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Modelling in the identification of threats to the functioning of technical systems

Modelowanie w identyfikacji zagrożeń funkcjonowania systemów technicznych

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Abstract. Modern technical systems used in practice (machines, vehicles, military technology) are subject to automatic degradation of the technical condition, which forces modelling to identify changes in this state. The available modelling methods in identifying changes in the technical condition of such systems make it possible to supervise the developing threats to the correctness of their functioning. The aim of the work was to present available methods and tools for modeling and identifying evolving threats to complex technical systems in terms of description and indication of the premises for their use. Modern technical systems (machines and military technology) are characterized by such features as: functionality, reliability, readiness, security, mobility, and operational vulnerability. Identification of threats to the functioning of technical systems through modeling therefore concerns the construction of models of the test object, the reconstruction of the state of the object and its prediction. The existing methods of identification can be divided into methods of identifying static and dynamic properties. The current availability of computers and simulation studies of the dynamics of objects allows attempts to identify the dynamic properties of objects throughout its life cycle, using various models. The considerations presented in this paper concern a modern approach to modeling the dynamic state of objects. The evolutionary dynamic models created in this way should improve the methodology and reasoning in the assessment of the dynamic state, often used for optimization and supporting operational decisions, which is the research niche of this article.

Keywords: modelling, identification, threats, state change, exploitation

Abstrakt. Nowoczesne systemy techniczne stosowane w praktyce (maszyny, pojazdy, technika wojskowa) podlegają automatycznie degradacji stanu technicznego, co wymusza potrzebę modelowania oraz identyfikację zmian tego stanu. Dostępne metody modelowania identyfikacji zmian stanu technicznego takich systemów pozwalają na nadzorowanie powstających zagrożeń dla prawidłowości ich funkcjonowania. Celem pracy było przedstawienie dostępnych metod i narzędzi do modelowania i identyfikacji ewoluujących zagrożeń dla złożonych systemów technicznych w zakresie opisu i wskazań przesłanek do ich wykorzystania. Współczesne systemy techniczne (maszyny i technika wojskowa) charakteryzują się takimi cechami jak: funkcjonalność, niezawodność, gotowość, bezpieczeństwo, mobilność, podatność operacyjna. Identyfikacja zagrożeń dla funkcjonowania systemów technicznych poprzez modelowanie dotyczy więc budowy modeli badanego obiektu, rekonstrukcji stanu obiektu i jego predykcji. Istniejące metody identyfikacji można podzielić na metody identyfikacji właściwości statycznych i dynamicznych. Obecna dostępność komputerów i badań symulacyjnych dynamiki obiektów pozwala na podejmowanie prób identyfikacji właściwości dynamicznych obiektów w całym cyklu ich życia, przy użyciu różnych modeli. Przedstawione w artykule rozważania dotyczą nowoczesnego podejścia do modelowania stanu dynamicznego obiektów. Stworzone w ten sposób dynamiczne modele ewolucyjne powinny usprawnić metodologię i rozumowanie w ocenie stanu dynamicznego, często wykorzystywanych do optymalizacji i wspomagania decyzji operacyjnych, co stanowi niszę badawczą.

Słowa kluczowe: modelowanie, identyfikacja, zagrożenia, zmiana stanu, eksploatacja

Introduction

The growing interest in the problems of obtaining information from research for the purposes of modern construction, production and operation of technical systems is commonly observed. The increase in reliability requirements along with the use of many objects in new areas of life (management, medicine, military technology) resulted in the development of computer diagnostic devices, enabling the detection and location of damage along with generated operational decisions, determined using artificial intelligence methods (Augustyn, Żółtowski, 1999; Cempel, 1989; Eickhoff, 1980).

Research on the dynamic properties and loads of modern technical systems is carried out directly on the objects and using their physical and mathematical models. However, direct testing of objects is very costly and laborious - they require a technically efficient object and often lead to its damage or destruction. To avoid many of these difficulties, in the process of creating new structures or modernizing the existing ones, methods and techniques of simulation of model testing are introduced more and more commonly and to a wider extent, instead of testing on objects (DD-4.22(A), 2017).

