

Data processing of experimental and computational results in machinery diagnostics

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Abstract Dynamic properties of machines influence on generated noise and vibrations, moreover they influence on service life, precision and quality of products; hence condition monitoring is a key factor in machine maintenance. They are two main methods in machinery diagnostics. The first relays mostly on experimental results, whereas the second method relays on computational results. The first approach is called symptom diagnostics, whereas the second is called holistic diagnosis. The experimentally obtained failure modes (symptoms) are functions of measured parameters. They can be non-dimensional without a physical interpretation, but they should be sensitive to condition of machines, which is a key factor. Whereas in holistic diagnostics two kinds of models are used: linear and non-linear. Linear models are wide spread, because they are relatively simple to use. Non-linearity is neglected in these models, which introduces an error, but makes computation easier. In contrast to this, non-linear models are more accurate, but their application is far more difficult. It should be mentioned that, those non-linear models have an important advantage; they can explain phenomena like multi-stability, fluctuations of measured amplitudes and jumps of amplitudes. These phenomena do not take place in linear models. A few examples are presented, to illustrate linear and non-linear models in machinery diagnostics. Moreover practical approach to signal processing is presented.

Keywords Non-linear vibrations · Rolling bearing · Machinery diagnostics

1 Introduction

Dynamic properties machines have a direct impact on the level of generated vibrations emitted noise, fatigue, controllability and stability of the structure. The analysis of the dynamic properties of machines identified by the construction of structural models (holistic diagnosis) or on the basis of experiments on real property (diagnostic symptoms). When building the model is principally the rights and axioms of physics, expressing the balance of forces, moments, describing the balance of forces, expenses, cash flow, the equations of continuity and geometrical relationships. They are expressed by ordinary differential equations, usually difficult to solve both analytical and approximate (numerical). Real systems are generally non-linear, non-linear decide where the rheological properties of the material, the occurrence of backlash, the nonlinearity dissipation strength and resilient characteristics. Limited capacity to analyze nonlinear differential equations tend to use linear models or use linearization procedures.

There is a large class of mechanical properties which limit the practice of precision can be represented by linear models. Generally the similarity between the model and the original can rely on structural similarity, showing the common features of the internal structure of the model and the object, or functional similarity, which is important convergence properties. The essence of the model is determined clear dependence between the characteristics and parameters of the signal, well described by linear differential equations. In this work, signaled to some problems of modeling (linear and nonlinear) and new tools for the study of dynamic machines. The issue

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is supported by the description of the processes of vibration destruction machines, supporting each machine immediately after its formation until the liquidation. Vibration descriptors allow you to create dynamic state of modern strategies for personalized computational technology in enterprise systems, ensuring the maintenance of modern machinery. This provides a basis for the rational use of machines in the newly created operating systems.

Monitoring of destruction processes of technical systems, and evaluation of technical state of machines are the primary aims of machinery diagnostics. Machinery diagnostics should be considered at each state of existence technical system – from designing to utilization. Many researchers previously found strong connections between physical phenomena like vibrations, temperature distribution, and technical state of machines [1–12]. In other words, physics and machine dynamics are foundation of machinery diagnostics; which refers particularly to vibro-diagnostics [6,8–10].

2 Dynamics and diagnostics

Into quality measures of machine's technical state (its dynamics), often uses of vibration, included mainly in level of vibration amplitudes. The quality of the technical state of the device (the dynamics) include vibration and measure specific to the individual components and parts. Identification in machinery diagnostics concern: experimental investigations, modeling and identification of model parameters. The identification leads directly to the problem of technical diagnostics, it means relation between symptom and technical state of a machine. The diagnostic identification tasks is different from general identification. It includes a number of additional stages:

- constructing models of signal generation,
- selection of measured signals,
- modeling cause - effective and relations,
- evaluating the accuracy of choosing variables in the model,
- determining boundary values of symptoms,
- classifying states and determining diagnosis periodicity.

Methods of identification can be classified according to the following criteria: the kind of identified model, the kind of experiment, identification criterion and estimation procedure. In consequence a number of diagnostic procedures (methods of analysis) is large and can be mentioned in the field: in time (analysis of time series), on frequency, correlation, regression, factor analysis, as well as methods described in works of many authors [3,6,8,9,13].

