Method of reduction of diagnostic parameters during observation on the example of a combustion engine

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Abstract. The article presents a method of selecting diagnostic parameters which map the process of damaging the object. This method consists in calculating, during the observation, the correlation coefficient between the intensity of damage and the individual diagnostic parameters; and discarding of those parameters whose correlation coefficient values are outside of the narrowest confidence interval of the correlation coefficient. The characteristic feature of this method is that the parameters are reduced during the diagnostic experiment. The essence of the proposed method is illustrated by the vibration diagnosis of an internal combustion engine.

1 Introduction

In vibroacoustic diagnostics, it is important to select the parameters of the vibration signal or noise that contain information about the characteristics of the examined object. While conducting diagnostic tests, many researchers measure arbitrarily selected or measurable diagnostic parameters [1-3]. After the studies are completed, scientists reduce the parameters which map selected or simulated object states. However, most of researchers measure only specific parameters of the vibroacoustic signal – usually speed and acceleration – and then they search for the relationships between them and the changed states of the object.

Methods for reducing the vector of diagnostic signal parameters are presented in works: [4-6]. In papers [4, 5], the author proposed selection of diagnostic parameters based on the passive diagnostic experiment performed in compliance with the algorithm of the BEDIND program (the name stands for "Bierny Eksperyment Detekcji Informacji Diagnostycznej" in Polish, which means "Passive Experiment of Detection of Diagnostic Information"). The program worked in two versions: non-standardized and standardized. In the non-standardized version, the covariance matrix is the basis for the selection of diagnostic parameters, so that the program selects the parameters that carry the maximum information about the state of the object. They are characterized by, among other things, a high dynamics of changes. In the standardized version, the basis for the selection is the correlation matrix, which enables the selection of parameters that are independent of each other and can carry information about two different damages. In the paper [7] the author proposed the choice of diagnostic parameters based on the correlation matrix (similarly to the BEDIND program) by selecting independent parameters.

The mentioned methods of reducing diagnostic parameters have one common feature: they select parameters without correlating their changes with the state of the object and they are realized after the experiment. The method of reducing diagnostic parameters proposed by the author of this work consists in choosing the parameters that measure the reliability of the object. What is important, this method enables reduction of the parameters during the diagnostic experiment. This approach enables the reduction of the parameters during the experiment on an ongoing basis. After the reduction is done, researcher obtains parameters that map the process of damaging the object, while the cost of the experiment is minimized. This method requires performing the passive diagnostic experiment and parallel registration of the damage done to the object.

2 Diagnostic experiments

The planning of every experiment is connected with the use of well-known experiment planning techniques [8-10]. However, these techniques are limited in case of planning of diagnostic experiments, which are often conditioned by the possibilities of their realization. Therefore, in diagnostic tests, aimed at defining the relationship state → signal, with the assumption of a cause-and-effect action of the diagnosed object, there are three types of diagnostic experiments distinguished [6, 7, 11, 12]:

- active,
- passive,
- active-passive.

Active experiment – consists in the observation of the signal after deliberately changing the value of state parameters. This type of experiment can, to a limited

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extent, benefit from the latest techniques of experiment planning and techniques of developing results [8].

Passive experiment – involves observing signal parameters without knowing the state parameters. It gives the possibility of control and interference. In this type of experiment two variants are distinguished. The first is to observe the diagnostic signals of the object from the beginning of its exploitation to its end or until the object is damaged. The second variant consists in simultaneous observation of signals of a particular group of objects in different states of exploitation.

Active-passive experiments – consist in observing signal parameters with simultaneous measurement of state parameters for one or two object state values or exploitation time without interfering in state parameter values. In most cases, exploited objects (before repair) are used as a single value of the state of the object. The two state values are: first value – the state of new objects (before use), and second value – for exploited objects (before repair).

The types of experiments presented here are partial experiments. The active experiment is related to simulated states, as the author presented in work [2]. However, in many cases the results of disassembly of the object are not connected with the exploitation. On the other hand, in the passive diagnostic experiment, the obtained results of measurement of diagnostic parameters are not related to the states of the object. Active-passive experiment refers only to two states of objects: usable and exploited, without information about intermediate states.

