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FORECAST OF A SYSTEM'S DESTRUCTION AS THE BASIS FOR A NEW STRATEGY OF SYSTEM OPERATION

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Abstract

The goal of the paper is to develop a new prognostic strategy of system operation required for maintaining high level of readiness of complex power transmission systems, where the basis of such strategy is an integrated prognostic procedure relying on the results of comparative research performed with the use of diagnostic models considering the useful state and in the state of developing degradation of their critical elements. Thanks to applying various forms of random load for hybrid simulation models, which combine the dynamic diagnostic models with causal models where a defect is the effect, the method of problem-solving that we adopted enables us to detect the hidden defects of system elements and to forecast the remaining operating time at a relevant level of likelihood.

The solution proposed in this project can be used in the decision-making process in operating systems of machines and vehicles, where similarly as in cars, machines and helicopters it is the toothed gear that is the critical unit of their power transmission systems which can be designed according to the "damage tolerant" rule. The method of solving the problem described in the paper enables foreseeing the subsequent stages of defect development, thus enabling operational decisions to be made in a manner similar to the procedures applied for use of systems designed according to the "damage tolerant" principle.

INTRODUCTION

Engineering practice as well as the results of scientific research indicate that the intervals between occurrence of majority of defects in technical systems are poorly correlated with the operating life.

As a result, conventional strategies are unable to meet the requirements set for the systems responsible for maintenance of expensive technical systems that are expected to have high level of operational availability.

The factor that conditions achievement of a correct solution is the possibility of forecasting defect development while accounting for the model of system degradation.

Research on applying model-supported vibroacoustic diagnosis in the examination and simulation of fatigue (wear and tear) and destruction-related processes [1] points to the possibility of applying such an approach in the tasks aimed at increasing the reliability of elements and units of machines, thus leading to reduction of the uncertainty of operational decisions.

At the same time the existing knowledge in the field of diagnostics enables not only the formulation of the diagnosis of a technical condition and detection of the period of cumulative wear, but also enables successful tackling of the problems related to diagnosis of early stages of development of degradation and of wear-and-tear processes. It should be stressed that numerous elements of power transmission systems of vehicles, machines and airships are subject to degradation as a result of erosion, friction, internal damping or development of cracks. One can list many such elements, including components of motors, toothed gears, valve systems and the like. The variety of phenomena, ways of diagnostic information coding as well as the big number of information carriers have contributed to the development of diversified diagnostic procedures.

An element which still remains unsolved in a satisfactory degree, even in spite of numerous achievements, is the issue of forecasting the period of time until the occurrence of a catastrophic defect.

The simplest division of forecasting methods, based on vibroacoustic signals, accounts for two groups – the symptom-based and the model-supported methods. In the case of the symptom-based methods we assume that it is the results of measurements at input and output points of a system that serve as the main source of information that provides deeper insight into the process of system degradation.

Assuming that the static data characteristics do not change until events occur in the system that disturb its serviceability, the problem boils down to detection of a diagnostically-essential change caused by a defect and development of a relationship defining the moment in time when the threshold value is reached. Symptom-based methods rely on statistical and learning techniques ranging from image recognition theory, multi-dimensional statistics methods (e.g. static and dynamic analysis of principal components of PCA), linear and non-linear discrimination analysis to black-box analysis methods that rely on neural networks that self-organize according to features, as well as systems with fuzzy structures.

It is worth quoting several examples so as to characterize the most interesting directions. [2] points to tracking the changes of vibration signal parameters, described by mixing Gauss distribution, as the possibility of forecasting defect development in a toothed gear. Even though AR parameters have no physical sense, still [3] points to their utility while forecasting the changes of temperature in a gas turbine. [4] in turn presents the DWNN (*dynamic wavelet neural network*) method in which the network is trained with the use of vibroacoustic signals coming from defective bearings with a varied degree of damage. Such an approach offers an opportunity for using this method for predicting the evolution of cracks while also accounting for fatigue-related damage. The main benefit of symptom-based methods is their ability to transform the multidimensional data with noise into reduced-dimension diagnostic information which is useful in the process of diagnostic-and-prognostic inference [5]. An essential drawback of this method is the heavy dependence of solution-efficiency on the quality of the system responsible for acquisition of input-output data.