Another method of describing and analyzing the dynamic state of machines is a modal analysis used as a theoretical, experimental and exploitation method. It uses natural fre-

quencies and forms of vibrations to describe the changing machine state. Moreover this methods is used to improve FEM (finite elements method) models. The presented procedures are based on the knowledge of the system models and conclusions drawn from the actions on the models depend on their quality. Depending on the aim of the performed dynamic analysis of an object, different requirements are set for constructed models and their evaluation is conducted with different experimental methods.

Dynamic properties machines have a significant impact on the level of generated vibrations, emitted noise, fatigue, controllability and stability of the structure. The analysis of the dynamic properties of machines is identified by the construction of structural models (holistic diagnosis) or on the basis of experiments on real object (diagnostic symptoms). When building the model is principally the rights and axioms of physics, expressing the balance of forces, moments, the balance of forces, expenses, the equations of continuity and geometrical relationships. They are described by set ordinary differential equations, which are usually solved with numerical methods. Real systems are generally a non-lineare, non-linearity is introduced by: property non-linear materials, large displacements es. Solution of nonlinear differential equations is difficult, thus most often linear models are used.

There is a large class of mechanical phenomena, which limit use of linear models. Generally the similarity between the model and the real system can rely on structural similarity, showing the common features of the internal structure of the model and the object, or functional similarity, which is important for convergence properties. The essence of this model is determined dependence between the characteristics and parameters of the signal (or vice versa), well described by linear differential equations. In this work, we signaled to some problems of modeling (linear and nonlinear) and new tools for the study property of dynamic machines. Description of the destruction processes of machines, is help for many methods diagnostic for each machine immediately after its formation until the liquidation. Vibration descriptors allow you to create dynamic and modern strategies ensuring the maintenance of modern machinery. This provides a basis for the rational use of machines in the newly created operating systems.

3 Linear modeling

The dynamic state of machine can be, in the simplest case, described with a model of single degree of freedom (see Fig. 1). This system is described by linear differential Eq. (1), which have the exact solution (2). Parameters of Eq. (1) m, k, c can be identified from experimental results, which provides information about technical state.

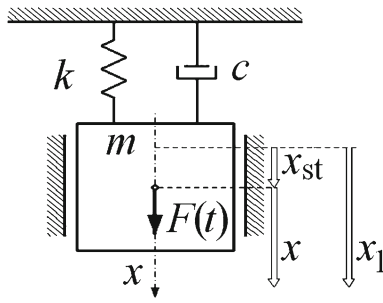


Fig. 1 Model of a system of 1 degree of freedom

$$m\ddot{x} + c\dot{x} + kx = F(t) \tag{1}$$

$$x = A \sin(\omega \cdot t + \phi), \tag{2}$$

$$v = \frac{dx}{dt} = A\omega \cos(\omega t + \phi), \tag{3}$$

$$a = \frac{d^2x}{dt^2} = \frac{dV}{dt} = -A\omega^2 \sin(\omega t + \phi) \tag{4}$$

Identification of this model (1) from the experimental side is the a, v, x measurements for different time instances, which reflects the changes of object state and is widely applied in vibration diagnostics. The solution to the task in the m, k, c , categories, however, requires a number of solution conversion of the Eq. (1) for determining:

$$c_{kr} = 2m\omega \quad c_{kr} = 4 \prod m f$$

$$k = m \cdot \omega^2 \quad k = 4 \prod m f^2 \tag{5}$$

Determining the value (5) requires realizing an identification experiment on the basis of which the frequency f or frequency ω can be determined. Here, simple identification or modal analysis directly giving the values of own frequencies ω from the stabilization diagram are useful (Fig. 2).

