOR GEARS MISALIGNMENT

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Summary

In the paper a dynamic model of spur gears was developed and compared with an experimental data in case of simulation of vibration signals. Comparison was done on the basis of the signals generated by the model and the real object.

The experiment was conducted on an experimental gearbox named DMG-1, that allows to introduce other failures of gears. During the experiment correct work as well as incorrect work of the gears due to misalignment were investigated. In the study a multi-body dynamics model of the gears was developed. The MSC ADAMS software was used for model development and tests. Simulations were conducted for different operation conditions; two values of rotational speed and loading were studied. Behaviour of signals features was similar in both experiment and model for investigated technical states (correct work and misalignment), this was observable by increase of amplitudes for high order gear meshing frequency harmonics, in the model occurs modulations of meshing harmonics by rotational speed, either.

To sum up, in the study it was shown that it is possible to simulate vibration signals by the model of the gears created in multi-body dynamics software, what is evidenced by proper generation of gear meshing frequency harmonics, dependent on rotational speed. For simulation of misalignment the model exhibits greater sensitivity by bigger gain of examined parameters.

Key words: rotating diagnostics, modelling and signal processing for CM, diagnostics of mechanical systems/machines/components.

MODEL KÓŁ ZĘBATYCH DO SYMULACJI SYGNAŁÓW WIBRACYJNYCH DLA WSPÓPRACY KÓŁ Z PRZEKOSZONYMI OSIAMI

Streszczenie

W artykule został przedstawiony oraz porównany z danymi eksperymentalnymi model dynamiczny kół zębatych. Porównanie zostało przeprowadzone na podstawie sygnałów generowanych przez model i obiekt rzeczywisty dla różnych stanów technicznych.

Eksperyment został przeprowadzony na demonstracyjnym stanowisku do badań przekładni zębatych DMG-1, które pozwala na wprowadzenie różnego rodzaju uszkodzeń. Podczas eksperymentu badana była poprawna praca przekładni oraz stan niezdatności związany z przekoszeniem osi jednego z kół. W artykule został przedstawiony model dynamiczny kół zębatych zbudowany na podstawie metody układów wieloczłonowych. W celu budowy modelu i przeprowadzenia testów zostało wykorzystane specjalistyczne oprogramowanie komputerowe. Symulacje zostały przeprowadzone dla różnych warunków pracy: różne wartości prędkości obrotowej oraz obciążenia. Trend zmian cech sygnału wibracyjnego był porównywalny podczas eksperymentu i badań modelowych dla badanych stanów technicznych (poprawna praca, przekoszenie) - wzrost amplitudy drugiej harmonicznej częstotliwości zazębienia. Dla sygnałów otrzymanych z modelu również pojawiły się wstęgi boczne wywołane modulacjami przez prędkość obrotową wałów.

Podsumowując, w artykule została przedstawiona możliwość zastosowania dynamicznego modelu kół zębatych opartego na metodzie układów wieloczłonowych do symulacji sygnałów wibracyjnych. Częstotliwości zazębienia generowane przez model są zgodne z założonymi warunkami pracy (prędkość obrotowa, ilość zębów). Podczas symulacji stanów niezdatności model wykazuje większą czułość na wprowadzone uszkodzenie niż obiekt rzeczywisty.

Słowa kluczowe: Diagnostyka maszyn wirnikowych, Modele dynamiczne kół zębatych, Modelowanie uszkodzeń przekładni zębatych.

INTRODUCTION

Toothed gears are commonly used in various power transmission systems. It is important to collect information about their degradation processes to prevent significant damages during exploitation. Properly registered and processed vibration signals may serve as a source of diagnostic information [2, 3, 4]. In the mechanical diagnostics it is very important to find vibration signature for monitored failures. For classification of vibration signals there are used other techniques e.g. advanced signal processing algorithms or artificial intelligence methods [5, 1]. Some authors [12, 16] focused towards features that are used for the detection of gear faults. In this works authors propose categorization of these features into five different groups based on their pre-processing needs. Modelling the dynamics of gearboxes in useful in condition monitoring, it allows to simulate signals for other states of a gearbox that sometimes cannot be checked in experimental way. There are several modelling methods for simulating behaviour of the gearboxes in case of generated vibration signals: mathematic modelling, computer based finite element methods and multi-body dynamics approach. The multi-body analysis seems to be the most suitable for such analysis, because it allows the time domain integration of the solution, which captures the nonlinear effects of bearing stiffness and clearances, gear backlash, large rotations and other nonlinear phenomena [14]. Specialized multi-body dynamics software like ITI-SIM, SIMPACK, LMS Virtual.Lab Motion and MSC ADAMS allow to model three-dimensional gear bodies, tooth microgeometry, global and local tooth stiffness. One of the study describing multibody approach for simulating vibration behaviour of the gears can be found in [6]. The model permits the dynamical simulation of planetary gearboxes, considering the stiffness characteristics. New approach for modelling gear systems was presented by S. Ebrahimi et al. [7]. It assumes that teeth and the body of gear wheels are rigid but they are connected by elastic elements. In the [14] authors present a methodology for calculation of gear bearing forces, in focus on estimating gear noise. Other paper which treats about multibody dynamic model developed in multi-body dynamics software MSC ADAMS are presented in [8, 11, 15]. Kong et al. [11] presented dynamic simulations of the gears in mesh for other states (as broken tooth). In the [8] three models (an equivalent model, rigid-body model, and frequency-based model) were compared in case of simulation of the meshing forces. The model which assumes nonlinear contact algorithm between teeth of gears and geometric defects of gears like chipped tooth and eccentric tooth was presented in [15]. Authors present behaviour of the model in steady and transition state conditions. Referring to the study [6, 7, 8, 11, 14, 15] there is no presented comparison of the results from computer simulations with the experiment. In the real object there are interferences of vibrations from all power transmission system e.g. bearings, couples or motors. In the articles authors do not present quantitative comparison of the parameters of the signals for correct and incorrect work of the gearbox which is useful in condition monitoring.

In the presented study a dynamic model of spur gears was presented. The model was developed in multibody dynamics software MSC ADMAS. The purpose of the modelling was to simulate vibration signals for misalignment of gears. Misalignment is one of the most common gears manufacturing failure, it is associated with increased noise and vibration level, as well as wear of gear teeth and bearings failures. Gear misalignment excites second order or higher gear meshing frequency harmonics [13, 17]. The model was validated with experimentation on the basis of features extracted from vibration signals.

1. THE EXPERIMENT

The experiment was conducted in the Laboratory of Mechanical Diagnostics at the AGH University of Since and Technology in Cracow. The workbench consists of a motor, elastic clutch, two pairs of gears with gear ratio 1:1 and hydraulic pump 5 MPa. There is possible to manipulate rotational speed by steering system of the motor as well as changing value of the loading by the hydraulic pump. The experimental gearbox allows to introduce other failures of gears such as misalignment, increased centre distance of gears and pitting. In the experiment acceleration signals were registered on the bearing support in the vertical direction, the PCB 356A15 accelerometer has been used. A laser tachometer was used for measuring rotational speed. All the signals were measured by National Instruments C Series module 9223, with a sample rate up to 1 MS/s and simultaneous analog-to-digital converters. The measuring system is presented on the fig. 1.

Fig. 1. Experimental gearbox and measuring system

During the experiment, correct as well as incorrect work of the gears due to misalignment were studied. All measurements were conducted in the steady-state conditions for other rotational speeds (400 and

800 RPM) and other values of the loading (1 and 3 MPa). The registered signals were filtered by cascade stop-band filter in such way to remove all frequencies, beside of first five meshing frequency harmonics. The width of the filter was set up to include second order sidebands.

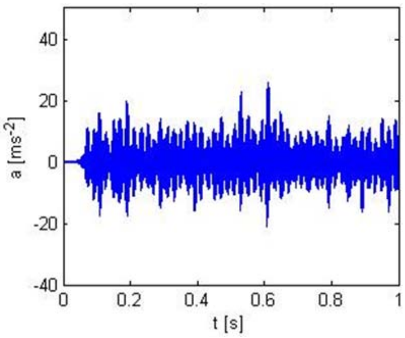

Fig. 2. Signal measured in the experiment for correct work of the gears, with high loading and rotational speed 800 RPM

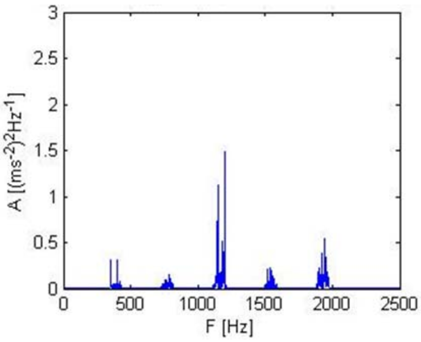

Fig. 3. PSD for signal measured in the experiment for correct work of the gears, with high loading and rotational speed 800 RPM

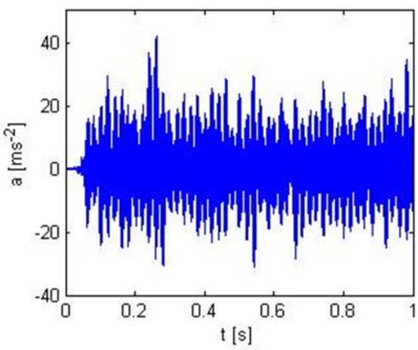

Fig. 4. Signal measured in the experiment for incorrect work due to misalignment of the gears, with high loading and rotational speed 800 RPM

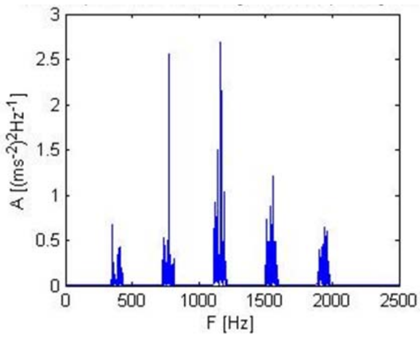

Fig. 5. PSD for signal measured in the experiment for incorrect work due to misalignment of the gears, with high loading and rotational speed 800 RPM

On the figures above example of the signals from the experiment were presented; the fig. 2 and fig. 4 present time signal for correct and incorrect state of the gears, the Power Spectral Density (PSD) of these signals was presented on the fig. 3 and fig. 5. On the presented figures it is observable that amplitude of the second meshing frequency harmonic significantly increase for misalignment.

2. THE MODEL OF THE GEARS

In the study a model of the gears was built in the multibody dynamics software MSC ADAMS. Firstly three dimensional CAD model of the gears was developed in the CATIA software. Next the CAD model was transferred into the ADAMS environment. In the multi-body dynamics software the model of the gears was properly constrained and the forces were applied. The parameters of the gears were presented in the table 1.

Table 1. Gear parameters.

Parameter	Symbol	Value
Teeth	z1, z2	29
Modulus	m	3.065
Pressure angle	a	20 [deg]
Pitch circle radius	rp	44,435 [mm]
Outer circle radius	ra	47,5 [mm]
Base circle radius	rb	41,755 [mm]
Root circle radius	rf	40,605 [mm]

Two variants of gears dynamics modelling can be distinguished; models where all phenomena occurring in a power transmission system are included and models which take into account only phenomena inside of a gearbox. In the first kind of models dynamics of motor, couples, gears and working machine are included. Other approach considers physical phenomena occurring only inside of a gearbox, the time varying stiffness, technology of gears mostly affect on dynamics. This approach is used for calculating of dynamic forces in teeth or to identify indicators of teeth failures [18]. In the real object meshing stiffness vary in time, it depends from number of intermeshing teeth and deflection of a tooth by the action of normal force during meshing. Across of a path of action stiffness is changing as a parabola function [18, 19]. In the presented model meshing stiffness depends on number of teeth in contact and parameters of contact algorithm which assume elastic contact between teeth. Depending from backlash teeth may lose contact or work on opposite sides, this may induce large impact forces associated with consecutive single-sided or double-sided impacts, wrongly designed backlash may cause teeth interference and undercut [18]. On the fig.6 model view in ADAMS software was presented.

Fig.6. CAD model of gears

In the model gears and shafts are considered as rigid bodies, contact surfaces between teeth are flexible, the backlash between gears was assumed, either. The fixed joints between gears and shafts and revolute joint between shafts and ground were used. Constant rotational motion was applied on revolute joint on the shaft of the active gear and a resistive torque on the shaft of the passive one. The model assumes ideal involute teeth geometry. On the fig. 7 the model was presented.

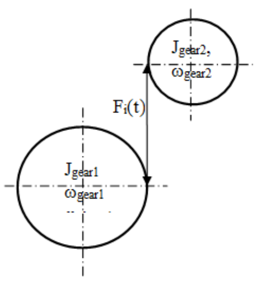

Fig.7. Model of gears

To simulate vibration signals during meshing, contacts and Coulomb friction between teeth of two gears were assumed. For contacts model the MSC ADAMS Impact algorithm was chosen, because of its robustness in numerical integration [15]. Equation (1) describes a contact force in the ADAMS Impact algorithm. The contact force is composed of two parts: the elastic component and the damping force, which is a function of the contact-collision velocity. By the definition of the step function (2), the damping force is defined as a cubic function of penetration depth [11].

$$F = \begin{cases} K(x_0 - x)^e + CS\dot{x} & x < x_0 \\ 0 & x \geq x_0 \end{cases} \quad (1)$$

$$S = \begin{cases} 0 & x > x_0 \\ (3 - 2\Delta d)\Delta d^2 & x_0 - d < x < x_0 \\ 1 & x \leq x_0 - d \end{cases} \quad (2)$$

In the equation (1-2) $\Delta d = x_0 - x_1$ describes deformation of a body, K contact stiffness, e force exponent, C damping parameter and penetration depth was assigned by d. Stiffness between teeth pair in contact can be described by the Hertz elastic contact theory (3). In this model stiffness was described by a pair of ideal cylinders in contact [9,11].

$$\begin{cases} K = \frac{4}{3} R^{\frac{1}{2}} E^* = \frac{4}{3}\left[\frac{i d_1 \cos(\alpha_t) \tan(\alpha'_t)}{2(1+i)\cos(\beta_b)}\right]^{\frac{1}{2}} E^* \\ \frac{1}{E^*} = \frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} \\ \beta_b = \operatorname{atan}(\tan\beta \cos\alpha_t) \end{cases} \quad (3)$$

In the equation (3) the R describes equivalent radius of two contacting bodies, E^* equivalent Young's modulus of two contacting bodies, i gear ratio, d_1 diameter of standard pitch circle, α_t', α_t transverse pressure angle at engaged and standard pitch circle, β, β_b helical angle at the pitch and base circle, v_1, v_2, Poisson ratio of the pinion and gear. The Young's modulus of pinion and gear are described by E_1, E_2, respectively. In the model it was assumed that the gears are made from steel with Young modulus $2.1 \cdot 10^{11}$ Pa, and Poisson ratio 0.3. The equivalent Young modulus for two bodies in contact $1.153 \cdot 10^{11}$ Pa. In the contact algorithm the damping coefficient was assumed as 0,1% of contact stiffness. Determination of the force exponent was based on the experiment. The material of the gears is alloy steel the parameters for Coulomb friction were taken from the literature [11, 15]. Parameters used in ADAMS Impact algorithm are presented in table 2.

Table 2. Contact parameters for MSC ADAMS.

Parameter	Symbol	Value
Contact stiffness	K	$2.9852 \cdot 10^5$ [N/mm$^{3/2}$]
Damping coef.	C	3000 [Ns/mm]
Force exponent	e	1,3
Static friction coef.	υ_s	0,1
Static transition vel.	V_s	1 [mm/s]
Dynamic friction coef.	υ_d	0,08
Friction transition vel.	V_f	10 [mm/s]

For dynamic simulation of the model the integrator WSTIFF and the Stabilized Index-2 (SI2) formulation were chosen. The integrator WSTIFF allows control the numerical integration of the equations of motion for a dynamic analysis [10]. Parameters of simulations are like follows: number of steps 6000, simulation time 1s, rotational speeds 400RPM and 800RPM. Two values of torque were used during simulations 100 and 200 Nm. During the simulation force signal was measured in vertical direction between gear and shaft. On the fig. 8 and 10 signals obtained from the model tests were presented.

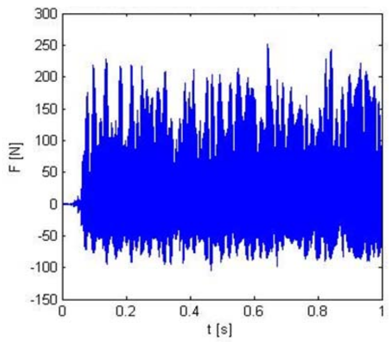

Fig. 8. Signal from model for correct work of the gears, with high loading and rotational speed 800 RPM

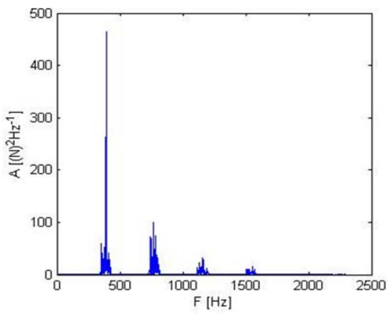

Fig. 9. PSD for signal from model for correct work of the gears, with high loading and rotational speed 800 RPM

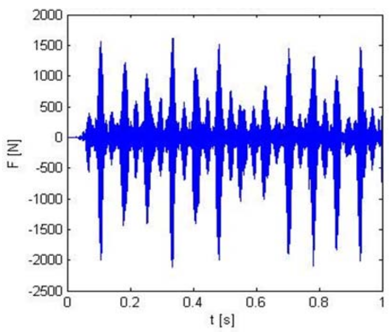

Fig. 10. Signal from model for incorrect work due to misalignment of the gears, with high loading and rotational speed 800 RPM

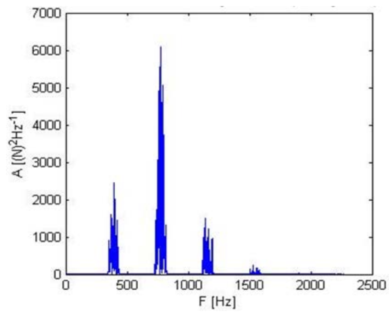

Fig. 11. PSD for signal from model for incorrect work due to misalignment of the gears, with high loading and rotational speed 800 RPM

On the plots above force signals between gear and shaft during the time of simulation are shown, as well as spectra of this signals. The signals were filtered by cascade pass-band filters in the same way as in the experiment; to receive only bands with harmonics of the meshing frequency. The location of the meshing frequency harmonics (fig. 9 and 11) is compliant with theory (4).

$$F_m = z * F_{rot} * n. \tag{4}$$

In the equation (4) F_m meshing frequency harmonic, z number of teeth, F_{rot} rotational frequency and n harmonic number. For gears with misalignment of the axes on the spectra, modulations of meshing frequency harmonics by rotational speed were observable, also there was significant increase of the second meshing frequency harmonic.

3. ANALYSIS OF THE RESULTS

In this chapter comparison of estimates of the signals from the experiment and the model was presented. Comparison has been done on the basis of energy value estimated in the bands for meshing frequency harmonics [12, 16]. Incorrect work of gears was due to misalignment of one gear axes about 1 degree. Measurements have been done for two rotational speeds: 400 RPM, 800 RPM and for case with low and high loading. In the study the signals were filtered by pass-band filter to receive signal containing particular meshing frequency harmonic and its second order modulation sidebands; in the study first five meshing frequency harmonics were considered. On the fig.12 the RMS values in the bands were presented, for signals measured during the experiment.

