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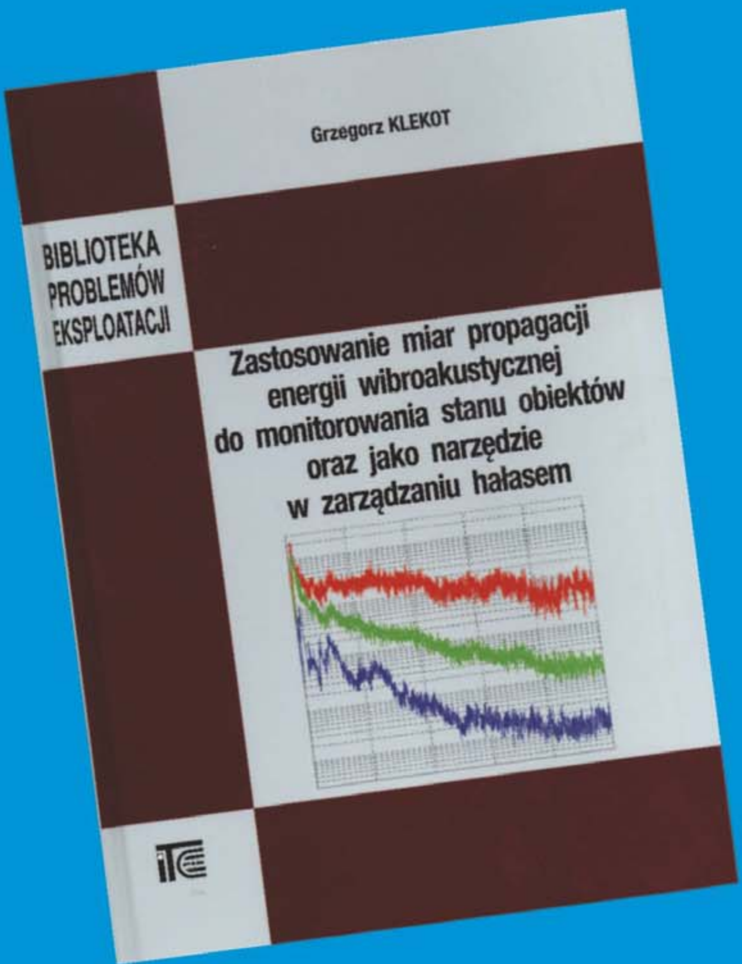

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USING DATA MINING TOOLS TO SHOW CORRELATIONS BETWEEN FAILURES OCCURRING IN CITY BUSES

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Summary

A failure in a bus or other technical device increases its operational costs. Apart from repair costs, a failure might make the work scheduled for the given time impossible, which leads to financial consequences equalling the value of the unaccomplished work or its effects. Because of that it is very important to run research aimed at improving reliability.

The following work presents application of data mining tools that show correlations between failures of various components. Such an approach enables improving the reliability of buses or other technical devices by pointing out design errors and defining control procedures that enable early failure detection.

The basket analysis done in this work is based on the databases in which baskets were created with the use of an innovative programme with a dynamic frame that segregated data.

Keywords: data mining, basket analysis, reliability of buses.

WYKORZYSTANIE NARZĘDZI DATA MINING DO OCENY AWARII AUTOBUSÓW MIEJSKICH

Streszczenie

Awaria autobusu lub innego urządzenia technicznego przyczynia się do zwiększenia kosztów eksploatacji. Poza kosztami napraw, awaria powoduje, że praca zaplanowana w określonym czasie może nie zostać wykonana. Pociąga to za sobą konsekwencje finansowe odzwierciedlające wartość niewykonanej pracy bądź jej efektów. W związku z powyższym bardzo ważne jest, aby wykonywać badania mające na celu zwiększenie niezawodności tych obiektów.

Niniejsza praca proponuję aplikację podejścia z wykorzystaniem narzędzi data mining do wskazania relacji miedzy uszkodzeniami poszczególnych części. Takie praktyki pozwalają na zwiększenie niezawodności autobusów lub innych obiektów technicznych poprzez wskazanie błędów konstrukcyjnych oraz procedur kontrolnych mających na celu wczesne wykrywanie uszkodzeń.

Analiza koszykowa przeprowadzona na potrzeby niniejszego opracowania korzysta ze zbiorów danych, w których koszyki zostały stworzone z wykorzystaniem innowacyjnego programu działającego w oparciu o dynamiczną ramkę dokonującą podziału danych.

Keywords: data mining, basket analysis, reliability of buses.

1. INTRODUCTION

Data mining is an analytical process used for examining large data sets in order to obtain regular patterns and systematic correlations between variables and evaluating the results by implementing the obtained patterns in new data subsets [1]. The data mining process is implemented mostly in fields such as banking, medicine and industry, but it can also be used in all applications in which computerised systems enable gathering empirical data in the form of databases. To obtain adequate patterns in a database, association rules can be used. An association rule is an implication in the form of (1):

$$X \Rightarrow Y \quad (1),$$

where X and Y are arbitrary subsets of elements from the β set and fulfil $X \subset \beta$, $Y \subset \beta$ i $X \cap Y = \phi$ [2]. The investigation of association rules was motivated by the Market Basket Analysis problem, implemented among others in hypermarkets in order to indicate groups of products often bought together – that can be found in the same basket. The gathered information can be used for such distribution of products on shelves that can result in higher sales. In case of city bus failures the association rules can provide information on simultaneous failures and on failures occurring in a specified sequence and on a given time. Thanks to such knowledge availability of buses can be increased by structural modifications or by optimization of maintenance services. The analyses of that type are especially useful in the economic analysis of buses' operation. For example, a failure that is cheap to service and seems insignificant may lead to a serious breakdown and put the vehicle out of action, which together with the service costs generates considerable financial loss [3].

The importance of association rules is described by variables such as support, confidence and lift, the threshold values of which are assigned by the user while he defines the analysis. Thanks to that the association rules with minimal importance can be ignored.

The **support** of a set is a fraction of records containing that set. In other words, it measures how often a single- or multiple-element failure has occurred. High support of a given element or a set of elements signifies its high failure frequency. In case of databases describing buses' failure frequency the algorithm used to obtain association rules should account for minimum thresholds of support. An example association rule (3):

$$\text{[brake pads]} \Rightarrow \text{[brake pad sensors]} \quad (3)$$

is going to have much greater support than the following rule (4):

$$\text{[air compressor]} \Rightarrow \text{[brake hose]} \quad (4)$$

In sequence (3) replacing brake pads and sensors is included in maintenance services and such a sequence is insignificant from the point of view of analysis goals. However, it may be important that air compressor causes brake hose failures. In case of high support settings such a sequence would have been ignored because of low occurrence of such failures.

Confidence is a conditional probability that a set containing element A will also contain element C. In other words, that rule helps to determine what is the probability of failure A in case of failure B. The rules with 100% support might be helpful in preparing repair sets, which should speed up the process of issuing parts from the storehouse. Such information is also useful in determining control procedures to be observed during technical inspections of buses. For example, if one detects a failure of part A and support of a rule 'if A then B' is 100%, the control procedure will have to include an inspection of part B.

Lift is defined on the basis of confidence and support. In a set 'if A then C' with 100% confidence (a failure A is always followed by a failure C) with little support of failure C (failure C happens rarely), the set will have high lift. In other words, high lift of a set 'if A then C' will mean that a failure of element C has been most probably caused by a failure of element A. The information about the lift can be used in both preparing repair sets and control procedures, however, above all it is an information for the designer. In case of sets with high lift he should consider methods of eliminating the dependence of those failures.

In order to find the association rules in the database a module of STATISTICA Data Miner – Sequence, Association and Link Analysis has been used. The described tool utilizes FP-growth algorithm (tree-based pattern) which is more effective than the apriori algorithm in case of low minimal support or dense data sets (sets that contain many big frequent itemsets) [4].

2. BUS DATABASE

In order to obtain output data on bus failures and resultant costs a cooperation with MPK (Municipal Transport Company) in Kraków has been established. The most adequate source of data that enabled analyzing various aspects was a list of components that had been issued from the storehouse during the period of three years. As a component is ordered in a storehouse when a similar one in a bus breaks down, such a list is a great source of information on failures. What is more, the database provides not only information on precise dates of failures, but also on the cost of their repair.

However, it should also be noticed that such a way of reasoning may lead to some mistakes. For example, in case of brake hose abrasion the worn part will be repaired with the use of brake hose connector, so one the basis of the database one could assume that it was the connector that failed. During planned maintenance services the whole bus is checked and that can also lead to mistakes as failures that might not be linked would be discovered at one time. To sum up, the biggest disadvantage of the approach is the lack of information on the forms of failures, causes of failures, types of failures and on the components used to deal with a given problem.

3. DATA PREPARATION

At the beginning of the analysis the data have to be properly prepared. The failures might not only be correlated inside superior systems such as suspension or pneumatic system but also in between systems. For example, during a maintenance service brake disks and a door button can be replaced. In such case the programme will look for the following sequence (5):

$$\text{[brake disk]} \Rightarrow \text{[door button]} \quad (5)$$

It is quite obvious that the brake disk failure has nothing to do with the door button failure, so we should not expect correlations between the braking system and the bus body. However, it is possible that a failure of suspension air bellows might cause a failure of pneumatic system, and the other way round. Because of that, the correlations between the given parts and their superior systems have been investigated. Those correlations are described by the block diagrams in figure 1 which enabled determining the group of objects for further analysis. Thanks to such an approach mistakes caused by data from maintenance services could be eliminated.

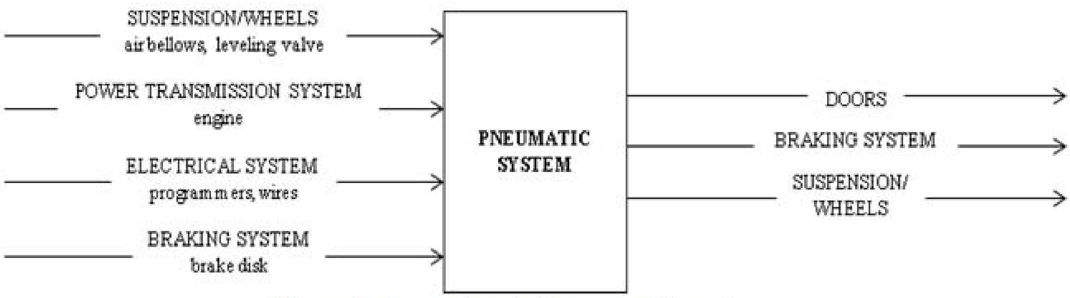

Figure 1. Interactions in the pneumatic system.

A crucial part in preparing data for analysis is determining the 'baskets'. In case of the described database each day may be such basket while all the parts collected from the storehouse to repair a given bus on that given day would be the items. However, such an approach might not always be correct as some repairs might last for two or three days, or even longer if a given part is not available in the storehouse. What is more, consequences of some failures might be visible only a few thousand kilometres later, so the parts that should be correlated would be placed in different baskets. The STSTISTICA data miner module mentioned before enables both sequential and non-sequential analysis. Sequential analysis enables creating sets (baskets) with the use of time parameter, so that the number of days in one basket can be defined. However, that solution is not correct in all cases. For example, if thanks to time parameter the programme created three-day-long baskets, a failure happening on the third day of basket *n* would not be linked to a failure that happened on the first day of the *n+1* basket. Because of that a programme in the Visual Basic environment had been written that enabled creating baskets with the use of a dynamically moving frame. An example in figure 2 explains functioning of the programme. It is assumed that revealing the consequences of each failure might take up to three days. If STATISTICA had been used together with the three-day-long time parameter sequential analysis, a failure from 3rd January would not be linked to the failure from 4th or 5th, because they would end in separate baskets. In case of the programme mentioned above that uses the dynamic frame, baskets can be defined in such a way that they contain a sequence of events. Input data in such a form enables using non-sequential analysis to finally solve the problem.

However, it is important to notice that such an approach might distort the real values describing the association rules. For example, the part 7364 appears in three baskets, while in reality its failure only happened once. Still, if we concentrate on the aim of the analysis, which is showing the correlations between failures, that distortion does not seem so significant

4. RESULTS

The results of the analysis were presented on network diagrams and rule diagrams on which the interpretation could be based. For example, figure 4 presents a network diagram of a failure in door system, in which the following correlations characterised by high lift can be distinguished:

1. bottom arm tip (4) ⇔ door hinge with a potentiometer (3),
2. bottom door track (1) ⇔ bottom guide (2),
3. left bottom arm tip ⇔ right bottom arm tip,
4. bottom seal ⇔ rotary post,
5. bottom seal ⇔ top door arm,
6. rotary post ⇔ top door arm.

Chosen elements of the door system are presented in figure 3.

DATA			Normal Frame		Dynamic Frame			
Bus no.	Date	Part code	Part code	ID trans.	Part code	ID trans.	Part code	ID trans.
DC501	1-01-2009	1356	1356	1	1356	1	7364	3
DC501	2-01-2009	2485	2485	1	2485	1	1124	3
DC501	3-01-2009	7364	7364	1	7364	1	3845	3
DC501	4-01-2009	1124	1124	2	2485	2	1124	4
DC501	5-01-2009	3845	3845	2	7364	2	3845	4
DC501	6-01-2009	4445	4445	2	1124	2	4445	4

Figure 2. An example of creating baskets in the programme written in the Visual Basic environment

Figure 3. Components of the door system: 1-bottom track, 2-bottom guide, 3-door hinge with a potentiometer, 4-door arm tip

In sequence 1 the bottom arm tip (4) wears quickly because of the difficult operating conditions and as a consequence doors operate with higher resistance and the door hinge with a potentiometer (3) also wears quickly. It should be noticed that repairs of the latter are the most costly repairs in the analysed bus. High lift in the sequence (2) is caused by the fact that its elements work together and wear one another. Such information might be used to point out errors in design and to establish adequate control procedures that would enable early failure detection.

Some of the presented relations might be obvious and have little importance in the context of requirements of the analysis. The sequence (3) does not mean that bottom arm tips influence each other's failure frequency. The relation is based on the fact that they are replaced at the same time because they work and wear alike. Similar is the relation with the bottom seal, which is replaced while the other elements are repaired. Such relations can lead to mistakes and are the result of complete lack of information on the forms of failures, causes of failures, types of failures and on the components used to repair a given failure.

5. SUMMARY

The described analysis with the use of data mining algorithm enabled pointing out a number of relations between failures of components in city buses. Such information can be used to increase the availability of buses or other technical devices.

On the other hand, a critical look on the form of the database used has to be presented. Above all, the database does not give information of how the failures happened, which makes the unequivocal assessment of association rules impossible. What is more, the credibility of the analysis is closely connected with the amount of analyzed data. If there had been access to more data (compared to the amount analyzed) it is very probable that more association rules would have been observed. Creating a huge database, for example in cooperation with other carrier companies, would also improve the analysis as each company's bus operation policy would be different and the condition of road infrastructure in various cities would influence the buses differently. However, the computerised systems that register the issued parts are a new introduction in many transport companies and differ one from another. Because of that the data collection process would have to be time consuming and would require individual approach to each company.

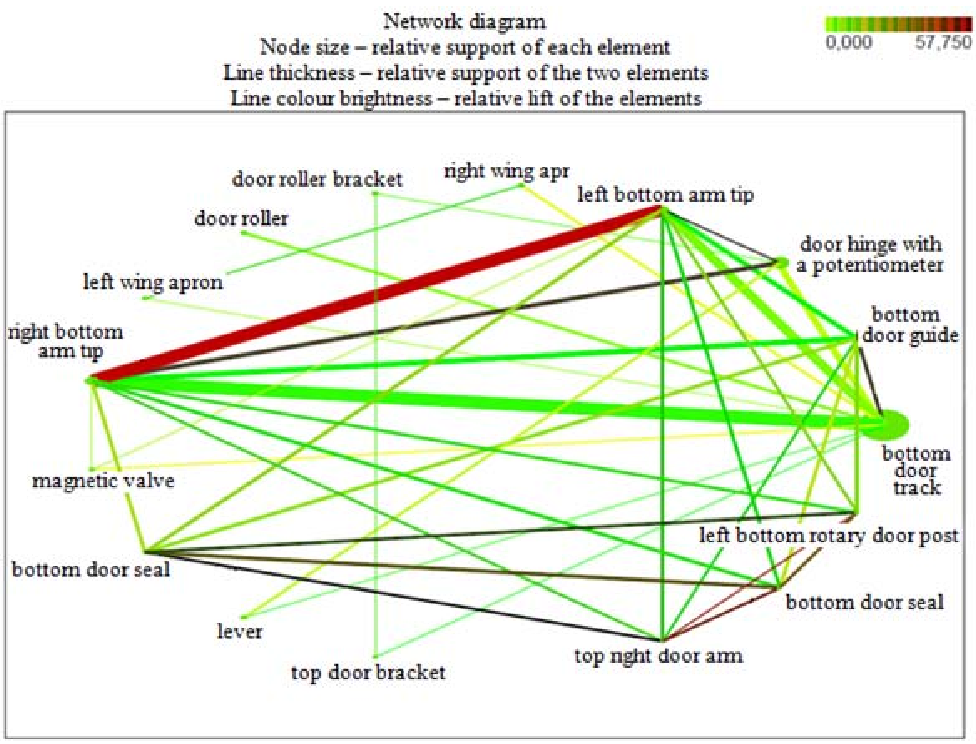

Figure 4. Network diagram of components of the door system

The described arguments show a huge need for a unified, computerised system that would gather empirical data on failures and service (repair anticipation time, repair time, number of servicemen etc.) and would be used to increase the reliability of city buses and to optimize maintenance services. The system would function on a website accessible for servicemen who would have their individual logins and passwords. Thanks to a user-friendly interface based on drop-down lists and predefined information base (with information such as vehicle types and designations used by a given transport company) data gathering would be very convenient for the users of the system. The amount of information expected from each user would be optimised and adjusted to the expectations from the system. In case of a system oriented on increasing bus' and its components' reliability, apart from basic information it would require data on form and causes of failure and in case of a system oriented on maintenance services optimization, data on repair anticipation time, reasons for anticipation, repair time and number of servicemen would be required. Such information could be also used for ranking the failures on the basis of repair time, number of servicemen or the cost of components used. An advantage of such a system would be the fact that it would contain ready data (without the need to process them first) that could be easily analyzed with the data mining tools.

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THREE-DIMENSIONAL REPRESENTATION OF DIAGNOSTIC FEATURES IN APPLICATION TO WIND TURBINES

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Summary

Wind turbine condition monitoring is essential task in the process of maintaining machine operation at the optimal level. It is related to ensuring the profitability of investment and the provision of security in the environment of the turbine. However, the working conditions of turbine associated with non-stationary nature of the stimulus which is wind, impede the correct diagnosis of the machine. In addition, a multitude of parameters adversely affects the clarity of predictions and setting alarm thresholds. In the article, the authors evaluate the impact of power generator and bearing rotational speed on the root-mean-square (RMS) value received on the generator bearing. The study was performed in various dynamic states of the bearing: the intact and after discovery of damage. It was possible due to long term monitoring of the system and further analysis of the RMS as a function of power and rotational speed. For this purpose the method that bases on calculation of arithmetic mean of the data in the segments corresponding to the chosen ranges of both rotational speed and generator output power. Results are presented in the form of three-dimensional charts, which allow assessing the impact of parameters on the estimator. As observed, a greater impact on the RMS has the power which reveals as more dynamic changes of RMS to the fluctuation of power. The variation of rotational speed does not affect RMS so rapidly. This was confirmed by an analysis of the slope the function obtained by linear regression. Therefore, it might lead to the conclusion that operational state of wind turbines should be assessed due to generated power level not in respect to rotational speed.

Keywords: wind turbine, vibration analysis, non-stationary operation, damage detection

TRÓJWYMIAROWA REPREZENTACJA PARAMETRÓW DIAGNOSTYCZNYCH W ZASTOSOWANIU DO TURBIN WIATROWYCH

Streszczenie

Monitorowanie stanu pracy turbiny wiatrowej jest niezbędnym zadaniem w procesie utrzymania pracy maszyny na optymalnym poziomie. Jest to związane zarówno z utrzymaniem rentowności inwestycji jak i zapewniania bezpieczeństwa w otoczeniu pracy turbiny. Jednakże warunki pracy turbiny związane z niestacjonarnym charakterem czynnika pobudzającego, jakim jest wiatr, utrudniają poprawną diagnozę stanu maszyny. Dodatkowo mnogość parametrów wpływa niekorzystnie na klarowność prognozy i ustawienie progów alarmowych. W artykule autorzy oceniają wpływ mocy generatora i prędkości obrotowej łożyska generatora na zmianę wartości skutecznej (RMS) wibracji otrzymanej na łożysku generatora. Obserwacja została poczyniona w dwóch stanach dynamicznych łożyska: w stanie nieuszkodzonym oraz po stwierdzeniu uszkodzenia. Umożliwiła to długoczasowa obserwacja turbiny pod kątem ww. parametrów, a następnie analiza zależności RMS w funkcji mocy i prędkości obrotowej. W tym celu zaproponowano metodę polegającą na obliczaniu średniej arytmetycznej wartości RMS w segmentach odpowiadającym wybranym zakresom prędkości obrotowej i mocy generatora. Wyniki przedstawiono w postaci trójwymiarowych wykresów, które pozwalają na ocenę wpływu parametrów na estymator. Jak zaobserwowano, większy wpływ na RMS ma parametr mocy generatora, co objawia się bardziej dynamiczną zmianą RMS w odniesieniu do zmiany mocy. Wahania prędkości obrotowej nie wpływają na estymator tak gwałtownie. Zostało to potwierdzone analizą współczynników kierunkowych funkcji otrzymanej przy pomocy regresji liniowej. Może to prowadzić do wniosku, że stan działania turbin wiatrowych powinien być oceniany ze względu na generowany poziom mocy a nie z powodu prędkości obrotowej.

Słowa kluczowe: turbiny wiatrowe, analiza drgań, zmienne warunki eksploatacyjne, wykrywanie uszkodzeń

1. INTRODUCTION

Over the last few years wind power is becoming an important sector of the energy industry. Therefore more and more attention is paid to the aspect of operation maintenance of the wind power generating machinery [1-4]. It does not only enable to limit the possible breakdown cost and time of repair, but in addition it provides higher productivity of the machinery [5].

Because of the fact that wind turbines work under non-stationary wind behaviour [6], thus the analysis of vibration-based diagnostic features might be misleading. Since load-dependent excitation of the system affects vibration-based features, it is proposed in [7-8] to use feature-load representation to present distribution of features against the operating conditions. As has been presented it provides better effectiveness in classification of data than simple statistical feature processing.

The issue of fault detection of bearings operating in non-stationary conditions has been widely investigated in the recent time. Many diagnostic techniques has been employed for this issue, including wavelets, the envelope analysis, adaptive filters and exploiting cyclostationarity of vibrations [9-11], etc. Unfortunately methods listed above are not applicable to the data acquired by online monitoring system. The offline processing for multidimensional features has been investigated in [12-13] and may include data processing using Principal Component Analysis, data projection technique, outliers analysis, etc. However, due to the economic reasons building of advanced feature extracting module for online processing is not economically justified and is expected to be simplified. Such difficulty occurs not only for wind turbines, but also in many fields where rotating machinery is employed, e.g. mining, marine or aviation industries. It is important to remember that condition monitoring on this field has yet found complete solutions and still needs improvement.

Therefore the main aim of this paper is to present the analysis of the influence of operation parameters on the vibration estimators on the example of root-mean-square (RMS) as it is in authors' opinion the most general analysis. For this purpose the power and rotational speed are investigated in two stages of the lifetime of the generator bearing: before and after recognition of fault. It was possible due to long term monitoring of the system. Such analysis can suggest the limiting of operation parameters used for observation of damage.

The paper is organized as follows. After the introductory part the investigated wind turbine design is briefly described along with placement of sensors used for the research. Next, the methodology of the investigation is explained step by step and presented in figures. The results of the research are described in the further section and followed by the conclusions.

2. INVESTIGATED WIND TURBINE

For the purpose of investigation, the commonly used turbine with nominal power of 1500 kW was selected. The turbine has two nominal states of operation which depend on the wind speed – except for the nominal operational mode it also is enabled to work on, so called, the "low" gear that corresponds to 1000 kW of generator output power.

In Fig. 1 one may find a kinematic system of the analysed wind turbine. The main rotor is driven by three blades and supported by the main bearing. It passes the torque to the planetary gearbox. Second bearing supporting the rotor is incorporated into the gearbox. The planetary gear has three planets, which are driven by the planet carrier. The planets transmit the torque to the sun gear, in the same time increasing the rotational speed. The sun shaft passes the torque from the planetary gear to the two-stage parallel gear. The parallel gear contains three shafts: the slow shaft clutched to the sun shaft, the intermediate shaft and the high speed shaft, which drives the generator. The generator produces AC current of a varying frequency. This current is converted first into DC power and then into AC current of frequency equal to the grid frequency. Electric transformations are performed by the controller at the base of the tower. The transmission chain changes the rotational speed from about 25 RPM on the main rotor to about 1800 RPM at the generator. In the considered case a diagnosed object is a bearing in electric power generator of a wind turbine.