The tested systems and their systems are treated as multi-input dynamic systems. The aim of the research is to obtain information about the dynamics of work (functioning) and the processes of forming loads and stresses taking place in it. The main information about the dynamic properties of systems and their models can be derived from the course of the amplitude-frequency and amplitude-phase characteristics. Their changes indicate the bands of resonant frequencies, vibration levels in steady states, as well as the areas of stability of the system (Uhl, 1997).

It should be emphasized that building a mathematical model of a working machine is not only about determining the structure of the model and describing the movement of its masses with an appropriate system of differential equations. Often a much more difficult problem is to determine the coefficients of these equations, including the necessary values of the stiffness and damping coefficients of the deformed elements of the model. The quality of solving this problem is strongly related to the results of identification studies (Żółtowski, Niziński, 2010).

Due to technical applications, modeling or identification is effective if it describes the behavior of the tested object in a certain amount of time (Cempel, 2000; Piesiak, 2009).

However, the situation is slightly different when changes occur in a component of a technical system under the influence of long-term loads. In such cases, the energy of the losses may be the basic measure of change. Its correct estimation, however, requires the introduction of an accurate model of vibration damping, considering not only viscous friction, but also, for example, motion resistance associated with dry friction. Therefore, it leads to the need to describe and apply a non-linear model. It is extremely interesting to determine the changes in non-linear elastic-damping characteristics of the tested element until its destruction. Changes in these characteristics over time can be a source of significant information about the durability of the tested element and give indications for use in diagnostics (DD-4.22(A), 2017; Żółtowski, Cempel, 2004; Żuchowski, 2003).

Significant development in this direction will be fully possible if methods for modeling and identifying dynamic mechanical systems can be developed in accordance with the appropriate variety of non-linear models (Mańczak, 1979; Morrison, 1996; Żółtowski, Cempel, 2004).

Modern technical systems (machines and military technology) are characterized by such features as: functionality, reliability, readiness, security, mobility and operational vulnerability. The development and maintenance of these features is possible with the extensive use of technical diagnostic methods that enable (Bendat, Piersol, 1996; DU-4.22, 2014; Żółtowski, Niziński, 2010):

- diagnostic construction and production of new technical constructions;
- maintenance of systems in a state of functional suitability.

The use of complex (mechatronic) systems is characterized by:

- sets of randomly variable times of correct operation;
- randomly variable start times and variable lengths of task durations;
- intensive work in a randomly variable period of use;
- impact of randomly changing operating conditions;
- different types of tasks performed in short periods.

The manufacturer interested in quality and subsequent sale is responsible for the product from the concept, through construction, production, and operation, to disposal after the liquidation of the facility. The manufacturer constructs and produces its products based on the latest achievements of technical thought, secures its products with its own maintenance service during operation, and also equips facilities with diagnostic means (Bishop, Gladwell, Michaelson, 1980; Parszewski, 1982; Wiśniewski, 1985).

The effectiveness of solutions in applying such a strategy for the existence of modern technical systems requires improvement (Bendat, Piersol, 1996; DD-4.22(A), 2017; DU-4.22, 2014)

- modeling and simulation studies of modern mechatronic technology;
- methods of diagnosing and forecasting states;
- economical, accurate and reliable diagnostic devices;
- principles of shaping diagnostic susceptibility;
- maintenance control algorithms;
- methods for evaluating the effectiveness of diagnostics and the operation system.

Identification of threats to the functioning of technical systems through modeling therefore concerns the construction of models of the test object, the reconstruction of the state of the object and its prediction. The existing methods of identification can be divided into methods of identifying static and dynamic properties. The current availability of computers and simulation studies of the dynamics of objects allows attempts to identify the dynamic properties of objects throughout its life cycle, using various models (Broch, 1980; Żuchowski, 2003).

Identification of the dynamic state of a complex object

The technical reality of modern systems is the result of the analysis of models that correctly describe it. The process to build the best operating model (mathematical or empirical) is called the identification process. It includes the following issues: modeling, experiment, estimation and verification of the model.