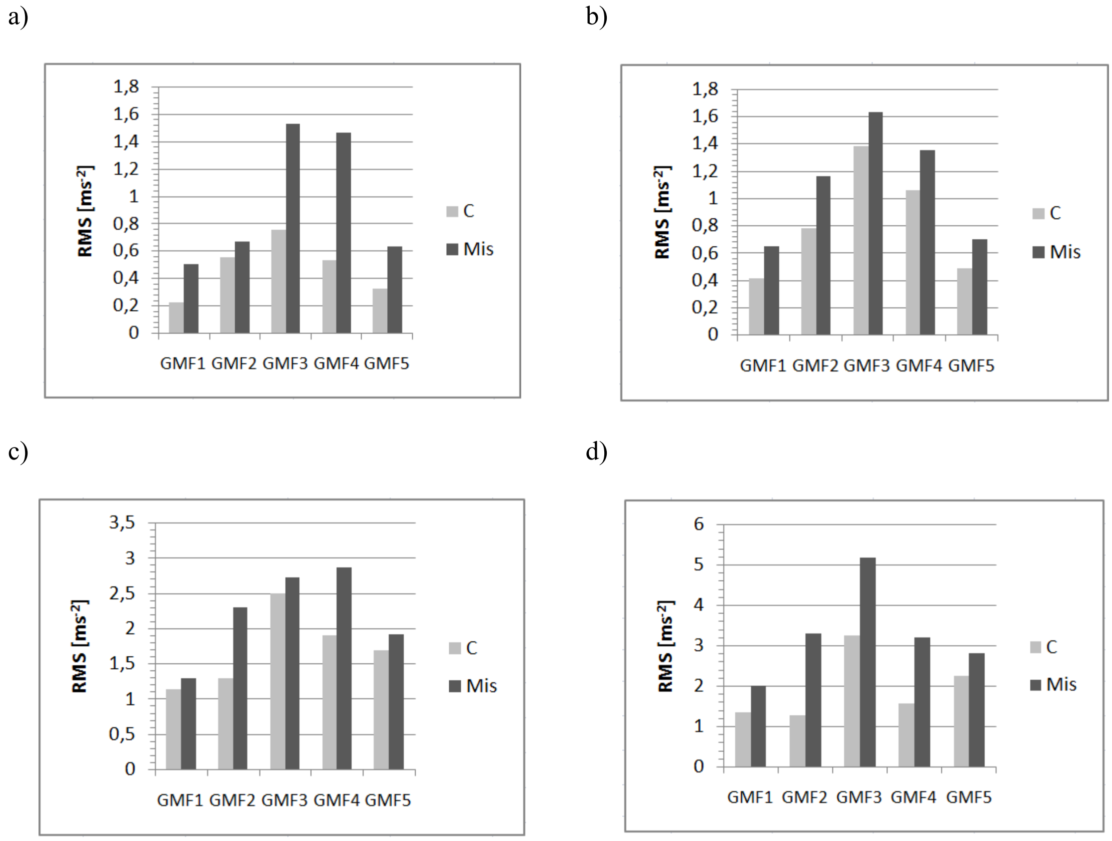

Fig. 12. RMS in bands for signals from experiment, a) 400RPM, low loading, b) 400 RPM, high loading, c) 800 RPM, low loading, d) 800 RPM, high loading. (C- correct state, Mis–misalignment)

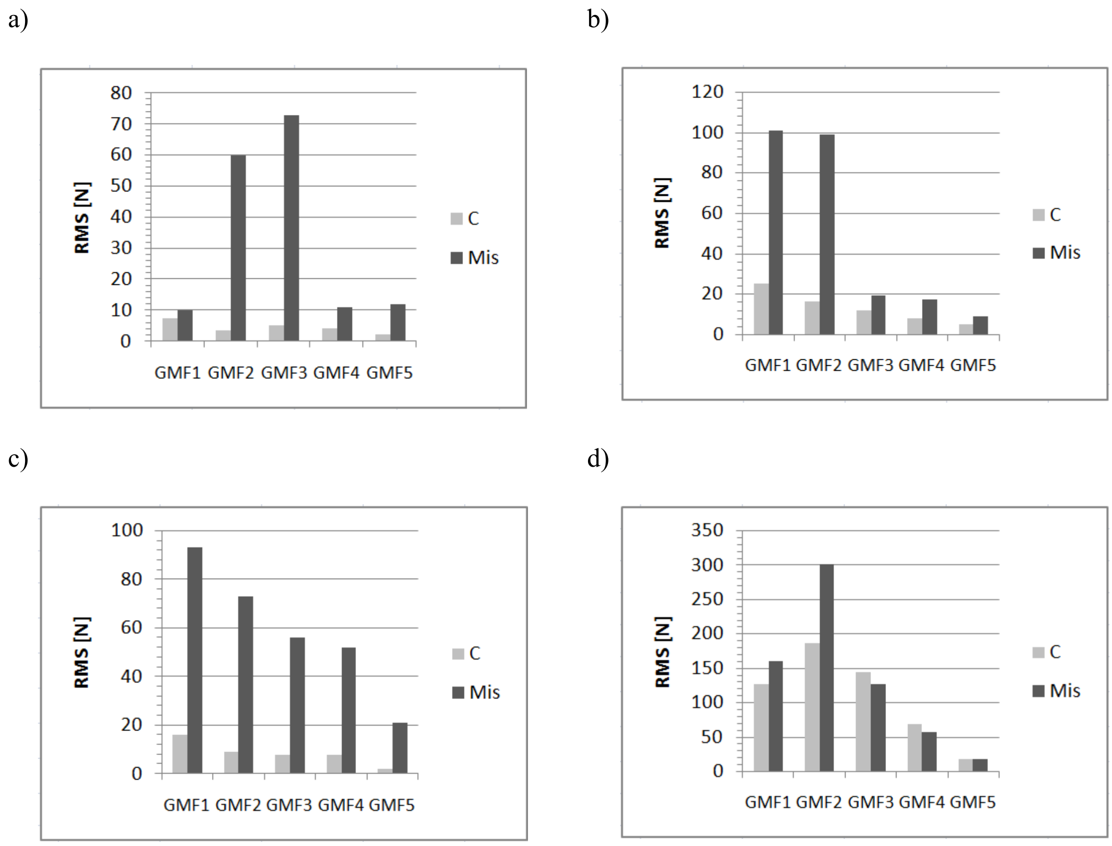

Fig. 13. RMS in bands for signals from model, a) 400RPM, low loading, b) 400 RPM, high loading, c) 800 RPM, low loading, d) 800 RPM, high loading. (C- correct state, Mis–misalignment)

It is observable that energy in bands increases for misalignment, particularly for higher harmonics. For experiment with low rotational speed increase of RMS about 20% was observable for misalignment of the gears comparing to correct state, fig. 12a) and fig. 12b). For second rotational speed, fig. 12c) and fig. 12d), the increase of energy in bands (about 30%) due to misalignment was observable, especially for GMF2, GMF3 and GMF4. For the model simulations behaviour of the examined feature was similar, fig 13. The significant gain of signal energy in case of gears misalignment can be observed. In every case there is significant increase of the second GMF.

To sum up, in the study it was shown that it is possible simulation of gears vibration signals by model of the gears created in multibody dynamics software, what was evidenced by proper generation of GMF harmonics. For simulation of gears manufacturing errors (misalignment) the model exhibits greater sensitivity than real object; bigger gain of RMS values in the bands due to misalignment comparing to the experiment.

3. SUMMARY

In the presented study the dynamic model of the spur gears was developed and compared with an experimental data in case of simulation of vibration signals for other technical states of the gears. In the paper manufacturing failure as misalignment of gears' axes were studied. To build and simulate the model of the gears MSC ADAMS software was used, simulations were conducted for different operation conditions of the gears. The model allows simulation of the force signals between shaft and gear during meshing, in the experiment the acceleration signals on the bearing support were measured, nevertheless indicators for misalignment were similar in both cases. It is observable by increase of amplitudes of higher order GMF both in the experiment and simulation, there also occurs modulations of GMF by rotational speed frequency in case of misalignment. The model exhibits greater sensitivity for misalignment what can be seen by greater increase of analyzed estimators comparing to correct work of the gears. This behaviour could be explained by simplifications assumed in the model like: lack of lubrication and application of rigid bodies for gears and shafts.

Presented three-dimensional model allows for simulation of vibration signals during meshing of the gears. In distinction from study conducted so far [6, 7, 8, 11, 14, 15] in the paper comparison of the model with experimental data was presented. The presented model should be improved. Instead of rigid-elastic model, fully elastic model could be build by application of flexible bodies, this allows to take into account deformation of a shaft and teeth in mesh. In the future model bearings should be included, either. Such improved model could be used for identification of vibration signature of gears failures in high-power machinery, what would be useful in condition monitoring.

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ACQUISITION OF REQUIREMENTS FOR DIAGNOSTIC SYSTEMS

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Summary

Defining the expected functionality of a designed diagnostic system is the most critical stage of the development process. In general, needs that describe such system can be determined by means of a requirement set pursued by the designed system. One important task during the requirement acquisition process is the problem of requirement management. Specific requirements can be defined based on information from multiple sources, and the acquisition process is reduced to that of a negotiation between a customer and a contractor. However, an immediate application of many well-known software engineering methods is impossible in the case of diagnostic systems. Issues arise due to difficulties in defining a customer in the negotiation process. The proposed approach relies on considering a technical object as a virtual customer in the negotiation process. The customer is represented by an expert system with a knowledge base in the form of a multimodal statement network.

Keywords: requirements management, diagnostic system, multimodal statement network, expert system.

GROMADZENIE WYMAGAŃ DLA SYSTEMÓW DIAGNOSTYCZNYCH

Streszczenie

Jednym z najtrudniejszych fragmentów procesu projektowania systemu diagnostycznego jest etap definiowania oczekiwanej funkcjonalności takiego systemu. Potrzeby opisujące taki system mogą być określane za pomocą zbioru wymagań stawianych projektowanemu systemowi. Ważnym zadaniem pojawiającym się w procesie gromadzenia wymagań jest odpowiednie zarządzanie tym procesem. Poszczególne wymagania mogą być definiowane na podstawie wielu źródeł a sam proces ich pozyskiwania zazwyczaj sprowadza się do negocjacji pomiędzy klientem a potencjalnym wykonawcą projektu. Bezpośrednie zastosowanie jednej z wielu znanych metod, rozwijanych w ramach inżynierii oprogramowywania, jest jednak w tym przypadku niemożliwe. Spowodowane jest to przede wszystkim trudnościami w zdefiniowaniu klienta dla procesu negocjacji. Zaproponowano sposób postępowania polegający na rozpatrywaniu obiektu technicznego jako wirtualnego klienta w procesie negocjacji. Klient ten reprezentowany jest przez system doradczy z bazą wiedzy w postaci wielomodalnych sieci stwierdzeń.

Słowa kluczowe: zarządzanie wymaganiami, systemy diagnostyczne i doradcze, wielomodalne sieci stwierdzeń.

1. INTRODUCTION

Modern technology development results in more and more complex systems and technical objects. As their complexity increases, it is necessary to develop diagnostic systems in order to minimize an operational risk. Technical objects under the development are characterized by complexity as well as innovative solutions. With such objects it is possible to observe various signals (process variables and residual processes). At the same time, an advanced signal processing and analysis methods often performed with artificial techniques and methods is critical to acquire reliable estimates of the systems condition. Due to the above, the process of designing diagnostic systems is not an easy task. In a majority of cases the process is multi-stage. It incorporates a need of recognition or a definition of a function that the developed diagnostic system should perform. Next, it is necessary to generate a set of solutions for meeting the defined functions as well as determining existing or likely constraints (limiting criteria). The final phase of this process includes establishing of selection criteria and selecting an optimum solution that meets all accepted criteria. While searching for subsequent solutions of a diagnostic system it is clear that operating principles of a technical object for which the diagnostic system is designed should be accounted for. The issue concerns both the object's internal structure as well as its operating conditions. Moreover, domain specific requirements (technical

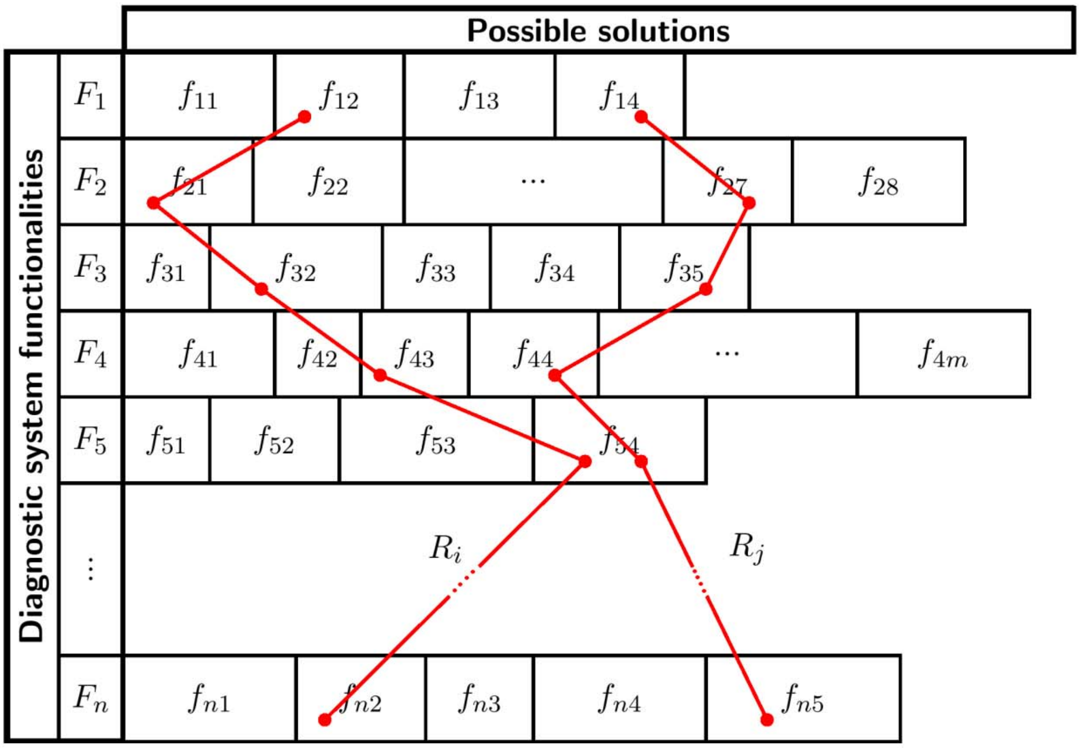

Fig. 1. Morphological table as a set of possible solutions

diagnostics) should be taken into account.

In general, a set of possible solutions of a diagnostic system can be represented using various techniques and methods. One such approach is the so-called morphological table [18] that is a common tool in the process of designing machinery and hardware. The morphological table concept is illustrated in Fig. 1. The successive rows of this table refer to the expected functionalities of the designed system. They incorporate row elements – variants of solutions to meet the expected functionality. The table size depends on two factors. Object characteristics for which the diagnostic system is developed influences the number of rows in a table whereas potential diagnostic methods and techniques determine the number of elements in particular rows.

Having a complete morphological table one may generate solutions of a diagnostic system (as shown in Fig. 1, for example) in the form of a combinations of selected variants of solutions to meet particular needs. In a generic scenarios and provided the table does not included repetitions it is possible to develop a set of solutions of the size

$$\prod_i card(F_i) \quad , \qquad (1)$$

where $card(F_i)$ is the number of elements of the row i of the table - i.e. the number of possible solution to meet the functionality i. Briefly, application of a morphological table guarantees that all possible solutions of a diagnostic system project will be included in the design process. However, note that the set of possible solutions may include solutions that would be technically infeasible, incomplete or simply irrational. They should be eliminated in subsequent stages of the design process e.g. by using the cross consistency assessment method (CCA) [14].

The process of selecting a final solution out of a general set of all solutions is an optimisation problem and a multicriterial optimisation one in particular. Given the k-dimensional vector of criteria, the optimum solution is searched for in a set of possible solutions (to be determined by the morphological table). The range of key criteria to be examined in the design process includes [6]:

- economic criteria (e.g. minimum cost, minimum risk),
- operational criteria (e.g. minimum response time),
- ergonomic criteria (e.g. personnel's maximum safety),
- manufacturing criteria (e.g. application of available materials and technologies), etc.

The process of defining a morphological table is a challenging task. It can be aided using a set of requirements that describe designed diagnostic systems.

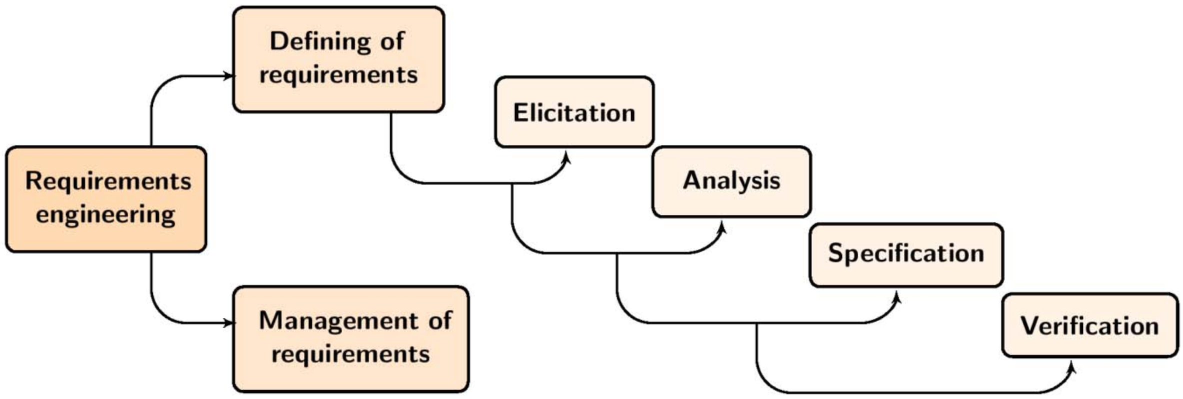

Fig. 2. Requirement engineering tasks

2. REQUIREMENT ENGINEERING

The concept of a "requirement" is defined in various ways in the available literature [8, 12, 16, 17]. The definitions are usually related to a specific branch of science, e.g. software engineering in which the concept is widely used. In order to generalize, a requirement is a statement that describes selected functions to be realized/performed by a solution that is a result of a project's implementation. Exemplary requirements for diagnostic system needs can be the following statements:

- *temperature field acquisition in an environment of the object's element X is necessary to positively determine a technical condition of the object,*
- *it's necessary to measure pressure in a pipeline supplying a working medium to the control valve ZR03.*

Defined requirements should not include any description of a specific problem solution but the description of a particular need only. However, at the same time it should be emphasized that the concept of a requirement is not identical to the term "need". In general, one need can be described with a numerous set of requirements, or different needs may results in identical or similar requirements.

1.1. Defining requirements

One domain that specializes in requirements is requirement engineering (see Fig. 2). The scope of requirement engineering incorporates two fundamental tasks (processes), i.e. requirement definition and requirement management. The process of requirement definition includes then four fundamental stages, i.e. acquisition, analysis, specification and verification of requirements.

One purpose of the requirement acquisition stage is the development of a set of requirements that describe properties of a designed system. In literature the stage is often called an accumulation, identification, formulation, determination or disclosure of requirements. Each term reflects the character of the acquisition process which depends on properties and characteristics of an object that it is designed for. Eliminating of conceivable contradictions occurring in a set of acquired requirements is carried out during the analysis stage. Next, one important stage in the requirement definition process is the specification of requirements that incorporates all actions related to recording and documenting of requirements into a form that is adequate for system designers. Possible format include natural languages, symbolic, graphics, etc. Finally, the last stage of the acquisition process includes a verification of a set of requirements involving tests for correctness, completeness and, e.g. importance of all acquired requirements.

Note that the described stages are often mutually dependent and realized simultaneously in a majority of cases. Effectively, the results influence each other [12, 16].

In a majority of projects requirements are often acquired from various sources which may include, e.g. project's team, end user, existing solutions, rules, standards, domain experts, law, final product prototypes, knowledge and experience of people executing a specific project, etc. The level of accessibility of particular sources of requirements depends on specifics of a domain in which a project has been realized. The acquired requirements should account for all operational aspects of technical means ranging from fundamental functional requirements describing principal characteristics of a designed object to specific requirements related to, e.g. safety, appearance, usability, etc. The size of the final requirement set depends on the object scale. Small-scale projects will involve hundreds of requirements whereas large-scale projects will utilize a huge set of requirements incorporating hundreds of thousands of requirements [12].

1.2. Specification of requirements

The process of defining requirements involves numerous requirements. In many circumstances they may not meet the accepted or imposed constraints or they are contradictory. Therefore, they should be rejected or modified at one of the requirement definition process stages (analysis and/or verification). The requirement set is then recorded in a document – requirement specification. According to the standard IEEE 830 [7] that defines requirements specification for IT (Information Technology) projects such document should be:

- correct – each requirement is a requirement to be met by a designed system,
- unambiguous – each requirement must be interpreted in only one possible manner,
- complete – the document contains a set of all possible and essential requirements,
- consistent – the set of requirements cannot contain contradictory elements,
- ranked for importance and/or stability – each requirement should have a granted priority (importance level) for a better management of the requirement set,
- verifiable – there must exist a (funded) process to determine whether specific requirements can be accomplished in a timely and realistic manner,
- modifiable – the specification document structures should allow for changes in the requirement set,
- traceable – the origin of each requirement as well as their mutual relationships should be identifiable.

1.3. Requirement management

One important task in the requirement definition process is its management. The course of this task warrants a final success (a correct form of the requirement set). The requirement management process can be aided with dedicated IT commercial as well as open-source systems [9,15]. They provide system designers with various methods and techniques for supporting of the definition process of requirement whose application depends on specific needs of a project team.

Such tools are mainly used in supporting the process of requirement acquisition during the development of IT projects. In the IT industry in numerous cases the process of requirement definition reduces to negotiations between a customer and a contractor. One common technique is the EasyWinWin methodology having its origin in the negotiation model called WinWin. The purpose of customer-contractor negotiations is to generate an equal level of satisfaction on either side (customer's and contractor's) [1]. According to the methodology, participants in the negotiations define successive requirements, assign them priorities, and then estimate the set of developed requirements in order to extract a subset of requirements describing designed objects or systems.

2. VIRTUAL CUSTOMER IN THE REQUIREMENT FORMULATION PROCESS

The EasyWinWin methodology assumes that the customer is competent and has a sufficient knowledge to allow him/her to formulate requirements.

This assumption can be difficult to fulfil with complex systems, and diagnostic system in particular. The end-user (customer) may not have a sufficient knowledge on the object it operates. In addition to that, he/she may not know technical diagnostics specifics. Therefore, in many cases customer are not able to formulate correct requirements. In an attempt to get out of this problem, it is possible to assume that a technical object takes the role of a virtual customer in the negotiation process. In order to enable such assumption, the technical object (virtual customer) can be represented by a formalized system - a knowledge carrier with the ability to generate requirements describing the diagnostic system under consideration. One viable possibility is the application of an expert system in which its knowledge base is represented by a multimodal statement networks [4].

2.1. Requirement management

By definition, a statement is a predicative sentence that describes observed facts or expresses an opinion. Each statement can be assigned a value that informs on the sentence's recognition.

Each considered requirement can be then interpreted as a statement. Therefore, they can be written down in the form of the following pair

$$s = < c, v >, \tag{2}$$

where c is the requirement's (statement's) contents, and v is the assigned value that can be interpreted as a belief measure on the purpose of considering the examined statement or as a preference of a requirement for application in a designed diagnostic system.

Defined statements (and requirements) can be combined into sets of statements (thesauri). Having such statement set, it is possible to present existing relationships between the statements with a statement network (see Fig. 3). A statement network is formally a directed graph

$$G = \langle N, E \rangle, \tag{3}$$

where N is a finite and not empty set of vertices (nodes) of this graph, and a E is a finite and not empty set of directed edges connecting selected vertices. Selected statement networks can span over shared vertices, thus developing a so-called multimodal statement network [3, 5]. Relationships between particular nodes of statement networks can belong to different classes. Acyclic Bayesian networks (belief networks) have been widely used in that regard [10, 11, 13]. In such networks the relationships between selected nodes are expressed with conditional probability tables (CPT) assigned to all nodes of the networks. It is also possible to use necessary conditions and sufficient conditions for the purpose of describing relationships between selected nodes of the network (approximate networks) [2]. Having defined a statement network, it is possible to perform a reasoning process. During the process and based on known values of selected nodes (reasons) unknown values of the remaining nodes (conclusions) are determined. One important advantage of using statement networks is the possibility of carrying out a reasoning process with an incomplete, inaccurate and partly contradictory knowledge.

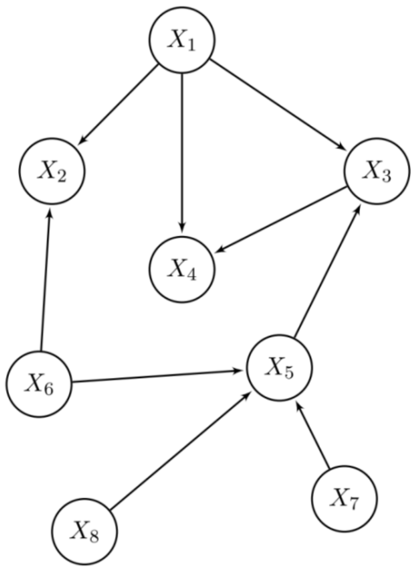

Fig. 3. Statement network

3. MANAGEMENT OF REQUIREMENTS USING MULTIMODAL STATEMENT NETWORK

While designing a diagnostic system it is necessary to possess an appropriate set of statements (requirements) describing examined task problems. The acquired set of statements includes two sorts of statements. One group of statements contains a requirement describing an expected or a required functionality of a designed diagnostic system. The other group includes statements describing a technical object, i.e. structure, components, possible inefficiencies and faults of selected components of the object, fault likelihood, repair and servicing costs incl. temporary lay-offs due to faulty components and subsystems, implementation costs of chosen solutions of a diagnostic system, etc. The statements describe the so-called project knowledge.