The problem becomes more folded for multi-degrees of freedom. The system parameters can be identified only from experimental results.

$$(K - \omega^2 M) \cdot q_0 = 0, \tag{6}$$

Equation (6) presents a linear system of homogeneous algebraic equations:

$$\begin{aligned} &(k_{11} - \omega^2 m_{11}) q_1 + (k_{12} - \omega^2 m_{12}) q_2 + \dots \\ &+ (k_{1n} - \omega^2 m_{1n}) q_n = 0 \\ &(k_{21} - \omega^2 m_{21}) q_1 + (k_{22} - \omega^2 m_{22}) q_2 + \dots \\ &+ (k_{2n} - \omega^2 m_{2n}) q_n = 0, \\ &\dots\dots\dots \\ &(k_{41} - \omega^2 m_{41}) q_1 + (k_{42} - \omega^2 m_{42}) q_2 + \dots \\ &+ (k_{nn} - \omega^2 m_{nn}) q_n = 0 \end{aligned} \tag{7}$$

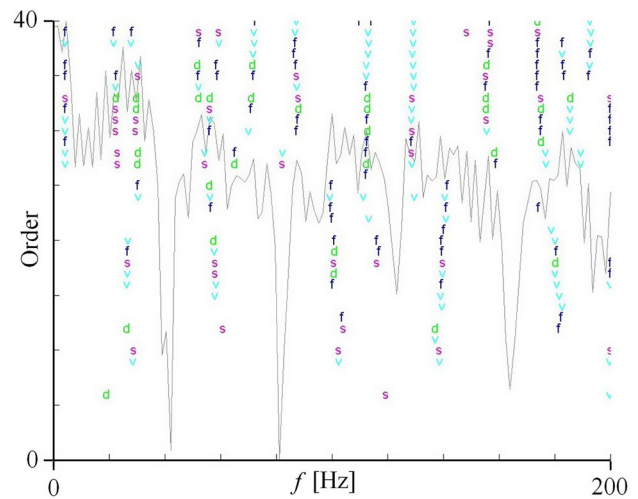


Fig. 2 Stabilization diagram for ω determination

There is a solution $q \neq 0$ exists when the main matrix determinant $(K - \omega^2 M) = 0$ i.e. $\det(K - \omega^2 M) = 0$. Solving the system of Eq. (7) gives the value of their own, for them the frequency necessary to identify the object ($\lambda = \omega^2 = \frac{k}{m}$). More information about linear models is presented in [14].

4 Nonlinear modeling

Nonlinearities are a common phenomenon in mechanical structures. For nonlinear systems, there are many factors that are not present in linear model, for example self-excited vibration, a change in the frequency of its own together with the amplitude change, the occurrence of the nonlinear response of the spectrum of bands not occurring in the forcing.

Causes of non-linearity are is very much, here you can show include such phenomena as friction, backlash, contact phenomena arising in construction cracks, used discrete components (springs, dampers) with characteristics of nonlinear etc.

In engineering practice non-linear elements are modelled using linear (linearised) models, which can lead to large errors. Using calibration methods, which were only approximations description of the dynamic behaviour of the object. In many modern technical applications, linearisation is not sufficient. These applications include; diagnosis based on the model structure, the analysis of vibration and stability of vehicles, in particular rail vehicles, the analysis of the phenomenon of flutter in aircraft, rockets, and turbine blades, vibration analysis of building structures, analysis and elimination of the phenomenon charter of machine tools and many others.

Identification of non-linear models of the structure is a very complex task, usually carried out in several stages. The

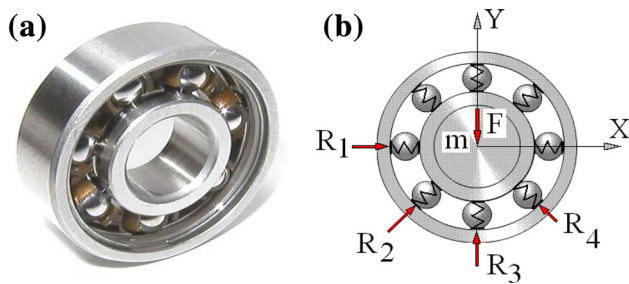


Fig. 3 The deep groove ball bearing (a) and its model (b) [6,23]

first step in this process is to determine whether the object is linear or non-linear. If it finds the existence of non-linearity, then the type of non-linearity is studied. The next step is estimation of model parameters as well as the verification of the identified model. The proper conduct of the identification of nonlinear models requires the use of specialized methods of measurement and signal processing. Using classical methods based on Fourier transform and the method of least squares (classical) can lead to incorrect results.

