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Simultaneous Analysis of Noise and Vibration of Machines in Vibroacoustic Diagnostics

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The article is a continuation of the authors' elaboration (Dąbrowski, Dziurdź, 2016). The aim of this continuation is to prove that a proposed way of modelling and using the coherent analysis to filter nonlinear disturbances is a useful technique in vibroacoustic diagnostics. The thesis was proved by solving the task of diagnosing the damage of the gear of the car gearbox on the basis of the measurement of mechanical vibrations and the noise in the engine chamber.

Keywords: mechanical vibration; noise; vibroacoustic diagnostics.

1. Introduction

Vibroacoustics as a separate scientific discipline came from the postulate that the processes of propagation of mechanical vibrations and noise should be spoken in one language (Batko *et al.*, 2008; Crocker [Ed.], 2007). There are different paths of energy propagation, usually parasitic, generated by a large number of interactions necessary for a proper operation of machines and equipment. It shows that the models which we use in practical tasks should describe complex multi-input and multi-output systems.

One would think that developing FEM and BEM techniques might allow engineers to deal with this task, however, there are works available which show the mechanism of generating the noise by particular systems (eg. Madej, 2003; Zhou, Crocker, 2010; Herrin *et al.*, 2010; Opperwall, Vacca, 2014) in the environment relatively little disturbed, and acoustic field between the elements of a complex drive system can be at most precisely measured (Batko *et al.*, 2006). Unfortunately, it does not solve the problem of modelling complex paths of propagation of vibracoustic energy inside the structure of the machine. This task will remain a challenge for researchers for a long time. Therefore, the issue of design of models at a higher level of abstraction still remains valid. The models are identified on the basis of the measurements (Konieczny *et al.*, 2015). The problem is very important. While proposing the model of propagation of vibroacoustic energy in a complex structure of the machine, we may face the following problems:

1. The relationship input ↔ output (where input is treated as the source of vibrations and noise, and the output is treated as the point where we are going to minimize vibroacoustic interactions or get the information about the technical condition of the "input" for the needs of technical diagnostics) is usually non-linear (Batko *et al.*, 2008).
2. The term "source" of vibration and noise in the created model is not unequivocal. Let's consider the example of a drive system of a machine equipped with a combustion engine. Of course, the main physical source of the vibroacoustic processes is the combustion inside the cylinders. However, there a question arises: what plays the role of the "source" inside the tight engine housing among the many mechanisms transferring the power (Komorska, Puchalski, 2013; 2015)? Curvilinear surfaces of the block and engine's head? Such a "source" is not described by any elementary model. For the rest of the machine together with the operator's stand which is situated nearby, the average noise inside the housing of drive system is usually the "source". It is generated by both the same engine and auxiliary mechanisms (electric generator, pumps, mechanical fans), and elements of the drive system (transmissions, clutches and bearings). Selected points with the highest intensity act as "the sources" for a description of external field of the

machine. The whole machine is reduced to the selected point (a dipole or other model source) for a description of simultaneous interactions of many machines in a defined space. The location of such points is made on the basis of the measurements, where mutual methods proposed by Professor Z. Engel (Batko *et al.*, 2006) may occur to be especially useful.

However, the term "source" or "input" of the system in modelling the paths of propagation of vibroacoustic energy is a term obligatorily defined for the needs of created algorithm.

Due to these two mentioned reasons in most algorithms used to model the vibroacoustic behaviour of a machine different kinds of simplifications are used. The most important simplification is a description of propagation paths of vibrations and noise independently. It is obviously contradictory to the postulate of vibroacoustics mentioned in the introduction. Therefore, it is necessary to ask whether at the current stage of the development of computational methods and modelling techniques it is unavoidable. Of course, a complex machine (or vehicle) is a particularly negative case contrary to the research of acoustic field and vibrations of the ground accompanying the movement of the train. However, in these two basic tasks, i.e. minimization of vibroacoustic dangers and in technical diagnostics, the research and description of mutual relations between propagation of different forms of vibroacoustic energy give positive results, even taking into account the necessity of modelling at relatively high level of abstraction. We think that the best way to convince the reader of this thesis is to show examples of technical applications. Dąbrowski, Dziurdź (2016) presented the proposition of algorithm of noise minimization at the machine operator's stand. To do this they had used coherent analysis allowing for identification of paths of vibroacoustic energy propagation. This article was devoted to a diagnostic task.