To acquire such statements it is possible to look up in available literature sources on an exploitation process of such an object and similar objects. Moreover, necessary statements can be formulated based on the knowledge and experience of domain experts as well as object's end users. Aside from the content and its assigned value, all statements can possess additional attributes, i.e. statement's author, priority, status, versions, notes, etc.

Using a developed statement set, it is then possible to deploy subsequent statement networks. The networks will contains an information reflecting a relationship between a possessed project knowledge and requirements describing a designed diagnostic system. The project knowledge is represented by nodes whose values are known, whereas nodes of unknown values are requirements describing the system. As a result of the reasoning process specific requirements (nodes whose values are unknown) are assigned estimates that are a result of research for an equilibrium condition in a specific statement network.

3.1. Defining of morphological table

Statement networks can support the process of defining a morphological table. The table development process can proceed in a two-step manner. At first, captions (titles) of subsequent rows of the table are determined. They describe required functionalities of a designed diagnostic system. Then, diagnostic methods and techniques are determined that are needed to meet a given need (functionality). Separating these two stages of the development process emphasizes the fact that a detailed knowledge on the object's structure and operating principles as well as a generic diagnostic knowledge are needed for the first stage. At the same time, only a generic knowledge on the object and a detailed diagnostic knowledge are necessary to complete the second stage.

Each stage involves developing necessary statement networks to determine selected elements of a morphological table, i.e. row captions and row elements. The number of considered statement networks depends on the project specific characteristics as well as the acquired knowledge quality. It is assumed that in order to establish elements of particular rows separate statement networks may be developed for each row of the table. While developing particular statement networks, various aspects of one's knowledge on a given object should be accounted for, i.e. operating principles, structure, diagnostic system functionality, etc. As a result of the reasoning process, nodes whose values are not known (requirements) in statement networks are assigned determined values (preference factor). The values can be interpreted as usefulness measures of a specific requirement that has to be taken into account by a diagnostic system to achieve assumed goals. Assuming that particular requirements correspond to specific functionalities of a diagnostic system it is then possible to obtain a full morphological table incorporating all possible solution variants of the system. The process of defining a morphological table is illustrated in Fig. 4.

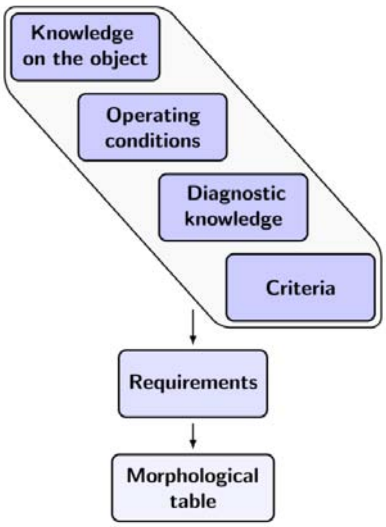

Fig. 4. Process of defining a morphological table

While developing a morphological table using a requirement set, it should be taken into account that the process usually involves a large set of requirements. It contains all requirements that may appear through the development process. However, quite often many of the collected requirements are contradictory to the assumed constraints. Therefore, during the reasoning process a full set of requirements is limited to a rational subset of requirements describing a required functionality of the system (morphological table rows) and related diagnostic methods and techniques (elements of table rows).

3.2. Searching for an optimal system

A morphological table allows for representing possible solutions of a diagnostic system. Their maximum number can be determined using Equation (1). One single solution of a diagnostic system can be considered an element in the *n*-dimensional solution space (multi-dimensional box, OLAP box), where *n* is the number of rows (expected functionalities) of a morphological table. In an exemplary morphological table shown in Fig. 5a, the solution is represented by a single element in the 3-dimensional box illustrated in Fig. 5b. The highlighted solution comprising the partial solutions *{x1,y2,z2}* is only one of the 60 possible solutions of a diagnostic system defined by a morphological table.

a)

Functionalities		Solutions				
	X	x_1	x_2	x_3		
	Y	y_1	y_2	y_3	y_4	y_5
	Z	z_1	z_2	z_3	z_4	

b)

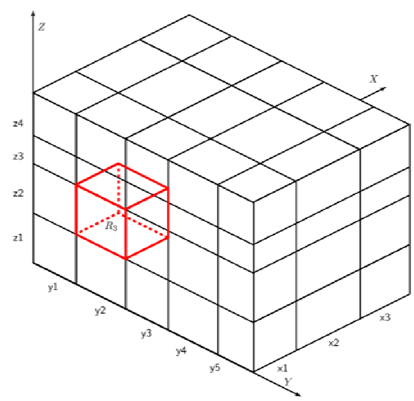

Fig. 5. a) Morphological table, b) corresponding 3-dimensional box of solution variants

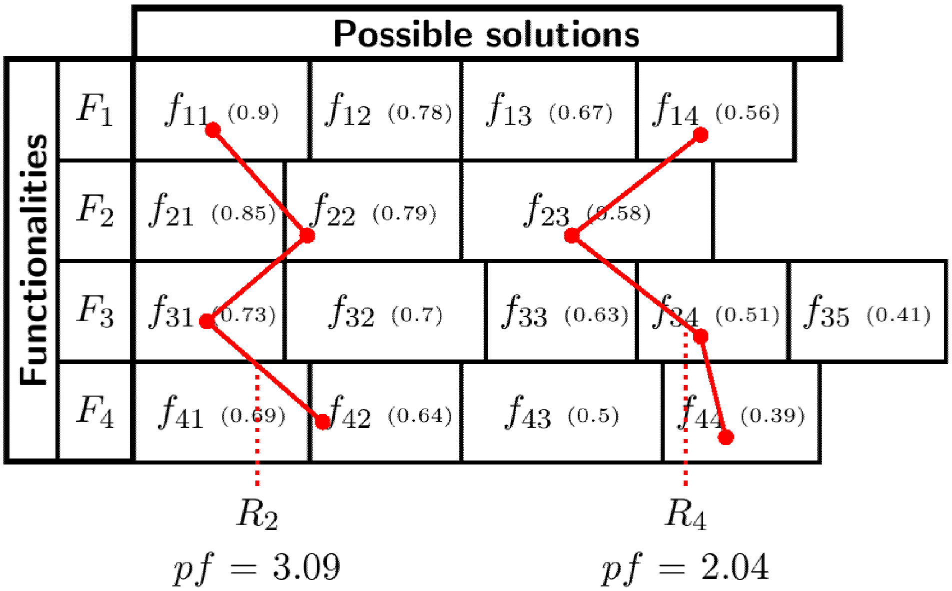

Fig. 6. Exemplary preference factors of particular elements of a morphological table (values in brackets) and selected solutions of a diagnostic system, pf – preference factor

While defining elements of subsequent rows of a morphological table, note that it permits repeated row elements between specific rows if it is used for a diagnostic system. Some of the defined functionalities can be realized using identical diagnostic methods, tools, sensors, etc. At the same time it is apparent that different diagnostic techniques (located within the scope of different functionalities) can be realized with one measurement system. Effectively, it leads to a reduction in the number of all solution of a diagnostic system project.

Each element of a morphological table (rows, row elements) can be assigned a preference factor (importance) that is determined during a reasoning process with statement networks. As such, it is then possible to order selected elements of the table according to the parameter value. At the same time it is possible to assign preference factors to particular solutions of a diagnostic system based on preference factors of specific elements of a solution. The obtained value can be then used for evaluating the solution quality. One example of such a procedure is illustrated in Fig. 6.

It is also possible to assign additional parameters (solution cost, risk, etc.) to particular elements of a morphological table. The parameters can be used in multicriterial optimization.

4. SUMMARY

The paper describes issues of requirement acquisition process for designed diagnostic systems. The authors explore the possibility of representing a set of possible solution of a diagnostic system with a morphological table. The process of defining such a table, i.e. defining of rows representing expected functionalities of a diagnostic system and row elements corresponding to possible methods and techniques can be carried out in two independent stages. To support it, a set of requirements describing the system can be used.

The approach that the authors propose relies on the assumption that a considered technical object takes on the role of a virtual customer in the requirements negotiation process. The virtual customer can be represented by an expert system in which a knowledge base takes the form of a multimodal statement network. Morphological table elements can be determined based on the outcome of the reasoning process performed on defined statement networks.

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SINGULAR VECTORS IN THE SYNTHESIS OF INDICES FOR ACOUSTIC ASSESSMENT OF OBJECTS

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Summary

The SVD (Singular Value Decomposition) technique makes it possible to transform a set of correlated data into uncorrelated ones without the loss of any information. The new system of mutually uncorrelated variables is comparable to the initial one. Apart from decorrelation of data, SVD makes full variable correlation possible, which ensures no copying of certain information during the addition of such new variables.

This article presents the application of the SVD technique for the construction of single-number indices for assessment of correlated object acoustic parameters using the methods of decorrelation and full correlation. Verification of the proposed single-number assessment indices was carried out using the example of sacral buildings. For one Roman Catholic church with flawed acoustics, the application of a single-number index for assessment of the variant of proposed acoustic adaptation of its interior was shown. The synthetic index applied for sacral objects, being an approximated general measure of assessment, can be a helpful tool for designers and during assessment of church interiors in terms of the acoustic functioning of the object.

Keywords: Singular Value Decomposition (SVD), decorrelation, index method of assessment.

WEKTORY SZCZEGÓLNE W SYNTEZIE WSKAŹNIKÓW
OCENY AKUSTYCZNEJ OBIEKTÓW

Streszczenie

Technika rozkładu względem wartości szczególnych (SVD) umożliwia przekształcenie zbioru danych skorelowanych w dane nieskorelowane, bez utraty jakiejkolwiek informacji. Nowy układ zmiennych wzajemnie nieskorelowanych jest porównywalny z układem wyjściowym. Oprócz dekorelacji, SVD umożliwia korelację zupełną zmiennych, zapewniającą brak powielenia pewnych informacji przy sumowaniu doskonale skorelowanych nowych zmiennych.

W artykule pokazano wykorzystanie techniki SVD do konstrukcji jednoliczbowych wskaźników oceny skorelowanych parametrów akustycznych obiektów metodami dekorelacji i korelacji zupełnej. Weryfikację zaproponowanych jednoliczbowych ocen wskaźnikowych przeprowadzono na przykładzie kilku obiektów sakralnych. Dla jednego kościoła-rzymsko katolickiego o wadliwej akustyce pokazano zastosowanie jednoliczbowego wskaźnika do oceny wariantu zaproponowanej adaptacji akustycznej tego wnętrza. Syntetyczny wskaźnik zastosowany dla obiektów sakralnych, będący przybliżoną miarą ogólną oceny, może być pomocnym narzędziem dla projektantów oraz przy ocenie wnętrz kościelnych, związanej z prawidłowym pod względem akustycznym funkcjonowaniem obiektu.

Słowa kluczowe: Rozkład względem wartości szczególnych, dekorelacja, wskaźnikowa metoda oceny.

1. INTRODUCTION

Assessment using indices is very useful from the perspective of diagnostics as a description of the current state of quality or usefulness of a given object for fulfilling its utilitarian function. Indices make it possible to show and analyze complicated phenomena in simplified way and measure changes in these phenomena. Index methods also have applications in the study of vibroacoustic processes [3]. In singular cases, single-number indices are used to evaluate these processes. Global indices being an approximated general measure of the assessment are a function of several partial indices, giving more accurate information on the phenomenon. A quality of a good index is that it can be understood not only by specialists. Depending on the degree of aggregation, indices can be oriented towards the general public, politicians, scientists, and researchers [1]. Sometimes indices that are understood by the general public do not necessarily have to be sufficient for scientific research.

The construction of a synthetic global assessment can take place by means of different methods. One of them is the statistical method that is multi-variate analysis of comparative, related to the analysis of complex phenomena. According to the definition given by K. Kukula [12], a complex phenomenon is understood as an abstract construct representing the directly measurable state of quality of actual objects, described by a certain number, that is greater than one, of so-called diagnostic variables. Multi-dimensional methods of statistical analysis applied, among other fields, in econometrics, make it possible to present variables (object qualities) in such a form so that they can be compared directly. When the additive formula is used, the single-number index is based on adding the products of the values of standardized qualities and their corresponding weights. According to this method, diagnostic variables should be weakly correlated with each other and strongly correlated with the variable being interpreted.

During diagnosis of the acoustic state of the object, there is often a need to evaluate many of its qualities (or indices describing those qualities), sometimes strictly related to the functions and scope of acoustic production of the object. These indices are not always independent from one another. During synthesis of correlated indices, the problem of copying certain information arises. An attempt to solve this problem, which was the goal of the many years of study of the author, has been shown in this article. The approach to the construction of the single-number index is based on the use of SVD (Singular Value Decomposition). SVD is a computing technique that is widely propagated in numerical linear algebra [6, 13] and has applications in many fields of science, such as diagnostics [2] and vibroacoustics [3, 4, 5].

Until now, attempts to apply SVD in single-number assessment of acoustic quality pertained to a certain group of objects, being sacral objects [7, 8, 9, 11]. Further studies related to the assessment of acoustic quality will apply to other public and industrial objects. In the article, a method of constructing the single-number global index of acoustic assessment of widely understood objects was shown, however verification of the proposed index was conducted using the example of sacral objects. The proposed single-number assessment of the acoustic quality of objects can be carried out using two methods, leading to the same results – the values of the single-number index. Factor analysis and Principle Component Analysis in particular (PCA), which is easier to use using SVD, makes it possible to transform a set of correlated data into uncorrelated ones, without the loss of any information. The new mutually uncorrelated system of variables (so-called common factors or principal components) is comparable to the starting system. Apart from index decorrelation, a second method is their full correlation, taking place with the application of SVD, ensuring no copying of certain information during the addition of perfectly correlated indices.

2. SINGLE-NUMBER ASSESSMENT OF THE ACOUSTIC QUALITY OF OBJECTS

2.1. Single-number index with the application of full correlation

Full correlation of partial assessment indices, dependent on one another, is carried out using the SVD technique [9]. In order to obtain singular vectors and values – the components of index W_{kz}, it is necessary to construct the so-called index and strucutre observation matrix **A** from partial indices, which will be decomposed to singular values. Singular value analysis makes it possible to identify the percentage share of the information interpreted by successive components. The first component is usually the most informative, and when it is large in comparison to the remaining components, the computational model can be simplified by using first-order approximation

$$\mathbf{A}^{*}=\sigma_1\mathbf{u_1}\mathbf{v_1} \tag{1}$$

where: $\mathbf{A}^*$ - matrix obtained as a result of first-order approximation (k=1), $\mathbf{u_1}$ – first column of matrix **U**, $\mathbf{v_1}$- the first row of matrix $\mathbf{V}^\mathbf{T}$, σ_1 the first singular value of matrix $\mathbf{\Sigma}$.

Matrix $\mathbf{A}^*$, approximating matrix **A** (with a certain Frobenius error), has components in the form of partial indices that are perfectly correlated with each other (the linear correlation coefficient between indices is equal to 1). Because new indices are perfectly correlated with one another, their sums can be calculated without obtaining redundant information that could appear in the case of adding indices that are not fully correlated. It is proposed to standardize the vector of obtained W_{kz} indices using the zeroed unitarization method, making it possible to obtain values in the interval from 0 to 1, according to the formula:

$$z_{ij}=\frac{x_{ij}-\min\limits_i x_{ij}}{\max\limits_i x_{ij}-\min\limits_i x_{ij}} \qquad \max_i x_{ij}\neq\min_i x_{ij} \tag{2}$$

Therefore, the single–number index obtained from full correlation

$$W_{kz_i}=norm\left(\sum_{j=1}^{n}a'_{ij}\right) \tag{3}$$

where: a_{ij}' – components of matrix $\mathbf{A}^*$ of the i-th object and j-th partial index.

Index W_{kz} can also be obtained by using only the first left singular vector $\mathbf{u}_1$, which is usually best correlated with the initial partial indices (components of the observation matrix). Values of the single-number index correspond to elements of vector $\mathbf{u_1}$, which are to be standardized using formula (2).

$$W_{kz}=norm(\mathbf{u_1}) \tag{4}$$

where: W_{kz} – the vector containing single-number indices of objects.

2.2. Single-number index using decorrelation

The problem of index decorrelation was described in [8], where it was proposed to get rid of singular values and add independent products of vectors **u** and **v**, obtained from SVD. Currently, it is proposed to use all products obtained from SVD for single-number assessment. Observation matrix **A** can be written as follows

$$\mathbf{A}= \sigma_1\mathbf{u_1}\mathbf{v_1}+\sigma_2\mathbf{u_2}\mathbf{v_2}+...+\sigma_n\mathbf{u_n}\mathbf{v_n} \qquad (5)$$

Successive products are related to independent object qualities, the variability of which is defined by singular values. The single-number index using decorrelation of W_d requires standardization. It is proposed to use the zeroed unitarization method for this purpose, as defined by formula (2). Index W_d is defined by the formula

$$W_d = norm\left(\sum_{j=1}^{n}\omega_j u_j v_j\right) \qquad (6)$$

where: ω_j - weights of the j-th product corresponding to the j-th singular value, $\mathbf{u_j}$ - the j-th left singular vector (in matrix **U**, obtained from SVD of correlated indices of matrix **A**), $\mathbf{v_j}$ - the i-th right singular vector (in matrix $\mathbf{V^T}$, obtained from SVD of correlated indices of matrix **A**).

Weights ω_j are calculate from the formula:

$$\omega_j = \frac{\sigma_j}{\sum_{j=1}^{n}\sigma_j} \qquad (7)$$

where: σ_j- the j-th singular value (in matrix **Σ**, obtained from SVD of correlated indices of matrix **A**).

Weights ω_j are calculated on the basis of a similar principle to that of the statistical method [12], in which quality variability coefficients (variance) are used for calculation of measures of relative informational value, being the weights. In the SVD method, measures of informational content are the singular components σ_j, used in formula (7).

3. VERIFICATION OF SINGLE-NUMBER ASSESSMENT OF CORRELATED INDICES USING THE EXAMPLE OF SACRAL OBJECTS

3.1. Studies of real objects

Values of calculated partial assessment indices have been determined on the basis of acoustic parameter measurements carried out in six Roman Catholic churches [9]. The strongly correlated three partial indices are: reverberation index W_P, music sound index W_M, and speech intelligibility index W_Z. The linear correlation coefficients between indices have been shown on table 1.

Table 1. Linear correlation coefficients between partial assessment indices

W_P <-> W_M	W_Z <-> W_P	W_M <-> W_Z
0. 9488	0. 9158	0. 9827

Using the Matlab software, SVD of observation matrix of three indices was carried out, as shown in Fig. 1. The first component is the most informational and contains 84% of information interpretation (Fig. 1). The methods of full correlation and decorrelation were used to determine single-number assessment indices W_{kz} and W_d (Fig. 2). In order to verify the full correlation of assessment indices, SVD was conducted again; this time, on matrix $\mathbf{A}^*$, containing perfectly correlated indices. A 100% information content of the first singular component confirms that the new variables in matrix $\mathbf{A}^*$ are perfectly correlated (Fig. 2a). Vector $\mathbf{u_1}$ can be successfully used to represent the data object of matrix **A** (formula (4)). The large values of linear correlation coefficients of vector $\mathbf{u_1}$ with initial indices (W_P, W_M, W_Z) as shown below are indicative of this: -0.9901, -0.9833 and -0.9598. Verification of index decorrelation (by carrying out SVD of matrix **B** – containing new uncorrelated variables) gave content of percent information interpretation by successive singular components equally divided between the new indices (Fig. 2b).

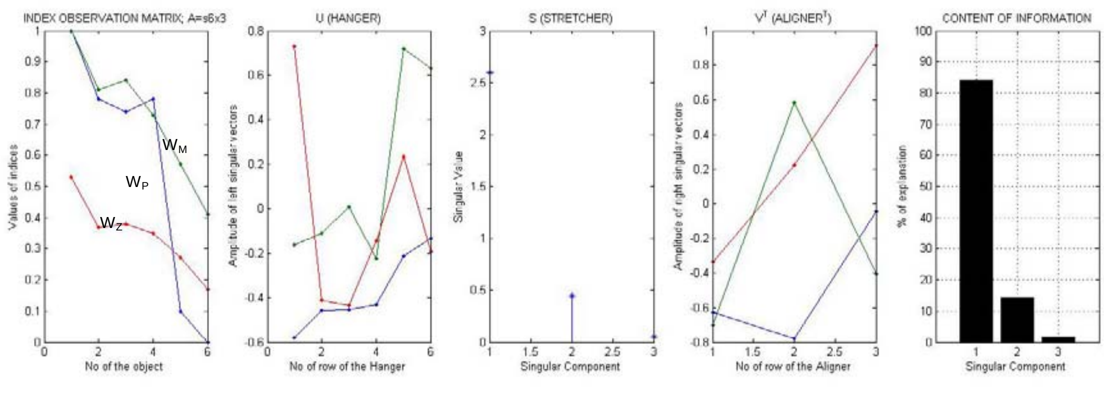

Fig. 1. SVD of a three-index observation matrix of sacral objects

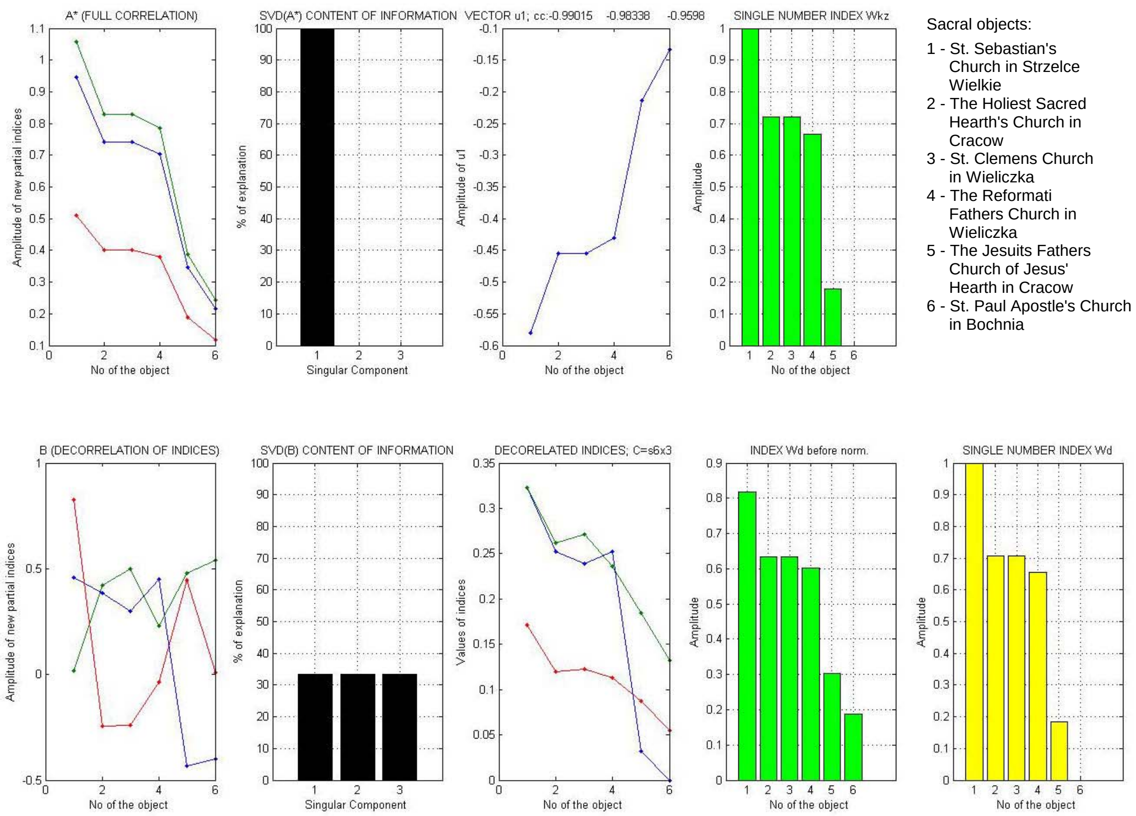

Fig. 2. Comparison of the full correlation method (Fig. a) and the decorrelation method (Fig. b) of correlated indices in the synthetic single-number assessment

The results obtained using the methods of full correlation and decorrelation in the form of single-number indices W_{kz} and W_d are identical (fig. 2). The best acoustic qualities were exhibited by the wooden church of St. Sebastian in Strzelce Wielkie (W_{kz}=1) and the worst qualities were exhibited by the churches of: the Jesuit Fathers in Cracow (W_{kz}=0.18) and the modern St. Paul the Apostle's Church in Bochnia, based on an elliptical lay-out (W_{kz}=0).