In order to identify the causes of changes in diagnostic parameters in a passive diagnostic experiment and to investigate the process of damaging in diagnostic parameters, a new type of experiment was proposed, called passive-reliability experiment.

This experiment consists of periodic measurements of selected diagnostic (vibroacoustic) signal parameters with parallel recording of all exploitation events in form of faults in the intervals between subsequent diagnostic observations [13]. The essence of this experiment is shown in Figure 1.

Fig. 1. Scheme of the passive-reliability experiment.

Periodic observations of the diagnostic parameters of the object result in obtaining the curves of the technical state of the object (life cycle curves), which are formed on the basis of the individual signal parameters.

Recorded damage information make it possible to describe the state of the object (reliability status, damage process) using reliability indicators. With diagnostic data in the form of the object's technical condition curve and with data of damages from the intervals between subsequent diagnostic observations, it is possible to select the parameters of the diagnostic signal that represent the reliability state or the object's damaging process.

3 Reliability characteristics for renewable objects

The obtained information about exploitation events (damages) of a diagnosed object can be used to determine the basic reliability characteristics describing the nature and intensity of the damaging process. Since mechanical objects are renewable, the assessment of their reliability may involve using reliability functions and indicators typical for renewable objects. In addition, the functions and indicators of reliability until the first damage can be used to assess the reliability of renewable objects in the initial period of their exploitation, i.e. until the first damage occurs [14, 15].

For the purposes of the sample, the research considers the following basic characteristics of the reliability of renewable objects [14]:

- renewal function

$$H(\Theta) = \frac{\sum_{i=1}^r n'_i(\Theta)}{r} \quad (1)$$

$n'_i(\Theta)$ – number of renewals in i -th sample until time Θ ,
 r – number of trials, covered by study, after n objects,

- availability ratio

$$k_g(\Theta) = \frac{n - n(\Theta)}{n} = 1 - \frac{n(\Theta)}{n} \quad (2)$$

$n(\Theta)$ – number of damaged objects in moment Θ ,

n – sample size, number of usable objects

Θ – operating time (exploitation measure of aging),

- cumulative distribution function

$$F_k(\Theta) = \frac{m_k(\Theta)}{n} \quad (3)$$

$m_k(\Theta)$ – number of damaged objects in the n -element sample in period $[0, t]$, counting since the completion of $(k - 1)$ repair of each of n objects,

- probability density function

$$f_k(\Theta) = \frac{m_k(\Theta, \Theta + \Delta t)}{n \cdot \Delta \Theta} \quad (4)$$

$m_k(\Theta, \Theta + \Delta \Theta)$ – number of damaged objects in the n -element sample in period $[\Theta, \Theta + \Delta \Theta]$, counting since the completion of $(k - 1)$ repair of each of n objects,

- damage parameter

$$\omega(\Theta) = \frac{m(\Theta, \Theta + \Delta\Theta)}{n \cdot \Delta\Theta} \quad (5)$$

$m(\Theta, \Theta + \Delta\Theta)$ – number of objects damaged in the time interval $(\Theta, \Theta + \Delta\Theta)$,

- average time of object usability between damages

$$\Theta_k = \frac{1}{n} \sum_{i=1}^n \Theta_{k_i} \quad (6)$$

Θ_{k_i} realizations of usability time between $(k - 1)$ and k -th damage.

Estimation of the presented reliability features and indicators for renewable objects is possible only after the completion of tests on a particular sample of objects. The specified reliability functions and indicators (especially the damage parameter) can be used to study the relationships between them and the diagnostic signal parameters. Finding the relationship between the reliability status of an object (described by selected reliability indicators) and selected vibroacoustic signal parameters may be the basis for the selection (reduction) of signal parameters correlated to the object's damaging process.

4 Reliability characteristics for a single object

For selection of diagnostic parameters it is important to determine the reliability indicators for a single object rather than a specific sample. Apart from that, the importance lies in the ability to estimate reliability indicators in the subsequent steps of diagnostic measurements. Determination of reliability indicators for a single object after each diagnostic measure will help to reduce the diagnostic signal parameters during the diagnostic experiment, so that only those are left, which are correlated with the process of the object damage.

