VIBROACOUSTIC MONITORING OF MECHANICAL SYSTEMS FOR PROACTIVE MAINTENANCE

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Summary

A relevantly defined operational strategy has decisive influence from the point of view of the ability to maintain and improve reliability and safety as well as from the point of view of maintaining manufacturing quality. The paper presents the main tasks and the method of implementing pro-active operation. Particular attention is paid to the issues of selection and adaptation of the methods of diagnosing the low-energy phases of defect development as well as use of a posteriori diagnostic information. Attention is paid to the importance of technical risk analysis.

Keywords: proactive maintenance, vibroacoustic diagnostic, low-energy stage of failure, bayesian updating.

MONITORING WIBROAKUSTYCZNY SYSTEMÓW MECHANICZNYCH W PROAKTYWNEJ STRATEGII EKSPLOATACJI

Streszczenie

Odpowiednio określona strategia eksploatacji ma decydujący wpływ na utrzymanie i poprawę niezawodności, bezpieczeństwa oraz utrzymanie jakości produkcji. W pracy przedstawiono główne zadania i sposób realizacji proaktywnej eksploatacji. Szczególną uwagę zwrócono na zagadnienia doboru i adaptacji metod diagnozowania niskoenergetycznych faz rozwoju uszkodzeń oraz wykorzystania aposteriorycznej informacji diagnostycznej. Zwrócono także uwagę na znaczenie prowadzenia analizy ryzyka technicznego.

Słowa kluczowe: proaktywna strategia eksploatacji, diagnostyka wibroakustyczna, niskoenergetyczna faza rozwoju uszkodzenia, bayesowskie uaktualnianie.

1. INTRODUCTION

The fact that the need for implementing the principles of harmonious development is treated as a rule of the development of modern economy creates a whole series of new challenges for more and more fields of science and technology. From the point of view of machine construction and operation this means adoption of design and operation principles which account for Life Cycle Engineering while rejecting the current, reactive principles of design, operation, maintenance and management which are focused on maximization of short-term effect. Now the goal is to maximize the long-term effects. This means adoption of an operational strategy whose integral elements include technical condition diagnosis as well as predictive models of functional tasks' realization and principles of pro-active machine maintenance and operation.

Thus the defined strategy accounts for a whole series of aspects of harmonious development, starting from economic analysis of individual lifecycles, ecological requirements, ergonomic requirements and cultural requirements, with the technical component of the management system being distinguished by its predictability, holistic approach and openness.

The predictive nature of the system means its ability to forecast the technical condition and the quality of realization of functional tasks by the system and by its individual elements.

The criteria of harmonious development and the resulting necessity of holistic approach become the basis for planning the maintenance-and-repair processes. The system's open nature means both the possibility of using selected modules of the system in specific applications as well as the possibility of using selected methods both within the system itself as well as autonomously, for the tasks realized outside the system. This last feature is the outcome of the assumption that that system development and adaptation are intended to fulfill the needs and meet the expectations of its users. This in particular concerns accommodation of the subsystem responsible for data registration preprocessing, development and adaptation of technical condition models, functionality assessment methods as well as the methods of optimization and analysis of maintenance and repair processes. Due to the predictive nature of the system and the inherent burden of uncertainty it is the analysis of probability distribution, while analyzing the condition as well as the development and use of degradation process models, that become particularly important. The scope of changes associated with the proposed approach is illustrated by the definition of a technical object's maintenance process which says that it is a combination of all technical and associated administrative actions taken during an object's lifetime in order to maintain that object or its element in a condition enabling performance of the expected functional tasks. The predictive nature of the proposed strategy defines in each case the scope and the nature of the activities. In practice various scopes of analysis are applied, depending on the method of defining the control, accounting for or not accounting for the consequences of failures or accidents [1].

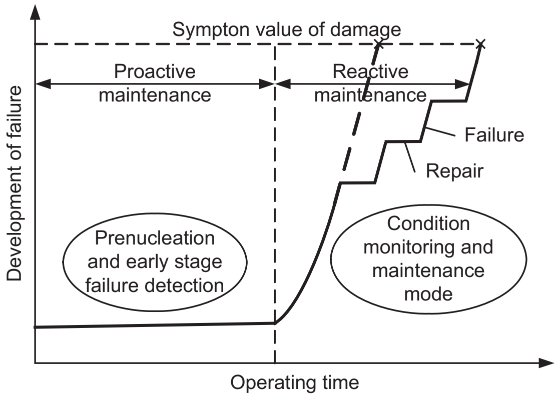

Fig. 1. Comparison of technical diagnostics goals in proactive maintenance versus reactive maintenance

From this point of view it is the implementation of proactive operational strategy that becomes particularly important. As is presented by Fig. 1, the essence of such an approach boils down to anticipation of preventive actions, in equal degree prior to defect emergence as well as during the period of development of low-energy phases of defects. This calls for developing and adapting relevant methods of diagnosis which are supported by relevant diagnostic models.