The identification process therefore includes (Augustyn, Żółtowski, 1999; Mańczak, 1979; Morrison, 1996):

- modeling (symptomatic or structural),
- identification experiment (simulation and/or real),
- estimation of parameters (state features or symptoms),
- inference.

Identification methods can be divided according to: the type of model being identified, the type of experiment, the identification criterion used, or the estimation procedure used. In general, these are: analytical methods (time, frequency, correlation, regression, factor analysis and iterative methods), discussed in the available works of several authors (Bendat, Piersol, 1996; Broch, 1980; Cempel, 2000; DU-4.22, 2014; Żółtowski, Niziński, 2010).

For simple objects, a good tool for assessing their changing dynamic state are simple identification methods using the amplitude-frequency spectrum. The search for the resonant frequency and the amplitude value in this frequency by means of impulse, harmonic and random tests are relatively well mastered in the research techniques of enterprises (Giergiel, Uhl, 1990; Wiśniewski, 1985).

Another way of describing and analyzing the dynamic state of machines is modal analysis, used as a theoretical, experimental and operational modal analysis. It uses natural frequencies and modes of vibrations to describe the changing state of machines and is used to improve the finite element method.

Each machine goes through four phases of its existence: **valuation (C)**, **design (P)**, **production (W)** and **operation (E)**. The increasing demands placed on machines have defined several criteria that are tested at each stage (Żółtowski, Cempel, 2004; Żółtowski, Niziński, 2010).

The process of identifying the dynamic properties of the system comes down to (Piesiak, 2009):

- determining the amplitude-frequency characteristics and a set of parameters resulting from these characteristics;
- determining the structure of the model, i.e. connections between inertial, elastic and dissipative elements and determining the values of these quantities. In general, there are:

1) direct identification consisting in determining the structure of the model and coming down to determining the mass matrix, stiffness matrix and damping matrix together with the method of connections and interactions between these elements in the machine;
2) parametric identification, which boils down to determination of dynamic characteristics (vibration modes, eigenfrequencies, damping).

In the field of dynamic analysis of mechanical structures, the following main thematic groups can be distinguished (Parszewski, 1982; Uhl, 1997; Żółtowski, Łukasiewicz, 2012):

- modeling and structural identification of mechanical systems using the dynamic compliance method and modal analysis methods;
- analysis and assessment of the dynamic state of mechanical objects;
- description of the energy model of the mechanical system.

The first group includes the latest publications in the field of modeling methods and identification of dynamic properties of systems, including mainly methods of dynamic compliance and methods of modal analysis (Żółtowski, Niziński, 2010). The second group of analyzed literature includes mainly works in the field of structural diagnostics, based on models of systems described in four-dimensional space-time *(x, y, z, t).* The third group includes descriptive works. energy models of systems, usually described in five-dimensional space *(x,y,z,t,Q*), which are the basis for operational diagnostics.

Modeling the structure of matter

Dynamic processes accompanying the wear of solids generate numerous physical and chemical phenomena, which greatly complicates the model presentation of the phenomena of matter destruction. Changes and mechanisms of wear, presented in terms of energy in accordance with the rules of non-equilibrium thermodynamics, are described in various intervals of the linear dimension and time (Cempel, 1989; Niziński, 1999).

A common feature of physical systems is the possibility of separating components in each of them, arranged in a specific structure. The properties of this structure are generally different from those of individual elements. Blurring of the features of individual elements results in the appearance of the same, average features of the structure. Hierarchical arrangement of the structure of matter, distinguishing six levels of matter properties described by the linear dimension and the duration of the phenomenon.

The level of elementary particles 1 is limited by a linear dimension of the order of 10^{-15} -10^{-14}m, which includes, for example, the nucleus of an atom and the duration of the phenomenon 10^{-22} - 10^{-18} s, characteristic, for example, for the period of radiation vibrations g. This level is rarely used in the interpretation of physical phenomena in mechanical engineering, due to the complete disappearance of the properties of matter essential for their analysis.