3.2. Simulation studies of the sacral object

The single-number index was applied for assessment of variants of proposed acoustic adaptation of the Church of St. Paul the Apostle in Bochnia [10], a object with flawed acoustics (W_{kz}=0). The observation matrix of 17 variants of adaptation and four correlated partial indices were subjected to SVD, as shown in Fig. 3. An additional partial index, besides the indices listed in section 3.2, was the sound strength index W_{St}, as defined in [10].

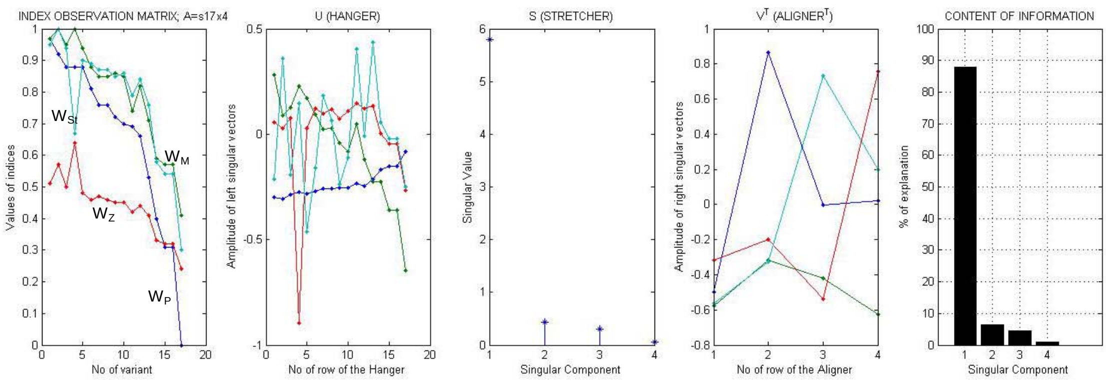

Fig. 3. SVD of the four-index observation matrix of acoustic adaptation variants for the church of St. Paul the Apostle in Bochnia

Simulation studies of adaptation variants were carried out using the CATT Acoustics v.8 software. Partial indices are strongly correlated with one another. Linear correlation coefficients between indices are shown on table 2. As shown in fig. 3, the first singular component contains 88% of information interpretation, and the three remaining components are below the limit of information noise, equal to 10%.

Table 2. Linear correlation coefficients between partial assessment indices used in the simulations tests

W_P <-> W_M	W_Z <-> W_P	W_M <-> W_Z	W_{St} <-> W_P	W_M <-> W_{St}	W_{St} <-> W_Z
0.9823	0.9188	0.9551	0.9207	0.8855	0.7475

The values of single-number indices for individual simulation variants using the methods of full correlation and decorrelation have been presented in Fig. 4. On the basis of the comparison of the values of indices W_{kz} and W_d (Fig. 4a and 4b), it can be stated that the obtained values for individual simulation variants are the same. The best simulation variant (variant 2) has a single-number index equal to 1, and the worst (wariant 17) – an index of 0. Selection of the variant of proposed acoustic adaptation of the church conducted using computer simulations along with a supporting tool – a single-number index, can facilitate the making of a decision by persons concerned with problems of adaptation and design of interiors of sacral objects.

4. CONCLUSIONS

The article shows that it is possible to evaluate object acoustic parameters using one number – a single-number index of selected correlated acoustic parameters. An example of public buildings in which correlated acoustic parameters are significant for the functioning of the building in terms of acoustics are sacral objects. Verification of the proposed computational procedures for the single-number assessment indices was carried out on Roman Catholic churches using two methods applying SVD: full correlation and decorrelation of indices. The article shows that the results obtained using both methods, in the form of single-number indices, are identical. Single-number indices were also used to evaluate simulations of adaptation variants of an acoustically flawed modern church. A synthetic index is a general measure that can support decision-making during selection of acoustic adaptation. Partial assessment indices can give more accurate information on acoustic parameters of a object. The single-number index of correlated acoustic parameters will be a component of the global acoustic assessment, which is a function of non-correlated indices and can be determined using the statistical method that is multi-variate analysis of comparative. Further studies will concern the verification of the proposed single-number assessment for other types of objects e.g. industrial halls, sports stadiums.

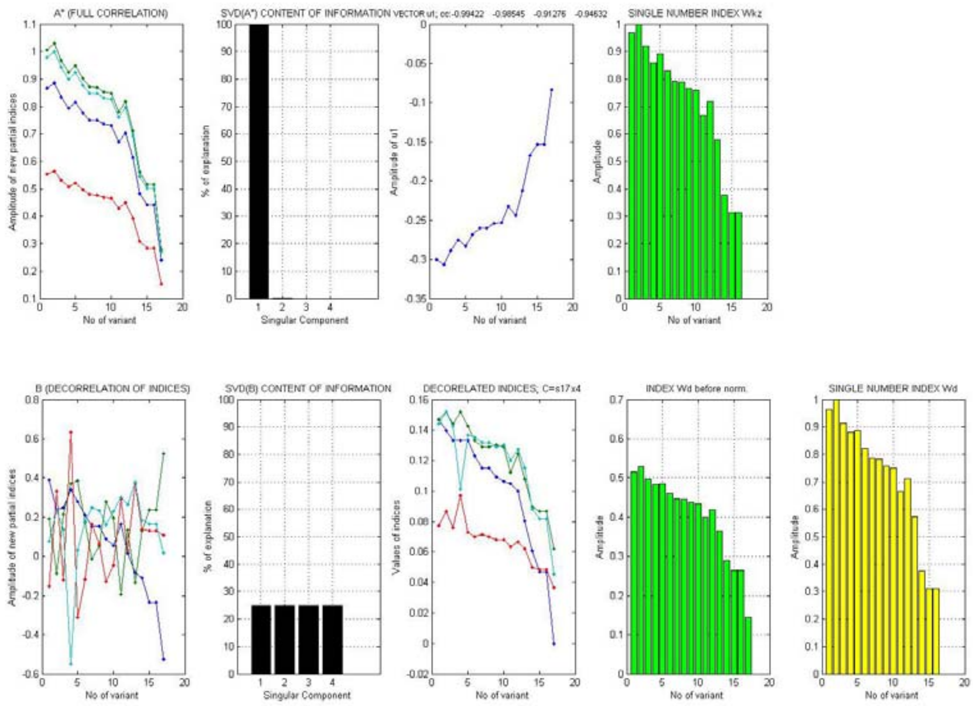

Fig. 4. Comparison of the full correlation method (a) and the decorrelation method (b) of correlated indices in the synthetic single-number assessment of acoustic adaptation of the studied church

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DIAGNOSTICS OF COURSE A WORK PROCESS IN CYLINDERS OF MARINE INTERNAL COMBUSTION ENGINES USING VIBRATION SIGNAL

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Summary

In this paper are presented a research results an applications of an acceleration vibration signals to diagnosis of the work cycle of medium-speed compression ignition engines. To take the problem was prompted a measuring errors a course of the cylinder pressures when the sensors is connected to indicator valves and the lack of these valves in some engines.

The investigations have been carried in operating conditions of the medium-speed marine diesel engines propelled a generator. In preliminary investigations for different fastenings of the acceleration vibrations sensor, an influence of relative load of the generating set on values of used diagnostic parameters was being checked. Receivers of electric energy or water resistor made the load variations of the internal combustion engine. The researches have been carried in time, amplitude and frequency domain.

In fundamental investigations an influence of the technical state on values of diagnostic parameters was tested as well and failures was localised. There have been selected the diagnostic symptom close connected at technical state and have been compared with other diagnostic symptoms.

Keywords: marine engines, work process, diagnostics.

DIAGNOZOWANIE PRZEBIEGU PROCESU ROBOCZEGO W CYLINDRACH OKRĘTOWYCH SILNIKÓW SPALINOWYCH Z WYKORZYSTANIEM SYGNAŁU DRGANIOWEGO

Streszczenie

W artykule przedstawiono metodę wykorzystania diagnostyki drganiowej do oceny obiegu w tłokowym silniku spalinowym o zapłonie samoczynnym. Do podjęcia problemu skłoniły błędy przy pomiarach przebiegu ciśnienia w cylindrach przy czujnikach mocowanych na zaworach indykatorowych oraz brak tych zaworów w niektórych silnikach.

Badania przeprowadzono w warunkach eksploatacji średnio-obrotowych okrętowym silników z zapłonem samoczynnym napędzających prądnice. W badaniach wstępnych dla różnych mocowań czujnika przyspieszeń drgań, sprawdzano wpływ obciążenia względnego zespołu prądotwórczego na wartości wykorzystywanych parametrów diagnostycznych. Zmiany obciążenia silnika spalinowego realizowano za pomocą załączania różnych statkowych odbiorników energii elektrycznej lub opornika wodnego. Badania prowadzono w dziedzinie czasu, amplitudy i częstotliwości.

W badaniach zasadniczych sprawdzano wpływ stanu technicznego na wartości parametrów diagnostycznych oraz lokalizowano uszkodzenia. Wyselekcjonowano symptomy diagnostyczne ściśle skorelowane ze stanem technicznym oraz porównano je z innymi symptomami diagnostycznymi.

Słowa kluczowe: silniki okrętowe, procesy robocze, diagnostyka.

1. INTRODUCTION

Course of in-cylinder pressure is the basic process of working in compression-ignition internal combustion engine. From the quality of this process depends on the operating effectiveness determined fuel consumption, efficiency and release of toxic exhaust constituents. This depends on the preparation of air-fuel mixture and the run of the combustion process. Both conditions show a need to develop effective methods to control the conduct of the original engine process, which is fuel combustion in the cylinder, and elaborating dynamic methods of estimation of that process.

Values of exhaust outlet temperatures from individual cylinders they are using for the estimatation of the combustion process. Often approximation line changes of exhaust gas temperature is tilted only slightly when changing technical state, while due to injector failure conversion is undergoing burning down of piston top. Similarly difficult to identify are leaks of combustion chambers.

Diagnostics of the cylinder pressures course of marine engines uses their registration and analysis, but engine producers are not equipped with indicator valves. Pressure measurements in cylinders of engines equipped with indicator valves are affected by large errors, and indicator valves are often in the unfitness state. One of the ways acquisition diagnostic information is measurement of vibrations generated by internal combustion engine. Therefore some authors, as well as the author of this work, made an attempt to evaluate piston internal combustion engines with using vibration signals in various directions [1, 2, 3, 4], of crankshaft torsion vibrations [5], simultaneous measurement signals pressure in the combustion chamber and vibrations [1, 6] as well as vibration and noise [7]. They were carrying out tests on the research single-cylinder engines [1, 3], railway engines [1, 3] or marine engines [2, 8]. The analysis has been made in the domain of time, the amplitude, frequency, time-frequency or angle-frequency [9].

2. RESEARCH PROGRAMME

The internal combustion engine is the object of extortion under the influence of the internal and external input. One of the extortion internal forces is gaseous power from the combustion process in the cylinder, which was observed. Research included in the different types of medium-speed marine engines which drive generators, and this work mainly manufactured under licence companies isle of MAN B & W type 6 and 7L16 / 24. Technical data of inspected engines were following:

- number of strokes = 4,
- bore = 160 mm,
- stroke = 240 mm,
- rated engine speed = 1000 or 1200 rpm,
- maximum combustion pressure = 18 MPa,
- cylinder power = 88,9 or 90,8 kW.

These engines are not equipped with indicator valves, and have in the system of monitoring of the outlet exhaust temperatures [10]. Engines have been tested in exploitation conditions repeatedly, in different technical states: before the maintenance, after maintenance, before and after failure and during acceptance tests. Diagram of the measuring system is shown in figure 1.

The sampling frequency was 100 kHz and an analog and digital filtration was applied. During data acquisition process, the rotating speed of the engine was kept at a constant rpm. In figure 2 shows the in-cylinder pressure course and time course of vibration acceleration signal perceived on bolt of the coupling cylinder head 6AL20/24D engine equipped with indicator valves. The maximum combustion and impetus vibration accelerations from combustion process are appearing in the same time.

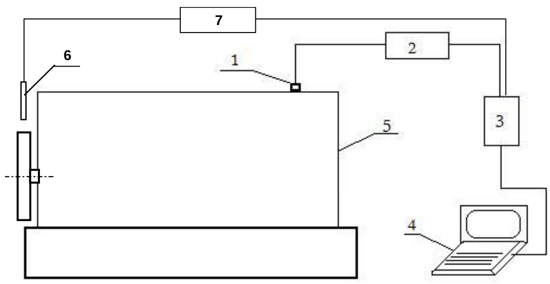


Fig. 1. Diagram of the measuring system: 1 – vibration acceleration sensor, 2 – preamplifier, 3 – terminal connection, 4 – portable computer, 5 – investigated internal combustion engine, 6 – location of the crankshaft sensor, 7 – power pack

3. RESULTS OF PRELIMINARY INVESTIGATIONS

For the selection of rational place of signals trapping have been used planning of the experiment, in which the influence of the direction and the place of fixing the sensor on the values of diagnostic parameters were applied. The cylinder head cover is fixed by 5 screws. In figure 3 summarises the impact of the 3 seats anchorages sensor on the value of the root-mean-square values of amplitudes accelerations vibration in one-third octave frequency bands. With the figure 3 shows that the most favourable fixing of sensor is on the screw no 1, as the values of the root-mean-square values of amplitudes in third octave frequency bands are highest. In preliminary investigations were also examined the influence of engine load on the values of the diagnostic symptoms, for 2 constant engine speeds.

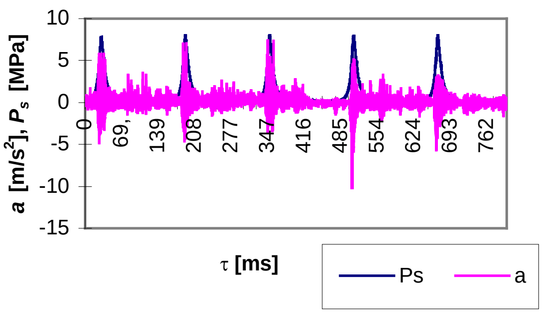


Fig. 2. Time courses: of accelerations vibration signal processed on the screw of the cylinder head and in-cylinder pressure of marine engine by the pressure sensor fastened on the indicator valve: *a* – acceleration vibration, P_s – in-cylinder pressure, τ – time

At work have tried to find a model between the course of the pressure in a combustion chamber and with course accelerations vibrations processed on the screw fixing the head. Such a model can be written in the form:

$$a = f(P_s) \tag{1}$$

Since values of the accelerations vibration signal represented the in-cylinder pressure course are matrices, it is possible to fill it with writing in the matrix form:

$$A(\tau) = \{a_1(\tau), a_2(\tau), \dots, a_n(\tau)\} \tag{2}$$

$$P_s(\tau) = \{p_{s1}(\tau), p_{s2}\,\tau), \dots, p_{sn}(\tau)\} \tag{3}$$

$$A = f(P_s) \tag{4}$$

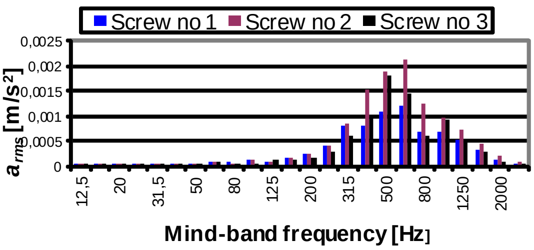


Fig. 3. Influence of the sensor location on root-mean-square values of amplitudes in third octave frequency bands

Signal analysis measuring was making in the time domain, the amplitude and the frequency, seeking frequency bands of analysis and diagnostic symptoms about the greatest usefulness. In figure 4 provides time course of accelerations vibration signal for one cylinder and of the position of the top dead centre of piston (TDC) processed by means of the photo-optical sensor. The time selection allowed distinguished pulses from the combustion process and functioning of the valves in the cylinder head. This way selected signals are characterized by a small level of interference and repeatability.

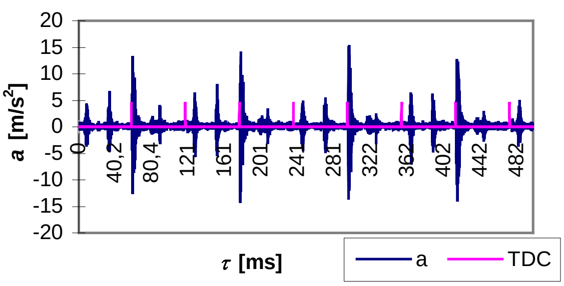


Fig. 4. Time course of acceleration vibration signal delivered on the screw fixing the cylinder head cover of medium-speed shipping engine 6L16/24 type do not have indicator valve together with the TDC positions

In figure 5 gives examples of the spectrum of signal accelerations vibrations, where there are growth amplitudes for frequencies proportionate to rotational of crankshaft.

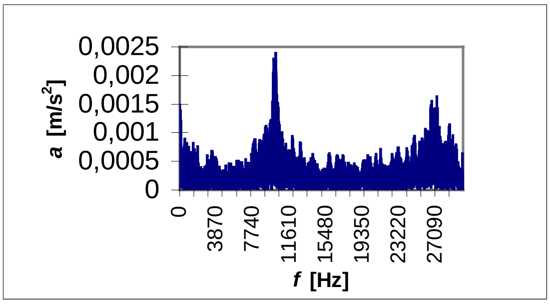


Fig. 5. Examples of the amplitude spectrum of accelerations vibration signal in the 0–30 000 Hz frequency band: rated engine speed 1200 rpm, f – frequency

Seeking useful methods of the signal analysis they used among others windowed time scope (fig. 6). Many temporary differing windows exist of baulk with one self with shape, from which every have been properties characteristic of oneself. You can see that the function of the window on scratches 6. Has maximum in the middle of the period and symmetrically is falling on both ends of the scope.

Was also applied a wavelet analysis in order to find a useful of signals processing. As a promising it was considered a decomposition of vibration signal using different digital low-pas and high-pas filters (fig. 7).

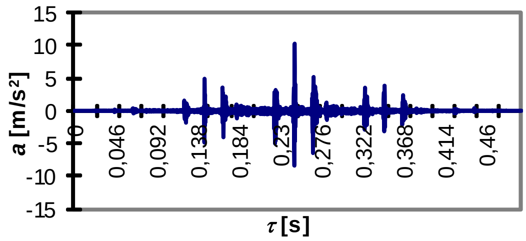


Fig. 6. Windowed time scope of acceleration vibration signal

4. EXAMPLES OF THE FUNDAMENTAL RESULTS OF INVESTIGATIONS

In fundamental examinations they were aspiring to the evaluation of the technical state of individual cylinders of inspected engines at with constant load. In figure 8 shows values amplitude estimates and exhaust outlet temperature from the individual cylinders. An important role to the dynamics of growth in the cylinder pressure, and consequently burden of piston-crank system, has the state of the injection – mainly of injector valve. Differences value of symptoms in the individual cylinders had been caused by the state of injection apparatus, which also assessed using accelerations vibration signals.