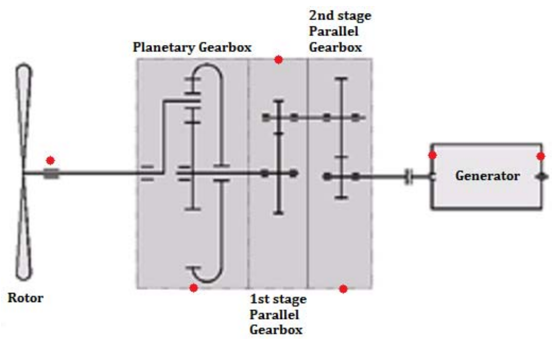


Fig. 1 Kinematic scheme of the analysed wind turbine with location of vibration sensors (red dots)

Typical requirement for wind turbine drive-train condition monitoring systems is to measure vibrations with six measurement channels that each covers separate area of drive-train [14]. Namely: main bearing, planetary gearbox, 1st stage of parallel gearbox, 2nd stage of parallel gearbox, front of the generator and back of the generator.

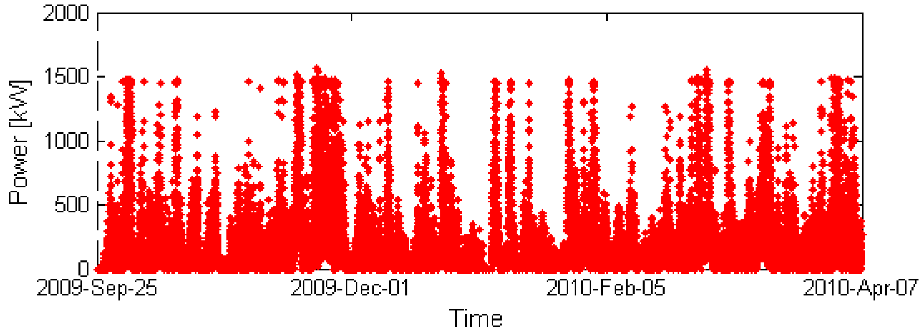
Additional required measurement covers rotational speed in order to asses acquired vibration data to proper operational state. In majority of condition monitoring systems dedicated for wind turbines value of generated power is measured as well as a supporting feature.

3. METHODOLOGY

The main objective of this paper is to present the vibration estimator – RMS as a two dimensional function of power and rotational speed. It is the authors' belief that such representation will provide better understanding of the influence of those parameters on these vibration-based features.

Presented study is performed for the wind turbine generator bearing in two different technical conditions: the undamaged and with advanced outer race fault. Data used in described investigation was obtained from industrial condition monitoring system operating on commercial wind-farm. Presented measurements were carried out on the described turbine for over six months (from 25th September 2009 to 7th April 2010), which resulted in 28575 samples for each parameter (RMS of vibration, RPM and generator).

a.



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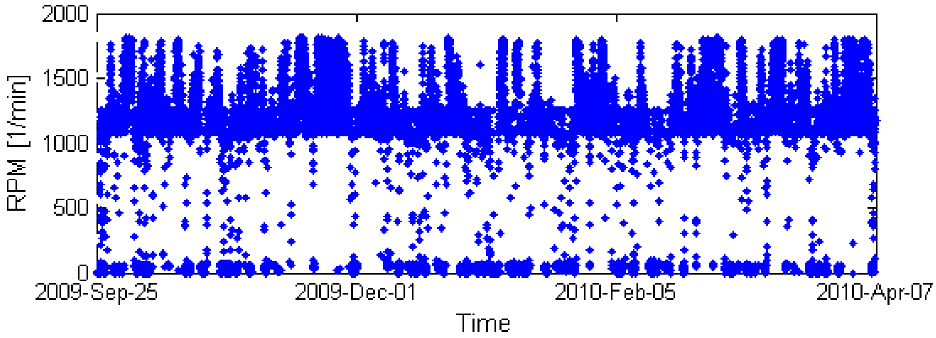

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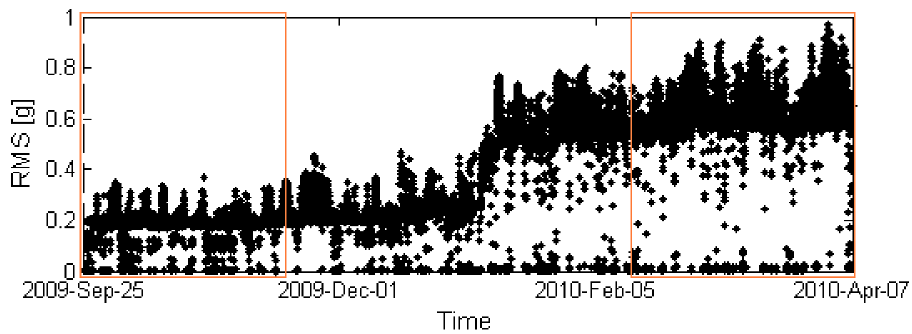


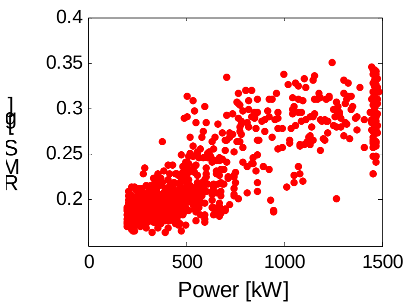
Fig. 2 Measurements acquired by condition monitoring system presented against number of samples: a. power, b. rotational speed (RPM), c. root-mean-square (RMS) with marked regions of undamaged and damaged bearing output power).

In Fig. 2a-c one may find plots of parameters in different, time-varying operating conditions. In Fig. 2c one may notice development of the fault of the bearing as increasing RMS value of the signal. The two sets taken for further investigation consisted of first and last 6000 samples of the total samples (for undamaged and damaged bearing, respectively). Selected regions are marked in Fig. 2c. RMS data used in presented case study was acquired for the wind turbine operating with rotational speed from 1050 RPM to 1800 RPM. Additionally, range of analysed data was limited to values corresponding to generator output power between 200 and 1500 kW. Such preselection of data for analysis was dictated by the amount of data available in database and it is the result of the operational character of the most industrial wind turbines.

In Fig. 3 and 4 one may find RMS in function of power and rotational speed, respectively. It is presented in two conditions of the generator bearing. In Fig. 3a and b it can be seen how often turbine was operating with its nominal power.

For each parameter the observer notice a large scatter of data, nevertheless the scatter of RMS in function of RPM is greater than in function of power. Furthermore the change in energy signal in

a.



b.

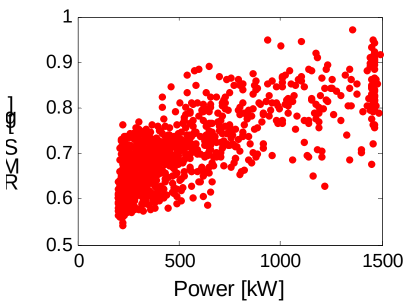
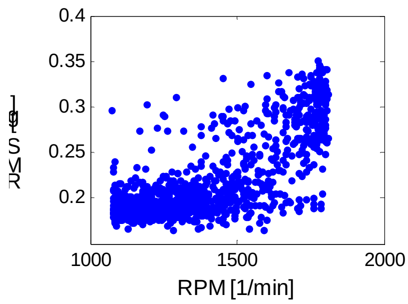


Fig. 3 RMS in relation to power for bearing: a. undamaged, b. damaged relation to the power is greater than for RPM

It is important to remember that the vibration estimators depend on two parameters, therefore those parameters should be considered together when analysing the fluctuation of RMS. Such three-dimensional analysis allows observers to assess the impact of the operational parameters. As observed, the RMS might be understood as a function of two variables: power and RPM (only if we consider different values of RMS for the same coordinates as their mean). Therefore, there is a possibility to create a structure from points with three variables: power, RPM and RMS. The motivation for this action comes from the fact that RMS can be compared to the energy of the measured signal, and thus be treated as the damage indicator. Since it is related to generator output power and RPM, the three-dimensional plot of these parameters would illustrate the influence of power and rotational speed on the damage diagnosis.

In order to present scattered RMS data as a three- dimensional surface that could be clear to analyse the authors wish to propose the method that bases on calculation of arithmetic mean of the data in the segments corresponding to chosen ranges of both rotational speed and generator output power.

a.



b.

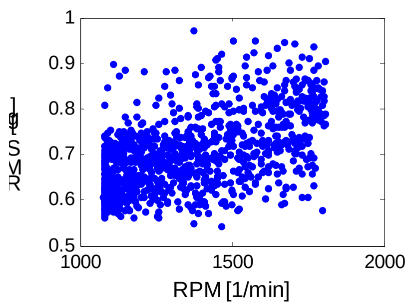


Fig. 4 RMS in relation to rotational speed (RPM) for bearing: a. undamaged, b. damaged

Mean value of RMS calculated for chosen segment is given by:

$$RMS_{\Delta RPM}^{\Delta P}(P,RPM)=\frac{1}{n}\sum_{n=1}^{n}RMS_{RPM'}^{P'}(n), \qquad (1)$$

$$P'\subset\{P-{}^{\Delta P}\!/\!_{2},P+{}^{\Delta P}\!/\!_{2}\}, \qquad (2)$$

$$RPM'\subset\{RPM-{}^{\Delta RPM}\!/\!_{2},RPM+{}^{\Delta RPM}\!/\!_{2}\}. \qquad (3)$$

where P stands for *Power*. ΔP and ΔRPM are range-widths power and rotational speed respectively $RMS_{RPM'}^{P'}(n)$ is the n^{th} RMS sample corresponding to the range of power P' and the range of rotational speed RMS'.

For presented study ΔP was equal to 200 kW while ΔRPM was equal to 100 RPM.

To better understand the behavior of the estimator, the RMS charts of power or RPM for two permanent, fixed values of each operating parameter are presented. The constant values are equal to 500 and 1300 [kW] of power and 1300 and 1600 RPM of rotational speed. Then, using linear regression straight lines were plotted. The slopes of the lines were recorded in the Table 1. Furthermore, the variation was obtained to give information about spread of the data.

4. RESULTS OF EXPERIMENT

The Fig. 5 and 6 show the relationship between the RMS and both power and RPM for bearing without and with damage, respectively. Please note that results for two cases are presented in different scales. However in order to better reveal the changes of RMS axes on both plots were scaled to cover the same range of feature variation (0.3g). The one may notice, the change is more abrupt for the state of damage. As observed, the greater impact on RMS has the power which is disclosed by more dynamic changes of RMS in relation to the power variation. The fluctuation of RPM does not affect RMS so intensely. It can even be assumed, that in the case presented in Fig. 5 for low power estimations, RMS is almost constant in relation to RPM. On the other hand, relatively dynamic changes of RMS in relation to power can be noticed. As generator output power increases, RMS value also increase rapidly. For both cases (Fig 5 and 6) it can be noticed that up to 1000 kW average RMS value increase almost linearly which confirms results presented in [7]. Additionally, for rotational speed values around 1400 RPM slight increase of RMS estimation can be noticed (especially for higher power values. It might be the result of local resonance of the system.

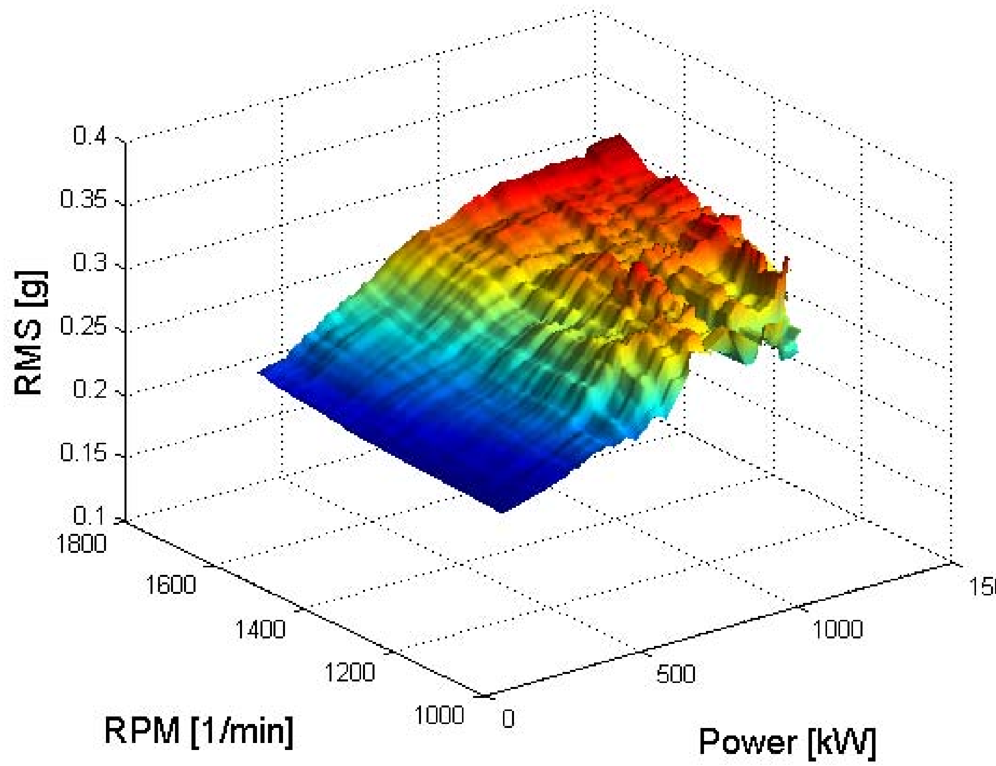


Fig. 5 RMS in relation to power and RPM presented for generator bearing in undamaged condition

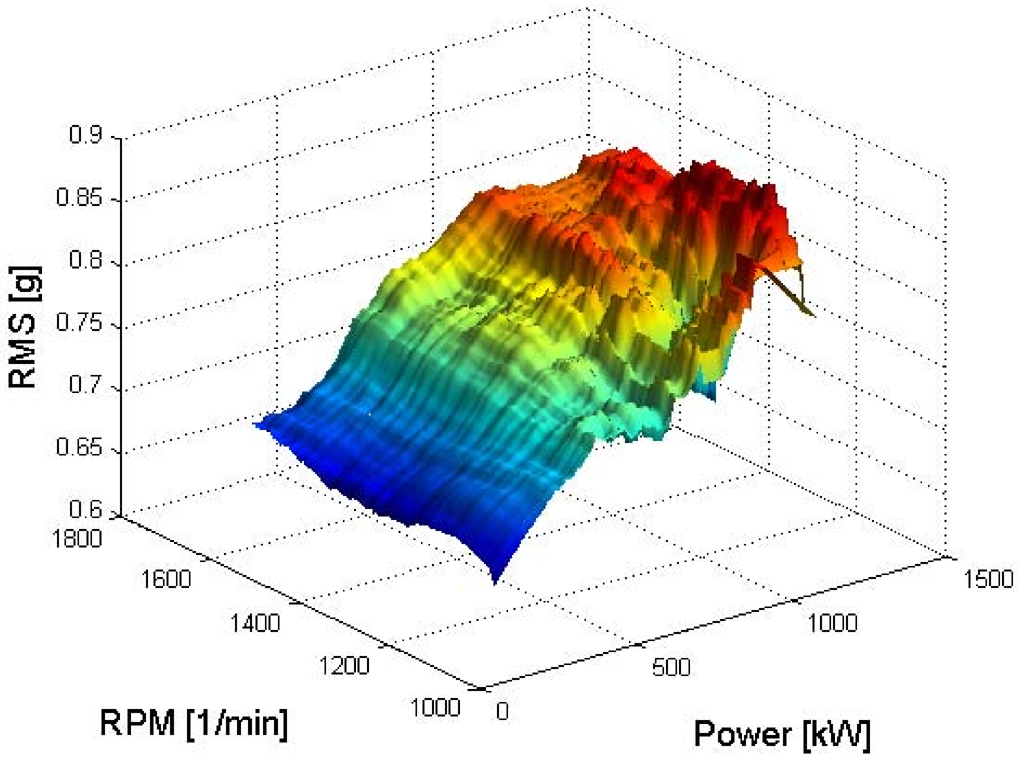


Fig. 6 RMS in relation to power and RPM presented for generator bearing in damaged condition

More interesting conclusions can be drawn from comparison of results obtained for bearing in undamaged and damaged condition. Beside clear increase of RMS value for damaged case (please notice different scaling of vertical axis in Fig 5 and 6), also dynamics of obtained results changed increase more rapidly with respect to the power. Additional increase can be noticed with respect to rotational speed, especially for power values up to sensitive mainly to the generator output power, but also in lesser extent to rotational speed.

In order to reveal the differences between RMS as a function of power and RPM, it was plotted with constant value of one of them.

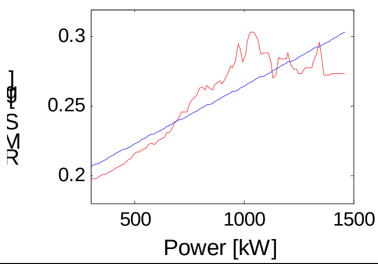
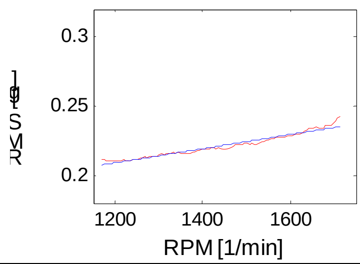
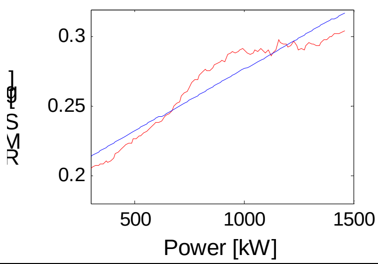
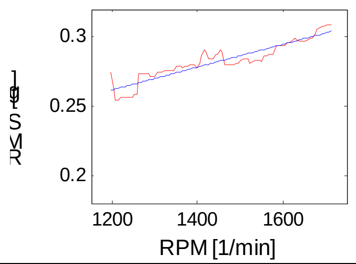
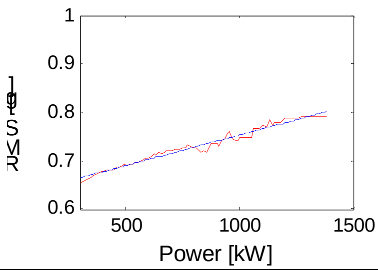
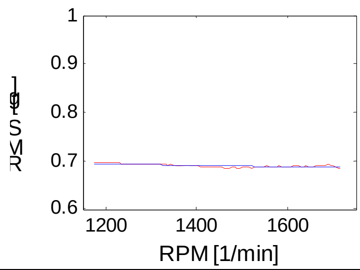
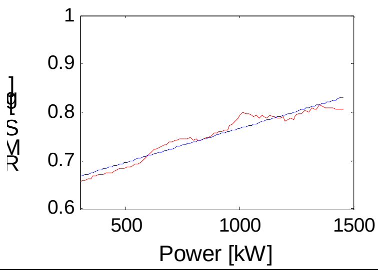
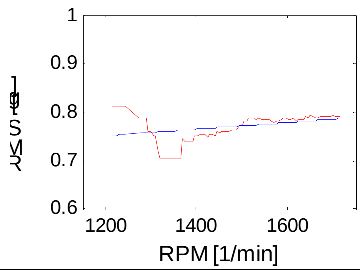
As stated, the values of the slopes in each of the analyzed cases are higher for variable power. It should be understood that the change of power more dynamically affects the value of the estimator RMS. This confirms the earlier observations. Interestingly that for a fixed, low-value output power of 300 kW, with an increase in RPM, the RMS is decreasing. This issue should be explored in the further investigation.

5. SUMMARY

The paper presents the dependence of RMS of vibrations measured on wind turbine generator bearing as a two-dimensional function of rotational and output power. Results are presented in the form of three-dimensional charts, which allow assessing the impact of parameters on the estimator. As observed, a greater impact on the RMS has the power which reveals as more dynamic changes of RMS to the fluctuation of power. The variation of RPM does not affect RPM so rapidly. Therefore, it might lead to the conclusion that operational state of wind turbines should be assessed due to generated power level not due to rotational speed. Unfortunately, majority of commercial industrial condition monitoring systems designed for wind turbines uses rotational speed as a reference value.

In general, it is the authors belief that representation of selected diagnostic feature as a function of two main operational parameters (rotational speed and power/load) can give comprehensive information about dynamic character of observed machinery. It can be a valuable source of knowledge not only about the influence of operational parameters on selected diagnostic feature but also about object resonances or the character of its operation.

Tab. 1 RMS graphs as a function of rotational speed and power for undamaged and damaged bearings, presented for different operating parameters. Linear regression lines with slope, and variation of the relation

<table>
<tr><td></td><td>RMS in function of power; constant value of rotational speed</td><td>RMS in function of rotational speed; constant value of power</td></tr>
<tr><td rowspan="2">Undamaged bearing, small value of parameter</td><td>
</td><td>
</td></tr>
<tr><td>Slope: $8.3606 \cdot 10^{-5}$, variation: 0.0010</td><td>Slope: $5.1101 \cdot 10^{-5}$, variation: $6.9777 \cdot 10^{-5}$</td></tr>
<tr><td rowspan="2">Undamaged bearing, high value of parameter</td><td>
</td><td>
</td></tr>
<tr><td>Slope: $8.9452 \cdot 10^{-5}$, variation: 0.0010</td><td>Slope: $8.2114 \cdot 10^{-5}$, variation: $1.8089 \cdot 10^{-4}$</td></tr>
<tr><td rowspan="2">Damaged bearing, small value of parameter</td><td>
</td><td>
</td></tr>
<tr><td>Slope: $1.2634 \cdot 10^{-5}$, variation: 0.0017</td><td>Slope: $-1.5184 \cdot 10^{-5}$, variation: $1.1390 \cdot 10^{-5}$</td></tr>
<tr><td rowspan="2">Damaged bearing, high value of parameter</td><td>
</td><td>
</td></tr>
<tr><td>Slope: $1.4066 \cdot 10^{-4}$, variation: 0.0024</td><td>Slope: $6.9516 \cdot 10^{-5}$, variation: $8.3034 \cdot 10^{-5}$</td></tr>
</table>

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IMPACT OF INSTALLATION ERRORS OF THE GEAR ON THE KINEMATIC DEVIATION

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Summary
The primary purpose of the study is to assess of impact of various installation errors on the transmission error of the bevel gear with circular-curved teeth. To achieve that, simulation possibilities were used as a tool accelerating the time of analyses and requiring small financial outlays for the tests. Solid body models of toothed wheels were generated in accordance with Gleason's method, then the virtual installation of toothed wheels took place, and the simulation was conducted in the CAE (computer aided engineering) program environment. Single flank of toothed wheels was simulated for weather conditions and thus for small speed and load. Faulty performance of wheels was not simulated, and friction was not taken into account. As a result of simulation, the transmission error (kinematic deviation) of the bevel gear was obtained for various positions of the pinion in respect of the crown wheel (installation errors). Positions with the smallest and the largest influence on the transmission error were determined.

Keywords: bevel gear, kinematic deviation, single flank, assembly error.

WPŁYW BŁĘDÓW MONTAŻOWYCH PRZEKŁADNI NA ODCHYŁKĘ KINEMATYCZNĄ

Streszczenie
Głównym celem pracy jest ocena wpływu różnych błędów montażowych na błąd przełożenia przekładni stożkowej o zębach kołowo-łukowych. Aby to osiągnąć wykorzystano możliwości symulacji jako narzędzia przyśpieszającego czas analiz i wymagającego małych nakładów finansowych na badania. Wygenerowano modele bryłowe kół zębatych zgodnie z metodą Gleasona, następnie dokonano wirtualnego montażu kół zębatych, a symulacja odbyła się w środowisku programu CAE (computer aided engineering). Symulowano współpracę jednostronną kół zębatych dla warunków metrologicznych a więc dla małej prędkości i obciążenia. Nie symulowano błędów wykonawczych kół i nie uwzględniano tarcia. W wyniku symulacji otrzymano błąd przełożenia (odchyłkę kinematyczną) przekładni stożkowej dla różnych położeń zębnika względem koła talerzowego (błędów montażowych). Ustalono położenia o najmniejszym i największym wpływie na błąd przełożenia.

Słowa kluczowe: przekładnia zębata stożkowa, odchyłka kinematyczna, współpraca jednostronna, błędy montażowe.