2. CHARAKTERISTICS OF A PROACTIVE OPERATIONAL STRATEGY

Let us note that the essence of thus defined a strategy is the extensive use of monitoring, diagnosis, forecasting and decision-making models for creating the possibilities of taking maintenance-and-repair actions while anticipating problems [2]. This denotes the need for developing and applying advanced monitoring, presentation of information on emergency states and values, selection of methods and means enabling monitoring and on-line inference in a way enabling early detection of growing disturbances and extracting from general signals the information on anomalies in operation which are characteristic of defects; controlling the defects and taking corrective actions by the operator in order to minimize and in particular to avoid undesirable developments leading to serious consequences; development of a forecast of future events based on current observations and registered permanent changes of parameters which have been detected by analyzing the results and the measurements collected in the database. The last item is particularly important when monitoring the condition of mechanical elements and units as well as the remaining components which are subject to degradation and wear and tear for which the detection of early phases of defect development may help prevent the occurrence of the catastrophic phase of defect development, including destruction of the whole system.

Thus reduction of the uncertainty of reliability estimations becomes a critical issue in the process of making the decisions which are intended to ensure technical safety of the system and minimize the costs.

One of the essential methods of reducing the epistemological uncertainty is to develop models and diagnose the degradation and wear and tear processes, thus reducing the variance of evaluations of the residual period until the occurrence of a catastrophic defect.

Realization of this goal calls for assessment of structural reliability of the system while accounting for detection and analysis of degradation processes affecting all the components during the previous and current period of use. This requires development of a relevant database containing information on potential defects of the system's components, knowledge gathered based on the experience acquired by relevantly trained personnel as well as procedures which account for the feedback and adaptation changes occurring in the system.

In the process of estimating the probability of of defect occurrence, the above enables us to account for the influence of operational conditions on the possibility of defect occurrence, the influence of earlier defects, quality, scope and intervals between inspections, the probability of defect occurrence in specific time in the future. The consequences are estimated in a similar manner, especially the magnitude of loss and the probability of worst case scenario occuring. Thus developed risk matrix serves as the basis for defining risk category, priority and scope of inspections, ways of changing the architecture of the monitoring system.

Idea of proactive maintenence system algorithm, was presented in literature [1, 2, 3] (Fig. 2).

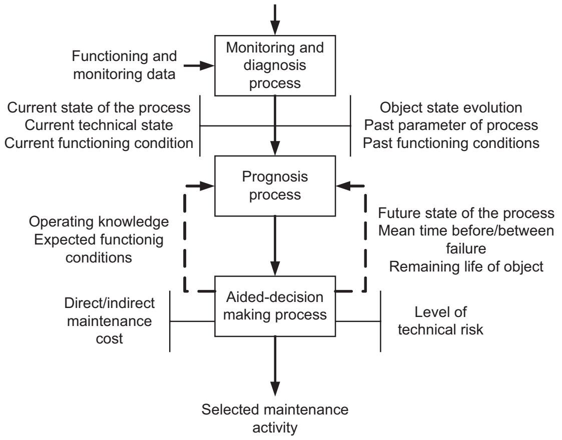

Fig. 2. Architecture of the proactive maintenance system

Let us note that estimation and modelling of the degradation process is one of the most effective methods of defect development anticipation and maintenance of system operation in terms of nominal parameters. In reality such an approach denotes compilation of several conventional methods of forecasting – probabilistic behavioral models and event models in particular. Probabilistic behavior and degradation models enable analysis of the type and extent of uncertainty which conditions forecasting reliability. Event models are a kind of a combination between the contemplated models and the actual system and they make up the basis for constructing and analyzing causal models which enable assessment of degradation and determination of the optimum scenario of maintenance-and-repair work.

Let us note that subsequent stages of the forecastng procedure make references to various models and types of knowledge. The a priori knowledge gathered from experiments serves as the basis for developing stochastic models of degradation processes while technical diagnosis and process monitoring are used for developing the indicators of an object's technical condition.