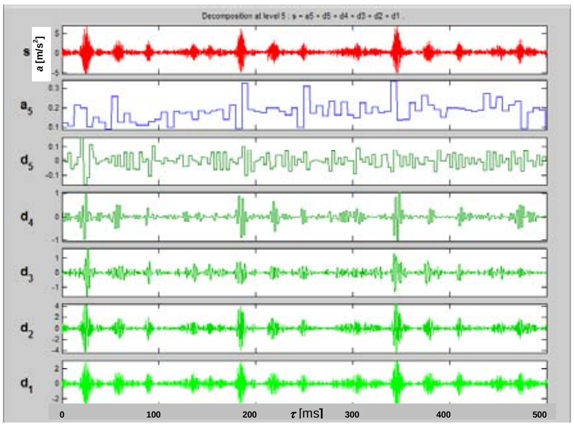
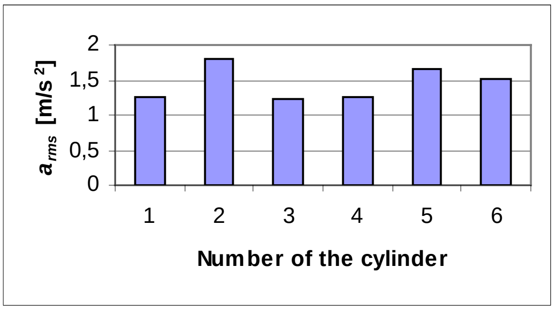


Fig. 7. Wavelet analysis of the accelerations vibration signal: s – registered basic signal, a_5 – low-pas filter, d_4–d_1 – high-pas filter

Were also made measurements accelerations vibrations of engine before the longer exclusion from the use during the shipyard maintenance (figure 9). In the cylinder no 1 was very small values of global measurement of accelerations vibration. After restart the engine was extensive failure in this basic subsystem: the cylinder head, valves, cylinder liner and the piston. Large resistances to motion of valves in the head and their collision with piston, which in these types of engines are often, have caused failure.

a)



b)

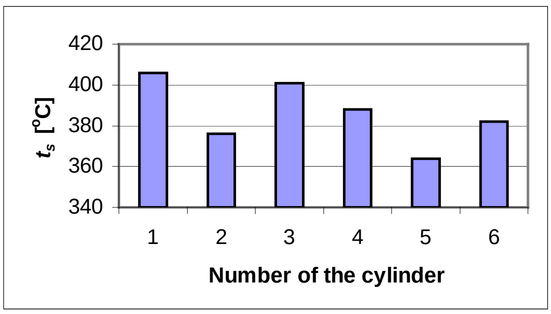


Fig. 8. The root-mean-square values accelerations vibrations a_{rms} (a) interdependent with the maximum combustion pressure in the individual cylinders and value of the exhaust outlet temperature t_s (b) for the individual cylinders

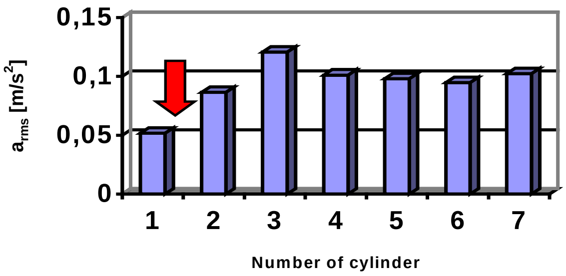


Fig. 9. Root-men-square values of accelerations vibrations signal by the sensor fastened on the cylinder head cover screws for 1–7 cylinders of 7L16/24 engine: ↓ – failed of piston-cylinder group after restart the engine

Between took valves and guides collect deposits, which increase the resistance significantly when the temperature node grating is low. Deposits are substances vibrations damping.

4. Conclusions

Experimental investigations carried out in the operating conditions have shown the possibility of working process diagnosis of marine combustion engines, which not equipped with indicator valves using signal accelerations vibration. Acceleration sensors well are attached to the pins clamping on the cylinder head or cylinder head cover with the thread.

Through the selection of the time course of the vibration signal a possibility of the identification of basic processes exists, as opening and closing of inlet and outlet valves, fuel injection and pressure course in the cylinder. Symptoms of accelerations vibrations signal shall contain information about the course of the combustion process, technical state of piston-cylinder group, valves in the cylinder head, injection apparatus, etc. The wavelet decomposition lets also allocate basic processes from the complex vibratory signal.

Further research will be reduced to choose the most useful diagnostic symptoms from among many in various domains.

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MARINE DIESEL ENGINE DIAGNOSTICS IN OPERATING CONDITIONS

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Summary

Most of marine diesel engines are turbocharged. Conventional maintenance methods for engine turbochargers depend on bearings clearances checks between rotor shaft and bearing housing. Some parts of the turbocharger have to be checked on the special stands or by using endoscopic methods. Fuel oil not burnt to the end and severe engine working conditions (long time idling) led to several typical turbocharger malfunctions and damages of it in some cases. Always it is easier to prevent malfunctions than take repair works on any assets. In the paper results of main and auxiliary ship's diesel engines turbochargers diagnostic investigations are presented. Methods presented in the paper based on vibration signals processing in time and frequency domain. Using these methods for checking technical condition of the turbochargers and its rotors and bearings without stopping the engine and dismantling it is possible.

Key words: marine diesel engine, diagnostics, turbocharger.

DIAGNOSTYKA OKRĘTOWYCH SILNIKÓW TŁOKOWYCH W WARUNKACH EKSPLOATACJI

Streszczenie

Większość silników okrętowych jest budowana, jako silniki doładowane turbosprężarką. Konwencjonalne metody diagnozowania turbosprężarek polegają na sprawdzaniu luzów łożyskowych pomiędzy wałem a tulejami łożysk. Niektóre części turbosprężarki muszą być sprawdzane na specjalnych stanowiska lub z wykorzystaniem metod endoskopowych. Niespalone do końca paliwo i ciężkie warunki pracy silnika (długotrwała praca na biegu luzem) prowadzą do występowania kilku typowych niesprawności a w niektórych okolicznościach uszkodzeń turbosprężarek. Zawsze jest łatwiej zapobiegać uszkodzeniom niż dokonywać napraw urządzeń. W artykule przedstawiono wyniki badań diagnostycznych turbosprężarek silników głównych i pomocniczych na okręcie. Metody prezentowane w referacie bazują na przetwarzaniu sygnałów drganiowych w dziedzinie czasu i częstotliwości. Stosowanie tych metod umożliwia ocenę stanu technicznego turbosprężarek wraz z ich wirnikami i łożyskami bez ich demontażu i zatrzymywania silnika.

Słowa kluczowe: silnik okrętowy wysokoprężny, diagnostyka, turbosprężarka.

INTRODUCTION

For many years technical condition assessment of ship diesel engines and its turbocharger has been done by engine compartment crew. At present, ship-owners most frequent outsources it in specialized companies. It is due to lack of proper qualification among crewmembers, sometimes due to ship-owner strategy focused on ship maintenance costs cutting [1, 2]. In some newest types of engines and turbochargers it is impossible to repair them on board the ship as it was in the past. In this paper complex engine and turbocharger diagnostic method which is used in Polish Navy is presented. The method based on wide range of different type diagnostic technics which are not always common especially in turbochargers diagnosing.

Since the technical condition of the turbocharger is strictly dependent on the engine condition, one should first make sure of the correct operation of engine as whole system and each engine cylinder systems separately. The best diagnostic method in this field is combustion processes evaluation under inside-cylinder pressure waveforms [4]. Turbocharger rotor and bearing system technical condition assessment based on vibration signal parameters analysis and finally verified by turbocharger flow channels endoscopic examination. The paper presents the chosen technical diagnostic results of two turbochargers type *PDH-35* installed on main propulsion engines and two turbochargers type *C–045/C* installed on auxiliary engines onboard navy vessel during sea trials.

1. THE OBJECTS AND METHODS OF RESEARCH

The tests involved the PBS Turbo type PDH-35 turbochargers installed on SULZER 8AL25/30 type main engines and NAPIER C-045/C type turbochargers installed on SULZER auxiliary engines type 6AL20/24. Engines basic technical data are shown in Table No. 1. The test apparatus used in the study consisted of an engine analyzer built in Polish Naval Academy. Turbochargers vibration parameters were acquired using SVAN 946A vibration analyzer. Endoscopic examinations of turbochargers were made by using a set of OLYMPUS fiberscopes and bore scopes.

Table 1. Basic data of SULZER diesel engines type 8AL25/30 and type 6AL20/24

Engine type	SULZER 8AL25/30	SULZER 6AL20/24
Turbocharger license/type	PBS turbo/ PDH-35 type	Napier / C–045/C type
No. of cylinders / Configuration	i=8 / „ L"	i=6 / „ L"
Cylinder nominal output at 750 rpm	Pcn= 140 kW	Pcn= 70 kW
Cylinder bore	D= 250 mm	D= 200 mm
Piston stroke	S= 300 mm	S= 240 mm
Compression ratio	ε= 12,7	ε= 12,7
Total displacement volume	Vss= 117,7 dm^3	Vss= 45,2 dm^3
Mean piston speed	cśr= 6 m/s	cśr= 6 m/s
Effective specific fuel consumption	ge= 212 g/kWh	ge= 212 g/kWh
Number of valves per cylinder	z= 4	z= 4
Fuel injection pressure	pw= 24,5 MPa	pw= 24,5 MPa

Fig. 1. PBS Turbo PDH-35 type axial-flow turbocharger on SULZER main engine type 8AL25/30 (left) and NAPIER C-045/C radial-flow turbocharger on SULZER auxiliary engine type 6AL20/24 (right)

Both tested engines types were high-speed marine diesel engine in line form, 4-stroke turbocharged with direct fuel injection. Fresh water in closed circuits is used in engines cooling systems, lubricating oil coolers and air coolers. PDH-35 type turbochargers are water-cooled units and C-045/C type turbochargers are air-cooled units.

2. THE TESTS RESULTS

In order to assess the technical condition of turbochargers on the basis of engine performance parameters the engines were introduced in a specific state of the load which were involved by vessel and weather external conditions. Close to the rated load the turbocharger rotor speeds, charging pressures, charge air temperatures and other parameters were read-out and recorded. The values obtained were compared with the values of parameters set from engines acceptance tests. To determine the engines load indicated power was measured using electronic engine analyzer which measuring capabilities are presented in paper [4]. Selected indicator diagrams recorded during the tests are shown in figure number 2.

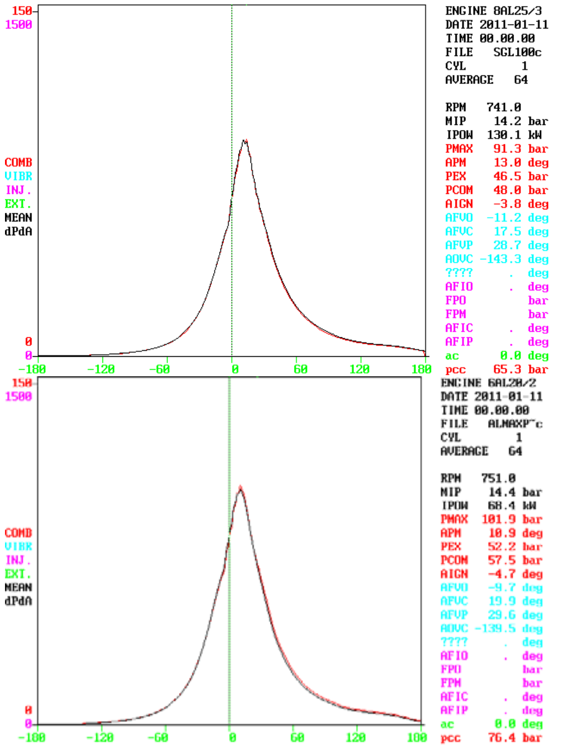

Fig. 2. Chosen engine cylinder pressure diagrams with other parameters for close to rated power load – main engine 8AL25/30 type (up), - auxiliary engine 6AL20/24 type (down)

2.1. Results of vibration signals investigations – the SULZER type 8AL25/30 main diesel engines with the PBS Turbo PDH-35 type turbocharger

Measurements were made for both main engines and with engines load and turbochargers speed ranges dependent on vessel operation mode.

Engines crankshaft speed has changed from 400 rpm to 750 rpm and engines load from idling (engine load index = 1,2) to engine load index = 6,3/6,8. Turbochargers speed varies from about 3300 rpm to about 19600 rpm (Tables No. 2 and No. 3).

Table 2. Values of chosen vibration parameters – Main Engine – port side

Date	11.01.2011	Main Engine LB			
Ambient temperature	18 °C				
Atmospheric pressure	1009 hPa				
Engine speed	[rpm]	400	550	750	750
Engine load index	%	1.2	1.5	4.8	6.3
Basic frequency	[Hz]	63	91	236	315
Turbocharger speed	[rpm]	3780	5460	14160	18900
Vibration acceleration [I harmonic] compressor side	a $[m/s^2]$	0.10	0.10	1.22	6.53
	a [g]	0.01	0.01	0.12	0.67
Vibration acceleration [I harmonic] turbine side	a $[m/s^2]$	0.11	0.12	1.33	6.38
	a [g]	0.01	0.01	0.14	0.65
Vibration acceleration [RMS]	a $[m/s^2]$	4.5	12.3	27.9	34.7
	a [g]	0.46	1.25	2.84	3.54

Table 3. Values of chosen vibration parameters – Main Engine – starboard side

Date	11.01.2011	Main Engine PB			
Ambient temperature	18 °C				
Atmospheric pressure	1009 hPa				
Engine speed	[rpm]	400	550	750	750
Engine load index	%	1.7	1.9	5.2	6.8
Basic frequency	[Hz]	56	92	273	327
Turbocharger speed	[rpm]	3360	5520	16380	19620
Vibration acceleration [I harmonic] compressor side	a $[m/s^2]$	0.32	0.20	0.24	2.69
	a [g]	0.03	0.02	0.02	0.27
Vibration acceleration [I harmonic] turbine side	a $[m/s^2]$	0.10	0.16	0.49	6.17
	a [g]	0.01	0.02	0.05	0.63
Vibration acceleration [RMS]	a $[m/s^2]$	3.4	10.0	24.8	24.3
	a [g]	0.34	1.02	2.53	2.48

Vibration parameters were measured on both compressor and turbine sides of turbochargers. According to technical specifications of turbocharger manufacturers values of the vibration level on bearing casing are the one of the most important diagnostic parameters. Values of vibration acceleration of I-th harmonic on both sides of tested turbochargers are lower than 10 m/s^2 which mean that turbochargers rotors and bearing systems are in good technical conditions.

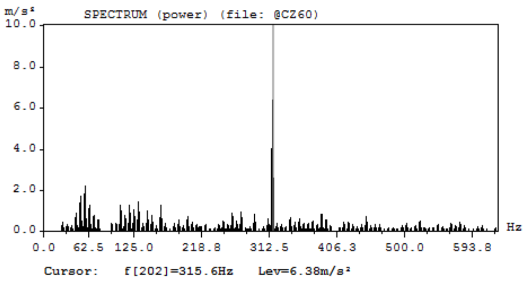

Fig. 3. Turbocharger amplitude of vibrations accelerations in frequency domain Main Engine – port side

Power spectra (fig. No 3 and fig. No 4) for both turbochargers shows the maximum values of the vibration signals (between 6,0 and 8,0 m/s^2) for the basic frequency 315 Hz and 326 Hz respectively.

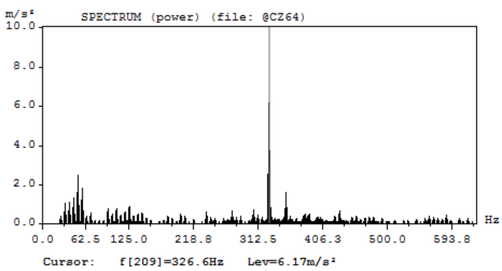

Fig. 4. Turbocharger amplitude of vibrations accelerations in frequency domain Main Engine – starboard side

Technical conditions of turbochargers were verified by endoscopic examinations which results are shown in the fig. No. 5 and No. 6.

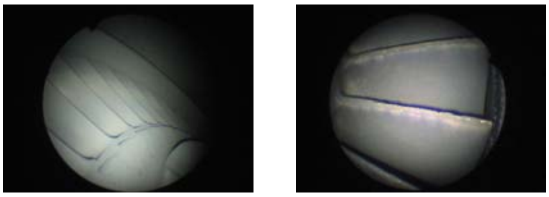

Fig. 5. Turbine (left) and compressor (right) wheels - Main Engine – port side

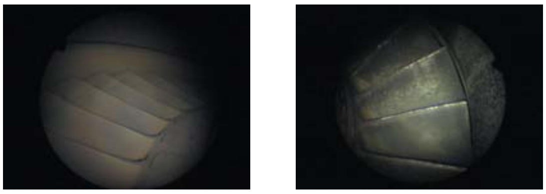

Fig. 6. Turbine (left) and compressor (right) wheels - Main Engine – starboard side

2.2. Results of vibration signals investigations – the SULZER type 6AL20/24 auxiliary diesel engines with the napier C–045/C type turbocharger

Measurements were made for both auxiliary engines and with engines load and turbochargers speed ranges dependent on vessel electric installation mode. In the paper chosen parameters mainly for engine load closed to rated load are presented.

Table 4. Values of chosen vibration parameters – Auxiliary Engine – Diesel Generator No. 1

Date	11.01.2011	Diesel Generator No 1		
Ambient temperature	18 °C			
Atmospheric pressure	1009 hPa			
Engine speed	[rpm]	400	750	750
Engine load index	%	2.7	4.3	6.0
Basic frequency	[Hz]	173	358	536
Turbocharger speed	[rpm]	10380	21480	32160
Vibration acceleration [I harmonic]	a $[m/s^2]$	0.13	0.67	0.76
	a [g]	0.01	0.07	0.08
Vibration acceleration [RMS]	a $[m/s^2]$	2.0	21.9	20.9
	a [g]	0.21	2.23	2.13

Vibration parameters were measured in one point on turbocharger bearing casing between compressor and turbine casing. Values of vibration acceleration of I-th harmonic on both tested turbochargers are lower than 10 m/s^2 which mean that turbochargers rotors and bearing systems are in good technical conditions.

Table 5. Values of chosen vibration parameters – Auxiliary Engine – Diesel Generator No. 2

Date	11.01.2011	Diesel Generator No 2		
Ambient temperature	18 °C			
Atmospheric pressure	1009 hPa			
Engine speed	[rpm]	400	750	750
Engine load index	%	2.8	4.6	6.3
Basic frequency	[Hz]	169	365	565
Turbocharger speed	[rpm]	10140	21900	33900
Vibration acceleration [I harmonic]	a [m/s^2]	0.16	0.72	2.43
	a [g]	0.02	0.07	0.25
Vibration acceleration [RMS]	a [m/s^2]	2.7	20.2	31.6
	a [g]	0.28	2.06	3.22

Power spectra (fig. No. 7 and fig. No. 8) for both turbochargers shows the local maximum values of the vibration signals - less than 1,0 m/s ^{2} for DG No1 at the basic frequency 536 Hz and about 2,5 m/s^2 for DG No 2 at the basic frequency 565 Hz respectively.

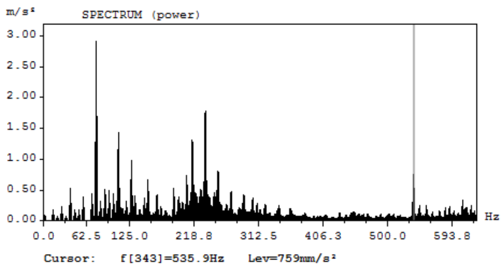

Fig. 7. Turbocharger amplitude of vibrations accelerations in frequency domain Diesel Generator No. 1

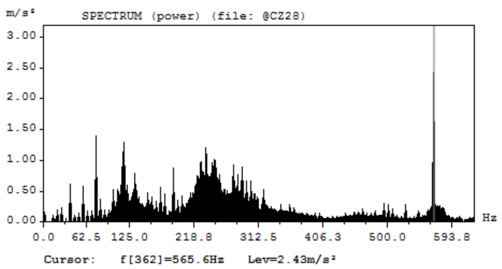

Fig. 8. Turbocharger amplitude of vibrations accelerations in frequency domain Diesel Generator No. 2

Technical conditions of turbochargers were verified by endoscopic examinations which results are shown in the fig. No. 9 and No. 10.

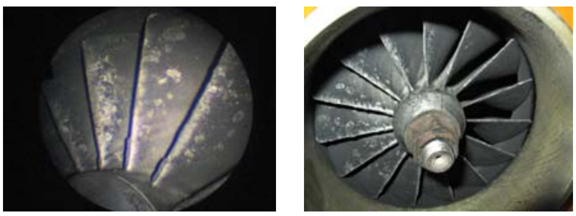

Fig. 9. Turbine (left) and compressor (right) wheels - Diesel Generator No. 1

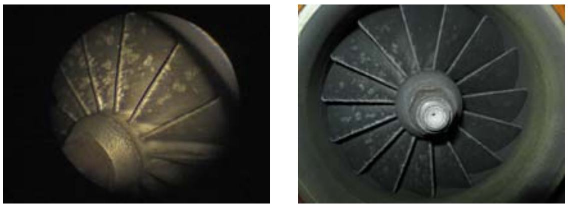

Fig. 10. Turbine (left) and compressor (right) wheels - Diesel Generator No. 2

3. SUMMARY

Diesel engines technical condition assessment is a very complex process. Some of the malfunctions and troubleshooting in diesel engine installations are generated by turbochargers. There are some diagnostic tools available to trace changes in technical condition such important assets as marine diesel engines turbochargers are. In fig. No. 11 some chosen results obtained during sea trials are presented. As it is seen tested turbochargers are in relatively good technical condition and values of I-th harmonic vibration acceleration amplitudes are much lower than acceptable in service.

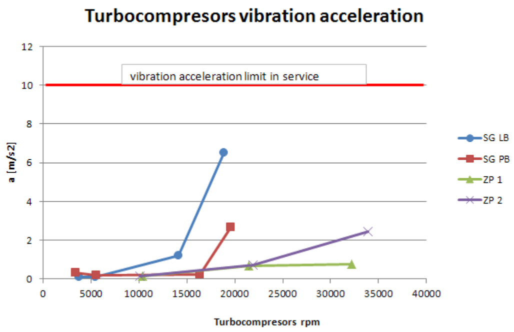

Fig. 11. I-th harmonic vibrations acceleration amplitude measured on turbochargers bearing casing versus turbocharger rpm
SG LB (blue line) – main engine port side,
SG PB (red line) main engine starboard,
ZP 1 (green line) - Diesel Generator No. 1,
ZP 2 (violet line) - Diesel Generator No. 2

Vibration signals processing methods seems to be effective in marine diesel engines turbocharger diagnostics [3] and could be used in onboard monitoring or diagnostic systems. Presented vibration methods gives opportunity to change the engine maintenance philosophy connected with turbochargers maintenance process. It is possible using on-line or off-line vibration monitoring systems to go from scheduled to condition based turbochargers maintenance without fear about real operating engine conditions.

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CONCEPT OF SYSTEM SUPPORTING SELF-STUDY PROCESS OF DIAGNOSTICIANS

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Summary

One of the element of the work of employees of maintenance services is a process of improving their knowledge. So it is important to prepare such a system which could help that process. The aim of this paper is a concept of the system that allow support learning process of maintenance service staff. In this paper the author presents two main parts of this system. The first one that is connected with representation of diagnostic knowledge. The second part of the system will help to decide which part of the knowledge is suitable for the employee. The author assumed that the system will be dynamically fit to the knowledge of the employee. The knowledge will be divided into small parts, so each of them could be used in many different themes. Basis of them the system could decide which part of them is adequate to the actual knowledge of the employee.

Key words: applications, artificial intelligence, education and training in CM, decision support for CM.