To evaluate the reliability of a single object at the end of the study and to present a rating after each diagnostic measure, reliability indicators have been proposed, basing on the damage parameter. For evaluation of objects after the observation, these indicators are:

- relative intensity of damages IU_w

$$IU_w(\Theta) = \frac{n_i(\Theta + \Delta\Theta)}{N \cdot \Delta\Theta_i} \quad (7)$$

$n_i(\Theta + \Delta\Theta)$ – number of damages in $\Theta + \Delta\Theta$,

N – total number of recorded damages,

$\Delta\Theta_i$ – interval length (interval between subsequent observations),

- cumulative relative intensity of damages SIU_w

$$SIU_w(\Theta) = \sum_{i=1}^n \frac{n_i(\Theta + \Delta\Theta)}{N \cdot \Delta\Theta_i} \quad (8)$$

For evaluation of a single object after each diagnostic observation (during the experiment), the proposed indicators are:

- current relative intensity of damages BIU_w

$$BIU_w(\Theta) = \frac{n_i(\Theta + \Delta\Theta)}{N_i(\Theta) \cdot \Delta\Theta_i} \quad (9)$$

$n_i(\Theta + \Delta\Theta)$ and $\Delta\Theta_i$ – as in dependency (7),

$N_i(t)$ – the total number of damages to the i -th interval (measurement),

- cumulative current relative intensity of damages $SBIU_w$

$$SBIU_w(\Theta) = \sum_{i=1}^n \frac{n_i(\Theta + \Delta\Theta)}{N_i(\Theta) \cdot \Delta\Theta_i} \quad (10)$$

$n_i(\Theta + \Delta\Theta)$ and $N_i(\Theta) \cdot \Delta\Theta_i$ – as in dependency (7).

Current intensities of damages are calculated beginning from the fourth interval (fourth diagnostic observation). Relative intensity of damages $IU_w(\Theta)$ characterizes in every moment of t (mileage) relative deterioration of the reliability of the object referred to the unit of mileage $\Delta\Theta = 1$.

The cumulative relative intensity of damages $SIU_w(\Theta)$ can be defined as a measure of the depletion of object's capabilities to perform a task.

5 Selection of diagnostic parameters mapping the damaging process

The method of reduction of parameters during the diagnostic experiment consists in determining the correlation coefficient between the values of the diagnostic parameters obtained from subsequent observations and the values of the damage intensity functions. It is done according to the following relation [16]:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (11)$$

x_i – subsequent values of the given signal parameter,

$\bar{x}$ – average value of all realizations of a given parameter,

y_i – subsequent values of a given reliability function,

$\bar{y}$ – average value of all realizations of a given reliability function.

For the determined correlation coefficient a confidence interval is estimated using the Fisher transform [16]:

$$Z = 0.5 \ln \frac{1+r}{1-r} \quad (12)$$

and reverse transformation, which results in:

$$r = \frac{e^{2z} - 1}{e^{2z} + 1} \quad (13)$$

If r is the empirical correlation coefficient of a random sample from a population of two-dimensional normal distribution, then the random variable:

$$Z = 0.5 \ln \frac{1+r}{1-r} \quad (14)$$

has a Fischer distribution, whose asymptotic distribution is the normal distribution:

$$N\left(z(\rho) \frac{1}{\sqrt{n-3}}\right) \quad (15)$$

Using the Laplace transform function table, the $z(\rho)$ parameter can be evaluated:

$$z_d(\rho) = z - \lambda_\alpha \frac{1}{\sqrt{n-3}} \quad (16)$$

$$z_g(\rho) = z + \lambda_{1-\alpha} \frac{1}{\sqrt{n-3}} \quad (17)$$

Thus, the lower bound of the confidence interval for the correlation coefficient will be:

$$R_d = \frac{e^{2z_d(\rho)} - 1}{e^{2z_d(\rho)} + 1} \quad (18)$$

and the upper bound of the confidence interval will be:

$$R_g = \frac{e^{2z_g(\rho)} - 1}{e^{2z_g(\rho)} + 1} \quad (19)$$

Having a defined correlation coefficient and its upper and lower confidence intervals, a researcher may proceed to select the signal parameters correlated to the engine's damaging process. This choice is based on rejection of these parameters, for which the correlation coefficient determined in the subsequent steps of observation goes beyond the boundaries of the calculated confidence interval. As further measurements are taken, the boundaries of the confidence interval become narrowed, thus making a more accurate representation of the damage process in those parameters that fall within the designated confidence interval.