1. INTRODUCTION

Among many factors having effect on durability and low-noise of toothed gear there is the stage of installation in the course of which correct placement of toothed wheels against each other is agreed [9]. This is possible owing to appropriate structure of shafts bearing in the bevel gear body on which the toothed wheels are embedded. In the case of roller gears, it is not possible to improve the mesh, because it is dependent on the accuracy of production of the gear elements [6].

The main criteria proving correct production and installation of the gears are a contact pattern and a backlash. A backlash can be measured in several ways. Most often, this is made using the shift sensor [7]. A contact pattern is determined in the course of installation for small load and small rotational speed, for verification purposes, it can also be checked for operating conditions [2]. Assessing the contact pattern, we check its position, size and shape. These three criteria are correct within certain limits. Apart from the accuracy of production of the gear elements, the quality of installation is also influenced by the installing assembly. This experience and qualifications influences the final correctness of installation.

In this study, analysis is conducted for various cases of bevel gear installation, during which correct installation distances were not reached, and thus the test covers the impact of errors of the toothed wheels position on the kinematic deviation (transmission error). This is done by means of a computer simulation of the single flank [8]. The whole of the issue has been implemented in the NX program by Siemens PLM Software and for processing the data from simulation and generation of charts, the Excel spreadsheet was used. On the basis of toothed wheels generated in accordance with the technology of Gleason processing, virtual installation of toothed wheels was done. Then, dynamic simulations were conducted for various positions of the pinion in respect of the crown wheel. Results have been exported to the spreadsheet, where their further analysis took place.

Single flank of toothed wheels is used mostly at serial production for current inspection and as the final inspection [7]. It allows to check the mesh error in real gear work conditions, as opposed to double flank [4,5]. Also the obtained results are easier in interpretation. In this article, the kinematic deviation (whose definition can be found in study [1]) is a measure of the installation correctness.

2. SOLID BODY MODELS OF TOOTHED WHEELS

The created models of toothed wheels (Fig. 1) correspond to the subject of the tests presented in previous studies, e.g. [3]. The number of the teeth for the pinion was 19, for the crown wheel it was 42, the transverse module was equal to 2.9 mm. Then, the virtual installation of wheels was done, by moving the pinion to different positions, in accordance with figure 2. In this figure, the rectangular coordinate system, marked with the letters H and V, was adopted, which is consistent with the system from Fig. 1. The shift in accordance with axis H is horizontal and with axis V - vertical. Four directions, along which the pinion was shifted, were considered. They have been shown in the form of various types of lines and by means of the suitable marking. Shifts took place every 0.1 mm from values -0.4 mm to 0.4 mm.

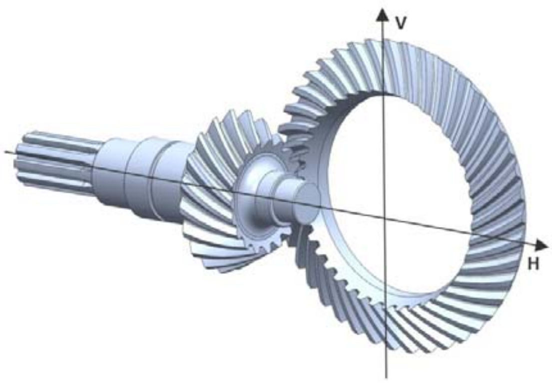

Fig. 1. Solid body models of bevel toothed wheels

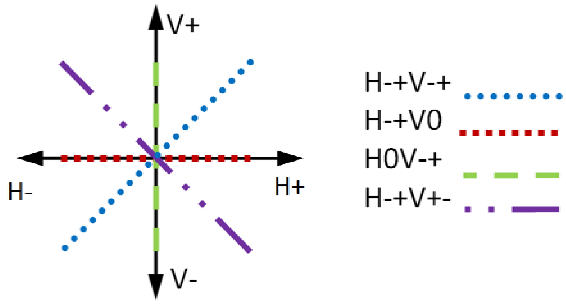

Fig. 2. Pinion shift directions:
H-+V-+ shift of the pinion by the same value on both axes in quarter 1 and 3 of the coordinate system, H-+V0 shift of the pinion only along axis H, H0V-+ Shift of the pinion only along axis V, H-+V+- shift of the pinion by the same value on both axes in quarter 2 and 4 of the coordinate system

3. SINGLE FLANK SIMULATION

As the material for the toothed wheels, steel has been adopted (density ρ = 7829 kg/m^3 , Young module E = 20694 x 10 ^{7} Pa, Poisson's coefficient ν = 0.288). Single flank simulation took place for conditions prevailing during the previously conducted measurements (for small rotational speed and small load). The pinion rotated with the constant speed of 0.01745 rad/s (1/6 rpm). The results of the simulation were recorded every half degree of the pinion rotation. To ensure continuous contact between cooperating teeth edges, a torque directed opposite to the rotation direction was applied to the crown wheel, with the value of 0.01 Nm. The simulation lasted for one rotation of the pinion. The tests did not include friction. Small load value allows to state that toothed wheels in this simulation can be treated as rigid solid bodies.

4. ANALYSIS OF RESULTS

As a result of the conducted simulation, the position was obtained for the crown wheel and the pinion. Data were exported mainly to Excel, where, as a result of simple mathematic operations, a chart of the kinematic deviation (transmission error) was obtained. The following charts (Fig. 3,4,5,6) present the results for four analyzed directions of the pinion shift. For each direction, there were nine measuring points.

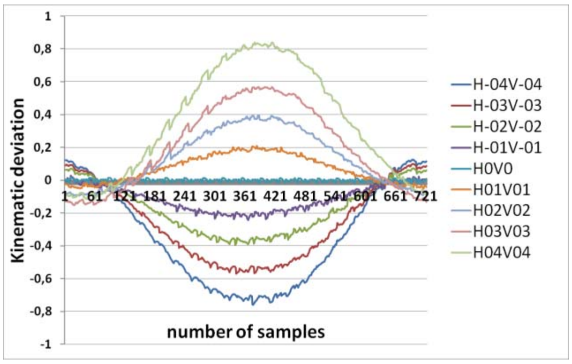

Fig. 3. Kinematic deviation for direction H-+V-+

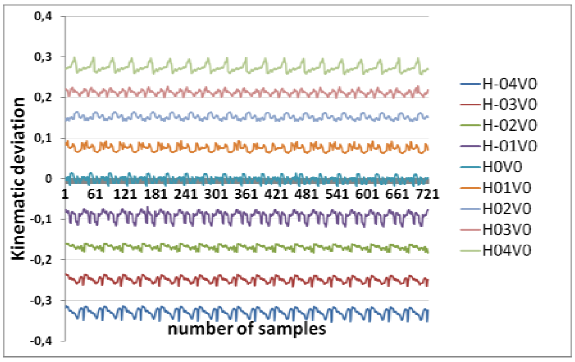

Fig. 4. Kinematic deviation for direction H-+V0

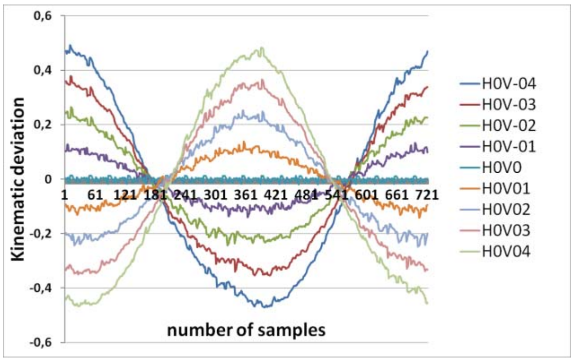

Fig. 5. Kinematic deviation for direction H0V-+

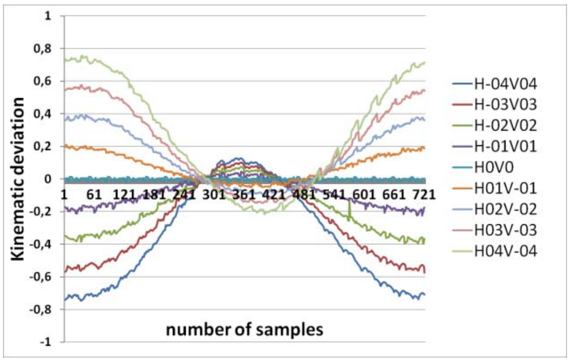

Fig. 6. Kinematic deviation for direction H-+V+-

To make it possible to compare the obtained results, not only in the graphic way, but also in the quantitative way, values of four measures were determined. In figure 7, we have the minimum value for four directions and nine measuring points. Similarly, in figure 8, the maximum value, the total transmission error calculated as the difference in the maximum and the minimum value (Fig. 9), as well as the standard deviation (Fig. 10).

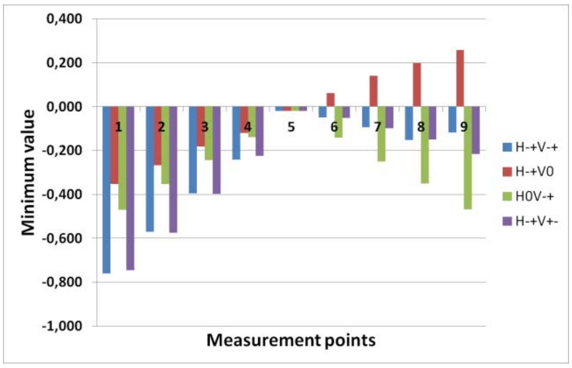

Fig. 7. Minimum value for the kinematic deviation

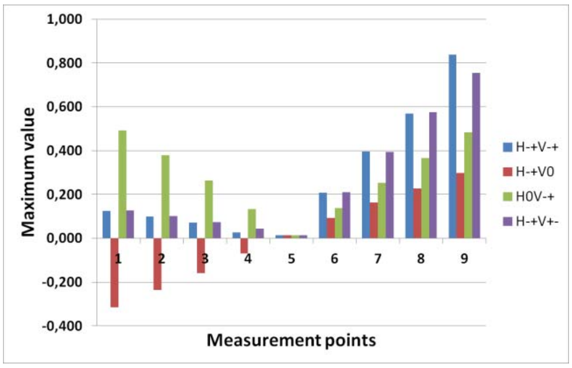

Fig. 8. Maximum value for the kinematic deviation

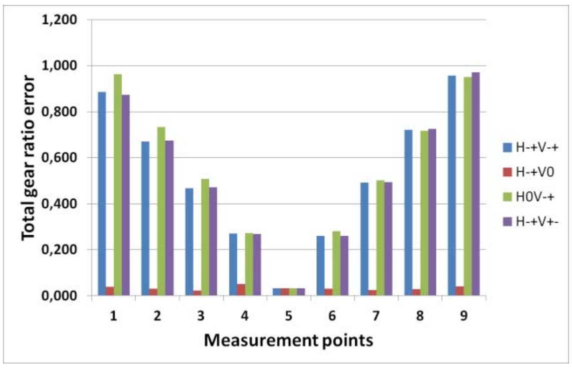

Fig. 9. Total transmission error

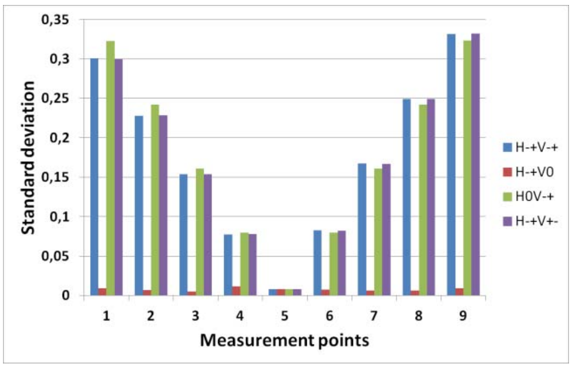

Fig. 10. Standard deviation for the kinematic deviation

Comparing the results for the maximum and the minimum value, the largest values were reached for the simultaneous pinion shift in respect of both axes, smaller ones in relation to the vertical axis and the smallest ones in relation to the horizontal axis, however, the largest differences between the directions are approximately double. It is different in the case of the total transmission error, which, for direction H-+V0, is smaller by the order of magnitude than the others. It means that the gear is least "sensitive" to installation errors related to the pinion shift in relation to its axis, if we talk about the transmission error. Also the standard deviation, which is the measure of size dispersion around the average value for the shift direction, consistent with the pinion axis, assumes the smallest values. In this case, the standard deviation may be interpreted as a measure of variability of the crown wheel's rotational speed.

5. CONCLUSION

Tests were conducted concerning the impact of toothed wheels position with respect to each other on the transmission error (kinematic deviation) of the bevel gear. Simulative tests have proven to be a useful tool, allowing to reflect the single flank of toothed wheels.

Analyzing the obtained results, it should be stated that the greatest transmission error occurs, when the pinion is shifted (from the correct position) in respect of both axes of the crown wheel and the larger this distance is, the greater the error is. The smallest sensitivity is present, however in the event of improperly selected installation distance of the pinion.

6. LITERATURE

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REVIEW OF THE NEWEST NDT EQUIPMENT FOR CONVEYOR BELT DIAGNOSTICS

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Summary

The length of steel cord conveyor belts successively increases in Polish brown coal mines [1]. Essential, emerging issue is the belt life and failure-free operation of the whole transport system. Changes in mine management rules cause that all service or maintenance activities related with machinery for muck hauling are carried out, more frequently by contractors. This in turn causes the problems with quality control and the scope of work ordered by the mine. Very helpful here is the diagnostic equipment, which apart from its basic functions may check and verify the quality of service activities. The paper will present the newest NDT equipment for belt conveyors diagnostics as well as potential of its application in Polish lignite mines.

Key words: conveyor belt, non-destructive testing, diagnosis, automatic detection.

PRZEGLĄD NAJNOWSZYCH URZĄDZEŃ NDT DO DIAGNOSTYKI TAŚM PRZENOŚNIKOWYCH

Streszczenie

W polskich kopalniach węglowych systematycznie rośnie długość taśm z linkami stalowymi instalowanych na przenośnikach taśmowych. Istotnym, pojawiającym się zagadnieniem jest trwałość taśmy oraz bezawaryjna praca całego systemu transportowego. Zmiany zachodzące w zarządzaniu kopalniami powodują, iż wszelkie czynności obsługowe czy konserwacyjne związane z urządzeniami do transportu urobku (coraz częściej) realizowane są przez firmy zewnętrzne. Taki stan rzeczy sprawia, że powstaje problem kontroli jakości i zakresu prac realizowanych na zlecenie kopalni. Z pomocą przychodzą tu urządzenia diagnostyczne, które oprócz swoich podstawowych zadań realizować będą funkcje sprawdzające i weryfikujące jakość wykonywanych usług. W artykule przedstawione zostaną najnowsze urządzenia do diagnostyki NDT taśm przenośnikowych oraz możliwości ich zastosowania w Polskich kopalniach.

Słowa kluczowe: diagnostyka NDT, automatyczna detekcja uszkodzeń, taśma przenośnikowa.

INTRODUCTION

In the biggest Polish open pit mines, the average of 200 to 250 kilometers of conveyor belts are installed. The share of steel cord belts is almost 75 % of the whole length of operating belts. Every year each mine replaces the substantial number of belts, which were simply worn out during their operation or because they were seriously damaged [2]. Annually, the mines replace the average of 30 to 50 kilometers of belts (fig. 1).

The increase the average belt life by one month reduces by 0.5 kilometer the length of annually replaced belts, what is essential from the point of variable costs of mine. Main damages of belts surface or their core are fractures, local cuts, perforations and longitudinal cuts [3]. Most of those damages occur after the long time of operation, thus there is a possibility to evaluate them and to repair the belt if necessary. Some damages such as longitudinal cuts are very serious and cause extreme financial losses, concerning both the belt conveyor and the whole mining system. One of the method of effective prevention is using the NDT – nondestructive diagnostics.

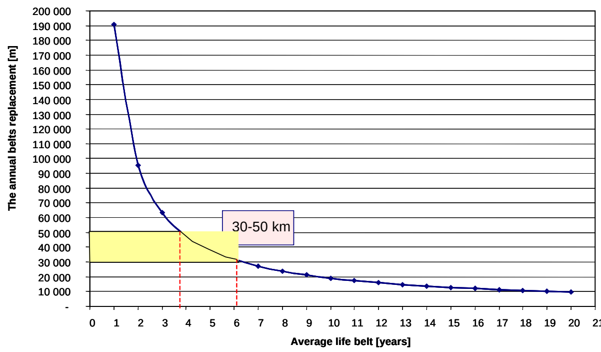

Fig. 1. Effect of average life belts on the amount of the annual exchange

1. REVIEW OF THE EQUIPMENT FOR STEEL CORD BELT CORE DIAGNOSTICS

The companies offering the St belt core scanners together with the relevant services exist on the market already from 30 years. Their newest equipment is the result of long term experience in conveyor belts diagnostics. The most important systems and their main characteristics are presented below:

- Beltscan Pty Ltd (Australia) –Belt Guard™ system. This system has several variants including the one with belt core scanning, measurement of covers thickness and longitudinal cuts preventing system. It is the only producer offering the high resolution system i.e. 200 channels for the2500 mm wide belt (fig.2).

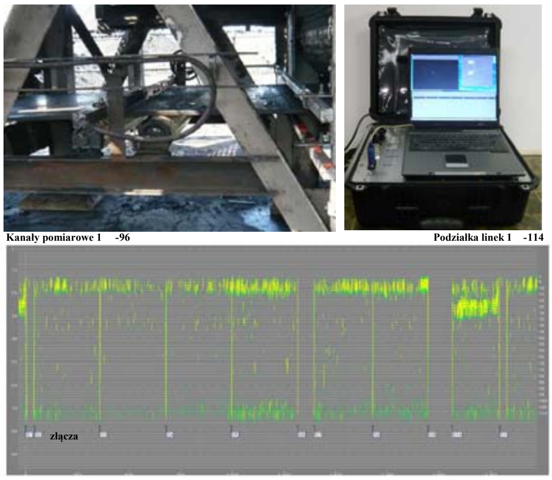

Fig. 2. The Belt Guard system, and the image after belt scanning (belt conveyor ST2200, 2307m x 1500mm) [www.beltscan.com.]

- **CBM Conveyor Belt Monitoring** (Australia) – The **s**ystem apart the damages detection offers also the forecast the operation life based on the velocity of covers abrasion (fig.3). Unfortunately the picture of *St* belt cores condition, like in case of almost all such systems, is difficult to understand and to interpret. Thus the analysis of damages and belt condition is made by CBM engineers from the long distance, what in turn substantially increases the cost of system utilization.

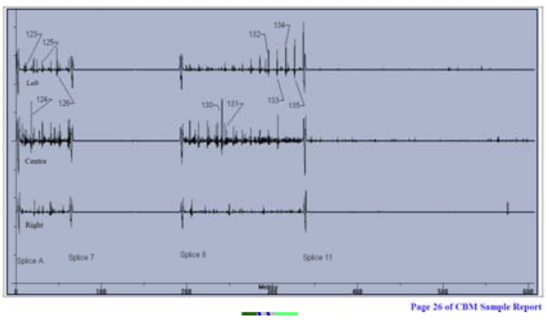

Fig. 3. Example image of belt damages after scanning [www.cbmi.com.au.]

- **CBT Conveyor Belt Technology** (USA) **-** The company offers *C.A.T.MDR™* system which has four components. The main element is a scanning head placed over the one side of belt. It has several 66 cm wide modules (from 1 to 4), which can be connected to cover the whole belt width. System of data collection for 2.64 m wide and moving with the speed of 7 m/sec belt, gathers 750,000 samples per second. Classification of damages in C.A.T.™ MDR system. Picture of the belt is a white band (rubber is transparent) and colors inform about damages and anomalies (fig.4). Red color indicates the decrease of weight in steel cord while green says about the increase of weight.

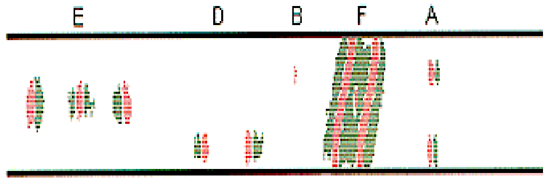

Fig. 4. A graphic image of defects in the system BELT CAT ™[http://www.cbtech.cl]

- **Conveyor Technologies** (CT Colorado and CT Pty. NSW Australia) Advanced opportunities for signals analysis allow for the remote access to all sensors in real time using the telephone wires. Special algorithm processing the measured values allow to select the spices between the belt sections, define their type and evaluate the damage level if it occurs. After finding the place of damage, the stress concentration rates are also calculated using the analysis of finite variances model (fig.5). Client receives the recommendations how to recover the belt strength and the previous level of safety factor.

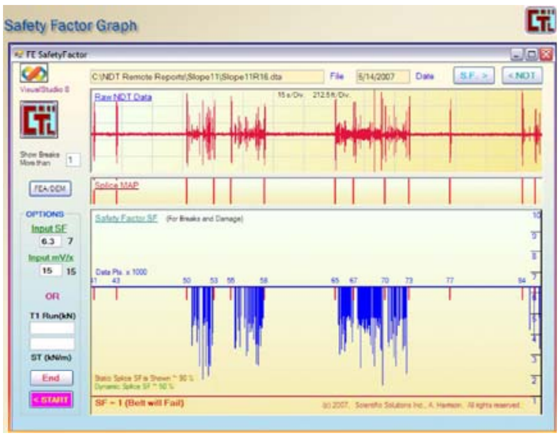

Fig. 5. Damages diagram of the tested belt (red) and the safety factor (blue) [www.conveyorscience.com]

- **Intron** (Russia) **– Introcon system.** It allows to monitor the 4 m wide belts, moving with the speed of up to 7 m/sec. Scanner may have 1-3 eddy-current modules and it is placed below or over the belt (10-20mm, fig.6). It is lighter that the equipment for magnetic field analysis. Measure values are transferred by cable to the field computer, and then to computer in the office. The device detects the damage or lack of 1 cord, corrosion, belt splices, and breaks between cords in splices.

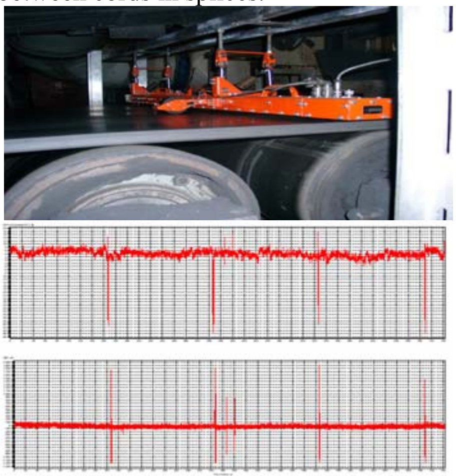

Fig. 6. Eddy current head mounted on belt conveyor and sample measurement result. [www.intron-plus.com]

- **TCK** (China) - ***TCK Steel Cord Conveyor Belt Online Automatic Inspection System***. TCK is a big company producing the equipment and testing the conditions of steel ropes, covering the 80 % of Chinese market. It employs the advanced technology of weak magnetic fields inspection using the unique sensors. The device may examine the belts from 600 to ~2400 mm wide. The accurate qualitative (98%) and locational (1mm) identification of cord damages: cord cuts and corrosion as well as slices integrity is provided at the distance between the head and belt form 70 to 110 mm.

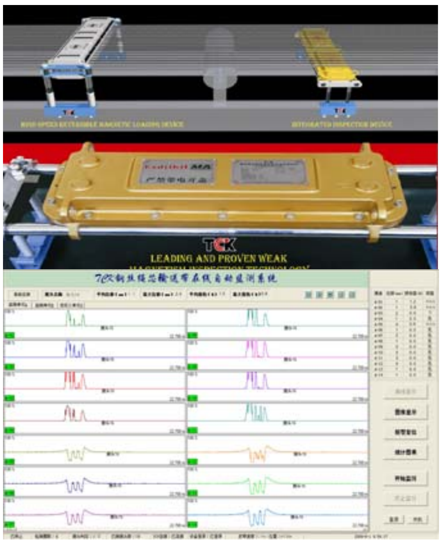

Fig. 7. View of the device and belt scan sample [www.tck-cn.com].

- **Veyance Technologies** (GoodYear) ***Cord Guard™*** system. System identifies the damages of single steel cord with location accuracy of +/- 15mm. System has widely developed additional functions such as notice about the damage by sms or e-mail, or at any time on demand the report about the current status in the form of PDF. The detailed list of damages location (length of belt, location of splices and damages) is generated as well as critical and no-critical alerts about the levels determined by the user. High resolution magnetic pictures of damages and splices do not need the expert to be interpreted (fig.8).