KONCEPCJA SYSTEMU WSPOMAGAJĄCEGO PROCES SAMOKSZTAŁCENIA PRACOWNIKÓW UTRZYMANIA RUCHU

Streszczenie

Jednym z elementów pracy służb utrzymania ruchu jest proces samodoskonalenia swojej wiedzy i umiejętności. Istotnym więc wydaje się opracowanie systemu, który mógłby wspomóc ten proces. Tematem tego referatu jest przedstawienie koncepcji takiego systemu, który wspomógłby proces samokształcenia służb utrzymania ruchu. W pracy autor przedstawia dwa główne elementy takiego systemu. Pierwszy element związany jest reprezentacją wiedzy diagnostycznej. Drugi z elementów systemu ma pomóc wybrać tę część wiedzy, która będzie najbardziej właściwa dla danego pracownika. Zakłada się, że system będzie się dostosowywał do wiedzy pracownika. Wiedza będzie podzielona na części, dzięki czemu będzie można je wykorzystać w wielu różnych tematach. Na tej podstawie system będzie mógł decydować jaką wiedzę należy przekazać pracownikowi w stosunku do posiadanej przez niego wiedzy.

Słowa kluczowe: aplikacje, sztuczna inteligencja, nauczanie i szkolenie w utrzymaniu ruchu, wspomaganie decyzji w utrzymaniu ruchu.

INTRODUCTION

Nowadays the maintenance is a very important part of industrial activities. The definition of maintenance that can be find in [1], describe it as series of all actions made during the life cycle of a machine, to retain it in, or restore it to, a state in which it can perform the required function.

On the Fig. 1. are presented types of maintenance defined by the European standard for maintenance terminology [2].

Preventive maintenance is carried out usually in specified time intervals or based on predefined criteria. So, the preventive maintenance can be divided into predetermined or on condition based. The predetermined maintenance is based on predefined schedules that are previously planned. In the condition based maintenance, the decision about reparation of the equipment is taken basis on the results of signal analysis and/or evaluation of the significant parameters of the degradation of the equipment. On the other hand we have the corrective maintenance. In this kind of maintenance the state is carried out after fault recognition. After that the equipment should be put into the state in which it can perform a required function. This kind of maintenance can be immediate or deferred.

The condition based maintenance (CBM) [1, 14] has been implemented in the industry with success. Because of complexity of industry processes and machines in many cases in the industry the condition based maintenance is use more often. All this is connected with [3]:

- manufacturing diversity,
- process diversity and complexity,
- accessibility to the site or process,

- development of the information and communication technologies which are implemented to improve maintenance practice,
- treated maintenance as a part of the whole production process.

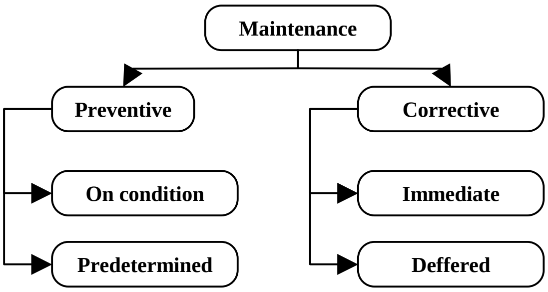

Fig. 1. Maintenance types describes in EN 13306:2001 [1]

In last few years new techniques and methods connected with information and communication technologies (ICTs) are developed or improved. It is worth to pay attention to several elements. The first one is connected with miniaturization technologies of equippments used for data acquisition. New smaller sensor systems and optical micro-sensors are developed. Miniaturization also applies to mobile devices. The dynamic development of such devices allows their use in maintenance. Devices such as PDAs or tablets have become convenient tools for maintenance systems. The second one is standardization for data and information communication. There are developed or improved standards for wireless communication like WiFi, Bluetooth or ZigBee. In implementations of maintenance systems usually is required an integration of a various hardware and software elements. With this in mind has been developed an open system architecture OSA. The open system architecture was prepared for condition based maintenance system. The standard is developed and supported by the operations and maintenance information open systems alliance (MIMOSA) [3, 4]. All these new developments has given rise to a new kind of maintenance which is called e-maintenance [1, 3]. The e-maintenance is "a new concept that can be defined as a maintenance support which includes the resources, services and management necessary to enable proactive decision process execution. This support includes e-technologies (i.e. ICT, Web-based, tether-free, wireless, infotronics technologies) but also e-maintenance activities (operations or processes) such as e-monitoring, e-diagnosis, e-prognosis …" [1]. The insertion of e-maintenance solutions can increase the efficiency of the work and reduce manufacturing costs. Maintenance tasks tend to be difficult because they require expert technicians. Because of that, the technicians permanently need to improve their knowledge about maintenance. International organizations have elaborate guidelines of competency requirements for maintenance functions. In Europe this kind of guidelines was specified by European Federation of National Maintenance Societies (EFNMS). The EFNMS has specified the competence requirements. Requirements have been developed for both technician specialists and maintenance management. Therefore, it seems that there is a need to develop a system that would help both deepen existing knowledge as well as enable the employee to acquire new knowledge in this field.

1. E-LEARNING

Nowadays, when many people use Internet, it is naturally to take a challenge for application of it to a e-learning medium. New technologies using in the Internet, let us to teach somebody more effective and flexible. In the Internet, knowledge could be transfer using different forms, like: text, pictures, sound, films, virtual models and virtual reality, live presentations etc. Many special systems using network environment like Internet and Intranet are prepared as e-learning solutions. Most of them enable courses as static hypertext presentations. But in the last few years, educational applications are developed that offer more that only static presentations. Some of them contain modules connected with artificial intelligence. Methods and techniques well known from artificial intelligence domain are used in e-learning. All this systems are called Adaptive and Intelligent Web-Based Educational Systems (AIWBES) [9, 10].

E-learning could be realised in different forms. Many of them have evolved and changed. So, it is possible to divide this learning methods into four main forms [11]:

- help database,
- online support,
- asynchronous method,
- synchronous method.

One of the first and relatively simple form used in e-learning are help databases. These methods are based on principle that users or students could prepare queries to database. Results of the queries are used for learning. Databases are used for example by software companies to help users in exceptional or emergencies situations. Information could be retrieve using keywords, context searching or table of contents.

Another form of e-learning is online support. This form of learning is quite similar to databases. In this method we could also search for information using queries. Moreover, users can exchange opinions on special discussion forum or read bulletins in this method.

The best known form of e-learning is asynchronous method. In this method, users are learning in their own individual speed. This education method could be led with or without a teacher. The main role of the teacher is to lead users through the course and answer questions. Users communicate with teacher by e-mail, discussion forum or bulletin. If course is lead without teacher, users are referenced to prepared materials.

In synchronous method the knowledge is transferred by a teacher in real time. At specified time all users and teacher connect all together. At this time, all connected users could view a virtual blackboard. On this blackboard, teacher explains discussed problems. All users may ask some questions and all users can read or hear answers. This kind of courses may be performed ones or be repeated periodically.

Analysing computer systems aiding e-learning, it is possible to notice that some of the elements are common. The basic elements occurred in this kind of systems are [11]:

- content,
- communication,
- virtual reality,
- work coordination,
- tools,
- grade systems,
- reports.

Content is the main element of every e-learning system. It could be relayed using different currier like video cassetes, compact discs or Internet. Very usefull for learning may be virtual reality. Using virtual, reality teacher could present virtual experiments, functioning of some machines, etc. Tools are usefull aid in contetnts preparation. Nowadays tools are very complex and could simplify the teachers work.

2. COURSE ORGANISATION METHODS

The process of working courses out for Internet e-learning solutions is a very complex and time-consuming. It is computed that preparing materials for e-learning take up many hours per course. Courses might be organised using different structures. The well known structures are as follows [12]:

- classic tutorials,
- activity-centred lessons,
- user customized tutorials,
- knowledge paced tutorials,
- exploratory tutorials,
- generated lessons.

In the classic tutorial, user start with an introduction. After that, it is proceeded a sequence of pages that learns progressively more advanced materials. At the end of this tutorial, user encounter some kind of summary or review and test or other activity measure method. The classic tutorials has many variants.

Next type of structure is activity centred lessons. This method is built on a single activity. It also possess an introduction containing a preparation page. After that the user is prepared for activity. After the activity the main elements of the activity is recaps on a summarise page. Special attention should be paid on preparation page. The following elements should be presented for example on this page [12]:

- goals of the activity,
- rules of the behaviour of the activity,
- links for needed information.

The user customised tutorial structure is very interesting. Some paths in a course branch in this method. This branching depends on knowledge or

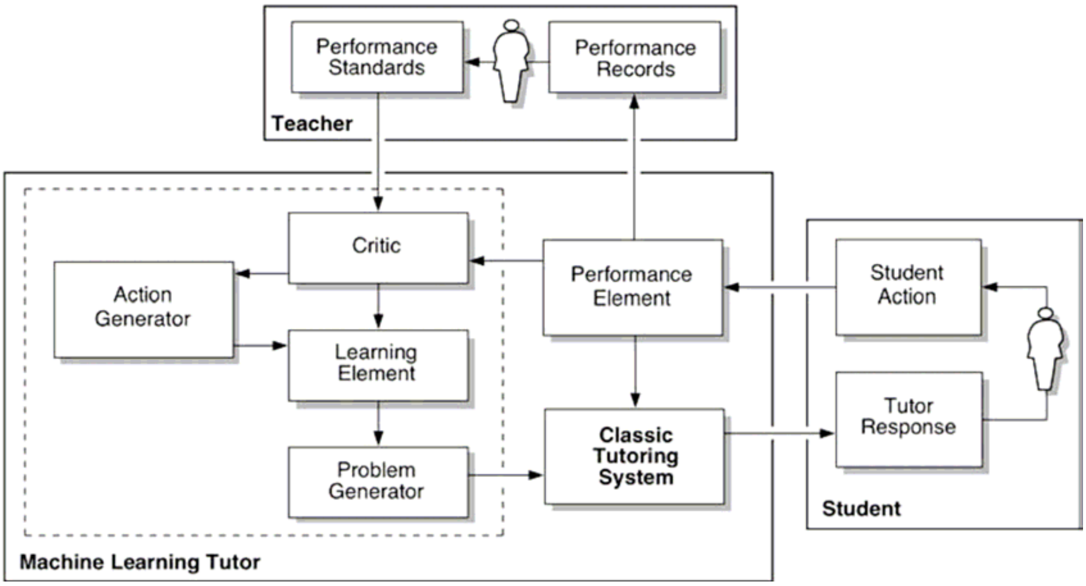

Fig. 2. Components of machine learning techniques integrated into an intelligent tutor [5]

desire of the user individual preferences. Like in former structures, in this method course is started with an introduction page and finished with an summary page. But user is able to choose different paths from start to the end. On the branch page, user should find list of paths to choose from. User also may be tested and automatically directed into chosen path based on the test results.

In the knowledge based tutorial user skip lessons that he already well know. To skip lesson user should pass a test. The next test is more difficult that the previous one. If the user fail to pass a test, he is directed into lesson which deals with materials required to the last test.

In exploratory tutorial, user has some goals and access into electronic collection of knowledge. He should explore this collection in order to achieve goals. After accomplishing each of the goals, user should pass a test.

The finally one of the architectures of courses organised structure is architecture of generated lesson. This method bases on answers to a test or questionnaire. Bases of these answers, course is generated automatically individually to the user.

3. MACHINE LEARNING TECHNIQUES

Modern systems to conduct the learning process in an automatic manner, utilize principles of machine learning techniques. Techniques of this type are used to observe and evaluate the tutor's actions. The reason for the application of machine learning techniques is to enable in this kind of systems experiences from learning process. In [5] we can read that machine learning techniques are used in intelligent tutors to acquire new knowledge about students, identify their skills and learn new teaching approaches. Using these technique can improve the teaching process. This is done by increasing tutor flexibility, reducing tutor costs and adapting to new student population. On Fig. 2 we can see the learning environment with machine learning elements. The environment consists of three types of models. Model of the student, model of the teacher and model of the machine learning tutor [5]. From a group of machine learning methods in the teaching process, the following methods are applied:

- Bayesian belief network,
- reinforcement learning,
- hidden Markov models,
- decision theory,
- fuzzy logic.

A short information about these techniques were described below.

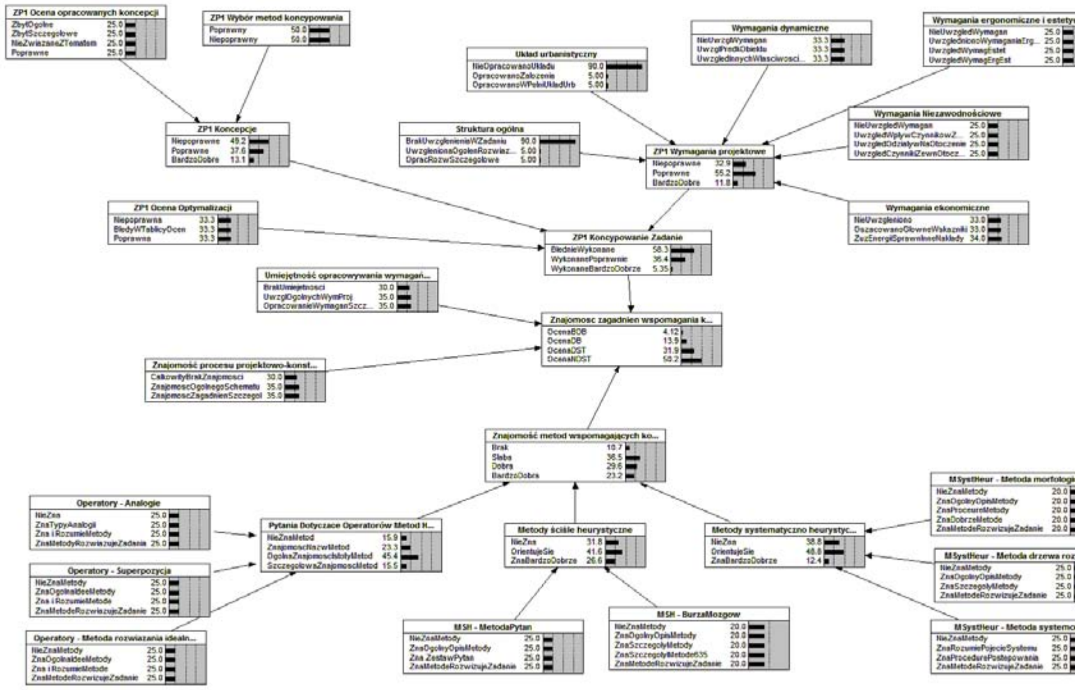

Fig. 3. Example of Bayesian belief network for improving learning process in machine designing

3.1. Bayesian belief networks

The concept of Bayesian belief network is based on the Bayes theorem. In this theorem we can calculate the probability between events and the conditional probabilities between these events. The meaning of calculated values depends on their interpretation. We have two types of interpretation of these calculated values: Bayesian interpretation and frequentist interpretation [7]. In the Bayesian interpretation the probability is a measure of degree of belief. The frequentist interpretation defines the probability with respect to a large number of trials. The Bayesian belief networks used the first of these interpretation.

Bayesian belief networks are widely used in various fields of knowledge. They are used to speech recognition, natural language understanding, user modelling, medical diagnosis, forensic analysis, fault diagnosis, visual tracking, data compression, and genetic analysis [5, 8, 9]. They are applicable in many diagnostic of machine systems [15, 17], several medical systems or nuclear power plants. This kind of knowledge representation is used also in teaching systems [16, 18, 19]. Bayesian belief networks are also used in automatic teaching process. In these solutions, they are used to [5]:

- support classification and prediction,
- student knowledge modeling,
- predict student behavior,
- make tutoring decision,
- determine steps on which students will need help and their probable method for solving problems.

On Fig. 3. Is presented an example of a Bayesian belief network prepared for an analyze of assessing the progress of students.

3.2. Reinforcement learning

The essence of this technique bases on principles that are used by humans or animals to gain experience through random trial and error. This method is an example of unsupervised learning. Referring to the comparison with nature, people or animals learn in this way without the teacher, who would point them the right way, by interact with an environment. In the computing environment like in reality, it is necessary to determine the participant's interaction with the environment. In the computing environment it is realised by agent-based solutions. Agents can be both humans and computers. The operation of such an agent is based on doing tasks to derive the maximum profits. Therefore, we use here the rewards and punishments method. Behavior leading to a particular purpose are rewarded and those that do not comply with the stated objective are punished. Because these methods are associated with high computational expenses, we should remember to retain a balance between exploration of new territories and exploitation (of current knowledge) [5].

An example of the system working on the principle of reinforcement learning is a system for learning to ride a bike [5]. The goal of this system is simply learning to ride a bike. System operation is based on gaining experience with riding a bike based on the position of the bike in relation to the road. If the bike leans to the left, we have two choices, lean even more to the left or lean to the right. If the system will strongly leans to left the bike fall over. If the system tilt the bike to the right, the bike will go on. In the next case, the bike leans to the right. The system remember that if the bike leans to the right it was a proper solution. But in this case this is of course bad solution. Just tilt the bike to the left to continue its journey with success. So, the next experience gathered by the system will be the direction of tilt. And so, through trials and errors the system learns how to ride a bike.

3.3. Hidden Markov models

A hidden Markov model (HMM) is a statistical Markov model in which the system being modeled as assumed to be a Markov process with unobserved (hidden) states [8]. The hidden Markov model is the simplest case of dynamic Bayesian networks. Using this model we can observed some changes of states without the observation of the states themselves. Instead of that we observe some probabilistic function of those states. A simple example, was proposed by by Jason Eisner in 2002 [9], "Ice Cream Climatology":

"The situation: You are a climatologist in the year 2799, studying the history of global warming. You can't find any records of Baltimore weather, but you do find my (Jason Eisner's) diary, in which I assiduously recorded how much ice cream I ate each day. What can you figure out from this about the weather that summer?"

Using hidden Markov model we can describe this scenario. We don't get to observe the weather on each day which are hidden states. But we can observe how many ice creams were eaten that day, which are a probabilistic function of the process.

This kind of model is used in many applications such as: speech recognition, handwriting, gesture recognition, part-of-speech tagging, musical score following, partial discharges and bioinformatics [8]. Hidden Markov models are also used in systems supporting the learning process. There are used for studies validation, to model student behavior, to model student's mastery of the knowledge [5]. An example of simple learning system using this method is presented in [13].

3.4. Decision theory

Decision theoretic networks are another machine learning technique that we can use in intelligent learning systems. This technique is based on decision theory, that is closely related with probability theory. The idea of using the decision theory in teaching systems, is to find a proper plan or action with minimal costs. These kind of technique we can use to determine the next step of learning process or to choose the next test perform when current tests were not sufficient. There are many application of using decision theory to intelligent learning systems like DT Tutor, More tutor or CAPIT System [5].

3.4. Fuzzy logic

The fuzzy logic technique was developed by Lofti Zadeh who proposed the fuzzy set theory. It was developed to expand the classical logic theory. It can be used to describe the ambiguity and contradictions. This method has been widely used in many engineering solutions such as control systems, expert systems or knowledge engineering. In intelligent learning systems the fuzzy logic is used to represent the uncertainty of knowledge. In these kind of system the fuzzy logic is used to convert the knowledge with subjective concepts into numeric values. We can use it also to formulate ambiguous descriptive terms in the responses of students or verbal evaluations of students' knowledge.

4. SUPPORT LEARNING PROCESS SYSTEM

One of the element of the work of employees of maintenance services is a process of improving their knowledge. So it is important to prepare such a system which could help that process. In this part of paper I wish to present a concept of a system that allow support learning process of maintenance service staff. This kind of systems should have two main parts. The first one that is connected with representation of diagnostic knowledge. The second part of the system will help to decide which part of the knowledge is suitable for the employee. Using the current knowledge about that systems it is assumed that it should dynamically fit to the knowledge of the employee. To do this, knowledge will be divided into small parts, so each of them could be used in many different themes.

4.1. Knowledge representation

The main element of any system that is aided by artificial intelligence methods is the knowledge base. In this system we need to use knowledge bases to save the knowledge about:

- supported object,
- object maintenance content,
- user personalized skills.

The knowledge about the supported object can be taken from maintenance system that are used on the object. If the object has no maintenance system built in, for the information about the object should be saved in database with MIMOSA schema. Very interesting part of knowledge is the knowledge about object maintenance. In many cases the

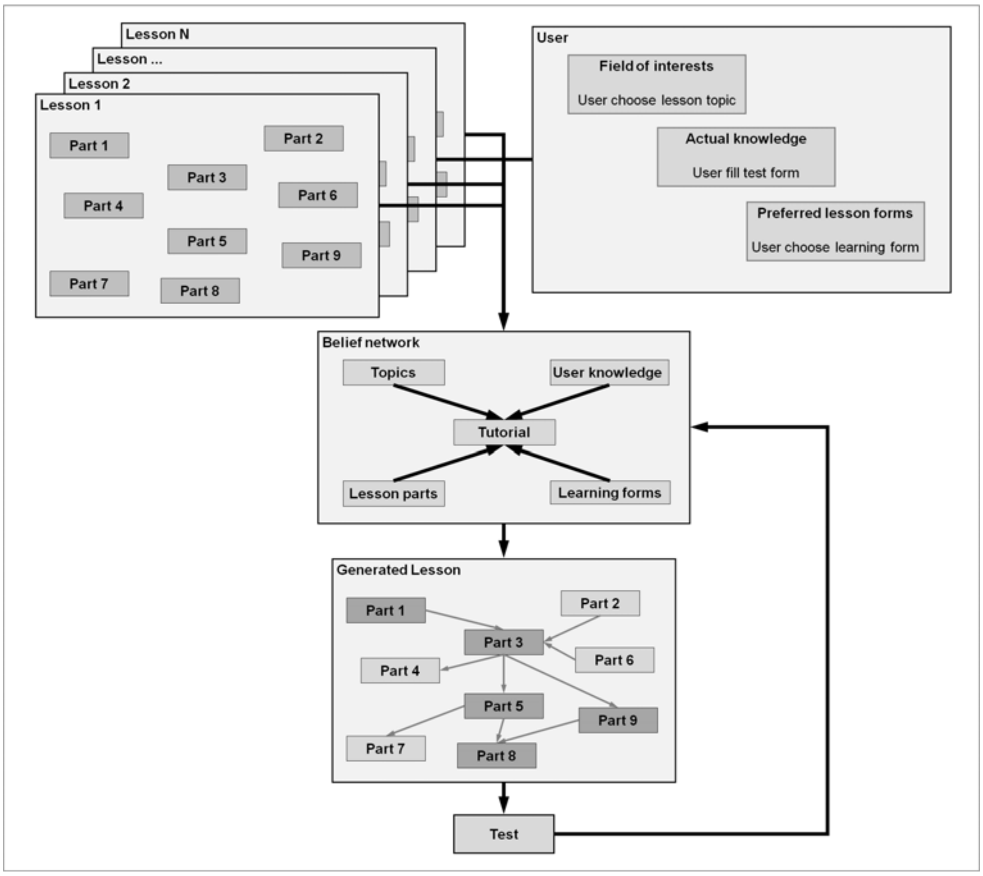

Fig. 4. Schema of the course organization environment

knowledge representation about maintenance of an object depends on the system that is used in the given factory. But in general I propose to use a mixed representation. For the maintenance data it is proposed a database with MIMOSA schema. That is a very useful and exchangeable standard. But we need to have also the knowledge about changing of the machine state. So it is proposed to use one of the machine learning technique for this. It is considered that a Bayesian belief networks or hidden Markov models will be helpful for this.