USE OF BAYESIAN ESTIMATION IN DEFECT-ORIENTED DIAGNOSTIC MODELS

The model-supported prognostic methods assume that a precise mathematical model is available that accounts for both the qualitative and the quantitative impact of destruction and fatigue (wear-and-tear) processes on the frequency structure of a vibroacoustic signal. While applying the comparative analysis of results of simulations relying on a mathematical model describing a system without defects and the results of measurements conducted for a real object, we obtain the diagnostic features (residua) which serve as the basis for formulating the diagnosis. However, when we have a model that accounts for the process of destruction, then we are able to formulate a likelihood forecast of the time in which a catastrophic defect will occur, while doing so relevantly in advance of defect occurrence so as to ensure effective operation. Statistical techniques are applied so as to determine the threshold values. There are numerous techniques for designating the residua, from Kalman filters [6] to defect accumulation models [7].

The main advantage of model-supported methods is the physical compliance of the degradation system and process, resulting in the feature vectors being strictly related to the model's parameters. In addition it should be stressed that more in-depth knowledge of the degradation process that we gain can be incorporated into a model and contribute to more precise solution of the task contemplated here.

Figure 1 presents the block diagram of the proposed, model-supported forecasting process.

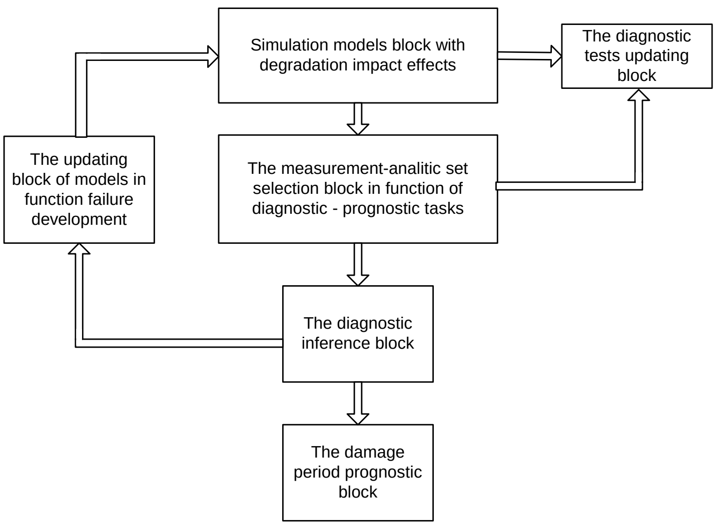

Figure 1 - Block diagram of an intelligent diagnostic-and-prognostic system

The essence of the modeling and simulation block involves creation of a possibility for entering the updated diagnostic characteristics that account for the relationship between the change of diagnostic parameters and the origin and development of defects. To this end we use the hybrid modeling method which involves combining the quantitative simulation models with cause-and-effect models which define the *defect-effect* type relations. Thanks to them it is possible to determine the effects of occurrence of defects, describe the physical changes in the object's behavior as well as select the statistical methods and techniques of teaching the models which will be able to account for the influence of defect development on the behavior of the system and of its individual components.

Important role in thus designed process of simulation model adaptation is played by the measurement-and-analysis system selection blocks and by the model-updating block. The first block, which relies on continuous evaluation of effectiveness, enables decisions to be made as regards use of additional sensors or use of analytical redundancy. Additionally, the efficiency of tests is evaluated from the point of view of detection and tracking of defect development. On the one hand the above mentioned evaluation accounts for the criterion of false alarm minimization, while on the other it accounts for the improvement of the ability to detect degradation trends and the analysis of the degree of catastrophic defect threat, which supports the activation of warning procedures.

The synthesis of the results of measurements takes place within the inference block, thus enabling assessment of the technical condition of the diagnosed object and conveying of the relevant data to the operations management system. In the case of an *on-board* system, the inference block prepares and sends the data to the maintenance-and-repair station so as to enable quick identification of replaceable components of the system and the scope of repair activities. Simultaneously the block launches the feedback branch in each case when the symbol of the defect is not recognized as one of the *defect-effect* relationships that have been identified to-date and introduced into the simulation model. This triggers the procedures of identification of a new defect relationship so as to update the diagnostic matrix.

The diagnostic information, obtained as a result of adaptation inference procedures, as well as the formulated diagnoses are used, in combination with a relevant part of managerial information, in the prediction block so as to forecast the time till occurrence of catastrophic defects of critical components of the system

An example of the possibilities offered by such an approach is the use of the simulation model developed in the Vibroacoustic Laboratory in the process of examining the fatigue-related breaking of a tooth in a toothed gear [1].