2. Diagnostic task

This example attempts to answer the question whether it is possible to diagnose the state of wear of the gear with a damaged tooth (Fig. 1) car gearbox based on observations of vibrations of the block of the engine or the noise recorded inside the engine chamber.

At first glans this task may seem to be absurd. "Classic" books on vibroacoustic diagnostics say that the measurement of vibrations and noise should be done in possibly close distance to the diagnosed mechanism or kinematic pair. However, it is not always possible and the signal observed from a short distance is not necessarily the least disturbed. In addition, a vibration sensor placed on the engine can be used for many other tasks and it is much more difficult to place the sensor on the housing of the gearbox. Finally, from the cognitive point of view the answer to the question if the diagnostic information can be obtained was intentional.

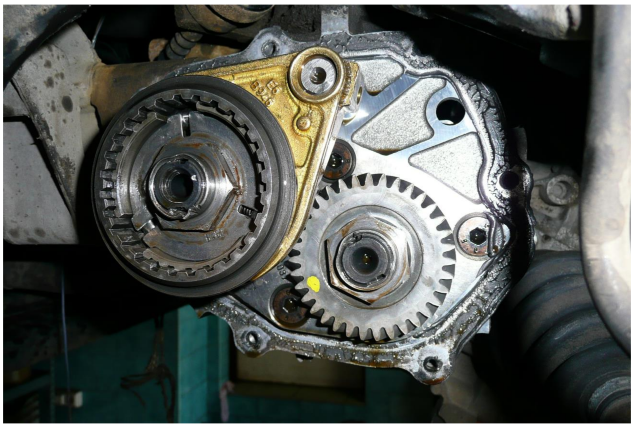

Fig. 1. The gear with denoted damaged tooth.

According to the notation adopted in (Batko *et al.*, 2006; Dąbrowski, Dziurdź, 2016; Dąbrowski, 1992) signal observed in the frequency domain can be written as:

$$X = \underset{\omega}{\mathcal{S}}\, \mathcal{F}\, \underset{t}{\mathcal{S}} \left\{ x(t, \theta, n, r) \right\}, \tag{1}$$

where: $\{x_i(...)\}$ – observed random process, which is generally a function of many variables, where the most important are: t – time of observation (dynamic time), θ – evolutionary time or another state variable used in technical diagnotics, n – serial number of the particular machinery (technical devices are not identical) r – coordinates of the measuring point.

$\underset{t}{\mathcal{S}}$ and $\underset{\omega}{\mathcal{S}}$ denote the operators of selection and averaging in time domain and frequency, so that it is possible to compare the determined model with the characteristics of a random process in the area which is a subject of analysis. The diagnostic task will be solved when the following relations is found:

$$x(t, \theta_i, ...) - x(t, \theta_j, ...) = \Delta_{ij} \;\Rightarrow\; \theta = \theta(\Delta), \tag{2}$$

where Δ is a diagnostic symptom. Dependency $\theta(\Delta)$ should be monotonous.

Following the ideas presented by Dąbrowski (1992) let's consider a simplified model describing the relation between the source of vibrations V_i, the vibration observation points X_i and the noise Y (Fig. 2).

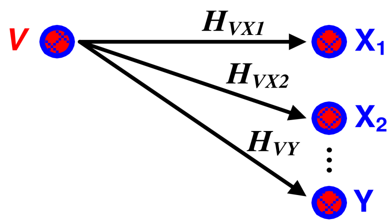

Fig. 2. A simplified model of propagation of vibroacoustic process.