The last part is the knowledge possessed by an employee. His/her knowledge will be represented as a Bayesian belief network.

4.1. Concept of course organization environment

One of the main question in preparing the systems is how to represent the knowledge and how to organize it. If the organization of the course is incorrect then it could disturb the learning process. If it is well organized, employee should assimilate knowledge quickly and more effectively. At this point, a concept of a course organisation method is presented. I set up that the main user of that system is an employee.

A concept of an environment appropriate for e-learning is proposed. In this environment, user is the main element of the learning system. Each of the user has different knowledge and experience. So the main task of the system is organize the course for the user personally. The concept of this method is based on architecture of generated lessons. In this method, lessons should be generated automatically, individually to the user. Topics presented in lessons may be described with the application of different forms. A part of the lesson is prepared for every form. Sets of lesson parts are defined in the learning system. Each of the part is used for description of one point of view. The main task of the system is to generate lesson from the parts. The question is how the system should choose the course and which of them may be preferred by the user. Selection of the lesson elements can be generated based on:

- information about field of interests of the user,
- his actual knowledge,
- information about forms of lessons preferred by users.

Field of interest should define area of knowledge which the user would like to discover or to improve. His actual knowledge is used to limiting knowledge area that he should learn. The most important is how he should learn new topics. What kind of learning forms is the best for him. Many users prefer learning based on samples. Others prefer learning based on theoretical aspects of topics. Some peoples would like to read text. Others prefer listen to it. So based on them, it is possible to define different reasons that could influence on the lessons content. Generating lessons mechanism is based on belief network.

It is proposed, that lessons are organised as belief network in this solution. Nodes in this network correspond to lesson parts, field of interest of the user, actual knowledge of the user and learning forms that are available in the learning system. The problem is how to calculate values of nodes in the belief network. At the beginning, values of all nodes are imposed. These values are changed during system running. There are many reasons that could cause modification of nodes values like:

- user topic selection,
- identification of actual user knowledge,
- user preferences about learning forms,
- lesson parts available in the system.

In the first step user should define learning topic. Based on them, system is able to limit content of the lesson. Content of the lesson is limited through modification of node values. In the next step, user is allowed to pass test. Based on results of the test it is possible to determine the actual user knowledge and also modify value of nodes. At the end, user should fill a questioner. In this questioner user identify its preferences about learning forms. Finally, user is able to start the learning process. At the end of the learning process, its efficiency is verified using test. If user passes the test the learning process could be finished. If not, values in nodes in the belief network are modified and a new lesson is generated.

5. SUMMARY

In this paper, the idea of e-learning environment, that could prepare personalized lessons for maintenance employees, is described. This idea is based on architecture of generated lessons. There is a set of lesson parts and system which should propose lesson content the most efficient for the user. Problem of selection of the lessons content is solved with the application of Bayesian network. In this article is presented only an idea of this system. The system is in project mode and will realized in small environment.

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FAILURE MODE DETECTION OF FEEDWATER HEATERS IN OPERATIONAL CONDITIONS BASED ON THE SIMPLIFIED FIRST-PRINCIPLE MODEL

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Summary

This work presents a model-based methodology for failure mode detection of feedwater heater line working in coal-fired power unit. The main objectives of this work are as follows: (i) introduce the problem of feedwater heater diagnostics, (ii) discuss techniques used for failure modes detection, (iii) introduce a diagnostic method based on mathematical model of a feedwater heater, and (iv) validate the method basing on real operational data from a 225MW power unit. The reason for developing a new methodology is that conventional methods, which are currently used, are not efficient and do not ensure early fault detection. Therefore a more advanced approach based on adjustable phenomenological parameters (i.e. heat transfer coefficients), that are estimated from measurement data, is proposed.

Key words: failure mode detection, feedwater heater, model-based diagnostics.

WYKRYWANIE USZKODZEŃ PODGRZEWACZY WODY ZASILAJĄCEJ W WARUNKACH ESPLOATACYJNYCH NA PODSTAWIE UPROSZCZONEGO MODELU

Streszczenie

W pracy przedstawiono metodologię wykrywania awarii podgrzewacza wody zasilającej pracującego w jednym z bloków elektrowni węglowej. Główne cele prowadzonych badań są następujące: (i) omówienie problemu diagnostyki grzejnika wody zasilającej, (ii) omówienie technik stosowanych do wykrywania awarii podgrzewaczy, (iii) wprowadzenie metody diagnostycznej opartej na matematycznym modelu podgrzewacza wody zasilającej, oraz (iv) weryfikacja metody w oparciu o dane zarejestrowane na 225MW bloku energetycznym. Powodem opracowania nowej metodologii jest to, że konwencjonalne metody, które są obecnie stosowane, nie są skuteczne i nie zapewniają dostatecznie wczesnego wykrywania usterek. Dlatego tez w pracy zaproponowano bardziej zaawansowane podejście oparte na dostrajaniu modelu (np. na współczynnikach przenikania ciepła) w oparciu o dane pomiarowe.

Słowa kluczowe: wykrywanie przyczyn awarii, podgrzewacz, diagnostyka oparta na modelu.

NOMENCLATURE

$\dot{m}$ [kg/s] - steam mass flow

$\dot{m}_w$ [kg/s]- feedwater mass flow

T_{w1}, T_{w2} [°C]– feedwater temperature respectively on inlet and outlet from the heater p_{w1}, p_{w2} [Pa]- feedwater pressure respectively on inlet and outlet from the heater

Ts [°C]– steam temperature

k [W/(m2*K)] – heat transfer coefficient

F [m2] – area of heat exchange

c_p [J/(kg*K)] – specific heat of feedwater

1. INTRODUCTION

Great advances in control and monitoring systems applied in thermal power plants have created a possibility to develop new efficient methodologies for diagnostics and condition assessment of power unit components. At the same time, increasing attention to safety and need for reduction of energy production costs have made a demand for such new methods.

This paper focuses on the performance 225MW power unit, being a subsystem of a power plant located in Polaniec, Poland. In particular, operation of a high pressure heater line is considered.

For detailed description of thermal power plant's regeneration circuit see [1] or [4].

The aim of the research was to provide a method that will enable quick detection of heater failure modes, basing on historical data. The engineering need standing behind this research is that performance of currently used diagnostic methods require improvement regarding early-warning towards typical malfunctions, such as tube bursting inside a heater or servovalve faults. Those methods are based on observation of measured operational parameters, and, as a result, they are not precise and do not ensure early detection of faults. At the same time, proposed method is able to detect symptoms of fault.

To achieve the goal, real operating data concerning operation of high pressure heater line was gathered from the power plant archives. The data taken into consideration corresponds to one year of operation, with sampling interval equal to five minutes. Additional data concerning periods, types and reasons of heater malfunctions was also analysed with relationship to raw data.

2. HIGH PRESSURE FEEDWATER HEATER INSTALLATION

1.1. Principle of operation

Typical regeneration system is shown in figure 1. Feed pumps pass the condensed steam (feedwater) from a condenser through heater banks, supplied by the steam extracted from the high, intermediate and low-pressure sections of a steam turbine [2]. The condensate is pumped to the deaerator, through the bank of low-pressure heaters XN1, XN2, XN3, XN4 and XN5, and further from the deaerator to the steam generator (boiler) through the bank of high-pressure heaters XW1, XW2 and XW3.

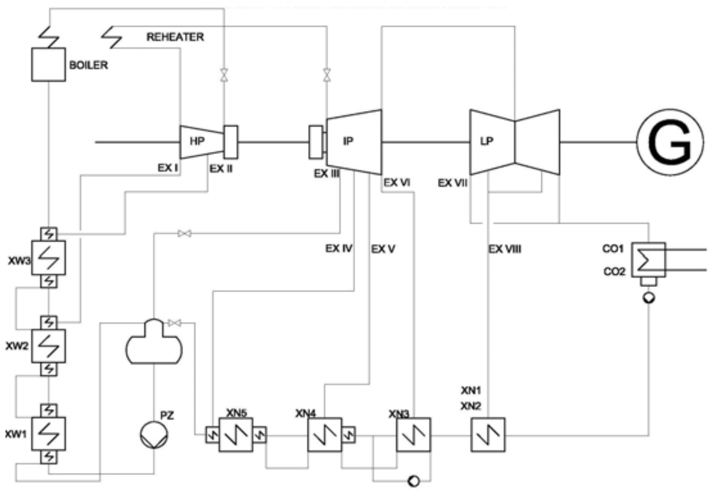


Fig. 1. Functional scheme of a power block [2]. (EX: steam extraction port; XW: high pressure heater; XN: low pressure heater; CO: condenser; PZ: main pump)

The drainage system of the feedwater heater consists of a drain removal path from each heater. The normal drain flow path is cascaded to the next lower stage heater, and the alternate path is diverted to the condenser. The heaters XN1 and XN2 assembled in the condensers are in continuous operation with the condensers CO1 and CO2. When the turbine is loaded at a given rate, steam is allowed to enter the bank of high-pressure heaters through extraction outlets and pipelines denoted by III, II and I to the heaters XW3, XW2 and XW1, respectively.

Feedwater heaters are typically designed as three-zone heat exchangers with a condensing section, desuperheater and integrated subcooler (Fig. 2).

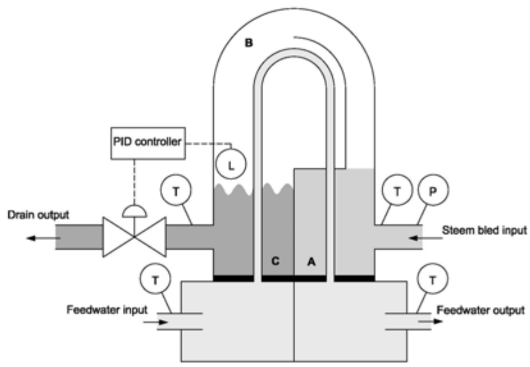


Fig. 2. Schematic representation of a three-zone feedwater heater [1] (A: desuperheating area; B: condensing area; C: subcooling area; T: temperature sensor; L: level sensor; P: Pressure sensor)

1.2. Control system of high pressure heater line

Regulatory control loops of the condensate level control are coupled to the power unit controller. The control system consists of the PID controller, which enables the condensate level variation to be compensated and maintains its constant level in the subcooling zone. Feedwater temperature control is realised by the steam pressure control valves regulating the pressure of the steam entering the heater [2].

Supervisory control over the whole heater line is realised by a SCADA (Supervisory Control And Data Acquisition) system.

1.3. Common malfunctions of a high pressure heater

Reliability of feedwater heaters is strongly influenced by their design, applied materials and operating conditions [8]. Most common faults of heaters concern piping systems. Tube bursting makes the feedwater flow into the external jacket of the heater, and consequently feedwater gets mixed with condensate. The leakages have several causes: (i) electrochemical corrosion, (ii)erosion caused by water or steam, and (iii) fatigue – due to mechanical vibrations. Details of each cause of fault, common places of occurrence and discussion on materials for heater's construction are provided in [8].

Moreover, operation of the heater may be influenced by faults of auxiliary devices, such as three-way servovalves regulating flow of fluids through the heater. There occur also malfunctions of control system elements, e.g. sensors measuring operational parameters of the heater and giving information to the controller.

Consequences of consecutive malfunctions for the whole power unit are described in [1].

2. DIAGNOSTIC TECHNIQUES CURRENTLY USED IN POWER PLANTS

In order to establish what techniques for heater condition assessment are practically used in power plants, a brief survey was made. On the basis on information obtained from a power plant representative the following conclusions have been made.

It is expected that the condensate level will always be constant. However, there are set two safety thresholds regarding that level: 500mm (warning) and 2000mm (faulty conditions). A possible malfunction, typically leakage of feedwater into external jacket of heater, is detected basing on observation of trends of opening of drain valve. Any leakages in feedwater circuit will generate an increase of condensate in the heater. That increase must be compensated by greater opening of a drain valve. If the value of drain valve displacement is quite different than normally the heater is considered to be faulty.

However, detection of heater fault is not always equal with shut-down of the whole unit. Typically, only few pipes are damaged. Influence of such fault on the heater performance is not significant until the regulator is able to compensate for the leakage. In those cases, heater usually operates till the next scheduled maintenance period, being carefully monitored.

In case of more serious damages, it is also not necessary to stop the whole power unit. Then, only the regeneration circuit is bypassed and operation of the other components of a unit is continued without active regeneration line due to economic reason.

3. PRESENTATION OF DEVELOPED METHOD FOR FAILURE MODE DETECTION OF FEEDWATER HEATERS

Due to the complexity of heater construction and strong nonlinear character of physical phenomena occurring there, creation of exact mathematical model of such system is computationally demanding and requires extensive field knowledge [1]. Moreover, not all parameters needed for precise object modelling are directly measured and registered by the plant monitoring system, due to low ratio of relevance to cost of such measurements. To deal with this lack of data, it is necessary to apply advanced identification techniques, e.g. 'grey box approach' [2], to retrieve missing data, increasing computational effort.

Taking all mentioned facts into consideration, it was decided to implement a simple model of heat exchanger, (Fig. 3) [3]. On the basis of a number of known operational parameters: feedwater temperature entering and leaving the heater, steam temperature and feedwater mass flow through a heater, the heat transfer coefficient of the heater is determined for every data sample.

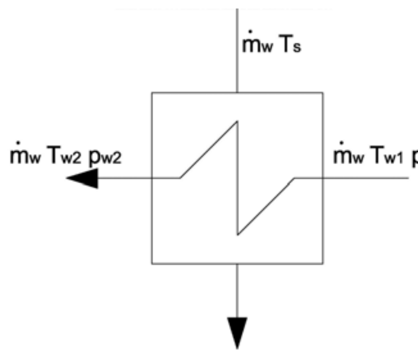


Fig. 3. Scheme of analysed heat exchanger [3]

In order to simplify the model numerous assumption considering feedwater heater must have been taken. The following facts are negligible [2]:

1. the exchange of the heat between the cavity and the external environment,
2. accumulation of the heat in the water,
3. the exchanges of the energy and the mass, caused by the surface phenomena at the interface between the condensing and the subcooling areas.

Additionally, it is assumed that:

1. all the areas where the exchange of the heat takes place are not distinguished and treated as a single chamber,
2. the pressure in the cavity is constant, uniformly distributed and equal to the steam pressure at the inlet,
3. the enthalpy is averaged over each of the areas based on the boundary conditions of each heater chamber,
4. the feedwater is in a liquid state and in a subcooling condition,
5. the pressure of the fluid in the tube-bundle equals the pressure of the feedwater at the inlet,
6. the physical properties of the tube-bundle metal are uniform, and the longitudinal heat conduction in both the pipe metal and the fluid is negligible.

Then, heat exchanger can be described with the following equation:

$$\mathrm{k}\cdot \mathrm{F}\cdot \frac{T_{w2}-T_{w1}}{\ln\frac{T_s-T_{w1}}{T_s-T_{w2}}} = \dot{m}_w \cdot c_p \cdot (T_{w2}-T_{w1}) \qquad (1)$$

Detection of feedwater heater condition is based on analysis of phenomenological parameters, i.e. change of heat transfer coefficient of the heater. It is assumed that heat transfer in the heater is affected by its typical malfunctions, such as leakages. Value of heat transfer coefficient is strongly correlated with other parameters of power unit, such as its instantaneous power or steam pressure on turbine extraction (Fig 4). In steady operating conditions higher power level corresponds to higher value of heat transfer coefficient k. In transient states, i.e. during run-ups, run-downs or shut-down periods, heat transfer coefficient takes arbitrary values, due to unsteady temperature and pressure of steam and feedwater. Therefore, mentioned periods were neglected and are not taken into consideration during analysis.

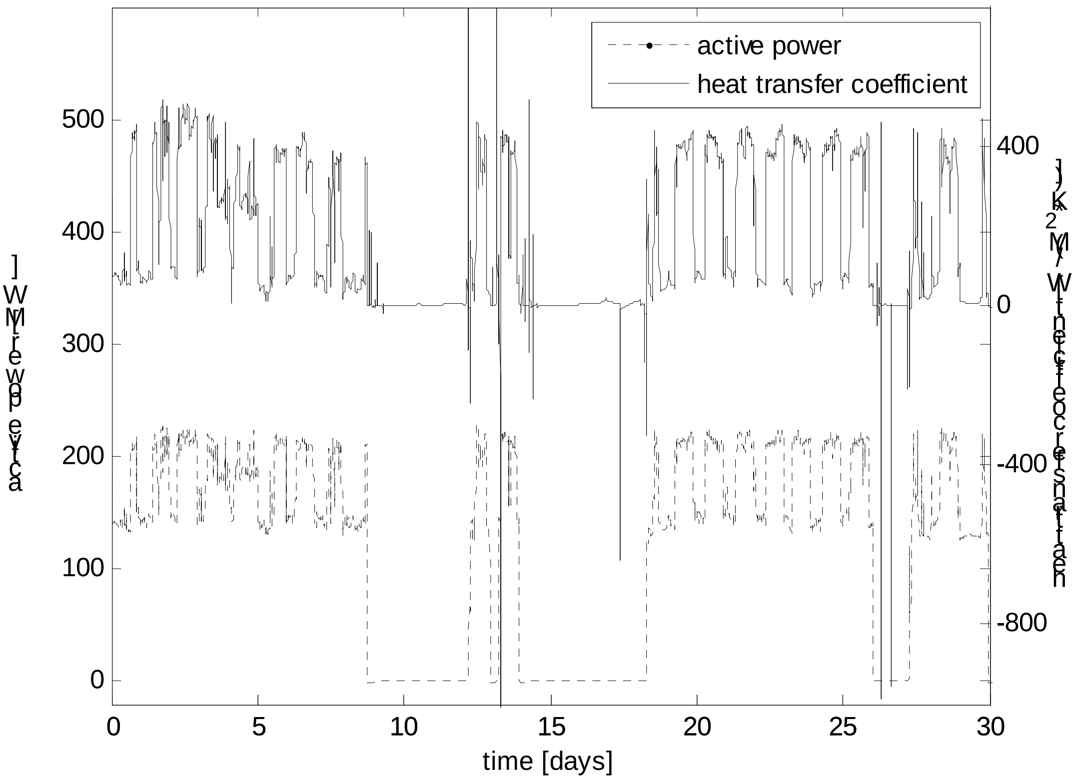


Fig. 4. Trends of heat transfer coefficient for heater XW1 and active power of the unit

A power unit frequently changes its operating point, due to fluctuating demands for electrical energy during day and night. Moreover, the heater possesses some thermal capacity and it does not heat up or cool down as fast as the generated power rate changes. Therefore, it is not that straightforward to determine if the observed change in heat transfer is caused by the power rate variation or any possible damage inside the heater.

To tackle with those problems, a method must have been proposed. There was provided the following solution: (i) application of a moving window and calculation of a mean value of heat transfer coefficient for each interval enclosed by the window, and (ii) division of operating range into a number of intervals with respect to power rate and treating them separately.

The reason for the application mentioned operations (i) is that considering historical data together with current value may reduce the influence of thermal capacity of the heater on its heat conduction parameter and provide more accurate results. The second (ii) operation is supported by the assumption that heat transfer coefficient should remain constant for long periods on condition that the same operating point is examined. Plotting calculated values basing on described procedure, it is expected to obtain several curves representing constant values. However, when malfunction of a heater occurs, those constant curves should be distorted.

4. VALIDATION OF THE METHOD ON THE BASIS OF OPERATIONAL DATA

According to previously made assumption, values of heat transfer coefficient during failure modes should vary significantly from typical values. Figure 5, which represents heat transfer coefficient versus unit power, supports this assumption.

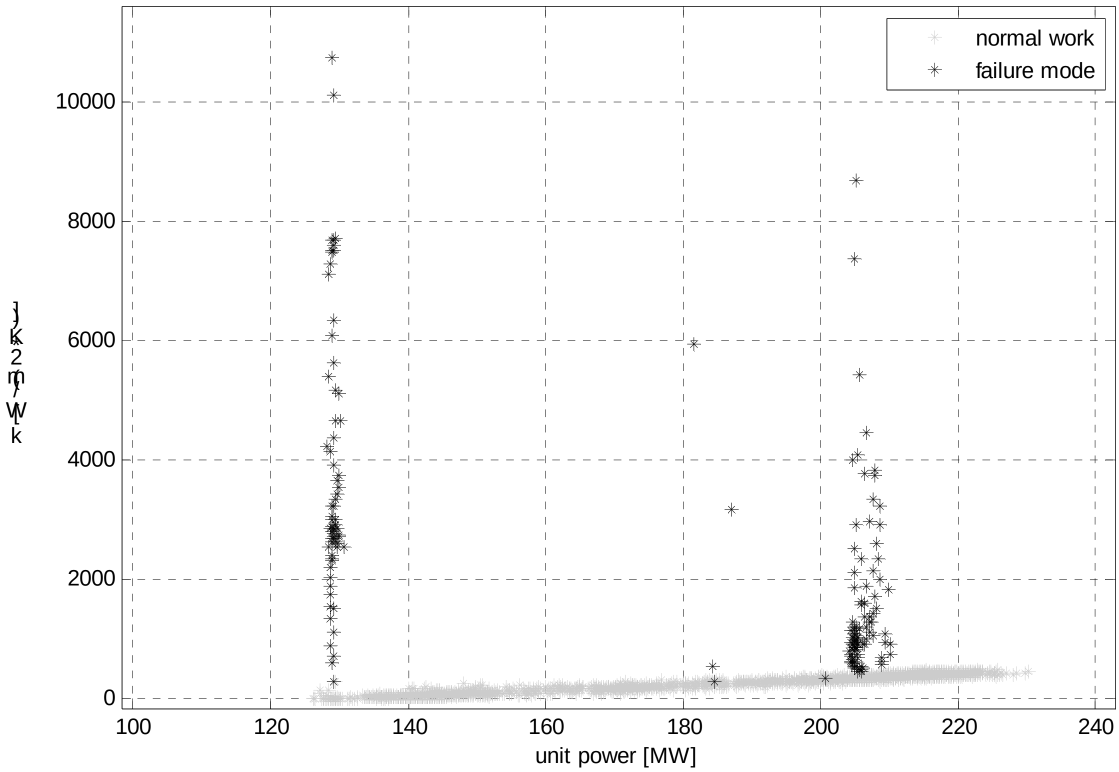


Fig. 5. Heat transfer coefficient versus unit power during normal operation and failure mode

An advantage was taken from possessing real operational data from the power plant, together with specified breakdown periods. This allowed to observe changes in heat transfer trend in correlation with pre-classified malfunctions of feedwater heaters. An algorithm which produced visualisations of results for different parameters was implemented in Matlab environment. The procedure was tested for all three high-pressure feedwater heaters (Fig. 6) and for several datasets regarding different periods.