6 Selection of diagnostic parameters on the example of an internal combustion engine

The basis for selection of diagnostic parameters correlated with the process of damaging the engine are: waveforms of diagnostic parameters (technical status curves) obtained from the diagnostic measurements of an engine [17] and relative and current intensities of engine damages, determined on the basis of the collected data about the damages [18]. The collected data on engine damage was

grouped into sections, where the end of each section was mileage, during which diagnostic measurements were made. Basing on such grouped information about damages, researchers proposed reliability indicators for the evaluation of a single engine, dependencies 7-10. Figures 2 show examples of standardized diagnostic parameters waveforms in relation to the first observation in a function of vehicle mileage.

Fig. 2. Waveforms of standardized diagnostic parameters of basic vibration magnitudes in the function of the vehicle mileage.

Figures 4 and 5 illustrate the waveforms of cumulative intensity damage values determined in dependencies (8) and (10). The waveforms of cumulative relative intensity of damages SIU_w and cumulative current intensity of damages $SBIU_w$ illustrate process of damaging the engine in the function of vehicle's mileage. The characteristic feature of the presented intensities is that they show high engine damageability in the initial period of its operation. This period can be counted as the engine's break-in period.

Fig. 3. Waveforms of standardized diagnostic parameters of coefficients of vibration magnitudes in the function of vehicle mileage.

Fig. 4. Changes of the cumulative relative intensity of damages SIU_w of the engine in the function of vehicle mileage.

The cumulative intensity of damages is most useful for selecting the signal parameters at the end of the tests. This is due to the fact that as the wear process of the engine elements progresses, the damaging processes increase and their intensity grows, resulting in new damages due to interactions between the engine components. Because of these phenomena, the process of damaging the engine is cumulative. It is best shown by cumulative relative intensity of damages SIU_w and cumulative current relative intensity of damages $SBIU_w$.

Fig. 5. Changes of the cumulative current relative intensity of damages $SBIU_w$ of the engine in the function of vehicle mileage.

The presented reliability characteristics for single engine evaluation after the completion of the SIU_w tests and for the assessment of engine reliability during the $SBIU_w$ experiment will be used to reduce the parameters of the diagnostic vibration signal of the internal combustion engine. The reduction of the signal parameters will be carried out for two options. The first will concern the selection of parameters based on the reliability indicator defined by the dependency (8) and will concern the selection of parameters after the completion of the test. The second option will concern the selection of parameters during the experiment, basing on the reliability indicator defined by the dependency (10).

7 Selection of signal parameters after the experiment

As previously noted, the reduction of the signal vector – to the signal parameters that best illustrate the process of damaging the engine – consists in determining the correlation coefficient between the various signal parameters and the proposed reliability indicators. For the determined correlation coefficients, the confidence interval boundary values were estimated in accordance with dependencies (18) and (19). To select the parameters correlated to the damaging process, researchers used the narrowest confidence interval for the parameter which best shows the damage process. For the analyzed engine this is Ask – the effective value of vibrations acceleration.

Figure 6 shows an example of the correlation coefficient values calculated – beginning from the fourth observation – between the signal parameters: Ask , Vsk , Vsz , Xsk , Ja , Jv , Jx , Fx , Fv , Hv and cumulative relative intensity of damages (SIU_w). The figure also shows

upper and lower boundaries of the confidence interval (bold dashed line).