Propagation paths are described with the following dependencies:

$$\begin{aligned} X_1 &= V \cdot H_{VX_1} + \Phi_1 , \\ X_2 &= V \cdot H_{VX_2} + \Phi_2 , \\ Y &= V \cdot H_{VY} + \Phi_3 , \end{aligned} \tag{3}$$

where H_{ij} indicate appropriate Frequency Response Functions, and Φ_i non-linear disturbances.

If disturbances Φ_i are small, we are able to eliminate them through appropriate signal processing, and the frequency response functions can be calculated according to the following formula:

$$H_{ij} = \frac{G_{ij}}{G_{ii}} . \tag{4}$$

When we put the first of such equations into the remaining two, we will obtain:

$$X_2 = X_1 \frac{H_{VX_2}}{H_{VX_1}} , \qquad Y = X_1 \frac{H_{VY}}{H_{VX_2}} . \tag{5}$$

This fact confirms the relativity of the source selection. In formulas (3) the observation point after the linear scaling of its spectral density X_1 acts as the "source". Linear scaling of spectral density of the input does not change the value of frequency response function because the vector of scale coefficients will "shorten" after expanding the dependency (Randall, 1987), which results directly from additivity of integration.

Let's make further considerations. Formula (1) indicates that the observed process $\{x(...)\}$ depends on several variables. From a theoretical point of view in the model of Fig. 2 spatial variable does not have to be the first characteristic of the measuring point (output) r, it can be also the state variable θ.

We may assume that the "input" in our system is the observation carried out at any measuring point, and the "output" is the observation carried out at the same point but for a different state of use (at a different time θ). The condition for the correctness of this reasoning is to provide "identical" work conditions of the machine (the same rotational speed), which is virtually impossible with a given accuracy, but the observed signals can be synchronized, e.g. with decimation technique or resampling technique specified in (Dziurdź, 2010; 2013). Thus, let's bring our model to the form presented in Fig. 3.

The states of use of the machine are the "outputs" of this model X_1 and X_2 and the state of appropriability is the "input" according to the given reasoning X_0. The measured spectral density at these points (in our case these are points of evolutionary variable θ) is shown in Fig. 4.

Z_1 and Z_2 in a discussed model indicated disturbances which in this case act as a diagnostic symptom (Fig. 3).

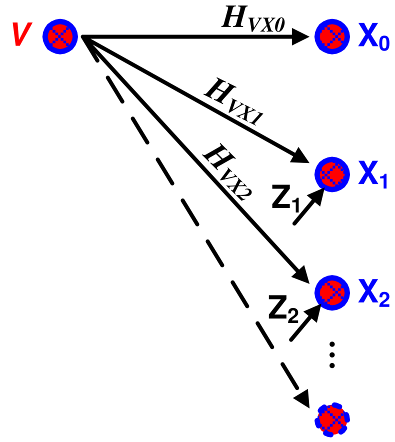

Fig. 3. Model of propagation of vibroacoustic signals adopted in a diagnostic task.

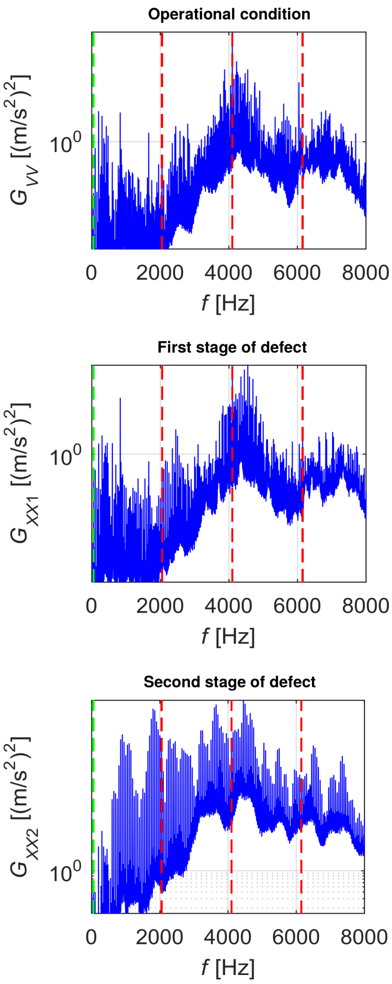

Fig. 4. The spectral density of power in different states of appropriability (X_0, X_1, X_2).