Interaction between the elements of the monitored object is described and forecasted with the use of cause-and-effect relations based on laws of physics in the form of model-aided forecast. In accordance with the definition [3], behavioral models contain both the description of functioning as well as the dynamics of a system. In the first case the system is analyzed as a set of many processes analyzed from the point of view of flow of materials, energy and information. The purpose of the system dynamics model is to offer description of conditions in which failures occur – in this case the modeling process points to two phases – in the first one the cause-and-effect relations are defined between the degradation process, the cause and the consequences. This is often done with the use of the EMECA method [4].

The estimation of probability of defect occurrence accounts for the influence of operating conditions on the possibility of defect occurrence, the influence of earlier defects, the quality and the scope of operational inspections, the probability of defect occurrence in specified time in the future. The consequences are estimated in a similar way, especially the gravity of loss and the probability of the worst-case scenario occurring. Thus, the developed risk matrix serves as the basis for determining the risk category, the priority and scope of the inspection as well as the method and directions of changes in the operation maintenance procedures. An exemplary division into categories is presented in [5] (Fig. 3).

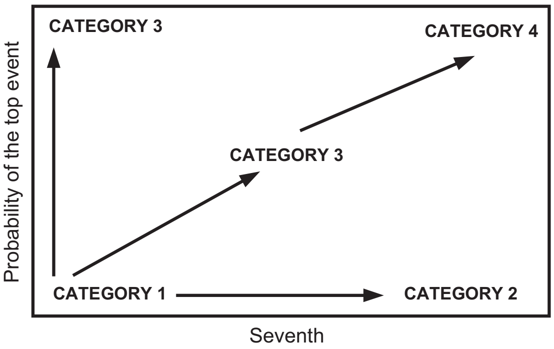

Fig. 3. Risk categories

The following scope of activities is assigned to each category respectively:

- category 1 – (acceptable),
- category 2 – (acceptable, inspection required),
- category 3 – (undesirable),
- category 4 – (not acceptable).

The influence of various degradation processes, including wear, cracking and corrosion, is modeled in the second phase.

In the to-date contemplated models the probability of defect occurrence was being defined on the assumption of invariability of examined distributions during operation of the object. In reality, as a result of wear and tear processes and associated changes of conditions of mating elements and kinematic pairs, we observed conditional probability distributions, however the relationship demonstrated itself both in quantitative terms (change of the parameters of probability density function) and in qualitative terms (change of the function describing the distribution). In addition the degradation processes accompanying the performance of functional tasks can cause similar variability of distributions of the probability which describes load capacity. In this case one can expect that the location of the separating line and the probability of defect occurrence will not only depend on the time of operation of an object but on the new dynamic feedbacks in the system, associated in particular with the development of non-linear relations and non-stationary disturbance.

3. VIBROACOUSTIC SIGNAL AS THE SOURCE OF DIAGNOSTIC INFORMATION

The central issue is how to extract the relevant diagnostic information and use it in the forecasting process. Thus the research focuses in particular on the methods of analyzing the relations between various frequency bands and their links to various types of defects or phase of their development. The value of the information contained in the bi-spectrum consists of, among others, the fact that it enables examination of statistical relations between individual components of the spectrum as well as to detect the components generated as a result of occurrence of non-linear effects and the additional feedback associated with the emerging defects. This results from the fact that in contrast with the power spectrum, which is positive and real, the bi-spectrum function is a complex value which retains the information on both the distribution of power among individual components of the spectrum as well as the changes of phase. Let us note that the bi-spectrum enables one to determine the relations between essential frequencies of the examined dynamic system. High value of bi-spectrum for defined pairs of frequency and combinations of their sums or differences will point to the existence of frequency coupling between them. This may mean that the contemplated frequencies, being the components of the sums, have a common generator, which in the presence of non-linearity of higher order may lead to synthesizing the aforementioned new frequency components.

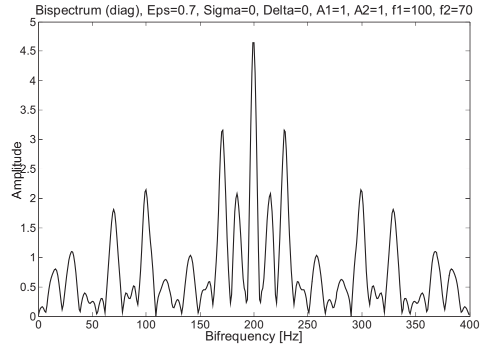

Fig. 3. Illustration of diagonal bi-spectrum in the case of square non-linearity

An example of using the diagonal bi-spectral measure for the qualitative and quantitative determination of the effect of non-linearity evolution is presented in Fig. 3÷5.