The diagnostic test, with a defect-oriented measure, involved change of distribution of probability of amplitudes of the spectrum generated by a pair of toothed wheels and had the form of the following relationship [8]

$$D = C_1\left(1 - \frac{K(\theta)}{K(\theta_0)}\right) \qquad (1)$$

where:

$C_1 = \frac{K(\theta)}{\left(K(\theta_0 - K(\theta_f))\right)}$ – scaling factor while $K(\theta)$ denotes Kullback's informational measure of probability distribution variation (2), however if $K(\theta) = K(\theta_f)$, then $D = 1$, while if $K(\theta) = K(\theta_0)$, then $D = 0$.

While using models analogous to those applied in the mechanics of fatigue-related destruction and the methods of forecasting the period of fatigue-related wear of bearings, in the face of the adopted measure of defect development the principle of accumulation of defects has been defined in the following way (Fig. 2):

$D = \frac{N}{N_f}$ – for linear rule of accumulation; (3)

$D = \left(\frac{N}{N_f}\right)^q$ – for accumulation defined by a curve; (4)

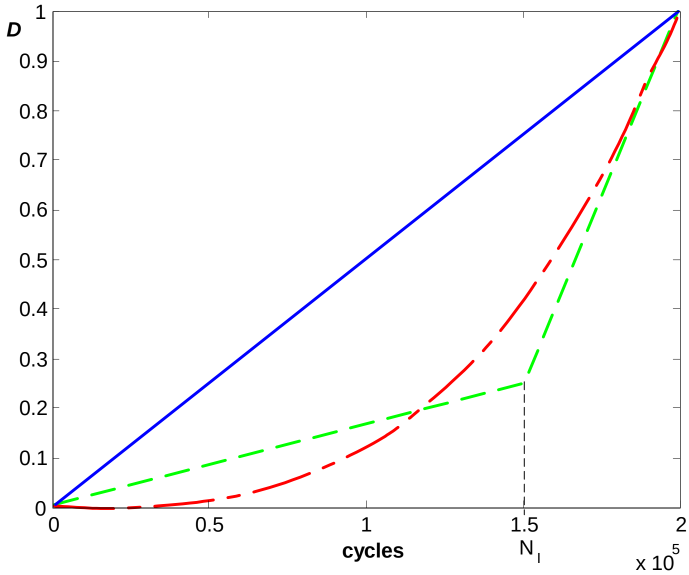

Figure 2 - Vibroacoustic diagnostic models of fatigue tooth failure

$D = \lambda \frac{N}{N_I}$ – for the phase of a crack initiation in the model of accumulation described by two sections of a straight line; (5)

$D = 1 + \frac{(1-\lambda)}{N_I - N_{II}}\left(N - N_{II}\right)$ – for the phase of propagation of a crack in the model of accumulation defined by two sections of a straight line. (6)

The research conducted in the Vibroacoustic Laboratory shows that crack initiation is accompanied by low-energy disturbance [1]. It is confirmed also by the results of principal components analysis [5]. At the same time the research clearly indicates that the information on defect initiation is hidden in the low-energy principal components (Fig. 3). Component no. 9 demonstrates a similar run to the principal component no. 4.