The correlation coefficients shown in Figure 6, determined after the subsequent diagnostic measurements, between the signal parameters and the cumulative relative intensity of damages SIU_w , enable – after the experiment – the selection of parameters correlated to the process of damaging the engine. The parameters best correlated (covaried) with the engine damaging process described by the cumulative relative intensity of damages are: the effective value of the vibration accelerations (Ask) and Rice frequency for the vibration velocity Fv .

Fig. 6. Changes in correlation coefficient between SIU_w and signal parameters.

8 Selection of signal parameters during the experiment

Reduction of diagnostic parameters during the diagnostic-reliability experiment consists in:

- determining – starting from the fourth diagnostic observation – the cumulative current relative intensity of damages $SBIU_w$,
- determining the correlation coefficient between the cumulative current relative intensity of damages $SBIU_w$ and individual signal parameters; estimation of confidence intervals' boundaries of correlation coefficient,
- selecting the narrowest interval of boundary value of correlation coefficient,
- rejection of such a diagnostic parameter for which, in three consecutive observations, the correlation coefficient value does not fall within the narrowest confidence interval of the correlation coefficient.

A diagnostic parameter whose correlation coefficient goes beyond the boundaries of narrowest confidence interval of the correlation coefficient does not map the damaging process and therefore should be rejected. With this procedure, in the following steps of observation the vector of parameters is decreased (reduced) to those that are covaried with the object's damaging process. As a result, at the end of the diagnostic-reliability experiment, only the parameter describing the damaging process will be obtained.

Figures 7 to 10 show the essence of the proposed method of selecting parameters (which map the damaging process) during the experiment, with the example of several vibrational diagnostic parameters.

Fig. 7. Changes in correlation coefficient between $SBIU_w$ and the coefficient of impulsiveness of vibration accelerations Ja .

Fig. 8. Changes in correlation coefficient between $SBIU_w$ and the coefficient of impulsiveness of vibration relocations Jx .

Fig. 9. Changes in correlation coefficient between $SBIU_w$ and the Rice frequency for vibration relocations Fx .

Fig. 10. Changes in correlation coefficient between $SBIU_w$ and effective values of vibration accelerations Ask .

The changes of correlation coefficient shown in Figures 7-10, for the sample four diagnostic parameters, show that the parameter that best maps the damaging process is the effective value of the vibration acceleration Ask (Fig. 10). The correlation coefficient for this parameter until the last observation falls within the confidence interval of the correlation coefficient. The coefficient of impulsiveness of vibration accelerations Ja can be discarded (not registered further) right after the eighth observation (Fig. 7). The coefficient of impulsiveness of vibration relocations Jx can be discarded after the eleventh observation (Fig. 8). The correlation coefficients of these parameters go beyond the confidence interval of the correlation coefficient and thus do not map the damaging process of the internal

combustion engine. Rice's frequency correlation coefficient for vibrations' relocations Fx moves beyond the confidence interval of the correlation coefficient only for the last observation.

The conducted analysis of the reduction of all recorded diagnostic parameters of the internal combustion engine during the passive-reliability experiment, presented in Figures 2 and 3 showed that the parameters that represent the engine damaging process are the basic vibration values (acceleration, speed and relocation). The damaging of engine is best mapped by the effective value of vibration accelerations Ask .

Conclusion

The proposed method of reducing diagnostic parameters during the passive-reliability diagnostic experiment enables selection of a parameter that is covariates with the progressive process of damaging the object. However, this experiment is labor-intensive because it requires a long time of object observation and recording of diagnostic and reliability data. Recording of diagnostic data in the form of diagnostic signal parameters is performed periodically with a given interval of time or mileage. Logging of reliability data requires continuous observation of the object and recording of all damages and the time or course of their occurrence.

This method can be used for diagnostically unrecognised objects, i.e. it is not known what parameters to measure to obtain maximum information about the object's state. It can be used for single objects because the analysis of the selection of diagnostic parameters concerns a single object. With the use of the presented method of rejecting subsequent diagnostic parameters which do not map the damaging process, research costs are reduced by performing fewer measurements and analyses.

The limitation of the presented method is that it can only be applied to complex objects. In the case of simple objects with a small number of elements, this method does not enable determining of the proposed reliability indicators and diagnostic parameters describing the damage process.

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