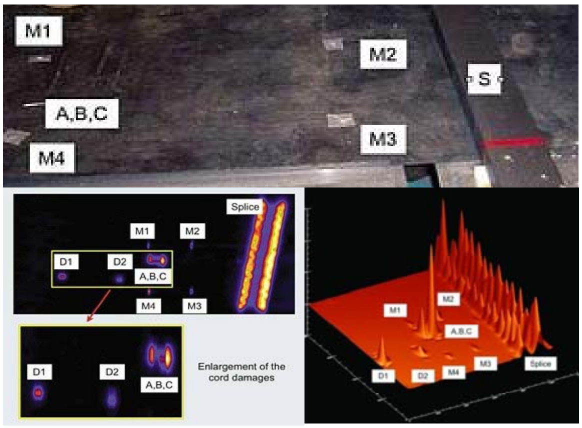

Fig. 8. Verification of visual damages of belt and splices illustrated in the Cord Guard system in 3D image [www.goodyearep.com]

2. NEW POSSIBILITIES FOR NDT EQUIPMENT USE

Costs optimization and simplification of the organizational structure are the reasons of changes in companies in Polish mine and power industry. They in turn result in commissioning, much more frequently, the maintenance and service operations concerning the transport equipment to the contractors. This situation causes the problems with quality control and the scope of work ordered by the mine. Diagnostic equipment is very helpful there. Apart from its basic task it can check and verify the quality of the service (fig.9).

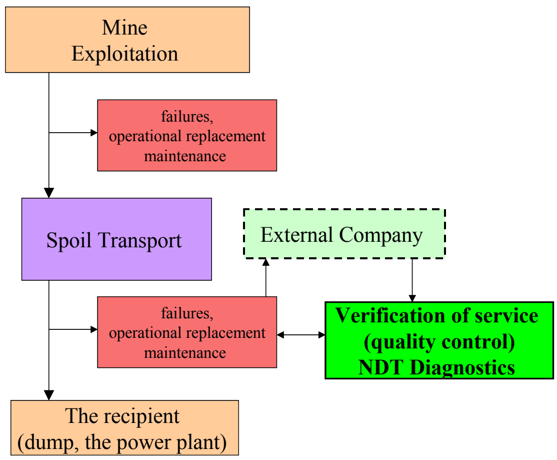

Fig. 9. Scheme to verify the quality of services provided by external companies

3. SUMMARY

Currently many companies are making the substantial changes in technologies applied and in equipment being offered. Some suppliers base on checked but old technology like Intron with Eddy-current technology or TCK with weak magnetic fields method. The offered equipment have different resolution in damages identification, differ in results displaying and in damages interpretation simplicity. The systems have also different prices. The prices of the cheapest systems without measuring the covers thickness or cut preventing option start from $40 000. This systems, however, despite of their advantages, have one main disadvantage – they do not offer the automatic evaluation of belt condition. The evaluation of belt scanning results is still made by the experienced diagnosis specialist in mine, or specialized team of experts in the companies delivering the equipment. It makes the costs of diagnostic much higher and widen the scope of the service [4]. Newly developed equipment should follow many additional criteria, such as:

- Automatic evaluation of belt condition directly on the conveyor, based on real time and historical data stored in the equipment memory
- Legible report and results visualization adjusted to the needs of the particular user (mine, power plant)
- Mobility, easy assembly, easy operation not requiring the high qualified personnel
- Low reasonable price, allowing to buy several devices by one client
- construction and software opened for modifications allowing for quick adjustment to new, changing needs of the user.

Meeting these requirements should enable the wider usage of NDT method for conveyor belts diagnostics, affecting positively on belts life and reduction of transport costs in mines. Possibility of adjusting the user interface to new, changing needs and requirements of users may be conductive while making the decision about its purchase and widespread usage.

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VALIDATION OF VIBRATION SIGNALS FOR DIAGNOSTICS OF MINING MACHINERY

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Summary

The paper presents the proposal of vibration signal validation algorithms for monitoring of mining machinery. Since several years vibration based condition monitoring is quickly growing, as there is an increasingly important focus on efficient operation and maintenance of very costly equipment used in mining industry. FAMUR Institute, the leading research and development center for FAMUR's Group – one of the biggest producer of mining machinery and equipment, develops machinery monitoring solutions, according to its e-mine strategy.

One of key issues in the analysis of vibration signals is the validation of acquired signals. It is a key prerequisite, before any further analysis should be performed. In the paper, a survey of a number of existing validation methods is presented. These methods has been successfully applied in industries such as power generation, wind turbines or railway transport. Presented methods are evaluated from the point of view of heavy industry applications especially for underground mining, where the most important thing is to record correct data without sending useless vibration signals for diagnostic inference.

The paper includes a case study, where the real vibration data from high power test stand are analyzed. The object of research was heavy duty gearbox. Proposed methods were also applied for the real data from machines working underground.

Keywords: Vibration, validation, condition monitoring systems, coal mining machines monitoring

WALIDACJA SYGNAŁU DRGANIOWEGO NA POTRZEBY DIAGNOSTYKI MASZYN GÓRNICZYCH

Streszczenie

W artykule przedstawiono propozycje metod walidacji sygnału drganiowego na potrzeby diagnostyki maszyn górniczych. Na przełomie ostatnich lat popularność systemów monitoringu maszyn górniczych opartych o sygnał drganiowy systematycznie rośnie, co jest związane z dążeniem do zwiększania czasu dostępności maszyn minimalizacją nieplanowanych przestojów oraz dążeniem do jak najwcześniejszego wykrycia symptomów zbliżającej się awarii. Zgodnie ze strategią przyjętą przez Grupę FAMUR, FAMUR Institute, Centrum Badawczo-Rozwojowe jest twórcą kompleksowego systemu e-kopalnia. W skład tego systemu wchodzi m.in. FAMAC VIBRO pozwalający na ciągły monitoring drgań oraz temperatur napędów maszyn górniczych.

Jak wynika z dotychczasowych doświadczeń autorów, jednym z najważniejszych zadań w analizie sygnału drganiowego jest przeprowadzenie rzetelnej walidacji zarejestrowanych sygnałów. Opisane w artykule metody zostały zaimplementowane w różnych gałęziach przemysłu (m.in. energetyce, turbinach wiatrowych oraz transporcie kolejowym). Obecnie metody te są rozwijane i dostosowywane do specyficznych wymagań rynku górniczego ze szczególnym uwzględnieniem ograniczenia przesyłania i zapisywania danych nieprzydatnych z punktu widzenia diagnostyki maszyn.

Opisywane w artykule metody walidacji sygnałów zostały przetestowane na danych pochodzących z eksperymentalnych badań przekładni przemysłowych przeprowadzonych na stacji prób napędów dużej mocy. Metody te obecnie są również zaimplementowane w podziemnych systemach monitoringu maszyn górniczych.

Słowa kluczowe: (drgania mechaniczne, walidacja sygnału, systemy monitoringu maszyn, monitoring maszyn górniczych,)

1. INTRODUCTION

In recent years utilizing of systems of monitoring and diagnostics (SM&D) machines with residual parameters such as vibration and temperature are becoming increasingly popular method of maintenance in coal mine industry. These systems allow to detect damage of rotary machinery (e.g. gearboxes, shearer loaders) in its early stage, which is very important with a view to avoiding unplanned machine downtime caused by breakdowns and maintain the continuity of work in coal mines [1, 2, 3, 4].

Very briefly, SM&D based on vibration signals consists of accelerometer, cables, data acquisition unit (with signal conditioning unit and ADC converter), data processing unit and supervisory unit (e.g. with data storage unit). [5, 6]. If system works under extremely difficult, non-stationary conditions and very noisy environment as well as compliance with the explosive atmosphere requirement (ATEX) its structure becomes more complicated. FAMUR Group proposed fully ATEX compliant system for vibration monitoring which was presented in [3]. There is a lot of additional connections between accelerometer and data acquisition unit, some additional equipment and sometimes signal path are very long which can cause numerous disturbances in the signals. According to these facts validation of vibration signals is the first and one of the most important procedure in signal analysis process [6,7].

In this paper authors present a study on vibration signals validation as a prerequisite to evaluate the accuracy of recorded data and their usefulness for future analysis and diagnostic reasoning.

2. SIGNAL VALIDATION

Signals, which in accordance with system configuration are qualified to record (e.g. machine is in acceptable state and time condition is fulfilled), are subjected to data validation process. This process is very important especially when dealing with systems for monitoring multiple machines working in non-stationary conditions. Due to that fact, that there is a lot of signals to analyze (in FAMUR's biggest implementation there are about 120 accelerometers), and no possibility to analyze them without automation. Before making any automation of data analysis one has to know, that analyzed signals are correct. Incorrect signals stored in database could be misleading: process of automation analysis could generate false warning or alert, which may expose condition monitoring service clients to high costs associated with unnecessary reaction of services stuff and unneeded repairs. According to this, through the cooperation of specialists in the field of analysis of vibration signals from the EC Group and FAMUR's Diagnostic Center several rules of vibration signals validation were developed, tested and implemented . These methods could be divided into two groups, which is presented at Fig. 1.

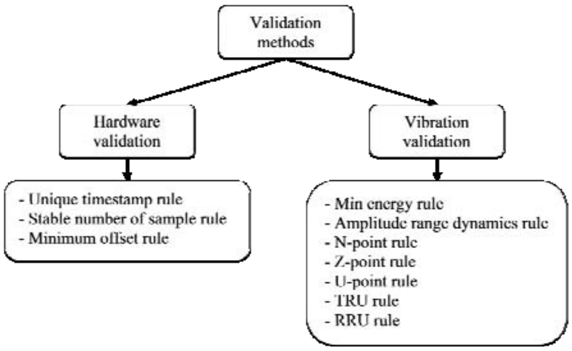

Fig. 1. Classification of validation methods

2.1. Hardware validation

Complete signal validation policy applied in vibration based monitoring system has to be structured in levels enabling to assess signal validity as it follows the path from sensor to the storage database. Such approach leads to implementation of two-steps signals validation, where first process is validation of proper hardware operation. This process consist of three simple rules:

2.1.1. Unique timestamp rule

Task of this procedure is to check if for one channel there is no signals recorded with identical timestamp. This procedure allows the detection of an error in the software for data acquisition, or problems with hardware (e.g. Real Time Clock) which resulted in saving the samples with the same timestamp. Standard visual inspection of the signals does not allow to identify problem as it is possible with automatic validation. As it is shown at Fig.2. this problems sometimes appear in real industry systems. Areas with dotted lines indicate multiple signals recorded with the same timestamp. It is obviously software bug or hardware failure. It is very simple method, but from presented at Fig. 2. Data set it was 50% data rejected due to unique timestamp rule.

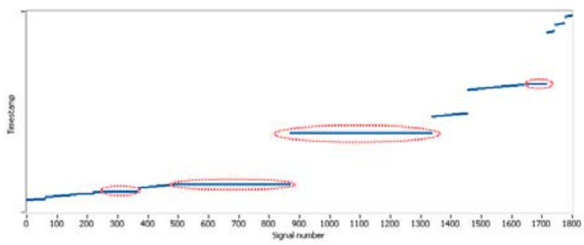

Fig. 2. Data set not valid due to unique timestamp rule

2.1.2. Stable number of samples rule

Stable number of samples rule specifies whether a number of samples in signal is different than that resulting from the system configuration. Wrong number of samples may have several reasons - error during writing to storage space, damaged file, errors in the database or problems with acquisition cards (such as a temporary buffer overflow). When dealing with signal with not valid number of samples, one should always consider problems with the signal continuity. Assuming that the missing bit is the beginning or end of the signal is not acceptable because lack of samples could be low level hardware problem difficult to identify in details.

2.1.3. Minimum offset rule

Generally, in correctly recorded acceleration signal offset should be close to zero [6]. Very simple way of describing offset is calculate mean of analyzed signals. When calculated offset is significantly different from 0, it is possible that the errors occurred in acquisition hardware. When this situation persists, there may be a need to replace the data acquisition module or sensor.

Thanks to above mentioned methods, we could react really fast against hardware fault and replace wrong sensor or module. It is really important especially in large industry monitoring systems, where there is no possibility to supervise system continuously, and service should be informed about any problems with the hardware.

2.2. Vibration validation

If recorded signals are correct due to above methods of hardware validation, automatic validation starts to validate data in terms of its suitability for data analysis and diagnostic information content about technical condition of monitored object. This process consist of following rules[6,7]:

2.2.1. Minimum energy rule

Minimum energy rule is a procedure based on calculating the root-mean-square (RMS) of the analyzed signal and comparing it with the specified limit [6,7]. It allows for the rejection of the samples recorded during downtime of machines - unimportant from the standpoint of diagnosis. These simple method is also useful for detection of total sensor failure or cutoff of cable which is quite frequent in large system of monitoring based on vibration for underground coal mines.

2.2.2. Amplitude range dynamics rule

Characteristic for large SM&D installed in underground coal mines is, that in one system different machines are monitored. There are gearboxes, where vibration levels are quite big because of excitation, but on the other hand we are monitored drums which rotation speed is small and external excitation are small. There is no economical reason to use another sensors or acquisition modules for each machine. In situation, when 16-bits ADC are used, it is very important to set correct measurement range. If range is e.g. +- 60g, and typically vibrations is about 2g (P-P), there may be a problem of low level of signal quantization, which problem is shown at Fig. 3. Following the Jabłoński [6,7] channel range should be set so that nominal data covers about 15-20% of total channel range.

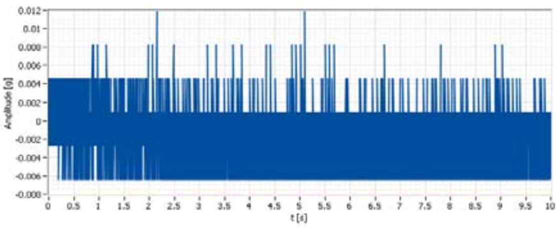

Fig. 3. Signal not valid due to amplitude range dynamics rule

2.2.3. N-point rule

This rule describes maximum number of consecutive samples in signals with the same amplitude value [6,7]. Proper setup threshold for this rule is very important and if it is set proper N-point good describes e.g. signal saturation as it is shown at Fig.4. Consecutive samples with the same amplitude are marked. High rate of N-point could also appear when channel range is too small and real vibration are much bigger than maximum channel range. In this case, N-point does not inform about invalid signal but about wrong system configuration. This threshold depends on resolution of ADC and sampling rate. N-point rule may be described as follow dependency Eq.1[6,7]:

$$(\forall_x \in X)(\neg\exists_x \in \exists)(\forall_{i=i,+1,\ldots,i+N-1}(x_i = x_i + 1)) \qquad (1)$$

Where:
X – set of signal values
x – single signal values
N – the N-point rule coefficient (threshold)

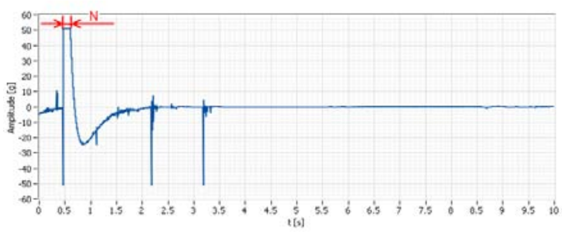

Fig. 4. Signal not valid due to N-point rule

2.2.4. Z-point rule

The results of the Z-point rule procedure is the maximum number of consecutive samples in signals with the same sign which can be an indicator of sensor saturation [7]. Signal with high z-point indicator is shown at Fig. 5. With red lines there is marked the area where the signal has a constant sign. This situation often occurs in vibration monitoring systems for underground machines (e.g. belt conveyors, shearer loaders).

2.2.5. U-point rule

Procedure for determining the number of unique samples in the vibration signals [6,7]. This type of signals by nature is highly volatile so this parameter is expected to be very high. In industrial systems of vibration monitoring 16-bits ADCs are quite common which means, that there is only 65536 possible unique samples (in case of full coverage channel range) so U-point is much more reduced than in 24-bits ADC, where 16777216 unique sample values are possible. In addition U-point is highly dependent on signal length (number of samples in signal) and total channel range coverage and it is relatively difficult to identify correctly the limit for that indicator. However, linking it with number of sample and total channel range shows the accuracy that can facilitate automatic selection of thresholds. This is especially important in the case of 24-bit ADC, where the acceptance threshold for u-point is much higher than for 16-bit ADC. Currently the authors are working on modification of this method into two others: TRU (time relative u-point) and RRU (range relative u-point). Problem of the u-point is illustrated at Fig. 6 and Fig. 7, where two signals are compared – valid and invalid due to U-point rule.

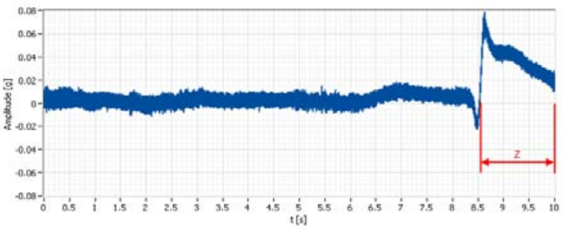

Fig. 5. Signal not valid due to Z-point rule

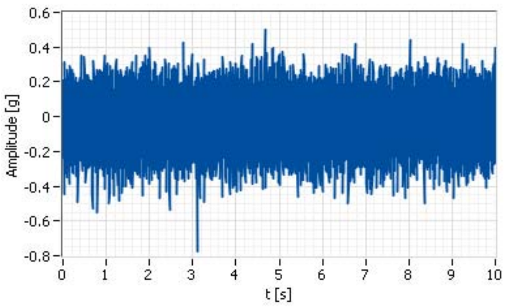

Fig. 6. Signal valid due to U-point rule

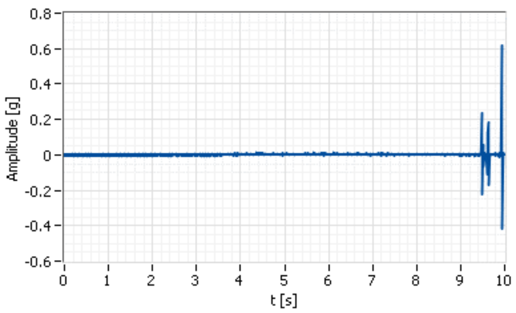

Fig. 7. Signal not valid due to U-point rule

3. CASE STUDY

Methods discussed in previous chapters were applied to vibration data recorded during simultaneous testing of two heavy duty gearboxes (about 300kW) on FAMUR's large scale high power drives test lab. Six channels where recorded (three per each gearbox) with 24-bits ADC resolution. System was configured to record signals with length of 10 seconds with sampling rate of 51,200Hz. During this test, rotation speed was constant (direction was changing) but load was variable.

As it shown at Fig. 7 signal recorded at nominal operating condition of monitored object has amplitude range 21,93 g. According to total channel range 100 g it is shown, that signal is valid due to amplitude range dynamics rule. Ratio of signal amplitude range to total channel range is about 20% for signals recorded at nominal operating parameters. These meets previously mentioned amplitude range dynamics rule criteria described in [6, 7].

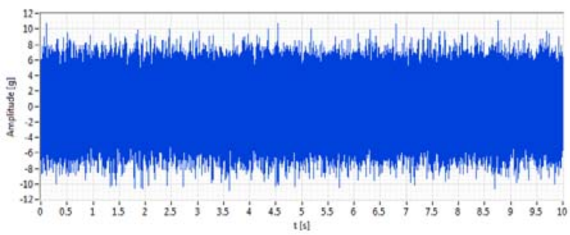

Fig. 8. Signal recorded at nominal operating parameters for observed gearbox

Table 1 illustrates results of validation procedure performed on data set of 4326 signals - 721 signals per each of six channels. To better illustrate functioning of individual rules for each signal complete calculation procedure was carried out. With this approach it is possible to illustrate which of rules exclude the signal from the data set.

In table 2 impact of each discussed validation rule on sample rejection is presented. A slightly different point of view is illustrated in Table 3 It shows the percentage of invalid signals according to various rules relative to all the rejections for the channel. This approach illustrates exactly which of the rules has the highest impact on the rejection.

From Table 1, according to Table 2 and Table 3 it may be concluded, that, some rules have almost no impact on rejection signal from data set, but on the other hand some rules (especially U-point) have nearly 100% affected the removal of the signals from the set. If some signals were found as invalid, it was almost always because of u-point rule. This may indicate that approach used for U-point for 16-bits ADC may be too sensitive for samples recorded with 24-bits ADC.

Table 1. Number of invalid signals due to discussed rules

	Gearbox A			Gearbox B		
Rule	Channel 1	Channel 2	Channel 3	Channel 1	Channel 2	Channel 3
Minimum energy	57	66	63	71	71	71
Maximum offset	1	0	1	0	0	0
N-point	1	0	1	0	0	0
Z-point	61	41	64	62	54	64
U-point	84	86	84	164	164	140
Total signals	**721**	**721**	**721**	**721**	**721**	**721**
Total invalid	**87**	**86**	**85**	**165**	**164**	**141**
Total valid	**634**	**635**	**636**	**556**	**557**	**580**

High amount of invalid signals due to minimum energy rule could be explained in fact, that there were few downtimes during this research. Removal of that signals is beneficent, because they will not be taken into account during the automated analysis, and even if they are properly registered, they do not bring anything in terms of diagnostic machines.

Small share of rejection according to offset and N-point rule should not be surprising. Minimum offset rule is closely connected to the operation of hardware and on the test stand there is high quality hardware dedicated to data acquisition. On the other hand N-point violation often occurs with signal saturation, and there were only few such signals associated with a strong impact near the sensor.

Significant part of rejected signals are signals invalid due to Z-point rule. Reason for this may be for example impacts near the sensor or the need for swapping cables during tests.

Table 2. Number of invalid signals due to discussed rules

	Gearbox A			Gearbox B		
Rule	Channel 1	Channel 2	Channel 3	Channel 1	Channel 2	Channel 3
Minimum energy	7,91	9,15	8,74	9,85	9,85	9,85
Maximum offset	0,14	0,00	0,14	0,00	0,00	0,00
N-point	0,14	0,00	0,14	0,00	0,00	0,00
Z-point	8,47	5,69	8,88	8,60	7,49	8,88
U-point	11,65	11,93	11,65	22,75	22,75	19,42
Total invalid	**12,07**	**11,93**	**11,79**	**22,88**	**22,75**	**19,56**
Total valid	**87,93**	**88,07**	**88,21**	**77,12**	**77,25**	**80,44**

Table 3. signals according to various rules relative to all the rejections for the channel [%]

	Gearbox A			Gearbox B		
Rule	Channel 1	Channel 2	Channel 3	Channel 1	Channel 2	Channel 3
Minimum energy	65,52	76,74	74,12	43,03	43,29	50,35
Maximum offset	1,15	0,00	1,18	0,00	0,00	0,00
N-point	1,15	0,00	1,18	0,00	0,00	0,00
Z-point	70,11	47,67	75,29	37,58	32,93	45,39
U-point	96,55	100,00	98,82	99,39	100,00	99,29

4. CONCLUSIONS

Paper dealt with validation of vibration signals. Despite the fact that data set analyzed in case study was obtained during laboratory testing, 10% to 20% of data for each channel was rejected due to validation rules. This fact indicates that the validation of vibration signals is very important especially if the signals are further dedicated to automatic analysis. Very often it happens that the vibration signal is disturbed by external factors, such as work carried out near the observed object. This was also true in this case, in part of the invalid signals were visible impact hitting most likely caused during the works near the gearbox. It often happens that in the case of experimental research are required minor modifications during the test and if not carried out the validation of vibration signals, the invalid signals can significantly disrupt the results of analyzes carried out in the future.

Additionally, the authors state that in the case of 24-bit ADC, some of the methods given in the paper should be modified to better mapping really false signals. The largest area for future research, the authors saw at dependence of U-point to the time of registration (number of samples) and the dynamic range of the signal. Given in [6,7] the method performs very well in the case of 16-bit ADC, but 24-bit ADC introduce additional complications, and methods described above should be modified.

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APPLICATION OF THE MODAL FILTRATION TO THE DAMAGE DETECTION IN TRUSS STRUCTURE

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Summary

A modal filter is an excellent indicator of damage detection, with such advantages as low computational effort due to data reduction, ease of automation and low sensitivity to environmental changes [4, 5]. The damage detection method has been already described and tested numerically by the authors [7]. To apply it in a real SHM system, the measuring diagnostic unit has been designed and built. The paper briefly describes the SHM system assumptions and presents results of its laboratory testing on the truss structure. The testing object was an element of the roof girder in reduced scale. It was mounted in the specially designed and built hydraulic stand [9, 10]. The laboratory test program included series of measurements on undamaged and damaged object. The main part of measurements, however was focused on analyses of damage detection.

Keywords: modal filter, damage detection, laboratory testing, truss structures.