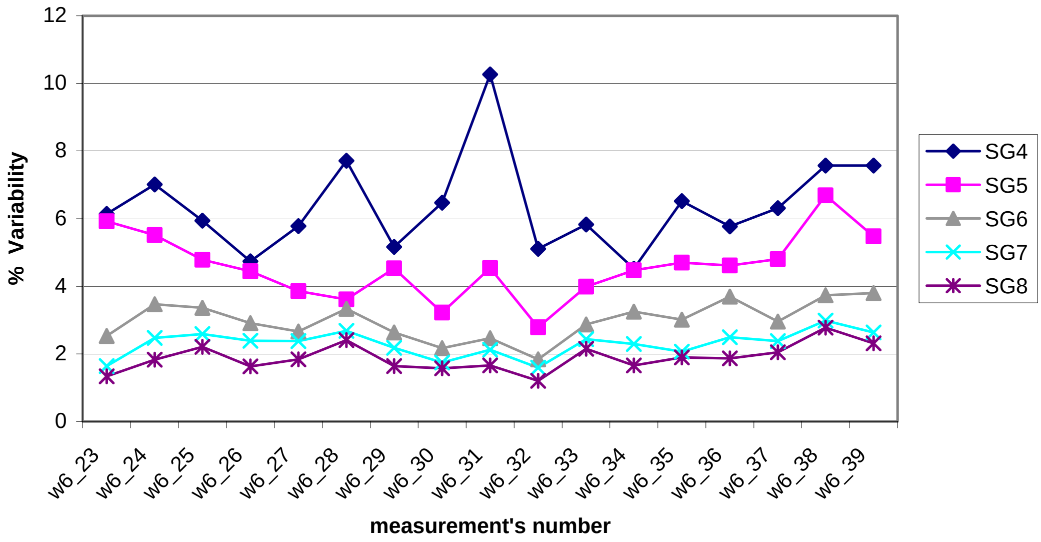

Figure 3 – Variability of principal components in function of failure development

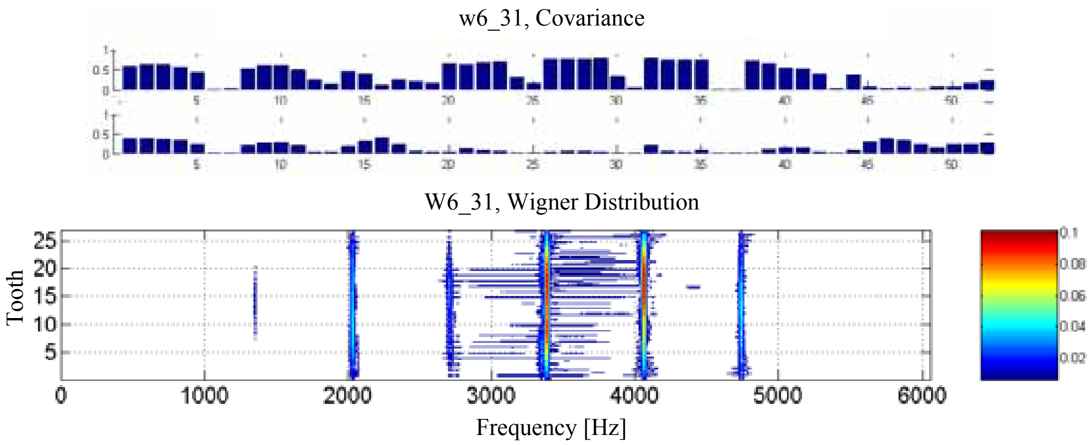

Figure 4 – Time-frequency representation of vibroacoustic signal and frequency structure of 4^{th} and 9^{th} principal components.

The analysis of the frequency structure of the principal components denoted as SG4 and SG9, which are presented in Figure 4, clearly shows that the information on the defect is contained in the bands located between the carrier frequencies. This means that for the purpose of analysis we should use signals that have been subjected to pre-processing aimed at eliminating the carrier components – in this case at least the harmonic frequencies of meshing.

By eliminating from the signal's structure the high-energy amplitudes connected with meshing harmonics and amplitude modulation, and also by eliminating the amplitudes resulting from generation of the signal by a non-defective toothed gear, one can reach the information on the type and magnitude of disturbance of a toothed gear's operation. For example, if for diagnostic research a differential

signal, should be created, we have to remove from the based vibroacoustic signal its meshing frequency, the components of this meshing frequency and the sidebands that are related to amplitude modulation phenomena.
Another example is the use of a residual signal, generated by removing only the meshing harmonic frequency from the vibroacoustic signal [9].