Rolling bearings can be modelled with linear Kelvin-Voigt model, which is obvious simplification [15,16]. In this case rolling bearings are described with linear equations; and are considered as passive elements, which only dump vibrations. Rolling bearings can be modelled as non-linear mechanical systems as well [5,6,17–22]. In this case rolling bearings can excite and dump non-linear vibrations at the same time, which is interesting phenomenon. Rolling elements circulate an inner race, which changes stiffness of rolling bearing, and excites parametric vibrations. On the other hand a lubricant damps vibrations. These two phenomena are observed in practice. Non-linear model of the studied rolling bearing 6203 (see Fig. 3) has been presented previously, thus only a short description is presented below [5,6].

In a rigid pillow block bearing the outer race is fixed; the pillow block bearing has not any degrees of freedom. Then, mass is attached to the shaft, whereas masses of balls are neglected. In consequence, the balls are modelled as massless non-linear springs. These springs model the Hertz contacts. Next, the inner race rotates in counter clockwise direction thus, balls circulate in the counter clockwise direction too. Finally, the circulation of balls changes stiffness of bearing, which in turn excites vibrations. The following forces act on the inner race and shaft. The first force is the inertial force, that is described by the Newton's second law of motion. Whereas, the second force is the external force F . A number of the spring (contact) forces R_n acts on the inner race, they are result of contact deflections of balls and races. The next force is the dumping force. And, the last forces are the rolling friction forces. This leads to non-linear second-order differential equations, that are solved with a numerical method [24].

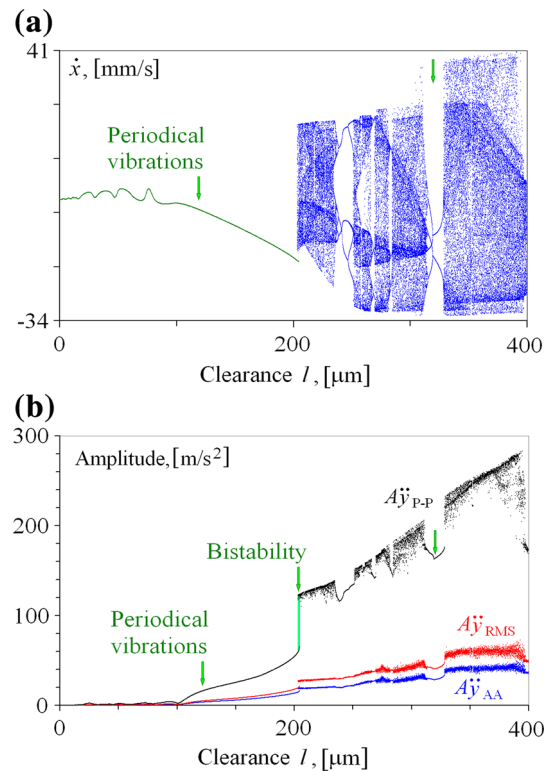


Fig. 4 Bifurcation diagram (a) amplitudes of vibrations obtained for magnitudes of clearance (b) [6]

The rolling bearing vibrations are studied for various magnitudes of clearance. First a bifurcation diagram is presented (Fig. 4a). Stable periodic vibrations, which period equals the excitation period, are presented with one solid line.

Whereas, if the vibration period is n times longer than the excitation period, then n lines represents these vibrations. A number of period doubling bifurcations are depicted in Fig. 4a. On the other hand, chaotic vibrations are represented with dotted area. Within this dotted area windows of periodical vibrations are observed, for instance for clearance being near 240 (μm) and 320 (μm). Moreover bi-stability area is observed for clearance being near 204 (μm), periodic or chaotic vibrations can be excited in this case. This shows that dynamics of rolling bearing is far from linear dynamics, for more information please see [5,6].

Next amplitudes of acceleration of shaft are studied (Fig. 4b). As is evident from the obtained results magnitudes of amplitudes dependence on clearance. Local minima, jumps of amplitudes, and bi-stability are observed. Moreover this local minima and jumps of amplitude are associated with bifurcation diagram, which shows that non-linear models can explain ambiguity obtained results. For chaotic vibrations various amplitudes of vibrations are observed, because these vibrations are not periodic.