ZASTOSOWANIE FILTRACJI MODALNEJ DO WYKRYWANIA USZKODZEŃ DŹWIGARA KONSTRUKCJI DACHOWEJ

Streszczenie

Filtr modalny jest bardzo dobrym wskaźnikiem wykrywającym uszkodzenie, posiadającym takie zalety jak niewielkie wymagania obliczeniowe, łatwość automatyzacji procedury i niska wrażliwość na zmiany warunków zewnętrznych [4,5]. Metoda ta była już uprzednio opisywana i testowana symulacyjnie przez autorów [7]. Aby zastosować go w rzeczywistym układzie monitoringu, zaprojektowano i zbudowano urządzenie diagnostyczno pomiarowe. W artykule krótko opisano założenia konstrukcyjne systemu, a następnie pokazano wyniki jego badań laboratoryjnych. Obiektem testów był element dźwigara konstrukcji dachowej zamontowany na specjalnym hydraulicznym stanowisku pomiarowym [9,10]. Program testów laboratoryjnych obejmował serię pomiarów na obiekcie bez oraz z uszkodzeniem. Główna część pomiarów dotyczyła wykrywania uszkodzenia.

Słowa kluczowe: filtr modalny, wykrywanie uszkodzeń, badania laboratoryjne.

1. INTRODUCTION

The vibration based methods are one of the widest described damage detection methods [1]. One of the techniques from this group is an application of modal filtration to the object characteristics. A modal filter is a tool used to extract the modal coordinates of each individual mode from a system's output [2, 3]. It decomposes the system's responses into modal coordinates, and thus, on the output of the filter, the frequency response with only one peak, corresponding to the natural frequency to which the filter was tuned, can be obtained. Very interesting way of using modal filtering to structural health monitoring was presented by Deraemaeker and Preumont in 2006 [4] Frequency response function of an object filtered with a modal filter has only one peak corresponding to the natural frequency to which the filter is tuned. When a local change occurs in the object – in stiffness or in mass (this mainly happens when damage in the object arises), the filter stops working and on the output characteristic other peaks start to appear, corresponding to other, not perfectly filtered natural frequencies. On the other hand, global change of entire stiffness or mass matrix (due to changes in ambient temperature or humidity) does not corrupt the filter and the filtered characteristic has still one peak but slightly moved in the frequency domain. The method apart from the earlier mentioned advantages, which results from its low sensitivity to environmental conditions has very low computational cost, and can operate in autonomous regime. Only the final data interpretation could be left to the personnel. This interpretation is anyhow not difficult and it does not require much experience. Another advantage of the method results from the fact that it can operate on the output only data.

Method described above was in 2008 extended to damage localization by K. Mendrok [5]. The idea for extension of the method by adding damage localization, bases on the fact, that damage, in most of the cases, disturbs the mode shapes only locally. That is why many methods of damage localization use mode shapes as an input data. It is then possible to divide an object into areas measured with use of several sensors and build separate modal filters for data coming from these sensors only. In areas without damage, the shape of modes does not change and modal filter keeps working – no additional peaks on the filter output. When group of sensors placed near the damage is considered, mode shape is disturb locally due to damage and modal filter does not filters perfectly characteristics measured by these sensors.

Because the method looks promising it can be applied in a real SHM system, however it first needs to be extensively tested both on numerically generated data and next on the laboratory test stand. The simulation verification was already performed and its results are described in [7].

General conclusions from these analyses can be summarized as follows. The following cases has been considered: verification of the method sensitivity to damage location, inaccuracy of sensor location in the consecutive experiments, measurement noise and changes in ambient conditions, such as temperature and humidity. Additionally the applicability of the method was examined for very complex structure – rail viaduct with elements made of steel, concrete, wood and soil. After these numerical tests it can be stated that the method detects damage with good sensitivity but users have to be aware that there is a significant impact of the accuracy of the sensor location in the subsequent measurements on the results of modal filtration. Also the temperature has some impact on the results, however it is lower than in other vibration based methods.

In this paper authors described the results of the laboratory measurements, which were performed on a single truss mounted on specially built test stand.

1. GENERAL ASSUMPTIONS OF THE MONITORING SYSTEM

As it was showed in the previous section the modal filtration can be a great tool for damage detection and further for structural health monitoring. For this reason the authors decided to implement as a practical measuring – diagnostic system. Its main assumption was that it should be completely independent. It means that the potential user should be able to perform full diagnostic procedure without necessity of usage of any additional measuring device or software. To fulfill above requirement the original 16-teen channel measuring – diagnostic unit MDU was designed and the dedicated modal analysis and modal filtration software was written. Generally the system composed of both hardware and software is supposed to work in one of the three modes:

I. Operation in dynamic signal analyzer mode for the purposes of the modal testing. In this mode the modal filter coefficients are estimated for the reference structure.

II. Operation in diagnostic mode:
- Acceleration / displacement of vibration measurements,
- Selected characteristics estimation (FRFs PSDs),
- Modal filtration of the above characteristics,
- Damage index calculation,
- Visualization of the filtered characteristics,

III. Operation in monitoring mode:
- Periodical acceleration / displacement of vibration measurements,
- Selected characteristics estimation (FRFs PSDs),
- Modal filtration of the above characteristics,
- Damage index calculation,
- Reporting of the object to the central unit.

3. MEASURING DIAGNOSTIC UNIT

From technical point of view the diagnosis process is divided into a few basic steps:
- simultaneous synchronous acquisition of analog signal (converted into digital domain) from 16 channels.
- digital signal processing applied to measured signal
- output processing results

The block diagram of MDU is described in Figure 1.

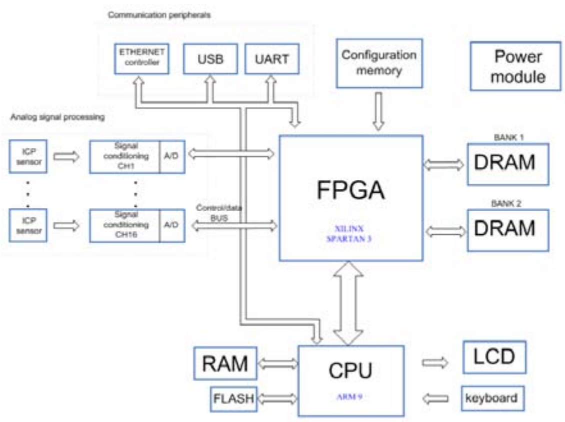

Fig. 1. Block diagram of design device

Diagnostic device contains of two fully independent and connected with each other modules: CPU and FPGA modules. The CPU module is included for control purposes – it implements user interface with some peripheral devices like keyboard, LCD display and communication peripherals. Using this interface it is possible i.e. to set gain or select required analog filter in each of 16 analog signal processing modules, or to start diagnostic process.

The FPGA module contains all logic modules needed for implementation of required digital signal processing. It is "seen" by CPU module as another peripheral device which can execute commands (like start data processing command) and send processing results.

In other words, the FPGA module act as a coprocessor, which shortens time necessary for full measure cycle and therefore allow for power savings.

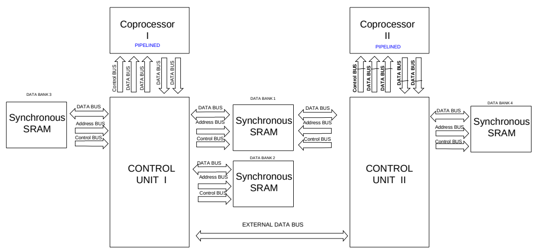

Fig. 2 FPGA processing module block diagram

The FPGA data processing module is designed using multi path, pipelined architecture, which can be easily extended to support more signal channels, and less processing time as required.

MDU also contains non-volatile memory for data recording purposes.

The MDU can be accessed via Ethernet or USB, which is needed in system calibration phase, or to read remotely processed results.
Analog signal processing module is shown in figure 3.

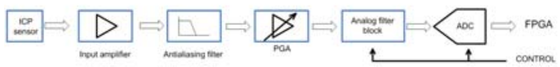

Fig. 3. Analog part of the circuit measuring

The input analog signal is delivered from ICP accelerometer sensors mounted on examined object. ICP signal standard is based on 4-20 mA current signal transmission, which main advantage is the ability of transmitting signal (with 1 kHz frequency band wide) without any distortion at ranges of 100 m and more.

Analog signal processing circuit also contains programmable gain amplifier (PGA) for three different values of gain: 1, 10 and 100. It also includes a set of analog antialiasing filters (with cutoff frequency set to: 10Hz, 50Hz, 250Hz, 500Hz and 1kHz) and 24–bit ADC converter.

MDU contains 16 identical analog signal processing channels, each for every analog input. The ADCs of every data channel are configured to provide synchronous signal acquisition, so that every sample gathered by first ADC is accurately synchronized in time with those coming from other ADCs.

With this hardware solution it is possible to detect and continuously monitor ICP status (whenever the input is shorted, opened or work in it is normal working conditions). It is also possible to detect input signal overshoots, so that device will not take such distorted data into account during measures.

4. DEDICATED SOFTWARE

The main goal of the software written for the described SHM system is the estimation of the modal filter coefficients. For this purpose, the application provides the following functionalities:

- Geometrical model definition of the tested object.
- Measurement points definition, namely the assignment of specific points of a geometric model to the sensors placed on an object.
- Execution of measurement and presentation of the results (time histories, PSD, FRF and coherence), and data archiving.
- Execution of modal analysis by:
  - calculation of stabilization diagram,
  - estimation and visualization of mode shapes for selected poles,
  - estimation of modal filter coefficients and visualization of filtration results.

The application was created in the .Net Framework 3.5 environment with use of additional external libraries:
- Developer Express v9.1 (tables and standard application controls)
- Steema TeeChart for .Net v3 (charts)
- Intel IPP (signal spectrum calculation)

All calculations related to the modal analysis are performed by the Matlab engine. The application provides the ability to debug these functions from Matlab level. For this reason, at the user-specified location, mat-files are stored that contain input parameters for the appropriate Matlab functions.

In Figure 4 the graphical user interface of described software allowing for impulse modal testing and mode shape visualization control is presented.

It was assumed that in order to fluently visualize the mode shapes it is necessary to refresh screen with a minimum speed of 30 fps. There are not available on the market sufficiently effective controls to allow the visualization and animation of 3D models with the assumed speed. Therefore, implementation of such control was done by using the XNA environment. The control uses a graphics accelerator which allows for refresh at 60 fps at 10,000 points of geometrical model.

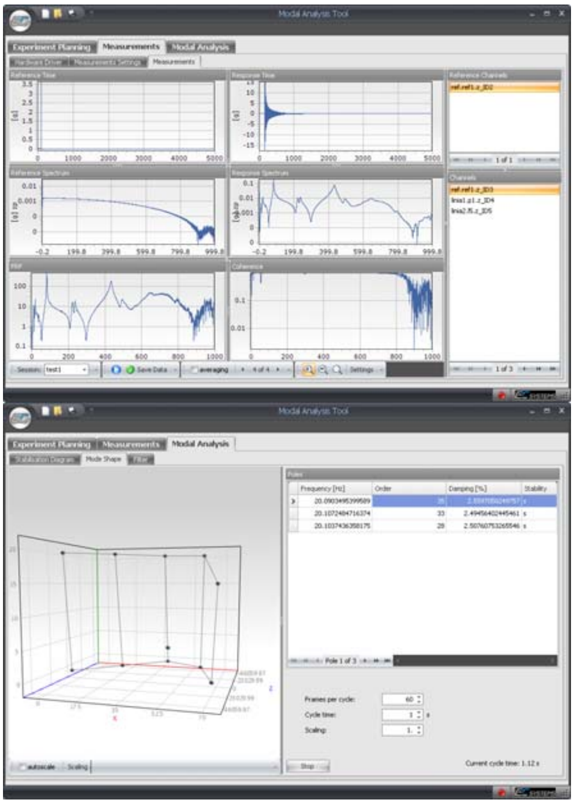

Fig. 4. GUI of described software

5. DESCRIPTION OF LABORATORY TEST STAND AND PROGRAM OF TESTS

The measurements could be successfully accomplished thanks to courtesy of interested staff members of the Faculty of Automotive and Construction Machinery Engineering at Warsaw University of Technology. The object of the test was a single truss shown in Figure 5 mounted on a specially built test stand in the laboratories of the Faculty of Automotive and Construction Machinery Engineering at Warsaw University of Technology [9, 10]. It is a typical element usually found in roof constructions, and it's damage may directly lead to roof crash. During the experiment a force was applied to the truss as shown in the figure.

The main goal of the test was to proof that modal filtration and designed system can be successfully used for damage detection for such objects.

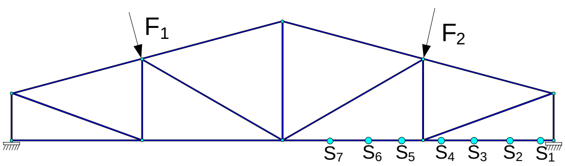

Fig. 5. Object of tests

A set of sensors was installed on the bottom beam of the truss.

A significant advantage of this approach is that it is not necessary to place a large number of sensors on examined object even if it is large. The user can place only a few sensors evenly distributed on the object.

The result in damage detection efficiency would be very similar. However a bit of experience is needed from the user to choose a proper area and sensors number.

What is more, position of each sensor cannot be changed during measurements, as it would affect damage detection quality [8].

As a matter of fact this method can be successfully used in applications where the measures are performed periodically. In this case sensors doesn't need to be installed permanently, however user have to ensure that every sensor is mounted exactly in the same point of the object as it was during reference measure. This can be achieved by using dedicated spacers (between object and sensors) mounted permanently on tested object.

At the very beginning MDU was connected to PC (with dedicated analytic software installed) in order to calculate modal filter coefficients for object in reference state. The reference state is defined as a state of object without damage in it's typical working conditions. In this case it was assumed a state of truss mounted on test stand with no force applied to it. The photo of MDU unit connected with PC is presented in Figure 6.

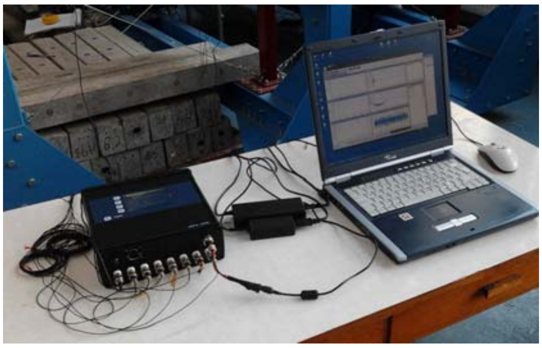

Fig. 6. MDU connected to PC

First step was to define object geometry. The software GUI used for object geometry definition is presented in Figure 7.

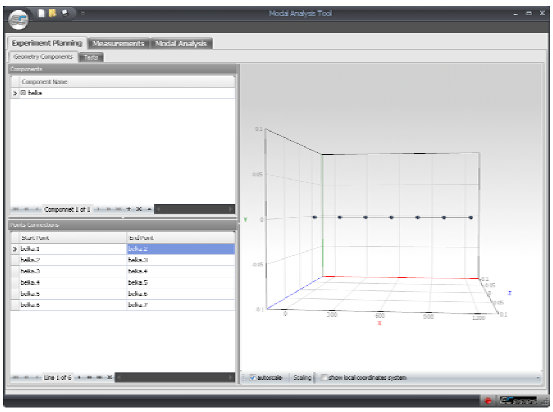

Fig. 7. Software GUI – object geometry definition

After that a set of measurements was performed. Every measurement had to be examined in order to check if it meet all requirements. If it does, it can be accepted and used further in model extraction phase. General rule is: more measurements performed – more accurate model will be generated. During measurements the sensors signal is presented in separate software GUI as shown in Figure 8.

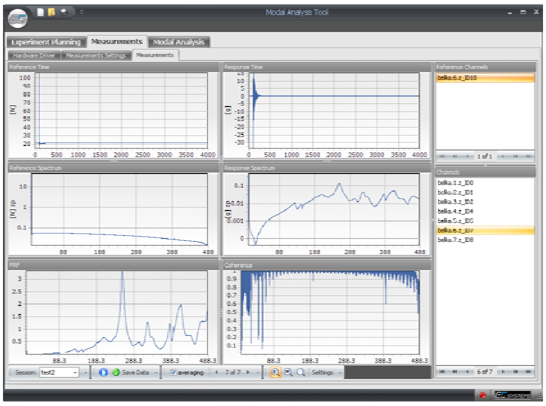

Fig. 8. Software GUI – measurements

After measurements there is possibility to visualize mode shape for each of the estimated natural frequencies.

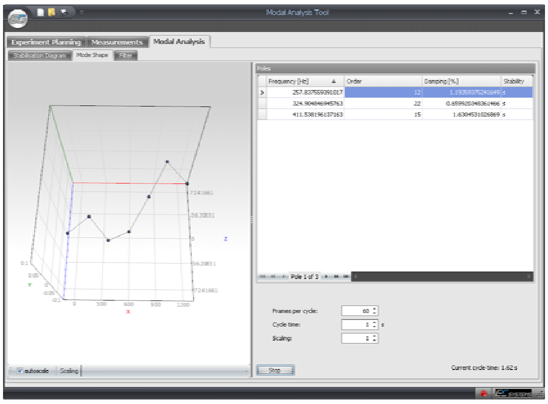

Fig. 9. modal shape visualization

Next step is to choose proper poles on stabilization diagram. This is actually the last phase when a bit of experience is needed from the user. Next modal filter coefficients are estimated. After model extraction user is able to verify quality of designed filter (which is shown below in Figure 11).

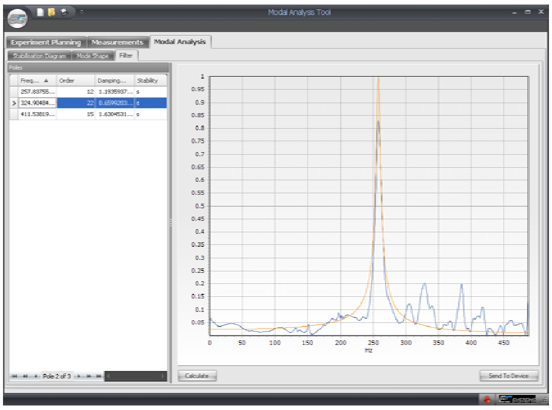

Fig. 11. software GUI – filter quality verification

As the result, three modal filters had been calculated, each for different natural frequency and corresponding mode shape.

Coefficients of these filters were then transferred to MDU, which enabled it to work independently and calculate damage index values for each defined filter.

Next step was to run reference measure in MDU, after which MDU was ready for measurements.

6. RESULTS OF EXPERIMENTS

In this section the results of analyses will be presented.

There was 7 sensors mounted on bottom beam as shown in Figure 5. Each sensor is connected directly to the measurement system, so that the truss state was continuously monitored.

During the experiment, load was slowly increased in several steps, until the first symptoms of damage appeared.

As an input to the diagnostic procedure based on modal filter only one type of characteristics was considered: FRFs.

All the results were evaluated with use of damage index proposed in [6]:

$$DI = \frac{\int_{\omega_s}^{\omega_f} \left| x_i(\omega) - x_{ref}(\omega) \right|^2 d\omega}{\int_{\omega_s}^{\omega_f} x_{ref}(\omega)^2 d\omega} \qquad (1)$$

where: ω_s, ω_f – starting and closing frequency of the analyzed band,
x_i, x_{ref} – characteristic in the current and reference state respectively..

The measure results are presented in Table 1.

No	Measure Results			comment
	DI[0]	**DI[1]**	**DI[2]**	
1	1.46E-02	4.53E-02	2.82E-02	REF. MEASURE F=0kN
2	8.07E-01	8.17E-01	4.00E-01	F=5kN
3	8.83E-01	7.59E-01	4.80E-01	F=10kN
4	9.60E-01	9.24E-01	6.98E-01	F=20kN
5	1.03E+00	1.11E+00	7.52E-01	F=25kN
6	1.11E+00	1.30E+00	8.31E-01	F=30kN
7	1.44E+00	1.31E+00	1.34E+00	F=35kN
8	8.54E-01	8.71E-01	7.10E-01	F=15kN
9	2.07E-01	4.39E-01	3.50E-01	F=0kN
10	1.35E+00	1.16E+00	1.13E+00	F=35kN

Table 1 measurement results

For every measure there are three damage index values calculated for different modal filter.

Measurement 1 was performed in object reference state. We can notice relatively small values, which may lead to conclusion that there is little or no change in truss internal structure since the reference measure was done.

Next step was to increase value of force applied to the object and measure damage index values for each step. As we can see in Table 1, larger force values means higher damage index values. This fact fully agree with theory, as internal structure stress have an impact on modal response.

The load was increased up to the value of 35 kN, when the object started to deflate.

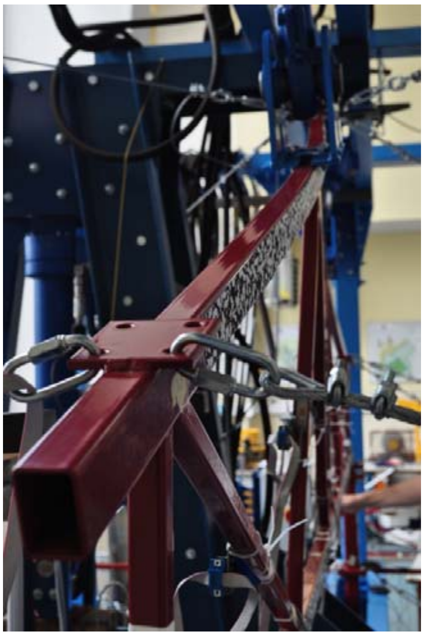

Fig. 12. deformed truss after first loading cycle

The object deflation was confirmed by other measurement techniques used in parallel with our system during tests.

After that a value of force was step-by-step decreased up to the point where no force was applied to the object.

Looking at Table 1, we can easily notice the difference in damage index values between Measurements 1 and 9.

If there were no internal change in the structure of truss, measured damage index values would be similar. However, these values are over 10 times greater, which means that internal structure of truss had changed. This conclusion had been confirmed by measures, as the object remained deformed after load removal.

Fig. 13. Deformed truss in the point of jack mounting

7. SUMMARY

The paper presents the results of laboratory tests for a damage detection procedure and monitoring system based on modal filtration. The object of test was a single truss mounted on specially build laboratory test stand, which imitate real working conditions for this object.

A general conclusion is that the SHM system detects damage with good sensitivity.

However, the sensors should not be replaced during system operation, as this could affect measurement results.

In the further development of the SHM system based on modal filtration, authors plan to install it on other type of real structures such as bridge to verify its monitoring ability.

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VIBRATION ENERGY HARVESTING IN THE TRANSPORTATION SYSTEM: A REVIEW

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Summary

This review presents different approaches of kinematic energy harvesting. Energy harvesting is the conversion at ambient energy present in the transportation system into electrical energy. Most vibration energy harvesters are based on spring-mass-damper systems which generate maximum power when the frequency of the ambient vibration fits the resonant frequency of harvester. The strategy of the reduction of this limitation is discussed in the paper. At first the periodic tuning of the resonant frequency is explained. Additionally the method of continuous tuning is presented. The emphasis is placed on maximizing the power transferred from the energy harvester to the output load. It is consider the possibility of using a dynamic magnifier in order to amplify the harvested electrical power. It is showed that the proper parameter selection of the magnifier the power can be enhanced and the effective frequency bandwidth of the generator can be improved. Next is presented a comprehensive review of the principles mechanisms of transformation the kinematic energy into electrical energy. The three main transduction methods are based on piezoelectric, electromagnetic and electrostatic phenomena. Piezoelectric harvesters use active materials that generate an electric charge when stressed mechanically.

Electromagnetic generators change the relative motion of conduction in magnetic field, on the principle at electromagnetic inductions. Electrostatic generators convert the relative movements between charged capacitor plates into electrical energy.

The advantages and disadvantages of each are described and evaluated and the relevant merits of each approach are concluded.

Keywords: energy harvesting, inertial generators dynamic magnifier, transolution mechanisms, frequency tuning.

ODZYSKIWANIE ENERGII Z DRGAŃ W SYSTEMIE TRANSPORTOWYM: PRZEGLĄD

Streszczenie

Publikacja prezentuje różne podejścia w odzyskiwaniu energii ruchu. Odzysk energii rozumiany jest jako konwersja otaczającej energii obecnej w systemie transportowym w energię elektryczną. Większość systemów (urządzeń) dokonujących tej transformacji bazuje na układzie sprężyna-masa-tłumik, które generują największą moc jeśli częstotliwość istniejących drgań odpowiada częstotliwości rezonansowej układu transformującego. W pracy została omówiona strategia zlikwidowania przytoczonego ograniczenia. Jako pierwszy został wyjaśniony mechanizm okresowego dostrajania częstotliwości rezonansowej. Fakultatywnie przedstawiono metodę ciągłego jej strojenia. Jednak głównie położono nacisk na maksymalizację mocy przekazywanej z układu odzyskującego energię do obciążenia wyjściowego. Rozważono możliwość zastosowania wzmacniacza dynamicznego, którego zadaniem jest zwiększenie odzyskanej energii elektrycznej. Zostało wykazane, że właściwy wybór parametrów takiego wzmacniacza, zwiększa wydajność energetyczną, jak również szerokość efektywnego pasma częstotliwości generatora. Kolejno przedstawiono obszerny przegląd zasad mechanizmów transformacji energii kinematycznej w energię elektryczną. Opisano trzy główne metody transdukcji, które opierają się na następujących zjawiskach: piezoelektrycznym, elektromagnetycznym i elektrostatycznym. System odzyskujący bazujący na efekcie piezoelektrycznym, wykorzystuje aktywne materiały, które generują ładunek elektryczny pod wpływem występowania naprężeń mechanicznych.