The confirmation of the importance of the changes of phase coupling is offered by the analysis of the process of diagnostic information generation during the low-energy phases of development [6].

While attempting to develop a model oriented on such defects one should on the one hand consider the issue of examining the signal's parameters from the point of view of their sensitivity of to low-energy changes of the signal and, on the other, the issue of quantification of energetic disturbances occurring in the case of defect initiation.

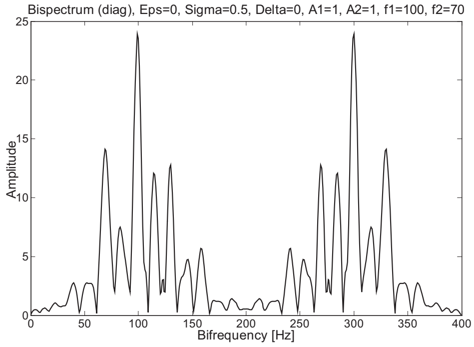

Fig. 4. Illustration of diagonal bi-spectrum in the case of the third order non-linearity

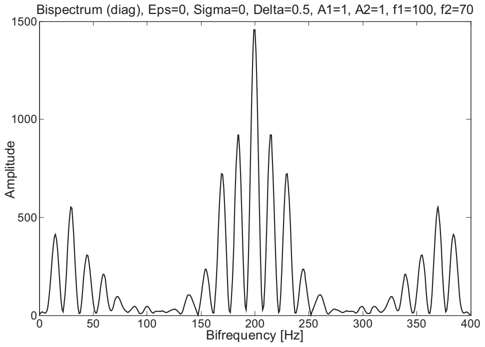

Fig. 5. Illustration of diagonal bi-spectrum in the case of the fourth order non-linearity

Let us assume that the degree of damage D is the dissipated variable that covers the changes of the structure's condition due wear and tear:

$$\mathrm{d}E_d(\Theta, D_0) = \\ = \frac{\partial E_d(\Theta, D_0)}{\partial D}\mathrm{d}D + \frac{\partial E_d(\Theta, D_0)}{\partial \Theta}\mathrm{d}\Theta \tag{1}$$

where:

$$\mathrm{d}E_d = \frac{df(D, \Theta, \gamma(\Theta))}{d\Theta}$$

$\gamma(\Theta)$ - the parameter describing how big a part of the dissipated energy $\mathrm{d}E_d$ is responsible for structural changes,

Θ - operating time.

Bearing in mind the possibility of diagnosis of the origin and the development of low-energy phases of defect formation, when the extent of the original defect can be different in each case, let us analyze this issue more precisely.

To examine this problem let us recall here the two-parameter isothermal energy dissipation model proposed by Najar [7] where:

$$\mathrm{d}E_{d_s} = \mathrm{d}E_d - \mathrm{d}E_{dq} = T\mathrm{d}s = \sigma_\Theta \mathrm{d}D \tag{2}$$

where:

$\mathrm{d}E_{d_q}$ - energy transformed into heat,
$\mathrm{d}E_{d_s}$ - energy responsible for internal structural changes,
T - temperature,
ds - growth of entropy.

The expression (2) shows that the growth of the dissipated variable D is attributable to the $\mathrm{d}E_{d_s}$ part of energy, which is the dissipated part of $\mathrm{d}E_d$ energy, that causes the growth of entropy ds.

The role of the multiplier determining the relation between the increments of dissipated variable and the entropy is played by the dissipation stress σ_Θ.