Then, non-dimensional parameters of vibration can be studied, which are failure modes. They are described by the

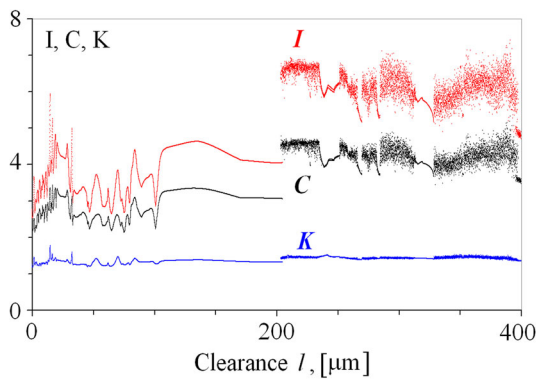


Fig. 5 Coefficients *I*, *C* and *K* obtained for various magnitudes of clearance

following equations:

$$I = A\ddot{y}_{P-P}/A\ddot{y}_{AA}, \tag{8}$$

$$C = A\ddot{y}_{P-P}/A\ddot{y}_{RMS}, \tag{9}$$

$$K = A\ddot{y}_{RMS}/A\ddot{y}_{AA}. \tag{10}$$

As is evident from the obtained results (see Fig. 5), they are not very good failure modes; because their graphs have local minima, and their magnitudes do not rise significantly with increase of clearance *l* (e.g. *K*).

Summarising, simulation non-linear vibrations provides an opportunity to explain phenomena observed in practice like: bi-stability, jumps of amplitudes and fluctuation of amplitudes. Which make machinery diagnostics difficult. This is the reason, why non-linear vibrations are studied in machinery diagnostics, and non-linearity is not neglected.

5 Identification researches software (SIBI)

More and more frequently conducted identification researches of dynamic state machine, used for the evaluation of condition changes, faulty, development and location of the occurred state causes, were the basis for creating a specialized software system. It allows acquiring and processing measurement data, creating many measures of diagnostic signals, examining their diagnostic sensitivity, statistic processing, and diagnostic concluding. The program is called Information System of Identification Researches (SIBI) [8–11]. The structure of the program is a modules construction which includes the following modules (see Fig. 6):

A—*Read unv* module which allows to process data from UNV format to XLS format.

B—*Symptoms* module which allows defining, determining and creating a matrix of many measures of vibration processes.

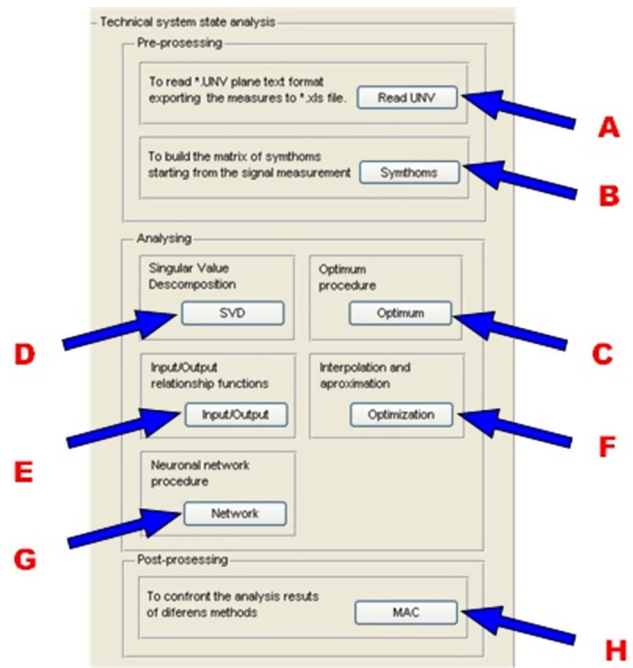


Fig. 6 Main dialog box of SIBI program [25]