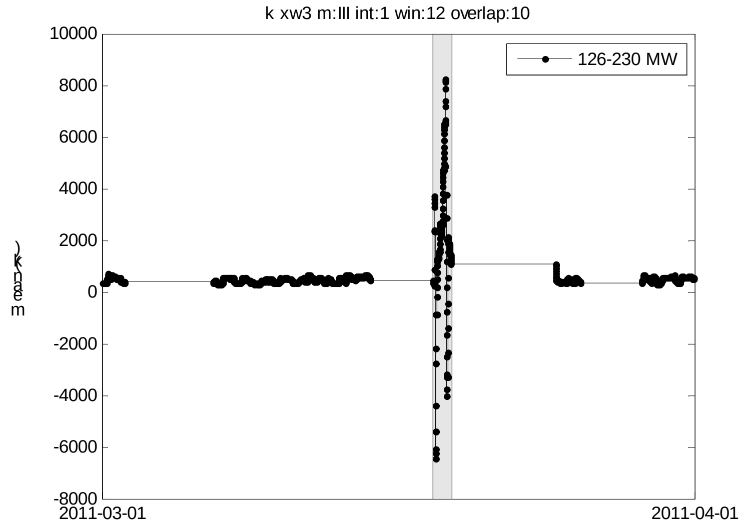
In order to find the best parameters, an experiment was designed. The scope was to find out what should be the optimal values of window length, overlap number and quantity of power rate intervals. Moreover, a choice should have been made to work either straight on consecutive values of heat transfer coefficient or use the difference between values of two following samples. In considered experiment, the objective was to enable clearest data visualisation, provide high precision and ensure early fault detection. To achieve this, several values of above-mentioned parameters were examined and, for each proposed parameter value, visualisations were made for the data considering the whole year period.

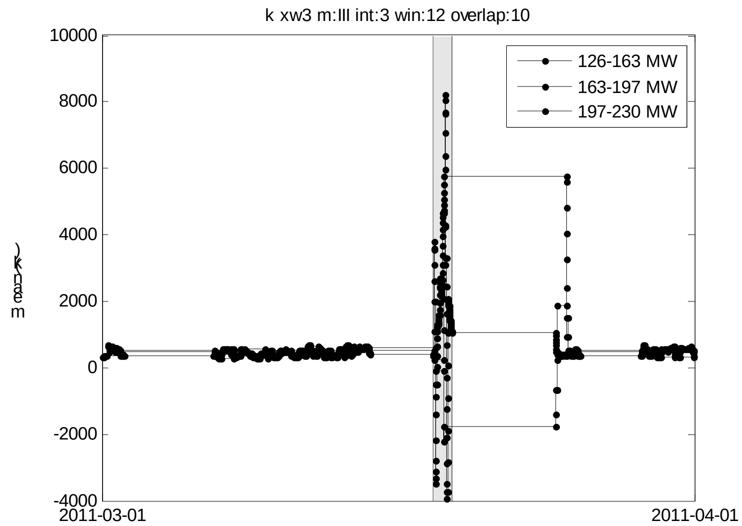
The results of experiment revealed that the maximum reasonable quantity of power rate intervals can be three, since increasing this quantity results in decreased clarity of the plots. The windows must consist of no more than 12 samples (1-hour windows), because otherwise some data may be lost due to averaging of longer period's data. Finally, an overlap number may be as large as possible, because it increases sampling rate of processed data. It was also decided to operate on consecutive values of heat transfer coefficient, instead of using the difference between values of two following samples. Although such solution requires tuning of warning thresholds for each particular case, it provides better potential for distinction between steady operation and faults.

Exemplary results are presented in Table 1. Breakdown periods corresponds to pipe leakages in heaters XW2 and XW3.

Table 1. Results of method application. Malfunction periods are denoted with shaded background

Leakage in piping system





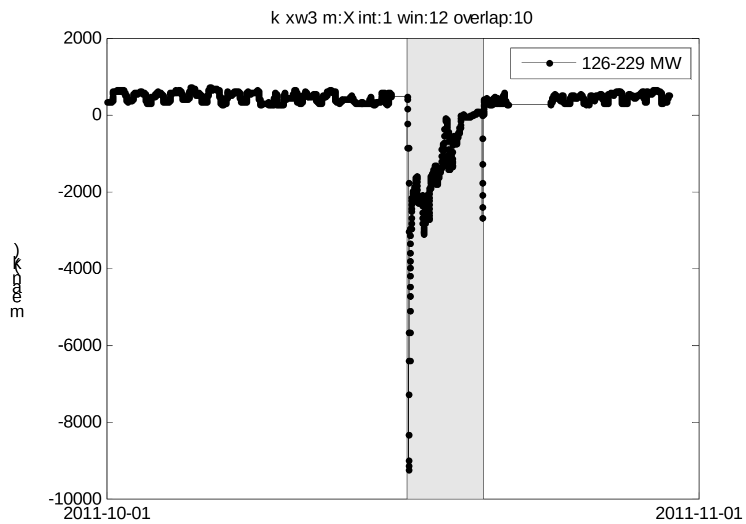
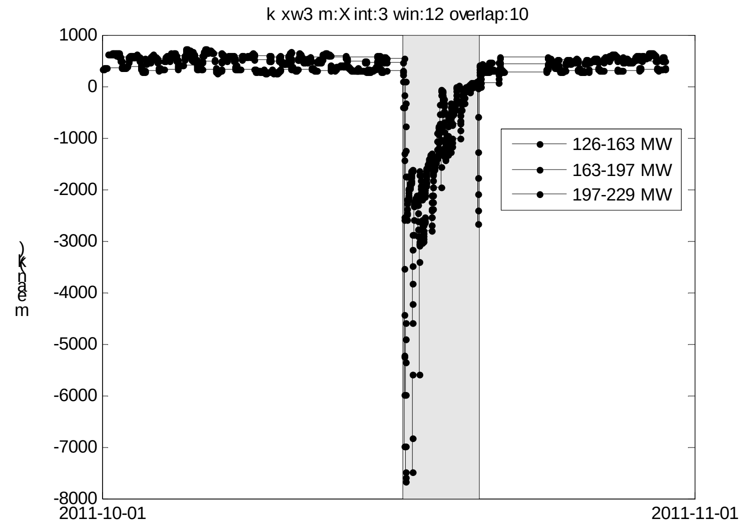


Table 1. Results of method application. Malfunction periods are denoted with shaded background

Leakage in piping system


The experiment has indicated that the idea to observe phenomenological parameter, such as heat transfer coefficient, may be applied to feedwater heater's failure mode detection. Basing on available datasets and knowledge about heaters malfunctions it has been proved that there is clear distinction between steady operation and faults visible. The accuracy of developed method depends on proper choice of parameters .

The algorithm used for determining the heat transfer coefficient may be applied to any feedwater heater system, on condition that required process parameters are measured. Since feedwater heaters have various designs resulting in different nominal heat conduction ability, it is necessary to determine operational range of heat transfer coefficient for each particular heater. Proper definition of that range enables setting warning or error thresholds, indicating heater faults.

Available data does not allow to estimate if the method is able to detect malfunctions earlier than it is possible with use of conventional methods. Each tested malfunction appeared right after the run-up of the power unit, so it was not possible to check the heater line's condition during shut-down.

It is believed that after proper tuning, the accuracy of developed method is sufficient for failure mode detection of feedwater heaters. Nevertheless, it should be marked, that all conclusions were made on the base of limited number of cases, however, some efforts are made to create a possibility of taking advantage of a larger dataset.

5. SUMMARY

A method for detection of feedwater heater failure modes described in this paper is valid in all tested operational data-based cases. It provides a simple and not computationally demanding solution for monitoring of heater operation, without the need of installing additional measurement devices in the heater line.

The parameter describing the heat transfer inside the heater is calculated as a simplified function of available measured quantities and it does not consider heater inner structure and phenomena occurring there. This may influence the accuracy of the method, however, in examined operational conditions performance of the method is sufficient. Implementation of advanced grey-box approach FPDD model of a feedwater heater will be investigated to check if it is able to improve the performance of proposed method.

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THE INVESTIGATIONS AID IN EXPLOITATION

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Summary
Exploitation systems are constantly improved by management methods and information techniques. Machines in operation are subject to degradation controlled by diagnostic methods. Obtaining information on the condition and its processing for the purposes of legitimate exploitation decisions is elaborated on in many aspects, considered as new herein. This involves information selection, dedicated diagnostic systems, the system of agreeing on decisions and cause-effect modelling. Selected aspects of this subject were discussed in this publication.

Keywords: management, exploitation, diagnostics, redundancy, product life cycle.

WSPOMAGANIE BADAŃ EKSPLOATACYJNYCH

Streszczenie
Systemy eksploatacji są ciągle doskonalone metodami zarządzania i technikami informacyjnymi. Maszyny w eksploatacji podlegają degradacji nadzorowanej metodami diagnozowania. Pozyskiwanie informacji o stanie i jej przetwarzanie dla potrzeb uzasadnionych decyzji eksploatacyjnych jest rozwijane wieloma zagadnieniami, rozwijanymi jako nowe w tej pracy. Dotyczy to selekcji informacji, dedykowanych systemów diagnostycznych, systemu uzgadniania decyzji oraz modelowania przyczynowo - skutkowego. Wybrane aspekty tej problematyki omówiono, z konieczności skrótowo, w tym artykule.

Słowa kluczowe: zarządzanie, eksploatacja, diagnostyka, redundancja, cykl życia produktu.

1. INTRODUCTION

The necessity of the technical state estimation is conditioned the possibility of making decisions connected with object exploitation and the procedure of next advance with object. The present development of automation and computer science in range of technical equipment and software creates new possibilities of realization of diagnosing systems and monitoring technical condition of more folded mechanical constructions.

Production system constitutes a deliberately designed and organized arrangement of material, energy and information used by men, for the purpose of manufacturing specific products – in order to meet diverse needs of consumers. Its proper functioning, in the light of production computerization and application of flexible production systems, almost starts a revolution in the methods of factory management. The practice of exploiting increasingly complex machinery shows that engineering knowledge, on a par with economic and organizational knowledge, becomes a necessity in market economy.

Detecting, measuring, recording and evaluating selected information and data on the condition of a particular system (organization, management, product quality, safety, environment, machinery exploitation) are used for the purpose of organization functioning, management and quality assessment (product, safety, environment, machinery) in terms of assumed task classification. The particularization of such decisions in the area of machinery degradation examination (task usefulness) at the stage of their exploitation is constituted by methods, procedures and measures of technical diagnostics, enabling a particularized (structural) assessment of system condition, generating a basis for further diagnostic - exploitation decisions [1, 2, 3, 4, 30, 32].

2. MANAGEMENT OF EXPLOITATION

The processes of technical system destruction extort the need to supervise the changes of their state, particularly at the stage of exploitation. Methods and means of modern technical diagnostics are tool diagnosing their technical state, which enables their rational and safe maintenance.

The present development of automation and computer science in the field of hardware and software gives way to new possibilities of realization of diagnosing and monitoring systems of more and more complex mechatronic constructions. These new possibilities are connected with new constructions of intelligent sensors, modular software and modules of communication and data exchange.

Any company operating in a competitive free market economy should choose an appropriate management method ensuring a strategic advantage. This includes an analysis of description and relevance of management methods with reference to enterprise specificity, with their brief characteristics, principles of functioning and possible benefits. In view of a large number of established management methods (more than 130 according to various sources), such as: management by objectives (MBO), management by communication (MBC), management by innovation (MBI), management by delegation (MBD), management by results (MBR), management by quality (MBQ), strategic management (SM), management by motivation (MBM), management by participation (MBP), with different: property forms, locations, branches and employment size – an analysis of the distribution of their use frequency indicates that management by objectives (MBO) and management by quality (MBQ are the most frequently used methods (fig.1).

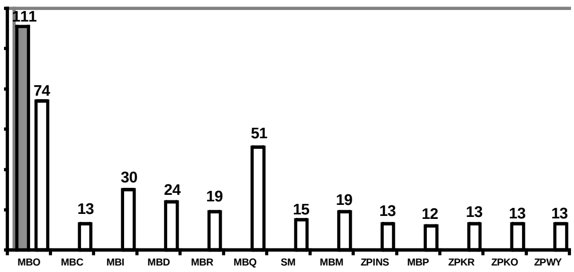

Fig. 1. The use frequency of management methods applied in organizations

Quality supported by information techniques has become the central problem of modern management. It is the whole of product characteristics and services affecting their ability to meet identified and potential needs.

Available commercial "product lifecycle" programs include a description and principles of managing the lifecycle of a machine at the stages of evaluation, design and construction, manufacturing and operation.

At the stage of design, the following are used: Autodesk, AutoCad, CAD, CAE (MES, FLUENT, ADAMS), PDM (documentation management), MICROSTATTION, CATIA, SOLIDWORKS, SOLIDEDGE, INVENTOR and ANSYS. In manufacturing, the following are available: CAM, IRIS, UIC. For exploitation description, the following programs can be used: ARETICS, CMMS Machine, TPM, AGILITY, MAXIMO, SUR-FBD, EUROTRONIC, THETA-CONSTELLATION, PREKION, PLAN-9000, "MACHINE" SYSTEM, PLAN9000 SYSTEM, REPAIRING SYSTEM API PRO, IMPACT XP 217 SYSTEM, IFS SYSTEM, ISA SYSTEM – BPCS. Product lifecycle integration is described by PLM, LCM, engineering knowledge management – KM, CATIA.

Hence, intelligent converters have adaptive proprieties, enabling to choose an algorithm of measurement appropriate for an investigated issue on the basis of conditions of measurement, item properties, requirements and limitations. Converter memory includes software with a certain set of algorithms and a programme of their choice. The choice is conditioned suitably to the realized function, accumulated knowledge, as well as information on conditions of measurement.

Presently, some initiatives relating to software and the selection of instrument structure are under development, enabling to automatically adjust to a realized task, which was partly presented below. The success of different conceptions of acquisition and diagnostic information processing is connected with improvement in the methods of obtaining symptoms of state, objective modelling and building self-diagnosing items [1-32].

3. INITIAL DATA PROCESSING

The observation of progress in wear and tear of an object is based on measuring various symptoms of the technical condition and comparing them with allowed values established earlier – for a specific symptom and in a particular application. The process of object wear and tear is usually not one-dimensional, and the dimension of damage degree increases with the degree of machinery construction complexity. This radically improves the dimensionality of condition vectors, signal and interference vectors. Diagnostic information available in the check-up becomes redundant, dimensionally complex and difficult to process.

This study presents the problems of information redundancy, assessment of individual measurements of diagnostic signal and multi-dimensional processing of diagnostic information in program research as key issues.

A set of signal diagnostic parameters stands out against the set of output parameters accompanying machine operation. Most frequently the criteria distinguishing these symptoms include conditions of their independence, unambiguousness and measurability.

Marking a set of failure-sensitive diagnostic parameters should include:

- the ability to imitate state changes during maintenance,
- information on the technical state of the transmission,
- parameter value sensitivity during maintenance.

The methods of marking diagnostic signals are as follows:

- the method of maximal parameter sensitivity to technical state change.
- the method of maximal relative value of diagnostic parameter change.
- the method of maximal information capacity of a diagnostic parameter.
- the method of maximal changeability of a diagnostic parameter.

The aforementioned methods enable to choose single - and multi-element sets of diagnostic parameters out of a set of output parameters, which is a significant advantage.

The criteria for the optimization of a set of diagnostic parameters are as follows:

- parameters should characterize the process of item destruction, and they should be closely linked with this process,
- parameters should be sensitive to the changes in the on-going process of capability deterioration,
- the number of parameters cannot be too big due to the fact that it hinders and sometimes makes impossible the familiarization and definition of the process of deterioration of item state,
- diagnostic parameters should be measureable,
- there have to exist reliable statistical and analytical data regarding tested parameters.

In practical applications, the pre-treatment of measurement data is an essential step in data classification, having impact on both the effectiveness of distinguishing between conditions, speed and construction simplicity, as well as learning the cause-effect model and its subsequent generalization. A recorded time signal of the tested process moved to an Excel spread sheet is the basis for further processing, for example in the field of time, frequency and amplitude, giving many measurements enabling the decomposition of the output signal to signals of growing individual disruptions.

The decision-making process consists of a series of operations starting with obtaining information on machinery status, its gathering and processing, until selecting and forwarding a fixed decision for implementation. At the beginning, however, three types of initial data processing need to be distinguished: data transformations, filling in the missing values and dimensionality reduction.

4. INFORMATION SYSTEM OF IDENTIFICATION TESTS

The possibility of rapid identification of damage while diagnosing the elements affecting the functioning of objects was the basis for the creation of SIBI program shown in fig.2. This program is an attempt of software implementation for the following purposes: acquisition of vibration processes, their processing, testing co-dependencies of vibration processes, testing symptom sensitivity, statistical inference, and visualization of analysis results.

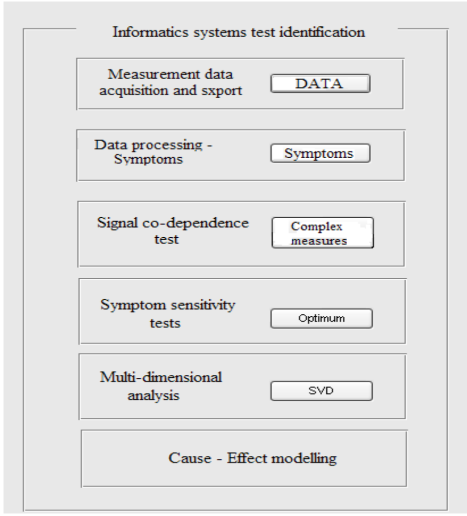

Fig. 2. Main dialog window of SIBI program

5. MANAGING PRODUCT LIFECYCLE

The procedures of rational exploitation can be characterized socially, environmentally and economically – fig. 3.

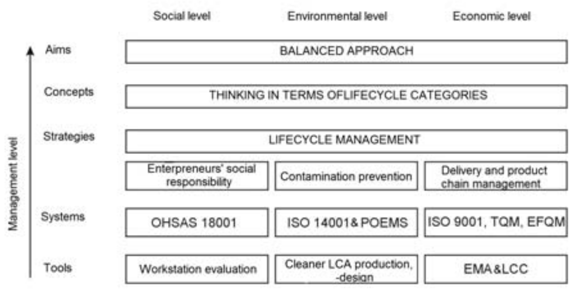

Fig. 3. LCM (Life Cycle Management) [21]

The explanation of shortcuts: OHSAS - safety and professional hygiene, POEMS - The system of the environmental management be well-versed about the product, TQM - the total management of the quality, FFQM - European Foundation for Quality Management, LCA - life-cycle analysis, EMA - Employers and Manufacturers Association., LCC - opinion of the costs of the life cycle.

On the market there are many CMMS systems (Computerised Maintenance Management Systems) in a wide range of prices and possibilities. An important issue for enterprise decision-makers is the choice of proper system supporting motion maintenance services. The analysis of methods of evaluation and selection of systems of this type and the subjective-scoring method of the assessment of the environmental usability of commercially available computer programs are shown in fig.4.

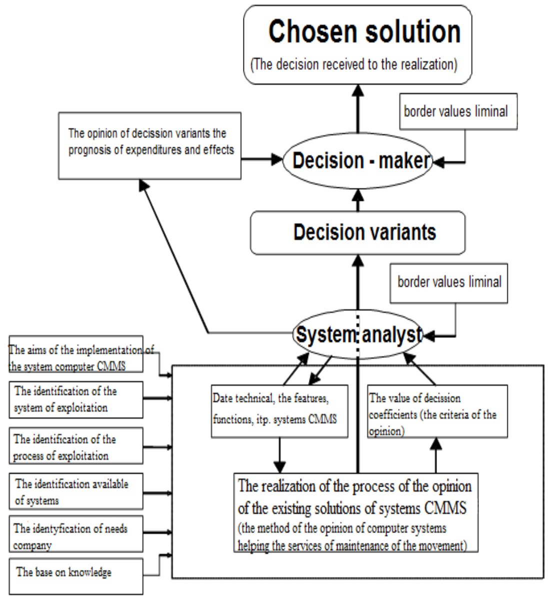

Fig.4. The algorithm of information system selection for exploitation monitoring [9]

6. CONCLUSION

The issues related to diagnosing complex technological items are constantly developed, and the procedures of obtaining and processing diagnostic information constantly improved. This paper deals with reduction redundancy for single state symbols and a multi-dimensional state test.

Selecting a method for the specificity of enterprise business depends on a number of internal or external factors. It is impossible, however, for an organization to survive without adopting any of the methods reducing the chaos and randomness of decision-making rules to a minimum. The methods should be well identified before implementation, and the decision on their implementation should be fully deliberate.

A new, simple and effective method of sensitivity assessment for individual measurements of condition was proposed – the OPTIMUM method; moreover, the essence of the SVD method, SIBI program and guidelines for the selection of rational commercial programs in the field of machinery exploitation were explained.

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- algorytmy, metody i urządzenia diagnozowania, prognozowania i genezowania stanów obiektów technicznych;
- metody detekcji, lokalizacji i identyfikacji uszkodzeń obiektów technicznych;
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- diagnostyka energetyczna systemów technicznych;
- diagnostyka systemów mechatronicznych i antropotechnicznych;
- diagnostyka procesów przemysłowych;
- diagnostyczne systemy utrzymania ruchu maszyn;
- ekonomiczne aspekty zastosowania diagnostyki technicznej;
- analiza i przetwarzanie sygnałów.

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- Experimental diagnostic research of processes, objects and systems,
- Analytical, symptom and simulation models of technical objects,
- Algorithms, methods and devices for diagnosing, prognosis and genesis of condition of technical objects,
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- Power energy diagnostics of technical systems,
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