The assumption of $T = \text{constans}$ results in independence of dissipation-related loss $\mathrm{d}E_{d_s} = \mathrm{d}E_{\Theta_s}$, thus following integration the expression (2) takes the following form:

$$E_{d_s} = T\Delta s \tag{3}$$

The derivative of defect development energy related to D, when $E_f(D_0) \le \frac{1}{2}E\varepsilon^2$, means the boundary value of deformation energy and takes the following form:

$$\frac{\mathrm{d}E_{d_s}}{\mathrm{d}D} = \frac{E_f(D_0)(1-D_f)(1-k)D^{-k}}{D_f^{1-k} - D_0^{1-k}} \tag{4}$$

For a defined initial defect of D_0 and for a defect leading to damage D_f, relationship (5) will have the following form:

$$\frac{\mathrm{d}E_{d_s}(D)}{\mathrm{d}D} = (1-k)E_{D0,f}(k)D^{-k} \tag{5}$$

Let us note that parameter $E_{D0,f}$ is an exponential function of power k, similarly as the whole derivative. While referring to the second rule of thermodynamics for irreversible processes we will assume the following in the contemplated model:

$$\frac{\mathrm{d}E_{d_s}(D)}{\mathrm{d}D} \ge 0 \tag{6}$$

Thus for the assumed model to be able to fulfill condition (6), the exponent must meet the requirement of $k \le 1$. In addition, while referring to the rule of minimization of dissipated energy, the conditions of permissible wear process show that the change of exponent k is possible as the defect develops.

To examine this problem let us assume that the exponent shows a straight line dependence on the extent of damage:

$$k(D) = a + bD \tag{7}$$

For damage of small magnitude the linear approximation seems to be sufficient and enables description of defects whose emergence is characterized by small growth of defect energy (see Figure 6).

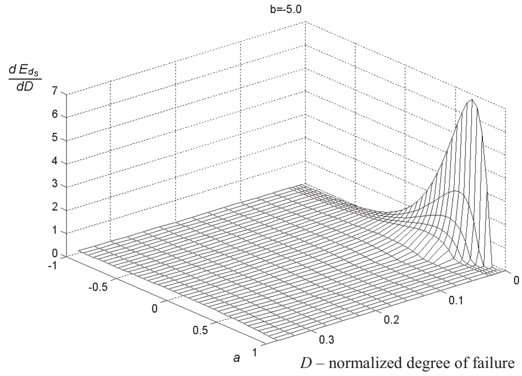

Fig. 6. Change of energy of defect development for small D

Thus while defining the set of diagnostic parameters we should pay attention to the need for selecting such a criterion so that it will be possible to identify defects whose emergence is characterized by small growth of defect-related energy.

While contemplating this issue let us assume that vibroacoustic signal is real and meets the cause-and-effect requirement, which means that it can be the base for creating an analytical signal.

In accordance with the theory of analytical functions, the real and the imaginary components are the functions of two variables and meet Cauchy-Riemann requirements.

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Please be reminded that the analysis of the run of the analytical signal will be conducted while relying on the observation of changes of the length of vector A and phase angle φ:

$$z(x,y) + jv(x,y) = A(\cos\varphi + j\sin\varphi) \tag{8}$$

Thus,

$$\begin{aligned} z\big(x(\tau), y(\tau)\big) &= A(\tau)\cos\varphi(\tau) \\ v\big((x(\tau), y(\tau)\big) &= A(\tau)\sin\varphi(\tau) \end{aligned} \tag{9}$$

means that the signal measured is the orthogonal projection of vector A on real axis.

Ultimately, while exploiting the Cauchy-Riemann conditions for variables $A(\tau)$ and $\varphi(\tau)$ we will obtain:

$$\frac{\mathrm{d}z}{\mathrm{d}\tau} = \frac{\mathrm{d}A}{\mathrm{d}\tau}\cos\varphi - A\sin\varphi\frac{\mathrm{d}\varphi}{\mathrm{d}\tau} \qquad (10)$$

As we expected the obtained relationship presents an equation that enables the analysis of the measured signal while observing A and φ. At the same time it should be noted that for low-energy processes, when we can neglect the changes of the vector's length and assume $A \cong \mathrm{const}$, the whole information on the changes of the measured signal is contained in the phase angle, or more precisely in the run of momentary angular velocity.

While accounting for the obtained results of the analysis of the process of low-energy defect emergence and detection of diagnostic information associated with the changes of momentary values of amplitude and angular velocity, let us analyze the conditions that must be fulfilled by a diagnostic model intended to enable observation of the influence of such disturbance on the form of the system's dynamic response.