The atomic 2 and molecular 3 levels, where the physical and chemical properties of atoms and molecules, the tendency to adhesive bonding, adsorption, diffusion, chemical reactions of atmospheric components with the material of the surface layer ii become important, inform about the nature of friction and wear. At these levels of observation, there are defects in the structure of matter and potential energy (chemical, electrical, mechanical, magnetic) associated with them. Atomic level 2 is limited by linear dimensions of the order of 10-^{14} – 10-^{10}m, corresponding to the diameter of the atom and a characteristic time range of 10-$^{20\,-}$ 10-^{12} s, defined by periods of X-rays (including infrared radiation, atomic vibrations 10-^{13} s). For the molecular level 3, a linear dimension range of 10^{-10} -10^{-9} m was assigned, corresponding to the diameter of the molecule and the duration of such phenomena 10^{-8} -10^{-7} s, characteristic of the frequency of atom displacement during diffusion.

At the level of molecular aggregates 4, there are crystallites, grain boundaries, various precipitates and phases, heterogeneities in the structure and properties of the substance (anisotropy) are observed here. The obliteration of the presence of individual atoms, molecules and elementary defects in the structure of matter at this level provides the basis for operating with the concepts of: temperature, stress, strength properties, thermal conductivity, etc. A critical concentration of structure defects may cause the reconstruction of a molecular aggregate defined in the range of m, as the diameter of the crystallite, while the time of processes of this level of 10^{-6} -10^{-3} s corresponds to the duration of contacts of micro-roughness of the surfaces of rubbing bodies.

At the level of macroscopic layers 5 (in the surface layer), there is a large variety of structure and properties of the substance, similarly to level 4. Some of the molecular aggregates have linear dimensions comparable to the thickness of the surface layer, and dimensions perpendicular to the thickness of this layer are comparable to the dimensions of rubbing elements. The diameter of the contact area of the micro unevenness as well as the duration of the phenomena of this level are identical to those in level 4, hence the distinction between levels 4 and 5 is often negligible. The thickness of the surface layer is often considered to be an elementary macroscopic dimension because the methods of macroscopic research are not used to study changes in physical values in this layer.

At the macroscopic level 6, there is homogeneity and isotropy of the physical properties of matter, enabling theoretical and experimental analysis of matter. The linear dimension of this level, 10^{-9}-10^{-4}m, corresponds to macroscopic real dimensions, and the duration of the phenomena here is practically defined in the range of 10^{-2} -10^{-4} s.

The occurrence of phenomena in different ranges of dimension and time, depending on the hierarchical level of the structure of matter, requires their separate recognition. The theory of quarks is used to describe phenomena at level 1, quantum mechanics at level 2, quantum mechanics at level 3, e.g. kinetic theory of gases, on levels 4 and 5-e.g. metallurgy, and at level 6 - e.g. mechanics of continuums, thermodynamics.

Therefore, the model presentation of the aging and wear processes of machines and structures should consider:

- the possibility of mathematical description of various transformations due to the fact that hierarchical levels occur in various finite intervals of linear dimension (volume) and time;
- the way of deciding on transitions between levels, especially the transition to the macroscopic level enabling the description of real material nodes of devices.

The mathematical description of all physical transformations, based on the concept of a function determined for finite intervals of space and time, therefore depends on the hierarchical level of the structure of matter. When describing a physical quantity, the characteristic values of space and time (large enough) should be selected in such a way as to eliminate the influence of the object's microstructure and to obliterate the influence of the macroscopic shape of the object (sufficiently small) on the value of the physical quantity (Cempel, 2000).

On each of the levels of organization of matter, there are separate properties of each structural level, and the apparent boundaries between them always determine a new quality in relation to the lower level. Thus, the whole exists thanks to its parts and their mutual interaction, and in order to isolate the whole, the time-space field of observation must be properly quantized and then only one of the hierarchical levels of the structure of matter should be taken into account.