These disturbances can be differently interpreted and selected. This paper similarly to (Dąbrowski, Dziurdź, 2016) assumes that the increase of damages of the gear tooth goes together with the increase of the not coherent disturbance of observed vibrations. With the use of filter properties of the frequency response function we can write (Bendat, Piersol, 2010; Randall, 1987):

$$H^{(1)}_{VX} = \frac{G_{VZ}}{G_{VV}} = \frac{G_{VX}}{G_{VV}} = H_{VX}\,, \tag{6}$$

$$H^{(2)}_{VX} = \frac{G_{XX}}{G_{XV}} = H_{VX}\left(1 + \frac{G_{ZZ}}{G_{XX} - G_{ZZ}}\right) \tag{7}$$

using the equation:

$$\gamma^2_{VX} = \frac{H^{(1)}_{VX}}{H^{(2)}_{VX}} \tag{8}$$

leads to the dependency:

$$(1 - \gamma^2_{VX})G_{XX} = G_{ZZ}\,. \tag{9}$$

Power and cross spectral densities were denoted by G_{ij}, and ordinary coherence function denoted by γ^2_{ij}.

The results presented in Figs. 5 and 6 were obtained due to limiting frequency band with the operator to the range 1900÷2200 Hz (i.e. around the first gear mesh frequency).

Let's continue early presented considerations. If linear scaling of spectral density of the source does not change the non-coherent spectral rest Z_i let us try to

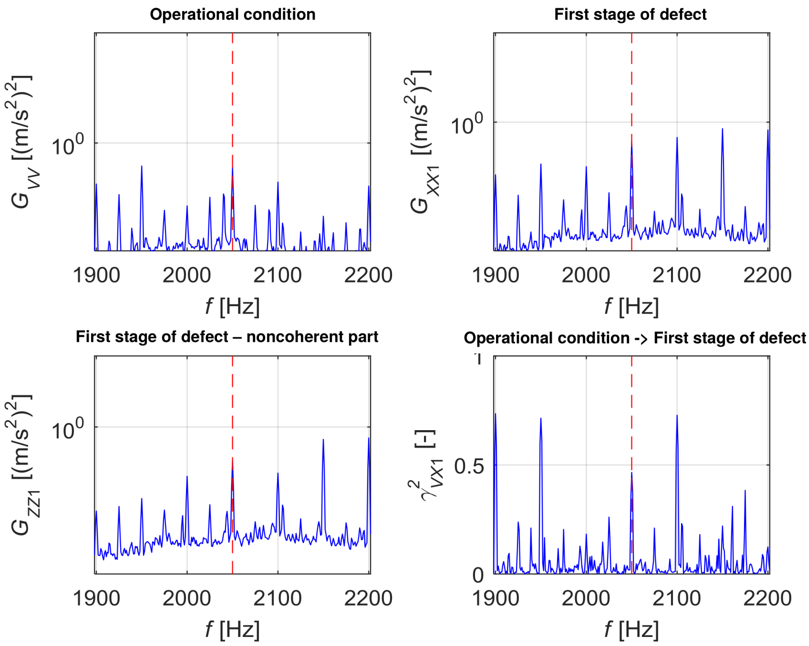

Fig. 5. Diagnosis of a "little" damage of the gear.