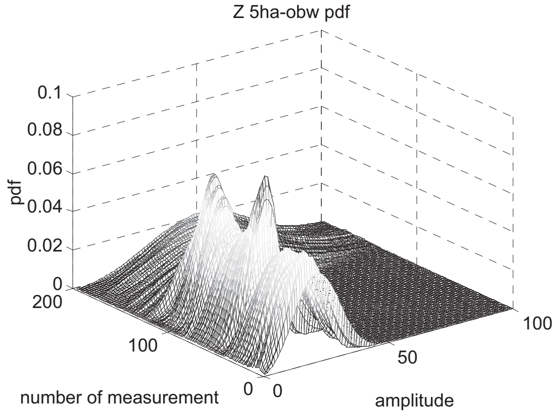

Fig. 7. Function of density probability distribution oh the envelope of 5th harmonics meshing frequency

This illustrates the problem of effective use of results of diagnostic observations in the task of diagnosis of early stages of defect development.

While referring to [8] we quoted the example of evolution of probability density distribution function for the value of vibroacoustic signal envelope, precisely the fifth harmonic frequency of meshing as calculated for the width of the frequency band corresponding to twice the frequency of the input shaft (Fig. 7). Fig. 8 and Fig. 9 accordingly present the values of shape and scale parameters corresponding to these changes. Let us note that both parameters depend on defect development while their values, the value of shape factor in particular, does not change monotonously.

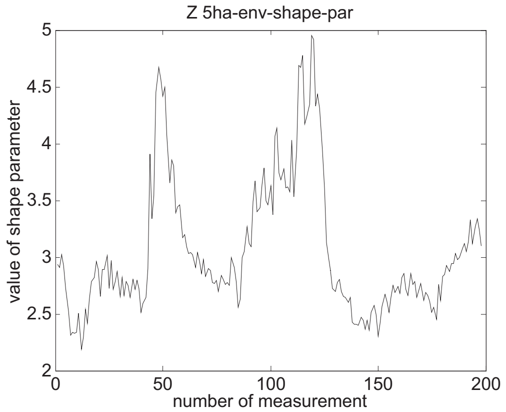

Fig. 8. Parametr of shape in function of mesurement number

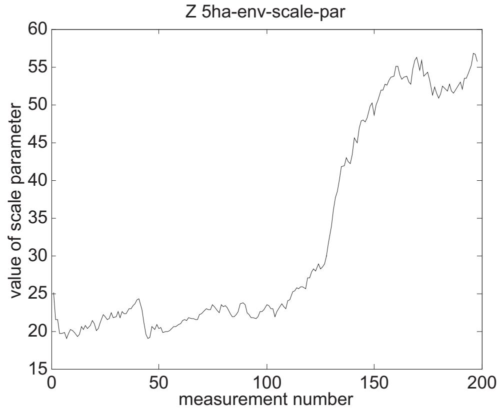

Fig. 9. Parametr of scale in function of mesurement number

In order to achieve higher efficiency in application of the results of vibroacoustic diagnosis, we should take into account, in a much bigger degree, the individual vibroacoustic characteristics which as defined during preliminary measurements and analysis.

Such an approach fully meets the requirements of Bayes methodology [9], including:

- the possibility of adopting randomness of the examined parameter in a probabilistic model;
- the possibility of obtaining the a posteriori estimate of the parameter based on the observation and measurement of a vibroacoustic signal as well as the a priori distribution in accordance with the requirements of Bayes' theorem;
- selection of the optimum estimator of a parameter in the sense of Bayes decision-making theory.

Assuming that detection, identification and location of changes of vibroacoustic properties of the monitored object is the outcome of vibroacoustic monitoring, the a priori distribution of probability of parameters can be determined on the basis of pre-defined vibroacoustic characteristics.

A good illustration of the discussed method of using the Bayes formula for evaluation of changes of distribution parameters based on the diagnostic information is offered by Cruse's paper [10] in which Bayes theorem is used for determining the value of parameters describing the growth of fatigue-related defect while accounting for the observation of crack development.

The essence of this approach involves updating of estimated parameters of the probabilistic model so as to achieve bigger alignment between the results of modeling and observations.

In accordance with the above presented assumptions it is assumed that unknown or uncertain parameters of distribution are random variables. Uncertainty of estimation of results can be linked to variability of random variables by means of Bayes theorem [11].