Models are used in every human activity, especially in designing, manufacturing, and operating. There are many definitions of models. Here are some of them:

- a model is understood as a conceivable or materially realizable system which, reflecting or reproducing the object of study, is able to replace it in such a way that its study provides us with new knowledge about this object (Uhl, 1997);
- a model is a tool that can be used to describe the system and its behavior in various external conditions (Cempel, 1989);
- the model is a theoretical description of the study of objects, which is characterized by the following features, i.e. it is (Cempel, 2000):
  - a certain simplification of reality,
  - in the sense of a certain criterion convergent with reality,
  - simple enough that it is possible to analyze it using available computational methods,
  - source of information about the research object.

Knowledge of the laws governing the phenomena, experimental data and other information should allow us to determine the structure of the model, i.e. the form of relationships that we believe will be able to properly express the relationships between variables.

Possible modeling methods

In the technique, the following goals of creating models can be distinguished:

- **for the purposes of design,** where the model is used to optimize the structure and parameters of the constructed object and is a tool for assessing the „quality" of the structure, eliminating weak links, designing supervision systems, (functional and reliability models);
- **for the purposes of diagnosing,** where the model is the basis for determining the diagnosing algorithm, which leads to the determination of the current and future state of the object;
- **for the purposes of operation and control,** using the model to make decisions with the operating object (range of maintenance activities, operational decisions).

The current dynamic state can be determined by observing the functioning of the object, i.e. its main converted energy (or product) output, and the dissipative output - where residual processes are observed, e.g. thermal, vibration, acoustic, electromagnetic (DU-4.22, 2014; Morrison, 1996; Żółtowski, Łukasiewicz, 2012).

Symptom modeling

The most general object model for the purposes of assessing the condition in terms of symptoms describes the functioning of the object, i.e., its main output of transformed energy (or product) and dissipation output, where we observe various types of residual processes (thermal, vibration, acoustic, electromagnetic) (Bendat, Piersol, 199; Cempel, 2000).

The presented object model is described by the vector equation:

$$G\ (X, S, E, Z, N) = 0 \tag{1}$$

The state of the object we are interested in can therefore be determined from the dependence:

$$X = g\ (S, Z, E, N) \tag{2}$$

Experimental implementation of the above dependence is possible after adopting simplifications assuming stability in the sense of mean values of vectors E, Z = 0, and resulting from the adopted model of the object. So we have:

$$X = F\ (S)_{Z,E= \mathrm{const}} + N \tag{3}$$

Taking into account the determinate domains of particular vectors of this relation, we obtain the basic equation of state in the form:

$$X\ (t, q,r) = A\ (r)\ S\ (q, r) + N\ (q,r) \tag{4}$$

The vector description of the structure of the object, its inputs: power supply, control and disturbances as well as power outputs (usable and residual) leads directly to the description of possible diagnostic relationships.

Structural modeling

A mechanical system can be described using a structural model in which its internal organization is needed to describe the internal organization of the tested object. There is also the correspondence of the elements of the model and the system as well as the convergence of the input-output relationship. Such a model shows the ***relationships between masses, elastic and damping elements, and excitations.***

This model can be discrete or continuous, linear and non-linear, stationary and non-stationary, static and dynamic, random and determinate.

The structural model of a mechanical system is most often described by a system of differential or algebraic equations, which can be derived based on the laws of dynamics, principles of variance, laws of continuity, etc. (Cempel, 2000; Mańczak, 1979).

The mechanical system can be described by ordinary, linear differential equations with constant coefficients, in matrix form (Uhl, 1997):

$$\mathrm{A}\left[D(\Theta)\right]\ddot{q}(t)+\mathrm{B}\left[D(\Theta)\right]\dot{q}(t)+\mathrm{C}\left[D(\Theta)\right]q(t)=F(t) \tag{5}$$

where: *A, B, C* - respectively matrices: masses (inertia), stiffness and damping;
$\ddot{q}(t),\dot{q}(t),q(t)$ - one-column matrices of accelerations, velocities and displacements;
F *(t)* – one-column matrix of external forces;
D(Q) – measure of destructive processes of wear as a function of object condition degradation.