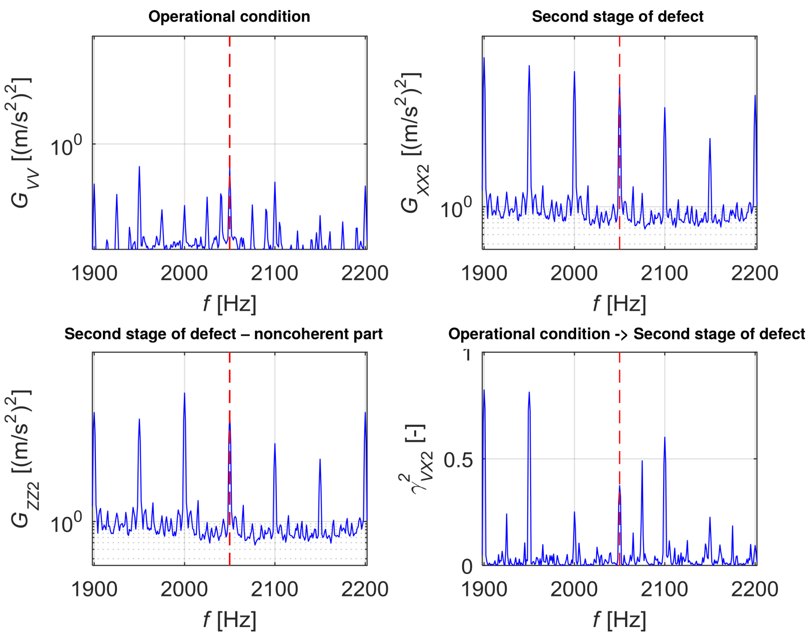

Fig. 6. The diagnosis of the "major" damage of the gear.

transform the source spectrum in accordance with the dependency:

$$G_{VV} = \frac{G_{VV}}{H_{VX0}} \cdot k - \Psi = G_{MM}\,, \tag{10}$$

where the vector of linear multipliers of frequency components was marked by k, and the filtered noise comprising lower components by Ψ which in effect leads to generating "artificial" abstract source assumed as a model whose spectral density is marked with G_{MM}.

It comes down to assuming the model spectrum uniformly distributed in frequency scale. This spectrum contains only dominant harmonic elements coherent with the outputs G_{X0} (zero state) GX_1 (minor damage) and GX_2 (major damage). Such a defined operation is presented in Fig. 7, and Fig. 8 shows the computation results.

To finish the presented argument let's use a developed procedure to check the sensitivity of acoustic signal which comes from a microphone placed inside the engine chamber to studied damage by a simple change of vibration spectra X_i on the noise spectrum Y_i. The selection operator and the model spectrum G_{MM} obtained from the analysis of vibrations is the same for the both spectra X_i and Y_i (Fig. 9). Taking the integral from spectral density of residual functions as a measure of damage (symptom), there were obtained the results presented in Fig. 10. Thus, the effectiveness of the proposed diagnostic technique is not a subject to discussion.

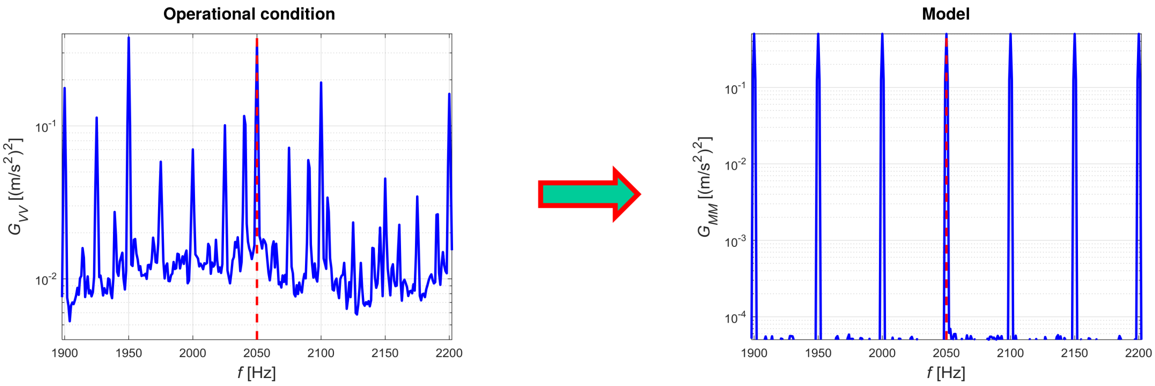

Fig. 7. The idea of replacing the spectrum of the input signal with a model signal.