Generatory elektromagnetyczne transformują ruch względny przewodnika w polu magnetycznym, na zasadzie indukcji elektromagnetycznej. Natomiast generatory elektrostatyczne zamieniają względne przesunięcia pomiędzy naładowanymi okładkami kondensatora w energię elektryczną.

Zalety i wady każdego ze sposobów odzyskiwania energii zostały opisane i ocenione a dodatkowo wyszczególniono zalety każdego z podejść.

Słowa kluczowe: odzysk energii, wzmacniający generator dynamiczny, mechanizmy działania, strojenie częstotliwościowe

1. INTRODUCTION

21st century, apart from being the time of intensive development of science and technology, has also brought four crises, growing population, decrease of available natural resources, degradation of natural environment and economic instability. These developments have led to further attempts of finding new ways out of this situation. It has become particularly important to find solutions which would help satisfy energy-related needs. According to the U.S. administration [1], crude oil, coal and natural gas were in 84% the original sources of the energy consumed in 2011.

These developments are accompanied by the growing excavation costs, expressed as the ratio of the energy consumed for excavation and construction of devices and infrastructure to the energy obtained in the process (EROI–Energy return on energy investment).

The above mentioned indicator fell from 30 in 1970 down to 10 now for crude oil and gas. It is forecasted that decrease of EROI down to the range of 3 to 5 could mean occurrence of substantial shortage of energy supply and disturb development of contemporary civilization. Hence, the research and development work, regardless of whether it concerns conventional, natural oil or renewable fuels, should focus on the technologies enabling reaching EROI > 5.

According to the data presented in [2], global demand for power is currently around 16TW. At the same time let us note that the power of the radiation emitted by the Sun in the direction of the Earth is 10^4 times bigger. Assuming that half of the solar energy reaches the surface of the globe, then even its small percentage, when transformed into electrical energy, could substantially contribute to solving mankind's growing energy problems.

On the other hand, the EU climatic package obligates Polish energy producers to buy 100% CO_2 emission rights from 2020 onwards. At that time, according to the experts a ton of CO_2 could reach the price of 63.5 Euro. Attention is drawn to the fact that it is only then that nuclear power plants will become profitable, in the same way as wind power plants. This could result in substantial growth of energy prices, both for the economy and for households. Hence the growth of interest in diversified energy production methods and prosumer system in power engineering. It is already in 2016 that the prices of fotovoltanic cells could be around 1000 Euro. Such cells, upon relevant modification of the energy law, could start generating profit already after 1000 hours of energy generation. Such solutions entail the necessity of development of intelligent power grids, which would help make use of energy recovery systems profitable also in households.

As a result, the issue of efficient use of energy has recently become central to the society and the economic-and-social organizations. The environmental protection requirements, growing prices of fossilized fuel, high prices of implementation of renewable sources of energy are yet further factors leading to growth of interest in these issues. Yet another element is the increasingly growing use of autonomous monitoring and management systems which enable equipment to operate without the need for any additional power modules to be installed.

Though in the case of monitoring systems the main problem is how to deliver power at the level of micro- and milliwatts while using such means as wind, water, solar energy and vibration, still in the case of vehicles it will be the lost heat and the kinetic energy that will continue to be the major sources of energy. It is the development of intelligent power grids that could contribute implementation of such solutions in vehicles, where electrical and hybrid vehicles will not only receive but also store and send electrical power back to the grid.

At present, while we are in the transition period, there is continuous search for new energy sources and technologies, with the search for the solutions which will improve the energy efficiency of the engines and drives used in transport systems being an additional task.

Hence the research and the analyses of the possibilities of increasing the power and the energy efficiency of the kinematic, thermoelectric and thermoacoustic process of energy recovery as well as the process of increasing the density of the energy accumulated in vehicles stir such high interest.

The central issues are those relating to energy harvesting from the vibration caused by a vehicle moving on an uneven surface, especially energy harvesting from the power transmission system and the suspension as well as from the sprung masses. The search includes a method of effective transformation of the kinetic energy of the mass of a mechanical vehicle's driver and his/her seat into electrical energy, efficient use of thermal-cells in the exhaust and cooling systems of a combustion engine as well as examination of the conditions for implementing thermoacoustic generators in vehicles.

Still another issue is that of positioning of solar panels in vehicles depending on the Sun's position, relevant location and shape of a fotovoltaic panel's surface.

Improvement of a power unit's efficiency calls for research in the field of modeling of hybrid, hydraulic-and-electrical power transmission systems which will harvest energy during braking. The research in this area is of key importance due to the need for constructing modern and ecological means of transport as well as development of modern energy processing solutions in mechanical-electrical-and-hydraulic systems. The research on energy recovery in vehicles should be supplemented by the research on increasing the density of the accumulated energy. E.g. use of electrolyte with lower solidification ratio should improve a cell's efficiency at low temperatures.

2. EXISTING STATE OF KNOWLEDGE

While analyzing the state of knowledge, attention should be drawn to two essential, diverse trends: development of energy harvesting methods for use in big industry as well as development of energy harvesting and accumulation methods for miniature, or even microscopic devices. The second trend enables development of energy-harvesting units for increasingly small devices.

The other factor which leads to minimization of energy-harvesting devices is the necessity of ensuring power supply to these devices without their connection to the electrical grid. In such cases batteries are used as a source of electrical power. The main drawback of a battery is the undefined operating time. Once a battery is dead, it has to be replaced, which is connected, at times, with the difficulties related to reaching the place where a battery has been installed. One must not forget about the costs of such an operation. The new techniques of energy harvesting include use of kinetic energy as well as use of the energy of the human body.

Examples include harvesting of energy from human motion (e.g. during sleep or a walk), from the heat generated by human body or even from the contractions of the heart.

Human motion is quite characteristic – it is characterized by high amplitudes and small frequency. For this reason design of a miniature generator which will operate while installed on a human body is quite difficult.

So far several devices have been manufactured which exploit the above methods, including:

- a watch which uses the heat of the human body to drive the mechanism and charge the battery,
- a ring with installed thermoelement which converts the heat of the human body into the electric energy needed to charge the battery [3],
- a heart pacer which will be powered by the movement of the heart.

One of more interesting ideas is a shoe which contains a generator. According to the research done, a man weighing 68 kg is capable of generating 67J of energy this way while walking. [4].

Unfortunately the devices used for these purposes allow for recovery of only several millijoules of energy, which reduces the possibility of powering any bigger devices this way. In the future the range of devices powered this way could be much bigger. There are plans for powering or charging mobile phones and portable computers this way.

The method which uses mechanical vibration is one of the most effective methods of energy harvesting. Electrical energy harvesting requires a mechanism which will generate electrical energy from motion. It is possible thanks to connecting a moving mechanism to a device which can generate electricity from the movement. In other words the device for energy harvesting from vibration consists of a device which converts kinetic energy into electrical energy.[5].

Thanks to this method we are able to generate electricity from deformation, e.g. of piezoelectric materials, from movement of a magnet (core) in a coil, etc. The power which generates mechanical vibration is usually acquired from the environment. Energy coming from vibration is converted into electrical energy and then stored e.g. in batteries.

At present there exist several methods which enable acquisition of energy from vibration. These include:

- the electromagnetic method
- the electrostatic method
- the piezoelectric method
- the magnetostriction method

The diagram showing the methods which harvest energy from vibration is presented in Fig.1.

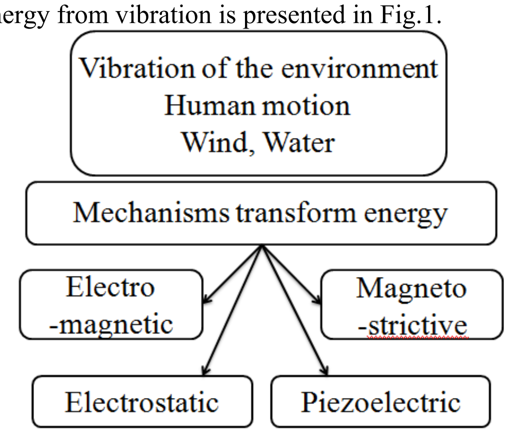

Fig. 1. A diagram showing conversion of kinetic energy into electrical energy and its examples

The piezoelectric method of energy harvesting is the method which currently draws most attention. The goal of the research related to this method of energy harvesting is the attempt to reduce the power required by small electrical devices, e.g. wireless sensors used for monitoring a man's condition (health). The main purpose of the research related to this method is to ensure power supply for the devices while using the vibration energy which is available from the environment.

Magnetostrictive materials are characterized by high coefficient of magnetic and mechanical coupling. The advantage of these materials is their high flexibility and high Curie temperature. Use of these materials involves change of the intensity of the magnetic field thanks to mechanical forces applied to the material which introduce flexible tension. The device for energy harvesting which relies on magnetostrictive materials is composed of: an energy converter, an energy regulator, a high capacity capacitor.

The electromagnetic method uses the kinetic energy of a vibrating mass to generate electrical energy. Electromagnetic devices for energy consumption exist in two configurations: standard and reverse.

The standard configuration: a magnet, whose task is to generate the magnetic field, is moving while the coil is fixed [6]. The reverse configuration: the magnet is fixed while the coil vibrates.

The electrostatic method consists of conversion of the kinetic energy of vibration into electric energy by means of a variable condenser which is polarized by an electrets (a dielectric which generates a permanent external electric field is an equivalent of permanent magnets [7]). The electrostatic generator contains two wires which are separated by a dielectric material which moves from one wire to the other.

The method is widely used but it is not as universal as the method which uses piezoelectric materials.

3. KINETIC SYSTEMS FOR ENERGY RECOVERY

3.1 Use of linear models

Harvesting of kinetic energy means use of a mechanism for electrical energy generation by coupling the vibrating system located in a vehicle with the input caused by a vehicle's vibration. Thus the analysis of the possibility of increasing the power density could be reduced to maximization of the effect of coupling between the source of kinetic energy and the mechanism which generates electrical energy based on a vehicle's motion. The inertial generator, whose elements are connected to a vehicle's structure, would be the most relevant electrical energy generator when the phenomenon of vibration is exploited.

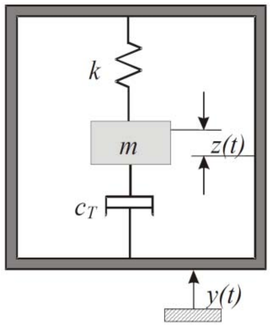

Fig. 2. A dynamic system with one degree of freedom subjected to a kinematic input [8]

Hence a supported mass can be subjected to vibration, leading to relative shift between these elements of the system.

Relevant selection of the vibrating system's parameters is required so that the frequency of proper vibration and the frequency of kinematic inputs are identical, or do not differ much from each other. Thus the mechanism of electrical energy generation could be used, as an outcome of damping in the resonant zone. The theory of inertial generators is well documented and it will be shortly presented here.

Assuming that a kinematic input can be described by means of a trigonometric function, the mean energy which is dispersed during forced vibration is described by the following formula:

$$P_{\xi_T} = \frac{m\xi_T Y^2 \left(\frac{\omega}{\omega_n}\right)^3 \omega^3}{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\xi_T\left(\frac{\omega}{\omega_n}\right)\right]^2} \quad (1)$$

Where: ξ_T is a damping coefficient.

The maximum level of dissipated energy is reached when the density of the input is equal to the frequency of proper vibration $\omega = \omega_n$, and hence:

$$P_{av} = \frac{mY^2\omega_n^3}{4\xi_T} \quad (2)$$

Equation (2) shows that the generated power is directly proportional to the mass, it increases at the rate of value of frequency to the power of three and depends on the power of the input signal. The above equations demonstrate that use of resonant systems requires the input frequency to be tuned to resonant frequency. For this reason, as well as due to the broadband inputs occurring in vehicles, the project will focus on the research on non-resonant generators which rely on dynamic non-linear system.

3.2 Non-linear model of vibroacoustic signal

Let us contemplate the possibility of generating a signal which would contain a non-linear component. Let us assume that the generated signal is multiplied by an additional value which is defined by the kinematic properties and that is transmitted to the measuring point via a linear transmission channel, which corresponds to a process with linear elements and multiplying factors which can be described by a Volterra series [9]. Examples of such a description can be found in [10, 11, 12].

After including the linear part of the signal, which in this case will be generated by the dynamic part of the system, as well as upon including the non-linear part of the process, which was defined earlier (Fig. 3), and while acting in accordance with the procedure proposed by [13], we have obtained the following relationship:

$$z(t)=\int_0^t h_1(\tau_1)x(t-\tau_1)\mathrm{d}\tau_1+\int_0^t\int_0^t h2(\tau_1,\tau_2)x(t-\tau_1)x(t-\tau_2)\mathrm{d}\tau_1\mathrm{d}\tau_2 \tag{3}$$

where:

$$h_1(\tau_1)=h_{Q_1}(\tau_1)*h_{p_1}(\tau_1) \tag{4}$$

$$h_2(\tau_1,\tau_2)=h_{Q_{22}}(\tau_1-\tau_3)\cdot h_{Q_{21}}(\tau_2-\tau_3)*h_{p_2}(\tau_3) \tag{5}$$

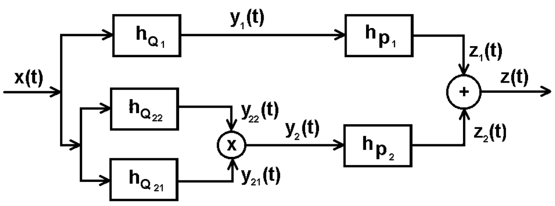

Fig. 3. Diagram showing generation of the linear and non-linear parts of the process.

Let us note that the complex mechanism of influence of non-linearity on the response of the system was reduced to generation of a signal by a system with relatively simple components which are easy to model.

While assuming, after Schetzen (1980), that the relationship (7) which defines the *n-th* element of the series is a function of variables $z_n(t_1,t_2,\ldots,t_n)$, we can apply the n-dimensional Fourier transform:

$$\begin{aligned}Z_n(\omega_1,\omega_2,\ldots,\omega_n)&=\int_{-\infty}^{\infty}\ldots\int_{-\infty}^{\infty}(\int_{-\infty}^{\infty}\ldots\int_{-\infty}^{\infty}h_n(\tau_1,\tau_2,\ldots,\tau_n)\cdot\\ &\cdot x(t-\tau_1)x(t-\tau_2)\ldots x(t-\tau_n)\mathrm{d}\tau_1\mathrm{d}\tau_2\ldots\mathrm{d}\tau_n)\cdot\\ &\cdot\exp[-j\omega_1 t-j\omega_2 t\ldots-j\omega_n t]\mathrm{d}t_1\mathrm{d}t_2\ldots\mathrm{d}t_n\end{aligned} \tag{6}$$

or

$$Z_n(\omega_1,\omega_2,\ldots,\omega_n)=H_n(\omega_1,\omega_2,\ldots,\omega_n)\cdot X(\omega_1)\cdot X(\omega_2)\cdot\ldots\cdot X(\omega_n) \tag{7}$$

where:

$H_n(\omega_1,\omega_2,\ldots,\omega_n)$ - transmittance of the *n-th* rank.

The last assumption, reducing the issue of Volterra series resolution down to determination of the higher order transmittance, enables extension of the methods used in linear systems to non-linear systems. While analyzing this issue, Storer and Tomlinson [14] point to calculation and interpretation-related issues in the case of higher order transmittance. Also the experimental methods are subject to relevant revaluation.

The literature on the topic presents methods of measurement of higher order transmittance for a sinusoid input [15]. Attempts are made at the same time to identify the Volterra series' terms. For example, publications [16, 17] take up the issue of estimation of the second order transmittance. The issue of identification of the third order transmittance is tackled by Liu and Vinh [18]. In that publication, the *n-th* order transmittance is determined from the following relationship:

$$H_n(\omega_1,\omega_2,\ldots,\omega_n)=\frac{S_{yx,\ldots,x}(\omega_1,\omega_2,\ldots,\omega_n)}{S_{xx}(\omega_1)\cdot S_{xx}(\omega_2)\ldots S_{xx}(\omega_n)} \tag{8}$$

where:

S_{xx} - the autospectrum of the input signal,

$$\begin{aligned}S_{yx,\ldots,x}(\omega_1,\omega_2,\ldots,\omega_n)&=\Im\{R_{yx,\ldots,x}(\tau_1,\tau_2,\ldots,\tau_n)\}=\\ &=X(\omega_1)\cdot X(\omega_2)\ldots X(\omega_n)\cdot Y_n^*(\omega_1,\omega_2,\ldots,\omega_n)\end{aligned} \tag{9}$$

Recent publications present results of non-linear systems analyses using simplified Volterra series [19].

4. CONCLUSIONS

Use of combustion engines for co-generation purposes is one of the elements of rational use of available energy carriers, which fits in with the tasks realized as part of energy security programs of countries and their systems. The most important feature of co-generation systems built while relying on combustion engines is the simultaneous production of mechanical or electrical energy (in the electrical power generator propelled by the combustion engine) as well as use of waste heat from the engine's systems. A serious drawback, which makes broader use of co-generation systems difficult, is the necessity of employing of efficient solutions for transforming the heat to mechanical or electrical energy .

The paper demonstrates that recovery of energy from mechanical vibration should hold a special place in the research.

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MODELING OF ANTENNAS FOR TELEINFORMATION SYSTEM WORKING IN WI-FI STANDARD

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Summary

The article is describing model projects, and simulation analysis of the antennas intended for the cooperation with wireless network cards working in the Wi-Fi standard, reported as applications for acquiring the protection right to the utility models. The projects assumed designing the omnidirectional antenna, and the directional one, providing the maximum possible value of amplifying the signal, at the simultaneous keeping the smallnesses of the size, so that the antennas could work in room conditions. Models, and simulations were performed with the help of a non-commercial program 4nec2, based on the method of moments. Moreover, for an every model, there was drawn up a model of the system fitting the impedance of the antenna to the signal line about the impedance of 50Ω.

Keywords: wireless diagnostic system, directional antenna, omnidirectional antenna, antenna modeling, antenna simulation, microwave.

MODELOWANIE ANTEN DLA BEZPRZEWODOWEGO TELEINFORMATYCZNEGO SYSTEMU DIAGNOSTYCZNEGO

Streszczenie

W pracy zostały przedstawione założenia bezprzewodowego systemu diagnostycznego będącego przedmiotem zgłoszenia patentowego [5]. System ten wykorzystuje w nadajniku metodę rozwijania sygnałów w szereg Fouriera.

Słowa kluczowe: bezprzewodowe systemy diagnostyczne, próbkowanie sygnałów, szeregi Fouriera względem wielomianów ortogonalnych.

INTRODUCTION

In the time of the current development of mobile techniques, and the distinct orientation for the miniaturization, a problem of guaranteeing stable wireless connections for the plug-in devices is becoming substantial. Choosing radio waves as the transmission medium, one should see to the assortment of the appropriate antennas, adapted for the required working conditions, since they have the direct effect to correct action and the productivity of the network.

In the article, projects, and simulation analysis of a directional antenna were described, and omnidirectional, reported as applications for acquiring the protection right to the utility models. These antenns were designed for wireless diagnostic system [5].

1. OMNIDIRECTIONAL ANTENNA

The first of the discussed antennas is the omnidirectional loop antenna, allocated to the work on the frequencies of 2.4 GHz. Figure 1 is showing the visual outline of the project.

The antenna consists of three loops (two vertical, and one horizontal) crossing under the right angle, mutually creating the spherical dipole, and from the plane of mass folded from two wires crossing at right angles. The dipole and the plane of mass are connected non-electrically with themselves, with the help of fittings carried out of the insulator. The soldering point for the so-called hot vein of the signal line, is in the lower part of the dipole, in an intersection of two vertical loops, however the soldering point for the plait is in an intersection of elements constituting the plane of mass.

The technical project assumed carrying out the elements of the antenna including the dimensions described in Table 1.

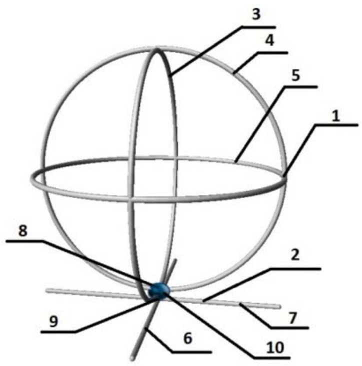

Fig. 1. Model of the omnidirectional loop antenna: 1 - dipole, 2 – plane of mass, 3, 4, 5 – loops creating the dipole, 6, 7 – wires forming the plane of mass, 8 – soldering point of the dipole, 9 – soldering point of the plane of mass, 10 – fittings of the cover

Table 1. Dimensions of individual elements of the omnidirectional antenna

Diameter of elements	1,5 mm
Internal radius of the loop	59,25 mm
Width of the dipole	121,5 mm
Length of elements of the plane of mass	120 mm
Distance of the dipole from the plane of mass	3 mm
Total height of the antenna	126 mm

In purpose of conducting the simulation of the work of the antenna, the geometry of the model was entered into the 4nec2 program. 288 steering cards responsible for handing over basic geometrical parameters of individual elements made the input data.

The simulation has been carried out in two steps:
- simulation of the distant field of the antenna put in free space
- simulations of the distant field of the antenna put at 1 m level above the real surface of the „moderate" type.

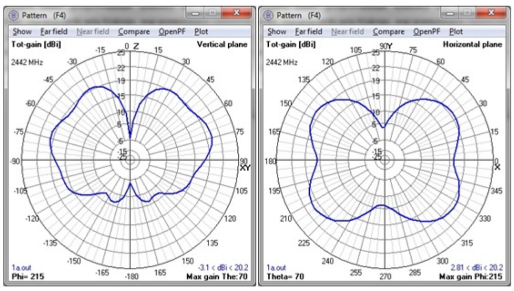

Fig. 2. Characteristics of the vertical (a) and horizontal (b) radiation

Figure 2 is showing the characterization of radiating of the antenna in the process of making a simulation for the model put in free space. Characteristics are clearly showing the omnidirectional character, whereby the horizontal characteristics is matching the theoretical deliberations for the loop about the equal λ,diameter, available in the literature (Szóstka 2006).

In the purpose of providing computational conditions similar to real conditions of the work of the antenna, a simulation of the model, put at 1 m level above the surface was conducted. Accurate parameters of the chosen base, including the magnetic penetrability, and parameters of the remaining areas were in detail described in the 4nec2 program manual.

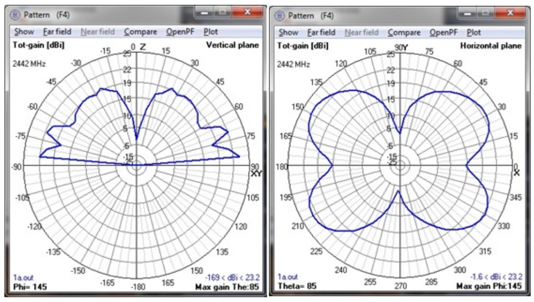

Fig. 3. Characteristics of the radiating of the antenna above the surface: vertical (a) and horizontal (b)

As a result of the change of the area of the antenna, we can observe in Picture 3, changes of the characteristics of the radiation in the vertical plane, caused by reflections of an electromagnetic wave from the ground surface. Horizontal characteristics didn't undergo any considerable changes, however bigger narrowings are noticeable on the edges of the loop.

The input impedance of the simulated antenna equals $Z = 2{,}52 + j24{,}7$. In the purpose of fitting the antenna to the signal line the impedance about 50Ω, one should use the system compensating the existing differences. It was decided to use two parallel connected condensers, described in Figure 4.

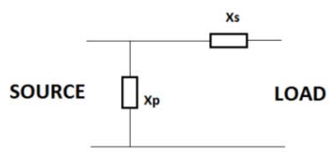

Fig. 4 System fitting the impedance

The used condensers have capacities appropriately:
-Xs=4,75 pF
-Xp=5,65 pF

The output impedance of the antenna after applying the system changed to the level $Z = 49{,}5 + j0{,}13$ and enables safe connecting to the signal line.

The designed antenna enables getting the signal amplified on the level of 23.2 dBi. Figure 5 is showing spatial characteristics of radiating of the designed antenna.