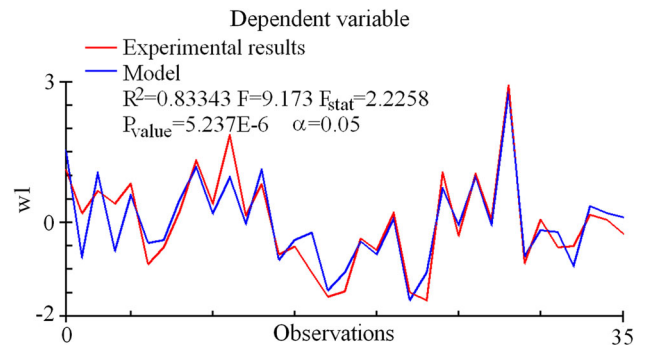


Fig. 7 Regressive model determination

Modules A and B are a part of software responsible for acquiring and processing vibration processes in order to acquire observation matrix of vibration estimators.

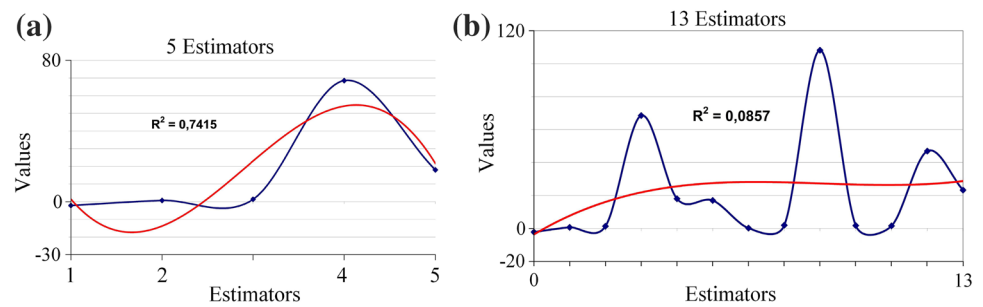
C—*SVD* (singular value decomposition) module is used for determining generalized damage measures, and for the evaluation of damage development. Using the SVD method allows a multidimensional description of the state of the examined object.

D—*Input/Output* module used for the analysis of similarities between vibration processes, and for determining different exploitation measures of the examined object.

E—*Optimization* module used for creating models and data in genesis (with approximation and interpolation methods), diagnosis and prognosis of object states.

F—*Optimum* module uses the method of ideal point for individual evaluation of the sensitivity of measured symptoms of vibration processes.

Fig. 8 Number of measures versus accuracy of a model, obtained for two examples [10]



G—*Network* module using neuron nets for state classification on the basis of obtained results in the form of time rows.

C, D, E, F, G modules are elements of two parts of the software, allowing the performance of statistic concluding and cause-and-effect relations, as well as visualization of the obtained results.

6 Cause-and-effect modeling

Many state measures acquired in experiments requires the reduction of over measurement, which is possible with the use of OPTIMUM procedure (statistic evaluation of separate measures) or SVD (for a multidimensional approach). Optimized set of symptoms is a basis for constructing cause-and-effect, most often regressive, multidimensional models (see Fig. 7) [10].

$$y = -2.68w_1 - 0.54row1 - 0.49x_1 + 2.01w_2 + 0.35row2 + 2.26x_2 - 0.03H(f) + 0.07H(f) + 92.01A_{RMS} + 12.99kurt + 239.69C - 200.58I - 44.38 \quad (11)$$

The wellness of a model is evaluated with the help of the determination coefficient R^2 , and the number of component symptoms determines its accuracy (see Fig. 8).

7 Conclusions

Considerations presented in this work concern the linear modeling of object dynamic state with the use of description and researches within the range of identification, distinguishing modal analysis and ideas directly supporting different methods of forming machine dynamics.

The knowledge of the dynamic state and structure of the system allows to describe its behavior, and allows to create prognosis models of system behavior in the function of dynamic evolution time, based on the model of technical state symptoms growth. Most often, however, there are no known equations describing behaviors of a system in the function of dynamic evolution time, which accounts for the need to apply new tools to examine the dynamic state. There is, therefore,

the requirement to experimentally verify analytical technical models as the proper one is a model which is verified in practice. An experiment is, therefore, often only an inspiration for further researches leading to the optimization of construction. In a study of non-linear models for processing the response signal is proposed to use wavelet transform, in particular the Morlet wavelet that best disengages the system vibration and facilitates the identification of the models.

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