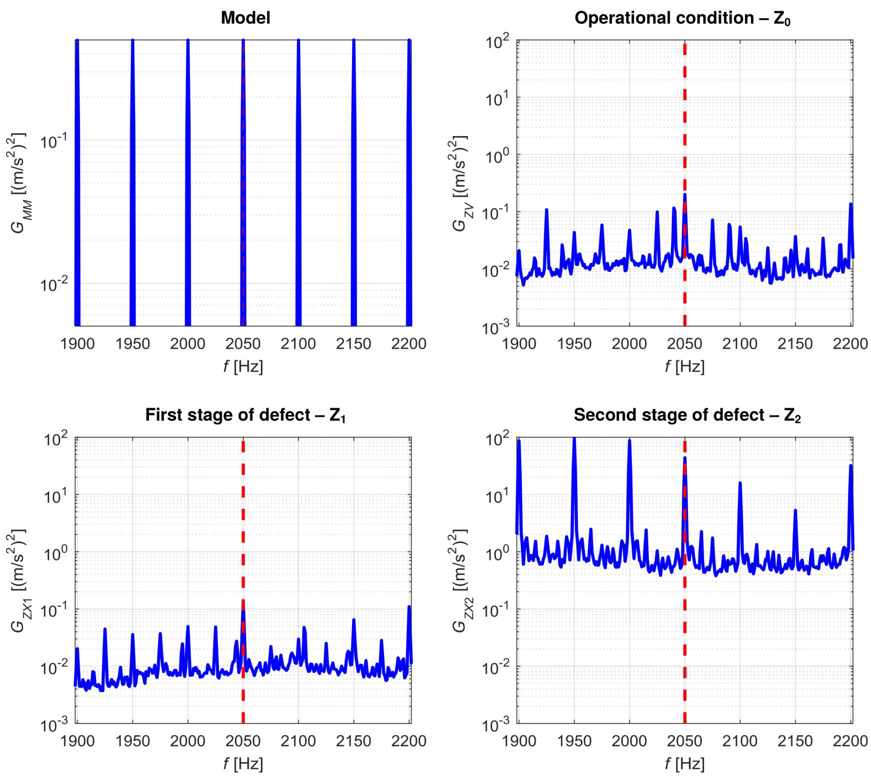

Fig. 8. The "residual" functions for different states in the diagnostic band for vibrations.