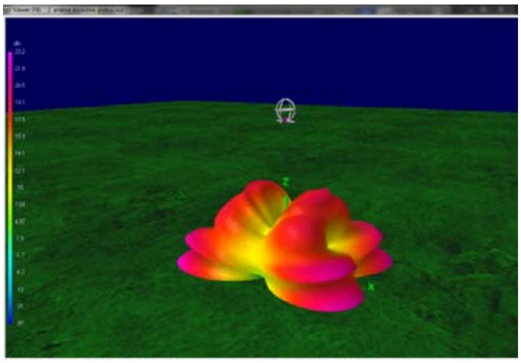

Fig. 5. Spatial characteristics of the omnidirectional antenna

According to the included legend, the maximum strengthening was achieved at the ends of the bottom leaves. As approaching towards the centre of the structure, the strengthening is gradually falling to the level of 10 dBi.

2. DIRECTIONAL ANTENNA

The second amongst the discussed antennas is a directional antenna, intended like the previous one for the work on the frequency of 2.4 GHz. This antenna constitutes the connecting of the loop antenna with the Yagi-Uda type antenna. Individual elements are created from diamond-shaped loops put along the shared axis. The model of the antenna was described in Figure 6.

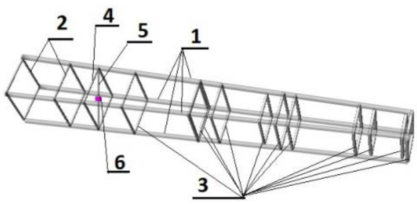

Fig. 6 Model of a directional frame antenna: 1 – casing, 2 – spotlight, 3 – director, 4 – loop dipole, 5 – rectilinear dipole, 6 – power point

It is a 14 element antenna, around which only a dipole constitutes the active element connected directly with the power cord. The dipole consists of two fundamental elements: the loop in the shape of the rhombus, and the rectilinear element going through her middle, connected with the loop in her acute angle. The soldering point of the power cord was put in the half of rectilinear element. Two loops put behind the dipole are acting as the spotlight, however the 11 remaining elements constitute the directors. All the elements are non-electrically connected with themselves through four fittings carried out of the insulator.

The dimensions of individual elements were put together in Table 2 according to the markings put in Figure 7.

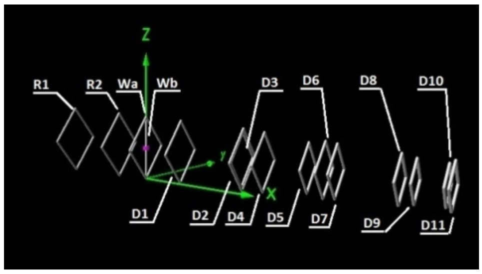

Fig. 7. Marking of elements of the antenna

Table 2
Dimensions of sides of the individual elements, and the rectilinear element

Radius of the elements	0,5 mm
R1	34,8 mm
R2	33,4 mm
Wa / radius of the element	30,2 mm / 1 mm
Wb – total lenght	25 mm
D1	30,6 mm
D2	28,5 mm
D3	25 mm
D4	26,4 mm
D5	20,8 mm
D6	23,6 mm
D7	22,2 mm
D8	19,4 mm
D9	9 mm
D10	8 mm
D11	10 mm

The prepared model consists of 57 steering cards responsible for implementing the geometry of the antenna.

The same as it took place in case of the previous antenna, two simulations of the distant field of the antenna were conducted for the model in free space, and for the one put above plane.

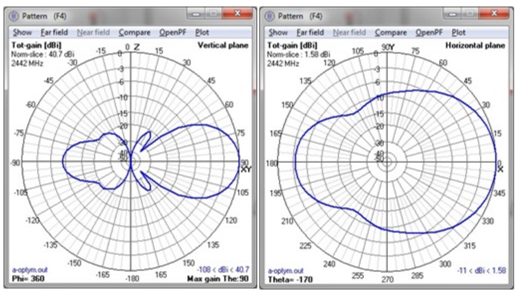

Fig. 8. Characteristics of radiating of the directional antenna: vertical (a), horizontal (b)

Characteristics of radiating of the model put in free space is shown in Picture 9. Easily noticeable is the directionality of the simulated model, however in vertical characteristics, a reactionary bundle, and little side bundles are clearly distinguishing themselves.

Entering the base into the simulation conditions is changing vertical characteristics visible on Figure 9.

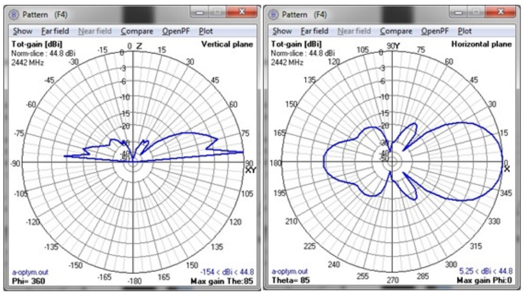

Fig. 9. Characteristics of radiating of the directional antenna above the surface: vertical (a), horizontal (b)

The generated field has a clearly directional character, with a little height in the vertical plane. The antenna isn't strongly directional what shows the wide main bundle visible on Picture 9b. In assumption, it enables covering with the signal a bigger space and facilitating placing the antenna regarding to the remaining antennas.

The initial entrance impedance of the model equals $Z = 1{,}77 + j455$. Using the modified fitting system introduced previously in Picture 4 causes the change of the impedance to the level of $Z = 40{,}3 - j3{,}35$. The modification refers to the change of the value of individual condensers for the following values:

- Xs=0,15 pF
-Xp=6,81 pF

The conducted simulation of the model of the antenna visible on Picture 10, is showing the getting of strengthening of the signal on the level of 43.8 dBi at the total length of 308.5 mm.

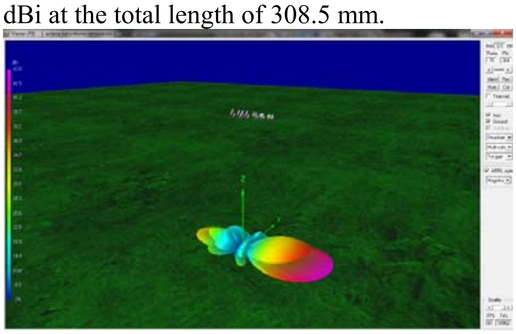

Fig. 10. Spatial characteristics of the directional antenna

3. CONCLUSION

The above article is showing the description of models of indoor antennas intended for the cooperation with devices of the Wi-Fi standard, reported as applications for acquiring the protection rights to the utility models.

In spite of using the specialist software assigned to model antennas, this process is proceeding multiply and still can procure a lot of problems. Unlike classic methods of the design, there is no need for basing on produced prototypes, however the process of optimisation of the acquired parameters itself sometimes requires total rebuilding of the created model. In spite of that, computer assisted designing is reducing the waiting time for the results of the project, and the expenditure associated with possible deviations from the assumed results.

The described models were designed with the thought about the work in room conditions. One of main assumptions was getting the possibly low dimensions, and reaching for the design increasing aesthetics of the lump of the classical antenna. The essential condition for the projects was also getting the biggest possible strengthening of the signal of the antenna, and the easiness of her free distribution with account of the remaining sources of the signal.

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CLASSIFICATION OF INTERNAL DAMAGES OF THE SAMPLE WITH A LAYER BASED ON ACOUSTIC EMISSION AND MICROSCOPIC OBSERVATIONS

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Summary

An acoustic emission (AE) method was used to detect internal damages of diamond-like-carbon (DLC) thin layer deposited on silicon substrate.

The AE signals were recorded during the entire indentation test using a broadband piezoelectric microsensor with measuring range 80Hz-1950kHz. Depending on the indenter's load, observations of surface by scanning electron microscopy (SEM) did not reveal any damage or showed single small cracks in the Vickers impression area. Therefore, it was assumed that the majority of the AE pulses originate from internal damages. Using the method of Focused Ion Beam (FIB) ion milling, indenter impression cross sections were performed. In this way, internal damages caused by indentation, such as decohesion of DLC-layer, DLC-layer cracking and the Si-substrate cracking, were revealed. As a result of microscopic and AE signal data comparison, it was possible to identify the type of failure and to describe the progress of damage during indentation.

The results will be helpful in the selection of parameters during hardness tests of layered materials and in the analysis of the strength properties of the samples with layers.

Keywords: acoustic emission, indentation, cracks, decohesion, FIB.

KLASYFIKACJA USZKODZEŃ WEWNĘTRZNYCH PRÓBKI Z WARSTWĄ ZA POMOCĄ METODY EMISJI AKUSTYCZNEJ I OBSERWACJI MIKROSKOPOWYCH

Streszczenie

W niniejszej pracy metoda pomiarów emisji akustycznej (EA) została zastosowana do detektowania wewnętrznych uszkodzeń cienkiej warstwy DLC nałożonej na krzemowe podłoże.

Uszkodzenia realizowane były w teście indentacji, a rejestracji sygnałów EA dokonywano podczas całego procesu obciążania i odciążania wgłębnika Vickersa. W zależności od wielkości maksymalnego obciążenia na powierzchni odcisków obserwowano za pomocą mikroskopu skaningowego brak bądź występowanie małych pęknięć warstwy DLC. Zarejestrowane sygnały EA pochodziły głównie z uszkodzeń wewnętrznych, które były ujawnianie za pomocą trawienia wiązką jonów. Zaobserwowano uszkodzenia różnego rodzaju, takie jak decohezja i pęknięcia lateralne warstwy i/lub podłoża. Za pomocą parametrów sygnału EA możliwe było określenie rodzaju oraz zasięgu wewnętrznych uszkodzeń.

Słowa kluczowe: emisja akustyczna, indentacja, pękanie, dekohezja, FIB.

INTRODUCTION

Deposition of layers, thin films or multilayered structures contributes significantly to technology in the field of electronics as well as in biomedicine or devices construction.

The determination if a method of deposition is suitable for technological application depends on the tests results including microhardness tests for scratching resistance and wear strength. For this group of materials in the first stages of damages the most common are decohesion of the layer and the substrate or internal cracks in the layer or substrate.

Observations of the surface morphology (scratches [1], impressions of indentation [2], wear traces [3]) are not able to reveal damages like internal cracks or delamination but the presence of these damages will affect the results of strength test.

Diagnosis of the actual state of the studied layer-substrate system has a major significance in the evaluation of properties and suitability of the technological – structural solution.

Simultaneous measurement of AE signals and performance of diagnostic tests is an example of complementary characterization methods. Registration of AE signals has been successfully applied in the detection of damages under heavy load conditions.

The aim of this study is determination of effectiveness of application of the AE method for a diagnosis of the first damages of a substrate with a layer.

Damages were introduced in the form of indenter imprints during microindentation tests. The authors undertook the study of micro- and nanodamages and investigated the relationship between AE data and the microscopic images, including the SEM micro cross-sections of impression. This study is supplementary to the previous work of other authors [6].

1. EXPERIMENTAL DETAILS

The indentation tests were executed with the Vickers indenter. The maximal loads of indentation test were 100mN, 200mN, 300mN 400mN and 500mN. We made a few tests with the same indentation load, and names of tests consist of the value of load and of a letter (a, b, c..) for subsequent tests.

During test indentation the AE signals were registered simultaneously. The AE measurement equipment was described in the publication [3].

The study concerns DLC layer deposited on monocrystalline Si substrate by RF PACVD (Radio Frequency Plasma Assisted Chemical Vapour Deposition). The thickness of amorphous DLC layer was 1μm.

The impressions were observed by the scanning electron microscope Auriga-type (Zeiss). Next, sequences of cross-sections of the impression were performed by milling system FIB (Focused Ion Beam) as shown in Fig.1.

The AE-signals were analyzed using PlexPro program and were elaborated in time and frequencies domains. From the total registered signal AE signals peak-type signals were extracted for which the maximum amplitude, duration, envelopes, and the signal energy (equivalent to signal strength) were determined. In the frequency domain was obtained STFT (Short Time Fourier Transformation) map.

2. EXPERIMENTAL RESULTS

The microscopic observations of imprints surfaces indicated that above the 300mN of load, the surfaces are damaged in each test. Due to the large number and variety of failures the imprints without any or with small surface damages, were selected for further analysis.

The increase of the maximal load causes the increase of the number of generated peaks of AE signals.

A presence of AE-peaks for indentation test at 100mN is presented in Fig.2.

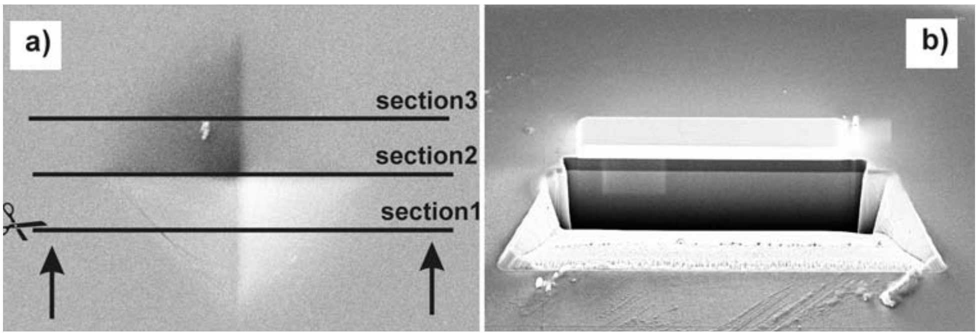

Fig. 1. The method of cross-section a) position on the impression,
b) example of cross-section by the FIB system

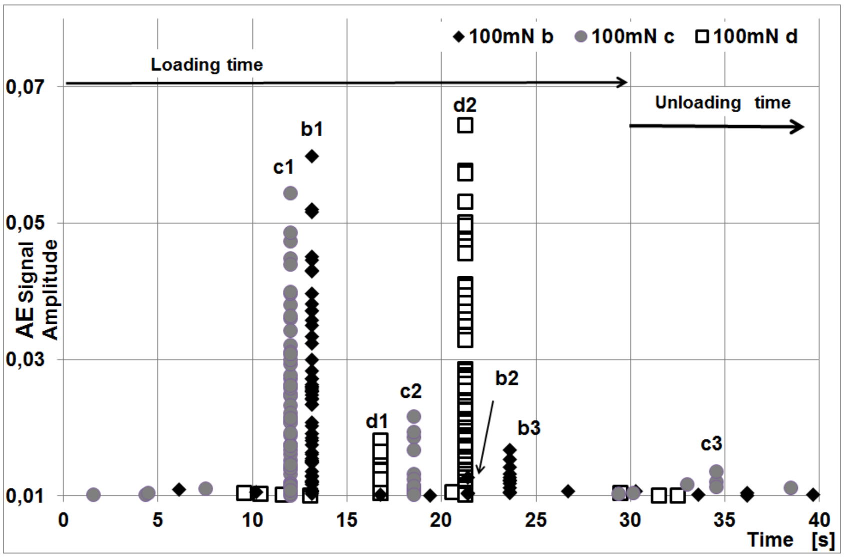

Fig. 2. The AE peaks registered during indentation tests under 100mN load

Under the load of 100mN two or three AE-peaks were generated. At load of 200mN 5 to 9 AE-peaks were observed, and at 300mN the number of AE-peaks exceeded 20. The maximal amplitude of the registered peaks increased up to 0.35V at 300mN. It was five times greater than the AE-peak amplitude at 100mN of load.

Even providing the same parameters of the indentation test it results in significant differences in damages. The 100b and 100e tests are carried out by generating just 3 and 2 AE-peaks, but caused damage of a completely different type, as shown in Fig.3.

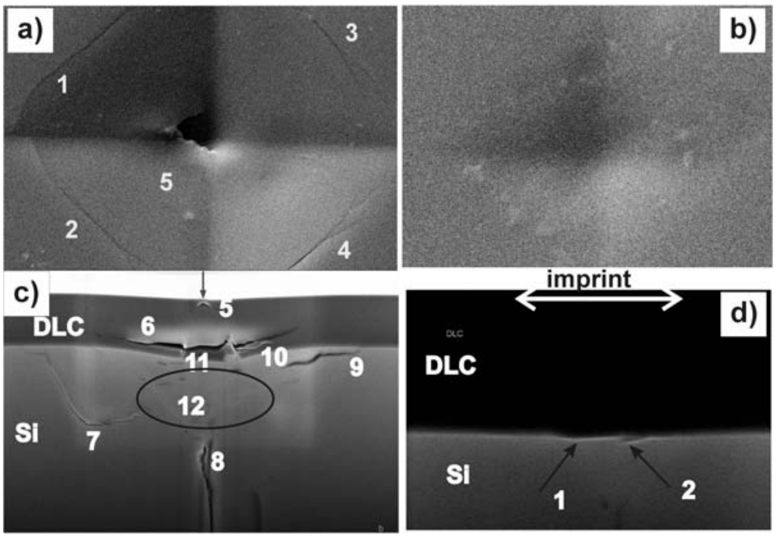

Fig. 3. SEM images of two impressions : a) top view 100b, b) top view 100d, c), d) correspondig cross-section made by FIB system, numbers indicated surface and cross-section failures

The surface of impression 100b, presented in Fig.3a is damaged with four circular surface cracks and one small hole in the center. Below the surface three large opened cracks of DLC and three extended cracks of Si-substrate were detected. Fig.3c. A total of twelve large defects detected at the surface consist of fife fissures and nine cracks of inside. In addition, the image reveals a very slight deformation of the Si material in the form of darker spots (near the side of the ellipse). All this destruction may be the source of the AE-signals. As shown in Fig.3b the look of 100d impression is quite different. The surface of the imprint is not failed. Visible is only the plastic deformation of DLC layer. The inside of impression is slightly damaged. The arrow1 indicated delamination at the DLC layer/ Si-substrate and the arrow2 highlighted the presence of a short diagonal crack at the Si-substarte. The size of this delamination is very small – about 200 nm long Determination of the kind of a failure, i.e. distinction between delamination or cracks, is possible basing on the values of the total signal energy of the registered peaks. This parameter is described by the formula:

$$\Sigma\int(AE)^2dt$$

This parameter describes the total amount of the AE signals power during whole indentation-test.

The value of total energy for AE peaks in test 100d is by 1/4 larger than the value calculated for AE-peaks from 100b test, for which damages were significantly larger. Fig.4. presents the bars of total energy values calculated for three indentation tests at 100mN load. The SEM images of 100b and 100d tests were presented in Fig.3. For the 100e test the types of damages were similar to that of 100d test, but the size of decohesion was slighthly larger. The smallest value of the Total Energy corresponds to the open damage and as shown in Figure 4. remains minimal even at numerous internal failures. The damages in the tests 100d and 100e are similar. The difference in Total Signal Energy parameter is not significant, but it rises with increasing size of individual defects.

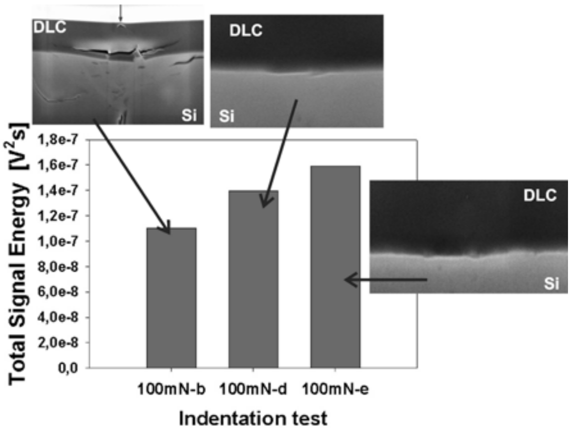

Fig.4. Comparison of the total energy for different damages under the 100mN load

Similar results were obtainded for the tests under 200mN load.

Fig.5. shows the results for two indentation tests, which caused defects of different types and size. The bigger Total Signal Energy value was calculated from the AE signals recorded during the 200b test. The damage resulting from indentation occurred only inside the sample as several lateral cracks of DLC layer and small cracks in Si substrate. The damages of smaller size and lower number in the test 200d were the source of a larger number of individual pulses. But these pulses correspond to smaller amplitude and shorter period of time as a result of which the calculated Total Signal Energy parameter is much smaller than that obtained for the test 200b. It should be noted that for the 200d test, one of the failures occurred on the surface of the DLC layer.

When failures become more extensive and their number increases, as it is at load of 300mN, the Total Signal Energies of AE-peaks at the imprints with damages on the surface are of a similar values.

The delamination can be related to the AE-peak with significantly smaller energy than the one originating from the crack. This relationship concerns similar damages and failures that are in a similar distance from the AE sensor.

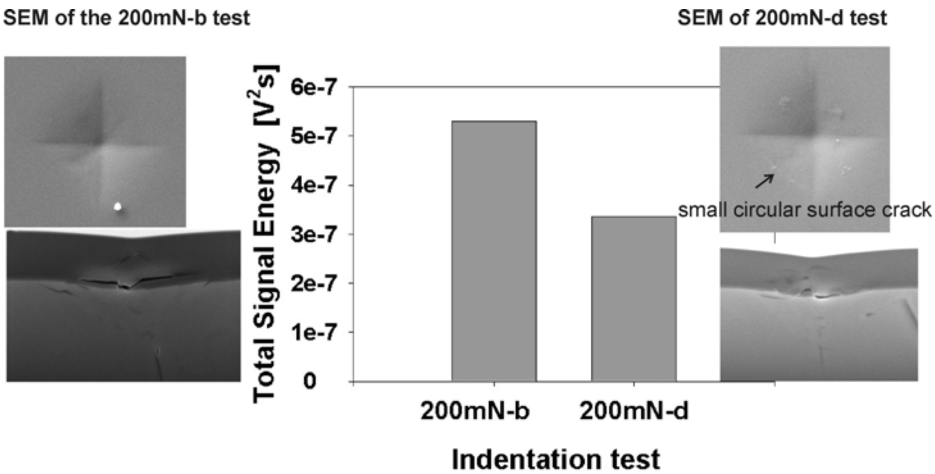

Fig. 5. Comparison of the total energy for different damages under the 200mN load

3. SUMMARY

Damages caused by the indentaion can be:

- Open, that are manifested on the sample surface.
- Internal, only inside under the surface of the sample.

The type od damage can by indicated by the parameter "Total Signal energy". It was found that for open damages this parameter is lower than for internal damages. But a similar number of defects is required in order to make the comparison reliable. The Total Signal Energy parameter calculated for a single pulse is also helpful to identify the type of a damage. Only for internal damades, when the value of Total Signal Energy increases, the AE signal was due to the decohesion of the layer from the substrate. When the value of Total Signal decreases, the source of AE signal was the internal crack.

The result of this research may be possibly applied to the investigations:

- Selection of the parameters of hardness measurements for thin films
- Determination of the origin of scattering of hardness results
- Application for quick comparative test of the adhesion of the layer to the substrate.

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ENGINEERING PARAMETERS AND CONTRADICTIONS IN APPLICATION OF TRIZ METHODOLOGY TO VIBRATION CONDITION MONITORING - VCM

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Summary

TRIZ methodology is a promising tool to obtain solutions of problems close to so called ideal final result - IFR. There are some introductory papers of present author posted on Diagnostic Congress in Cracow [Cempel 12] and this year Wisła Machinery Diagnostic Conference. But it seems to be a need to make such an approach from different sides in order to see if some new knowledge and technology will emerge. In doing this we need at first to define the ideal final result (***IFR***). As a next we need a set of engineering parameters to describe the problems of vibration condition monitoring (VCM) in terms of TRIZ parameters, and a set of inventive principles possible to apply on the way to IFR. This means we should present the machine VCM problem by means of contradiction matrix of TRIZ. When specifying the problem parameters and inventive principles, one should use analogy and metaphorical thinking, which by definition is not exact but fuzzy, and leads sometimes to unexpected results and outcomes. The paper undertakes this important applicational problem and brings some new insight into system and machine VCM problems. It follows from the paper that one can use one set of inventive principles to solve specified contradiction of VCM problem, and also another set of inventive principles to enhance obtained solution.

Key words: vibration condition monitoring-VCM, TRIZ, ideal final result-IFR, engineering parameters, contradictions, inventive principles.

PARAMETRY INŻYNIERSKIE I SPRZECZNOŚCI W ZASTOSOWANIACH METODOLOGII TRIZ DO DRGANIOWEJ DIAGNOSTYKI MASZYN

Streszczenie

Metodologia TRIZ to obiecujące narzędzie dla rozwiązywania problemów innowacyjnych, bowiem daje możliwość zbliżenia się do rozwiązania idealnego- IFR. Autor napisał kilka prac na ten temat, każda z nich oświetla inny fragment tej metodologii prowadząc do wzbogacenia wniosków. Tym razem pokazano że zasady wynalazcze TRIZ można stosować nie tylko do rozwikłania sprzeczności w parametrach, ale także w tym przypadku kiedy takich sprzeczności nie ma. Wtedy uzyskujemy możliwość polepszenia naszego rozwiązania na drodze do idealnego wyniku końcowego - IFR.