Then, while assuming that we will be estimating the parameters of a priori distribution of parameter *a* of the function of probability density *f*(*a*) and that *D* is an observation set enabling reduction of a priori uncertainty on the condition of the results of the observation being included, we should be able to conduct the estimation of a posteriori distribution parameters by means of the following formula:

$$f(a/D)=\frac{f(D/a)f(a)}{f(D)} \qquad (11)$$

Where:

$$f(D)=\int_{-\infty}^{\infty} f(D/a)f(a)da$$

In addition we can assume that the denominator, which is described by the integral of the a posteriori probability density function, is constant and that *f*(*D*/*a*) is the probability of observation which can be expressed by the credibility function. In such a case equation (11) can have the following form:

$$f(a/D)=K_B\cdot L[D/a]\cdot f(a) \qquad (12)$$

where:

K_B – standardizing constant

$L[D/a]$ – credibility function

To be able to determine the probability of a defect in the analyzed timeframe, the information contained in the observations should account for both, occurrence of a defect and non-occurrence of a defect. For the exponential form of the function describing the distribution, the credibility function will be noted in the following form:

$$L[D/a]=\prod_{i=1}^{n} p(\theta_f/a)\times\prod_{j=1}^{m}\left[1-P(\theta_f/a)\right] \qquad (13)$$

where:

n – denotes the set of detected defects

m – denotes the set of events defining non-existence of a defect.

Let us note that Bayes formula can be simplified by accounting for proportionality of a posteriori and a priori distributions only :

$$f(a/D)=\frac{f(D/a)f(a)}{f(D)}\propto f(D/a)f(a) \qquad (14)$$

In a similar way the probability density is proportional to the square root of Fisher's information matrix factor [12]:

$$f(a)\propto(\det \mathrm{I}(a))^{1/2} \qquad (15)$$

where:

$\mathrm{I}(a)=-E\left[\frac{\partial^2 \ln f(D/a)}{\partial a^2}\right]$ – is calculated as the matrix of average second derivatives from the credibility function logarithm based on the results of the experiment.

Thus formula (11) is finally written in the following way:

$$f(a/D)\propto L(D/a)(\det \mathrm{I}(a))^{1/2} \qquad (16)$$

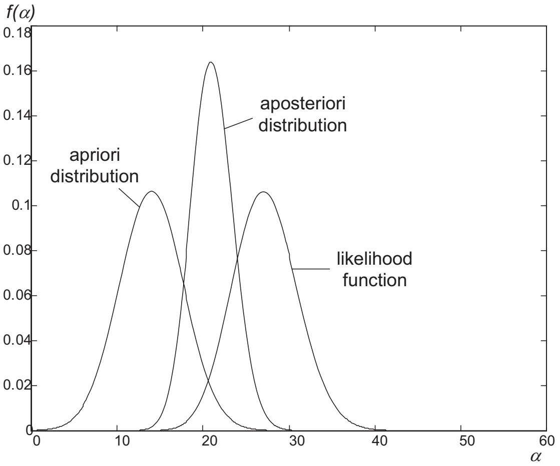

Fig. 10. An example of using diagnostic information in bayesian updating

Thus the presented method of using the risk analysis method, supported by vibroacoustic diagnosis, in the process of making operational decisions refers on the one hand to the definition of risk and the associated estimation of probability of occurrence of undesirable incident as well as to estimation of the extent and value of loss accompanying such an incident. On the other hand it refers to the possibility of using the results of a diagnostic experiment in the task of reducing the uncertainty related to estimation of parameters of a posteriori distribution of intensity of defects. Use of Bayesian models enables direct application of the results of diagnostic observation in Bayesian estimation of a posteriori distribution as well as tackling the problem of selecting the a priori distribution. The results of such an analysis are presented in Fig. 10. As has been demonstrated in this example, such use of diagnostic information enables one to solve the problem of determining the conditional probability distribution for the parameters of defect intensity while relying on the results of the diagnostic experiment.

4. CONCLUSIONS

While summing up the methodology of a proactive system of operations based on risk evaluation, attention should be drawn to the necessity of tackling the following issues:

- Identification of elements of the system as well as factors and persons responsible for controlling the system and its functioning;
- Defining a wide area system for control and analysis of the system's functioning;
- Development of the behavioral model of the system accounting for the physical mechanisms of degradation processes affecting the system's elements and their mutual interactions,
- Modeling of events, incidents and defects in the system in a way enabling inclusion of the results in the decision-making processes,
- Development of a forecasting model enabling integration of the models of events with the behavioral model of the system,
- Developing a man-machine communication program focused on psycho-physical capabilities of the operator.

The methodology of designing and implementation of a proactive operational strategy, developed according to such assumptions, relies on a combination of probabilistic models of development of degradation processes and dynamic monitoring architecture accounting for changes in the models of events as supplemented by developed man-machine communication systems.

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