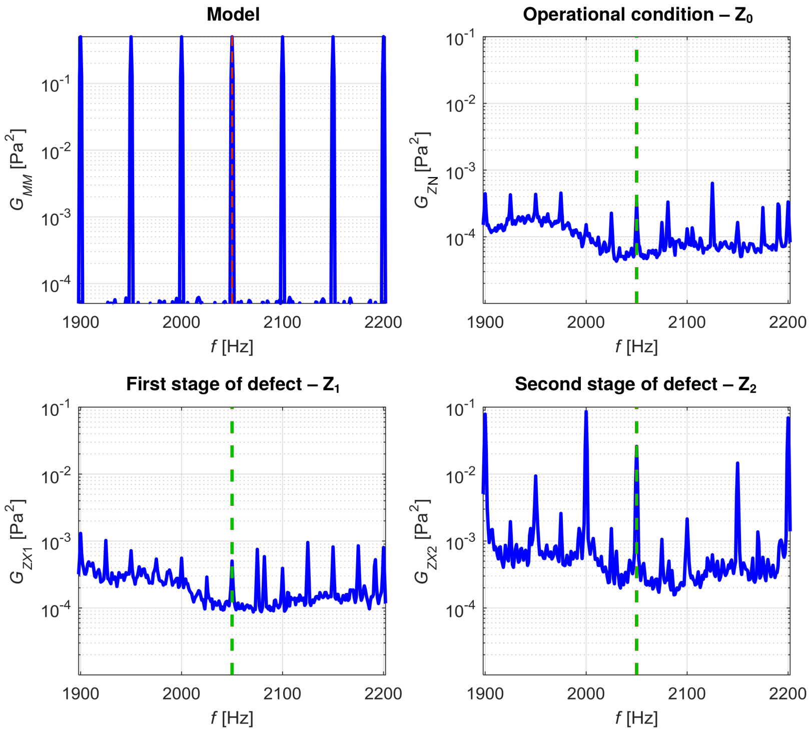

Fig. 9. The "residual" functions for different states in diagnostic band for the noise.

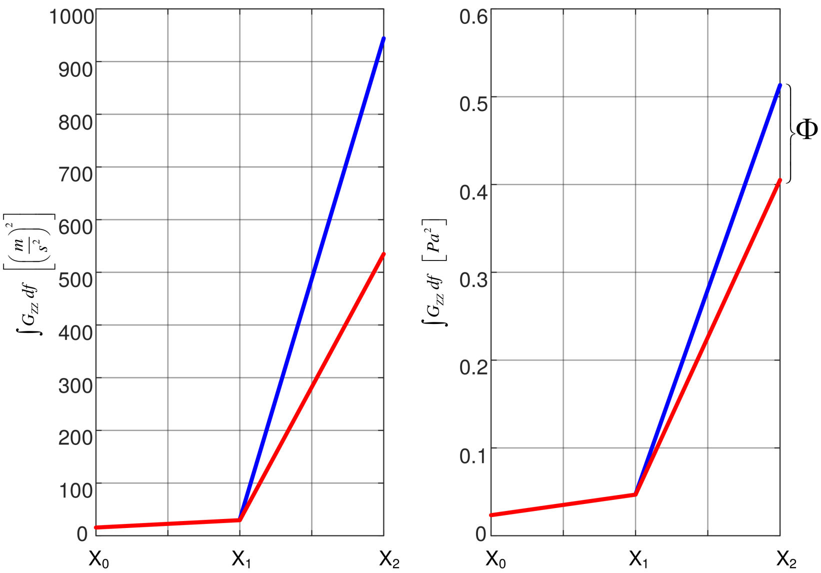

Fig. 10. The resulting diagnostic symptoms of damage development for the measurement of vibrations and noise.

3. Conclusion

Solving effectively complicated task of vibroacoustic diagnosis it has been demonstrated on the example of the validity of the postulated in the introduction also, in particular: Effective effective solution of a complicated vibroacoustic diagnostics showed validity of the theses stated in the introduction, especially:

- The relativity of choice of the "input" in modelling and identification of paths of vibroacoustic energy propagation.
- It has been shown that the coherent analysis, which gives an opportunity to separate uncorrelated part of the signal treated as a disturbance which changes in the function of variables θ (state) or r (position) can in effect lead to a monotonic measure which is a diagnostic symptom.
- Spectral frequency response functions (ordinary coherence functions) do not have to concern the relation between the physical extortion and the response of the system. They may be treated as

useful characteristics of multidimensional process. The method of studying these dependencies related to a model is particularly useful. The choice of the model used to assess the noise may be made on the basis of the analysis of mechanical vibrations. Damage of the gear is the source of the vibroacoustic process, where the part of energy is propagated in the vibration form and another part in the form of air noise.

- The last of these conclusions confirms the main thesis about the total usefulness of vibration and noise analysis in a diagnostic task like in the task of minimization of vibration and noise dangers.

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