Słowa kluczowe: diagnostyka drganiowa, TRIZ, idealny wynik końcowy, parametry inżynierskie, sprzeczności, zasady wynalazcze.

1. Introduction

During the machine operation (*life*) its condition deteriorates, what one can be observed as evolving faults typical to a given machine type. Condition monitoring of machines (*systems*) is the science and technology for the assessment of condition by means of observation of machine phenomenal field – mostly vibration, where symptom of condition can be captured and measured and condition inferred (*see for example [Collacott 77]*). This means that we are trying to determine the fault space of the machine, its dimensionality and fault advancement, by some observed symptoms of condition, creating in this way machine **observation space**. The primary concept of machine condition, the **fault space** of a system (*machine*) can be defined by some prior knowledge taken from the experience with the other running machines, and the same concerns with symptom observation space.

Fault space of every machine is multidimensional, for example we have usually unbalance, misalignment, bearing faults. The similar multidimensionality is needed in our observation space, and as usually it needs some redundancy too. This is because the symptoms which we measure are usually interdependent, and by means of some symptom processing procedures, we can determine the dimensionality of observation space and so called generalized fault symptoms (*see for example [Tabaszewski,Cempel 10]*). These results enable us to infer on the machine fault space and intensity (*advancement*) of the main faults which evolve during the machine operation in its lifetime θ.

Condition monitoring is mostly applied to critical machinery, where by special monitoring system we can observe thermo and vibroacoustical phenomena carrying needed information on system condition. This means that by some measurements of these phenomena and respective signal processing we can create symptom of condition, like for example the velocity vibration amplitude measured at the bearing pedestal, or some other location of machine casing. What is important here that by means of special signal and symptom processing procedures, one can determine the type of fault, and its advancement. We can calculate also the symptom limit value $\mathbf{S_l}$ and symptom reliability **R(S),** which is analogous to lifetime reliability **R(θ)** of the machine [Cempel 91].

In summary, one can say, that having some experience on machine life and running, and a prior knowledge concerning processing of received signals and measured symptoms of condition, we can asses the current machine condition and make forecasting of future condition with a high probability of success. This concerns also the fault type and a date of stopping machine for the renewal, etc. But up to now machine condition monitoring has not been approached seriously by TRIZ[1] practitioners, and the knowledge of TRIZ methodology has not approached from many sides. Some introductory thinking to connect TRIZ with VCM problems has been already made [Skoryna], [Cempel 12]. And this paper, as a prolongation of previous, deals mainly with determination of a set of contradictions in vibration condition monitoring. These contradictions can be resolved next by set of inventive principles defined by TRIZ, approaching in this way ideal final result - ***IFR***. But it seems to that inventive principles can be used also for the enhancement and betterment of obtained solution of VCM problem. Such is the main purpose of the paper.

2. The ideal final result in diagnostics of machinery

This type of thinking, looking explicit for ideal final result (***IFR***) coming from TRIZ methodology is new in machine condition monitoring (MCM). Hence let us imagine, what we really need here? Self repairing machine, like in military aircrafts, it seems to be too early. But if we integrate advanced symptom CM system with the machine and with proper signal and symptom processing, our resultant **IFR** can be as follows.

The machine itself is signaling approaching work stoppage, a type of fault, and a time, when it should be handover for renewal.

In order to do this one can imagine that integrated CM system should contain: thermal, acoustic, and vibration transducers with signal preprocessing, in order to form several symptoms of condition $\mathbf{S_i(\theta)}$, n=1,2..n. In this way multidimensional machine observation space is created, which is monitored continuously, and symptom readings are taken with the proper life time distance $\boldsymbol{\Delta\theta_j}$, depending on the machine type and the wearing intensity [Cempel 91].

These successive symptom readings by VCM system, are forming so called symptom observation matrix (SOM), with columns presenting different type of monitored symptoms[2] and rows giving the values of discrete symptoms readings at $\boldsymbol{\theta_j}$, $j=1,\ldots m$. This rectangular matrix, with the growing number of rows, is the only source of information concerning the overall condition of the machine. One can extract this information applying singular value decomposition (SVD) [Cempel 07], or principal component analysis (PCA) [Tumer 02]. The special processing of SOM can give also symptom **limit value $\mathbf{S_l}$** which may control the stopping of the machine, and also symptom reliability **R(S)** which assesses the potency of residual running or functional ability of the machine [Cempel91].

Knowing this one can say that by proper SOM processing method, SVD for example, we are **projecting** the observation space on the fault space of the machine. In this way we are gathering wanted information concerning fault evolution, their types and their advancement.

As many symptoms of condition depends on the current machine load, controlled by a production process, special processing of SOM should be elaborated and taken into account [Cempel 11], [Cempel,Tabaszewski 10], which gives the results being almost immune against the load variability and other disturbances as well. When these precaution and preparations are successfully applied into the processing of signals, processing of symptom readings in SOM, the defined above IFR of TRIZ seems to be under the reach of contemporary technology of MCM and signal / symptom processing and computation.

3. The contradiction subset and matrix for machine vibration condition monitoring –VCM

One of the main Altshuller ideas in TRIZ is the **contradiction matrix** enabling to resolve contradictions by means of the use of inventive principles and other TRIZ tools [Savransky 02], [Orlov 06], [Nakagawa 06], [Mann 04]. The space and the dimensionality of contradiction matrix is defined by a specific set of engineering parameters describing every innovative problem in given area of engineering. We will take into account at first 39 engineering parameters used in mechanical engineering in its broad meaning, as described in many books and articles concerning TRIZ methodology. Our introductory analysis [Skoryna 10] connected with a broad interpretation convinces us, that out of these **39** parameters the ten or even less engineering parameters will be enough to describe VCM problem properly.

Special comment should be given to choose two newly introduced parameters; the fault space and observation space, the most important entities in

[2] *From one broadband vibration signal, received at some location of the machine body, several symptoms of condition can be created and measured during machine operation.*

VCM. In a normal interpretation of parameters No **3** and **4** of TRIZ, they describe the length of stationary and moving parts of the machine. The length itself is some dimensional coordinate, and when the dimension is taken with plural we can have **fault space** of the machine (***Dimension–I***), the primary entity in condition monitoring with the coordinates being the different faults evolving in a machine during its life θ.

The same reasoning lead us to the second parameter **Dimension-II**, which symbolizes **observation space** of phenomenal field of working machine, with coordinates being the measured symptoms of condition $\mathbf{S_i(\theta)}$, $i=1,\dots n$. The rest of engineering parameters of VCM of machines are as follows; symptom **reliability**, **accuracy** in detection measurement and processing, information loss, **energy loss**, **durability** or lifetime, **ease of use** or running, **repairability** (*maintainability*), and the **temperature** of machine critical parts or casing. Considering the information carried by thermo field of the machine one can notice it is multidimensional spatial information source. While thinking about energy loss as an engineering parameter one can see it is only one dimensional and in many practical cases its dynamics is very low. Hence, we can drop from consideration this engineering parameter and concentrate our diagnostic problem around **9 dimensional** descriptions of many diagnostic problems.

However, in some special cases of working machinery, especially with **variable** load and other working conditions, like rotational speed and the like, we must introduce additional descriptive parameter, which can be interpreted like the **speed** of change, variable load, or better the **variability** of working conditions. Narrowly thinking it may be associated with parameter **9** of TRIZ, but it is far more than this, hence we will introduce additional parameter **40, as variability** of working conditions. So, in a case of unstable working condition we will have **10** engineering parameters to describe our VCM problem, and contradiction matrix as well.

Having chosen all important descriptive parameters of machine condition monitoring let us think creatively, how to describe **inherent contradictions** connected with these parameters, which can be encountered in the improvements of machinery diagnostics problems. Some important contradictions are described below in Table 1a.

Table 1a. The list of main contradictions found in VCM problems

1	The **variable load** of machine influences negatively the **accuracy** of signal detection, processing and information (*symptoms*) processing
2	The **variable speed** and **load** can increase the **information loss** in a diagnostic system
3	The **variable load** and **speed** are against the **ease of use** of a machine
4	The high **working temperature** lowers the **durability** or residual lifetime of the machine elements
5	The high **working temperature** is also against **accuracy** of measurements
6	The high **working temperature** may induce additional **faults** and/or increase the intensity of present faults
7	The dimension of the **observation space** (*number of symptoms*) makes troubles in calculation of symptom **reliability**
8	The dimension of the **observation space** (*number of symptoms*) is against **accuracy** of condition estimation
9	The dimension of the **fault space** (*number of faults*) is against **repairability**, it may prolong the downtime of the machine
10	The dimension of the **fault space** (*number of faults*) is usually against **accuracy** of signal detection, information processing, and symptom processing as well
11	The high dimension of the **fault space** makes trouble in **reliability** calculation (*assessment*)
12	The higher the dimension of **fault space**, more sophisticated **observation space** should be
13	The **loss of information** during the machine operation is against its **repairability**, because we may not know exactly, what is going on in a machine, when to stop it and what to repair
14	Improper choice of **observation space** can increase **information loss**

Tab.1b Primary contradiction matrix (see 14 **V***) of TRIZ for machine vibration condition monitoring (VCM) problems*

Directions of ⇓ ***contrad. summation*** ⇒	**Fault space** (*dimens.I*)	**Observation space** (*dimens.II*)	**Reliability** (*symptom reliability*)	**Accuracy;** (*detection / measurem/ processing*)	**Variable working conditions** (*speed,...*)	**Informa-tion loss**	**Durability/** *lifetime*	**Ease of use/** *running*	**Repair-ability,** *mainten.*	**Tempe-rature**	*Sum of contrad-ns*
Fault space (*dimens.I*)	X →	V	V	V					V	V	**5**
Observation space (*dimens.II*)		X →	V	V		V					**4**
Reliability (*symptom reliabil.*)			X →								**2**
Accuracy; (*detect./measurem. /processing*)				X →	V					V	**4**
Variable working conditions (*speed,..*)					X →	V		V			**3**
Information loss						X →			V		**3**
Durability/ *lifetime*							X →			V	**1**
Ease of use */running*								X →			**1**
Repairability, *maintenance*									X →		**2**
Temperature										X →	**3**

*Tab. 2 Inventive principles (**No**) able to solve and enhance VCM problems in comparison to primary contradictions (V) of table 1a.*

Improving ⇒ ***Directions of*** ⇓ ***contrad. summ.*** ⇒	**Fault space** (*dimens.I*)	**Observation space** (*dimens.II*)	**Reliability** (*symptom reliability*)	**Accuracy;** (*detection /measurem./ processing*)	**Variable working conditions** (*speed,...*)	**Information loss**	**Durability/** lifetime	**Ease of use/** running	**Repair-ability,** mainten.	**Tempe-rature**	*No of inv. principles: different/all*
Fault space (*dimens.I*)	**X→**	**V, 5, 10** ↓	**V, 11**	**V, 1, 2**	|[1] ↓		**15**		**V, 26**	**V, 1**	**7/ 8**
Observation space (*dimens.II*)		**X** →	**V,1,2,16,19, 20, 23, 26**	**V, 5, 10, 19,9, 26**	↓	**V, 1,2,16 19,20**			**16, 20**	**26**	**10/ 22**
Reliability (*symptom reliabil.*)			**X** →	**9, 10, 15, 16**	| ↓	**1, 9**	**11, 16**	**11, 20**	**11, 16**	**3**	**13/ 21**
Accuracy; (*detect./measurem. /processing*)				**X** →	**V, 16, 19, 26** ↓	**9, 15**				**V, 1**	**11/17**
Variable working conditions (*speed,..*)					**X** →	**V, 16, 19, 26**		**V, 16, 19, 26**			**3/ 9**
Information loss						**X**			**V, 10**		**11/13**
Durability/ lifetime							**X**	**34, 35**	**34, 35**	**V, 1**	**6/ 8**
Ease of use /running								**X**		**3**	**8**
Repairability, maintenance									**X**	**3**	**8/9**
Temperature										**X** →	**3/ 7**

[1] *Reading direction of inventive principles set for a given parameter, an example.*

This means VCM we will take into consideration 10 by 10 contradiction matrix, but if needed in some special cases, this dimensionality can be extended easily or diminished a little (*i.e. temperature, or load variability*). Table 1a shows the one sided contradiction matrix of VCM with marks **V** displaying contradictions between particular engineering parameters. One can see there, that almost every parameter possess at least one contradiction, and some of them have 5 like **fault space**, and **4** for the **accuracy** and **observation space** (*see the last column*).

It is well known in methodology of invention and TRIZ that the change of one engineering parameter in the direction of improvement may be the source of worsening of another one, and the only way outside of this loop is to apply some of **40 inventive principles**. Which one to use is usually the matter of careful analogy thinking, and the prior knowledge in the given area of science and engineering.

To solve 14 contradictions shown in table 1a and 1b, we will use inventive principles of Altshuller, giving them the meaning taken with mechanical engineering area and extended with the knowledge of metrology and the diagnostic signal / symptom processing. The numbering of inventive principles shown in Tab.2 is in accordance with that given in TRIZ references, and its diagnostic meaning and prescribed actions are given below.

1. **Segmentation** – segmentation of the frequency spectrum of vibration /acoustic process, band analysis and /or Fourier spectral analysis, cepstral vibration analysis for gearboxes, and also thermal **separation** of machine elements.
2. **Extraction,** rejection – rejection filters for cutting of unwanted signal interferences, like rotational frequency f_o or the mains frequency 50Hz in Europe.
3. **Local quality** – the use of thermal or acoustic barrier, ear mufflers, the hardening of the shaft ends, etc.
5. **Integration,** merging – the vibration transducers with preamplifier, signal preprocessing, wireless transmission, integrated with a machine at specially chosen points and directions.
9. **Prior counter-action** – the forecast of signal distortion and compensation before transmission and processing.
10. **Prior action** – introductory analysis of a fault space (*dimension I*), and symptom observation space (*dimension II*) of the machine, in order to chose probable machine faults, and respective observed processes and a location/ direction of vibration transducers, on the machine body.
11. **Prior cushioning** – safe shut down procedure in rotating machinery diagnostic systems, assessment of symptom limit value $\mathbf{S_l}$.
15. **Dynamics** – elastic mounts or spacers, in order to diminish or filter vibration transmission inside machine body.
16. **Partial or excessive action** – use of SVD / PCA[4] analysis of SOM to filter noise and obtain singular components /values, also signal demodulation for detection of diagnostic information, and symptom value forecast.
19. **Periodic action** – synchronic averaging of signal, signal sampling with preprocessing, over-sampling of vibration process to detect periodicity and reduce noise.
20. **Continuity of useful action** – constant load of a machine in a production process, constant use of condition monitoring subsystem.
23. **Feedback** – monitoring of diagnostic oriented residual processes of phenomenal field of the machine for the assessment of the machine condition to increase its reliability.
26. **Copying, model** – infrared picture of the machine and / or acoustic map of its surrounding, to reduce preheated / prestressed areas of a machine, symbolic or mathematical model of the machine symptoms evolution, to elaborate its condition recognition and a forecast.
34. **Discarding and recovering** – self balancing systems in rotating machinery, small regulations and repair during the running of a machine.
35. **Parameters change** – change of mass, stiffness and damping (*passive or active*) in order to reduce excessive and harmful vibration and noise, at some parts of a machine.

One can notice from the above that for the solution of 10 by 10 contradiction matrix in machine condition monitoring, we may use **15** inventive principles interpreted in terms of machine use and signal / symptom processing knowledge and technology. They can be used altogether for the best (*see table 2*), or some of them can be omitted due to lack of knowledge (*see principle 9*), technology (*see principle 5*), or lack of need (*see principle 15*).

Looking once more for the inventive principles allocated in the contradiction matrix (*Tab. 2*), and described broadly in above listing, one can say, they present contemporary knowledge and technology of VCM. This includes the broad meaning of the inventing principle No 26, where **copy** may mean also the **model** of the symptoms evolution during the machine lifetime, to make condition assessment and forecast. It can be simple regressive model or much sophisticated with artificial intelligence and model updating [Tabaszewski 10].

What is important here, that it was possible to describe VCM problem by means of minimal number of engineering parameters, and to notice importance of two abstract entities; the **fault space** and **observation space**. We should notice also their common definition and influence on symptom reliability, the ease of running and repairability (*maintainability*) of the machine.

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[4] *SVD=singular value decomposition, PCA= principal component analysis; for SOM orthogonal decomposition.*

Concerning the problem of minimal dimensionality of engineering parameter set to describe MCM problem, it seems to that minimal dimension of engineering parameter set, can be reduced to a number of **nine** or **ten** parameters only, if needed. Also it is possible to extend this number by other engineering parameters; like accuracy of production (*manufacturability-32*), productivity (39), or harmful side effects (31), in some special cases of machine or engine diagnostics.

Applying TRIZ to MCM area it is also interesting to know which engineering parameters are the most important to define, and solve the contradictions on the way to IFR? To answer this question a special column was appended (*yellow numbers*) to contradiction matrix, which enumerate the number of contradiction to solve on the way to IFR. As we can see (*table 1b*), there are three engineering parameters; the **fault space** and **observation space** of the machine and also the **accuracy** of detection, measurement and processing. They include respectively **5** and **4** contradictions to solve on the way to ideal final result – IFR of vibration condition monitoring - VCM.

The similar question should be passed when we look for set of inventive principles solving these contradictions. Table 2 shows the numbers of these inventive principles, and some numbers are in shadowed area, when they solve contradictions of table 1b. Also there are some additional numbers of inventive principles, which can help and ease our way to IFR in VCM. What is more to see in a table 2, some principles are encountered a few times. This means they can be applied to enhance our quality of VCM problems solution, and even more some inventive principles, if applied, can solve or enhance not one contradiction only. For example, principles number; 16, 19, 26 (*see table 2*), can solve contradiction **1** of increasing accuracy of signal and symptom processing, contradiction **2** of reducing information loss, and also the contradiction **3** in extending the ease of use and running of the machine.

One can see also from the table 2, that we have some inventive principle numbers without contradiction sign (**V**), like in case of reliability parameter. There is no direct contradiction found in reliability horizontal row, but ***8*** different inventive principles namely; ***1, 3, 9, 10, 11, 15, 16, 20*** can be used for the enhancement or betterment of the VCM problem.

In summary one can see from table 2, that in 14 cases we use some inventive principles to solve some contradictions, and also we have 14 cases of using them without direct contradiction presence. This seems to be good side of the TRIZ application in VCM, that we can find inventive principles to solve contradictions, and also to use them for the enhancement or betterment of VCM solved problem.

4. Conclusions

It follows from the above it was possible to transfer creatively the current science and technology of machine vibration condition monitoring into the formal TRIZ tools and goal, that means to the ideal final result (***IFR***), contradiction matrix, and inventive principles. Due to that, the relative importance of the definition of machine fault space and observation space has been elucidated, and taken into account. Also it has been proposed that the minimal number of engineering parameters for VCM problem description and solution can be taken as ten parameters, including the most important observation space and the reliability of the machine.

The number of engineering parameters depends on the type of machinery, when the operating condition are mostly stable, like in turbosets, we can use **9** description parameters, but having machine with variable operating condition we should use **10** engineering parameters and respective contradiction matrix. In order to solve contradictions present in MCM problem one can use altogether **15** inventive principles with the **14** mostly used. And when using proper dimensionality of observation space and software for SOM processing and decomposition we can make machine condition assessment and forecasting with a reasonable accuracy.

The paper reveals one more feature of TRIZ important to VCM, mainly one can use a set of inventive principles to solve contradictions, and also another set of inventive principles for the betterment of obtained solution.

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Grzegorz KLEKOT

Zastosowanie miar propagacji energii wibroakustycznej do monitorowania stanu obiektów oraz jako narzędzie w zarządzaniu hałasem

Monografia zawiera syntezę rezultatów badań prowadzonych przez autora dotyczących propagacji energii wibroakustycznej i wykorzystania informacji zawartych w mierzonym sygnale wibroakustycznym. Zauważenie, że aparat badawczy i narzędzia stosowane do rozpoznawania i minimalizacji zagrożeń wibroakustycznych są podobne do wykorzystywanych podczas oceny stanu obiektów, pozwoliło sformułować propozycję metodyczną wykorzystania analizy propagacji energii wibroakustycznej w procesie konstruowania i eksploatacji obiektów technicznych.

Zdefiniowano miary globalne i wykazano ich konkurencyjność z opisem szczegółowym, mogącym skutkować wzrostem błędów sumarycznych uzyskiwanych rozwiązań. Bazując na ogólnym modelu propagacji energii wibroakustycznej zaproponowano koncepcję oceny oddziaływań w układzie dynamicznym, pozwalającą uwzględniać wpływ nieliniowości strukturalnych obiektu podczas prognozowania postaci sygnału wyjściowego.

Przedstawiono wyniki niekonwencjonalnych eksperymentów badawczych zrealizowanych na różnych obiektach rzeczywistych, które potwierdziły, że przy właściwej identyfikacji dróg propagacji nieskomplikowane miary globalne wystarczają do rozwiązywania złożonych zadań inżynierskich. Opisane eksperymenty i analizy dotyczą: struktury o własnościach zbliżonych do bryły sztywnej, wielowarstwowych płyt dźwiękoizolacyjnych, pojazdów, pomieszczeń o różnych gabarytach i przeznaczeniu, oraz przestrzeni otwartej.

Monografia zawiera rozważania nad metodyką wykorzystania analizy propagacji energii wibroakustycznej w procesie konstruowania i eksploatacji obiektów technicznych. Przedyskutowano koncepcję energetycznego modelu propagacji energii wibroakustycznej. Z użyciem wybranych deskryptorów sygnału wibroakustycznego analizowano znaczenie tłumienia energii wibroakustycznej w aspektach konstrukcji i eksploatacji obiektów technicznych.

Modelowanie właściwości materiałów i struktur oraz identyfikację parametrów modelu na podstawie rezultatów eksperymentu laboratoryjnego zastosowano podczas badania wpływu cech konstrukcyjno-materiałowych na efektywność barier akustycznych. Użyteczność informacji niesionych przez fale akustyczne pokazała klasyfikacja pojazdów metodą analizy skupień; inne przykłady zagadnien należących do tej grupy tematycznej to rozpoznawanie pojazdów specjalnego przeznaczenia na podstawie hałasowej miary różniącej oraz akustyczna lokalizacja oddalonego źródła dźwięku. Podobnymi metodami oceniono wpływ fali akustycznej na drgania konstrukcji świetlika Dużej Auli Politechniki Warszawskiej.

Zastosowanie miar do oceny zagrożeń hałasem zilustrowano przykładami: prognozowania wpływu pojazdów w tunelu wisłostrady na hałas środowiskowy, ustalenia przyczyn i eliminacji dokuczliwego hałasu w kabinie kierowcy samochodu ciężarowego, oraz wykorzystania elementów o nieliniowych charakterystykach sprężystości do minimalizacji hałasu w kabinie prototypowego pojazdu elektrycznego.

Monografia zawiera również opis algorytmu kształtowania klimatu akustycznego, w którym czas pogłosu jest traktowany jako podstawa oceny własności akustycznych pomieszczeń. Bazując na tym algorytmie między innymi obniżono zagrożenie hałasem pracowników w niewielkiej hali fabrycznej.

Walory diagnostyczne miar efektywności propagacji drgań zaprezentowano na przykładzie ich zastosowania jako wskaźnika stopnia uszkodzenia sprężonej belki betonowej.

Przedstawione przykłady potwierdziły, że przy właściwej identyfikacji dróg propagacji energii wibroakustycznej nieskomplikowane miary globalne wystarczają do rozwiązywania złożonych zadań inżynierskich. Dowiedziono konkurencyjności metodyki bazującej na miarach globalnych w stosunku do badań symulacyjnych prowadzonych z wykorzystaniem modeli szczegółowych. Szeroki wachlarz tematyczny przykładów świadczy o uniwersalności koncepcji i dobrych perspektywach dalszego jej wykorzystania.

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Diagnostyka

APPLIED STRUCTURAL HEALTH, USAGE AND CONDITION MONITORING

Obszar zainteresowania czasopisma to:
- ogólna teoria diagnostyki technicznej
- eksperymentalne badania diagnostyczne procesów i obiektów technicznych;
- modele analityczne, symptomowe, symulacyjne obiektów technicznych;
- algorytmy, metody i urządzenia diagnozowania, prognozowania i genezowania stanów obiektów technicznych;
- metody detekcji, lokalizacji i identyfikacji uszkodzeń obiektów technicznych;
- sztuczna inteligencja w diagnostyce: sieci neuronowe, systemy rozmyte, algorytmy genetyczne, systemy ekspertowe;
- diagnostyka energetyczna systemów technicznych;
- diagnostyka systemów mechatronicznych i antropotechnicznych;
- diagnostyka procesów przemysłowych;
- diagnostyczne systemy utrzymania ruchu maszyn;
- ekonomiczne aspekty zastosowania diagnostyki technicznej;
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- 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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