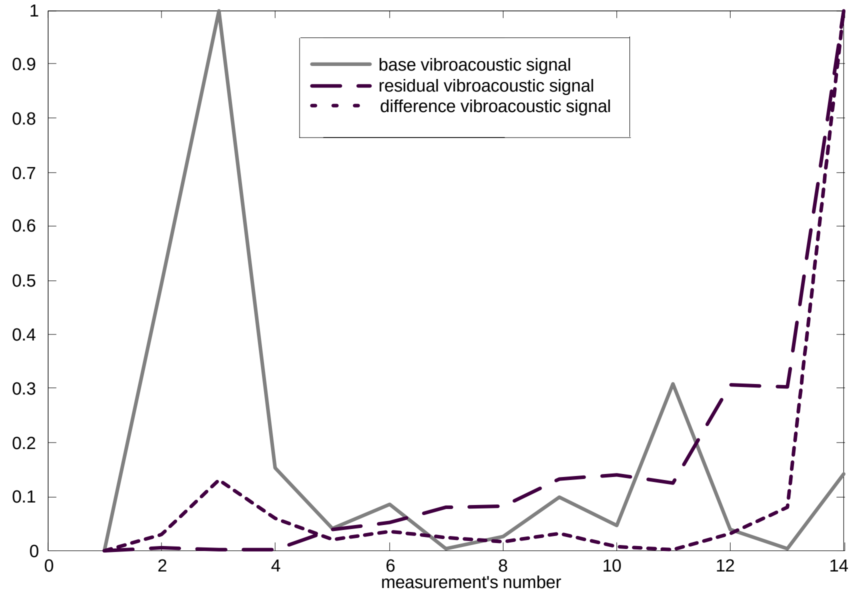

Figure 5 – Change of normalized Kullback's measures during the diagnostic experiment up to crack damage of tooth of gear

An example confirming the presented method of analysis while using PCA are the results obtained by means of Kullback's measure which relies on change of variance In the case of differential signal we obtained positive results enabling detection of the occurrence of fatigue-related damage while the run of Kullback's measure for a residual signal points to the possibility of detection of initiation and propagation phases (Fig. 5).

SUMMARY

The methods described here can be applied in detection of early stages of defect development in those cases in which the development of a defect results in change of the density of the probability function of a signal's parameters. It is particularly the reference to the possibility of using the diagnostic information hidden in the low energy part of the signal that creates the possibility of detecting a defect in the early stage of its development.

The solution proposed in this project can be used in the decision-making process in operating systems of machines and vehicles, where similarly as in cars, machines and helicopters it is the toothed gear that is the critical unit of their power transmission systems which can be designed according to the “damage tolerant” rule. The method of solving the problem described in the paper enables foreseeing the subsequent stages of defect development, thus enabling operational decisions to be made in a manner similar to the procedures applied for use of systems designed according to the “damage tolerant” rules.

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REFERENCES

[1] ZAWISZA M., „Wykorzystanie informacji zawartej w sygnale wibroakustycznym do oceny prawdopodobieństwa wystąpienia awarii w przekładni zębatej”, rozprawa doktorska, Politechnika Warszawska. (Use of Information Found in Vibroacoustic Signal for Evaluation of Probability of Occurrence of a Toothed Gear Failure. A Ph. D. thesis, Warsaw University of Technology - in Polish) (2004).
[2] YANG W., “Towards Dynamic Model-Based Prognostics for Transmission Gears”, SPIE Conference Proceedings, **4733**, 157-167 (2001).
[3] WANG W., Wong A., “Autoregressive Model Based Gear Fault Diagnosis”, Journal of Vibration and Acoustics, **124**, 172-179 (2002).
[4] WANG P., VACHTSEVANOS G., “Fault Prognosis Using Dynamic Wawelet Neural Networks”, in Maintenance and Reliability Conference, MARCON (1999).
[5] JASIŃSKI M., „Empiryczne modele w szczegółowej diagnostyce przekładni zębatej”, Rozprawa doktorska, Politechnika Warszawska (Empirical Models in Detailed Diagnosis of a Toothed Gear. A Ph. D. Thesis, Warsaw University of Technology - in Polish) (2004).
[6] BAR-SHALOM Y., LI X.R., KIRUBARAJAN T., “Estimation with applications to tracking and navigation”, (John Wiley and Sons, INC 2001).
[7] ADAMS D.E., , “Nonlinear Damage Models for Diagnostic and Prognosisin Structural Dynamic Systems”, in SPIE Conference Proceedings, **4733**, 180-191 (2002).
[8] RADKOWSKI S., ZAWISZA M., “Naprężeniowo-drganiowe modele diagnostyczne zmęczeniowowych uszkodzeń kół zębatych” (Stress-and-vibration Diagnostic Models of Fatigue-related Defects of Toothed Wheels), 3rd International Congress of Technical Diagnostics “DIAGNOSTICS’2004”, Poznań 06-09.09.2004. PTDT, „Diagnostyka”, **30(2)**, 85-88 (2004).
[9] DECKER H.J., “Crack Detection for Aerospace Quality spur Gears”, NASA/TM-2002-211492 (2002).