During the operation of a technical object, due to corrosive, erosive, fatigue and abrasive wear, its dynamic properties change, i.e. inertia, deformability and energy dissipation. Therefore, by measuring the values of the relevant parameters of the system, it is possible to assess the technical condition of the object.

The dependence of matrix elements *A, B, C* on the degree of wear of the object *D(Q)* may, for example, be exponential [Uhl, 1997]:

$$\begin{gathered}\text{mass: } m(D)=m_0(1\pm\alpha_m D)^{\alpha_m};0\le\alpha_m\le1;\alpha_m\ge0\\ \text{attenuation: } b(D)=c_0(1\pm\alpha_b D)^{\alpha_b};0\le\alpha_b\le1;\alpha_b\ge0\\ \text{stiffness: } c(D)=c_0(1\pm\alpha_c D)^{\alpha_c};0\le\alpha_c\le1;\alpha_c\ge0\end{gathered} \tag{6}$$

In order to diagnose a technical object, it is necessary to identify the coefficients and exponents occurring in relation (6). Having established the values of these quantities, it is possible to track the change in the state of a technical object in the process of its existence.

Modeling using an energy processor

The similarity of the wear of various types of machines and their components leads to the search for general models of the evolution of life, mapped by the observed symptoms of the condition. This is possible for models built based on physical and energy considerations, for which the principles of energy flow and transformation are already known. Each case of a change in the state of the system is a reaction of a material object to excitations caused by direct or indirect energy impact. This reaction may be immediate, or it may be delayed until conditions permit its disclosure (Bendat, Piersol, 1996; Eykhoff, 1980).

Diagnostics is therefore a study of the object's reaction to energy interactions that cause a change in its state. The energy acting on the system, changing its state, changes itself. A quantitative or qualitative change in the energy itself can be a source of information about the state of the system, as can a change in the system caused by an energy interaction. This allows the use of energy as an information carrier when it is inherently related to the existence of the object, and also when it is supplied from the outside only to determine the state of the system on its basis.

The actual change in the state of the object is caused by a different form of energy than the one whose transformation is used for diagnostic purposes. The energy transformation used diagnostically is caused by the state of the object, and its characteristics are related to the structure and properties of the tested object. However, regardless of this, each energy transformation falls into one of the following model variants:

A. The subject of the tests are changes in physical quantities describing the energy emitted outside the system, diagnostic information is contained in the values of these quantities or the intensity of their changes. In this model, two cases can be distinguished resulting from differences in the way energy is diagnosed; either it is energy with known quantitative and qualitative parameters, or these values are unknown, only the effect of internal transformations in the system, visible in the energy emission, is examined.

B. The cause of the transformation is energy, but the symptoms of its interaction with the system are visible in material transformations - diagnostic information is contained in the values of physical quantities characterizing the quantity or quality of matter. Two cases can be distinguished here as well. The first, when the energy is supplied in the form of a specific stream, and the second, when the energy carrier is a material body, usually one of the elements of the system. These effects can be located in the material of the system element or in the energy derived from it, e.g. exaelectron emission, acoustic wave emission, etc.) or in the material of the energy carrier.

C. The cause of the transformation is the release of the energy accumulated in the system, taking place under the influence of the changed conditions of its existence. Diagnostic information is contained in the intensity of energy emission and in the spatial location of the emission source and may concern both changes in conditions and object properties.

Therefore, for the energy model of the machine in general terms, the following can be determined:

- estimation of distributions and mean symptom operators;
- limit values of condition symptoms;
- residual dimensionless lifetime of the object;
- the remaining number of cycles to failure;
- predicted values of condition symptoms;
- the date of the next diagnosis of the condition.

Energy object model

In general systems theory, a machine can be thought of as an open operating system with mass, energy, and information flows purposefully constructed to perform a specific mission. Thus, these are systems that transform energy, with its inherent internal and external dissipation. Thus, the input stream of mass (material), energy and information is converted into two output streams, useful energy in the form of its other desired form or product being the design goal of a given object. The second stream is dissipated energy, partly exported to the environment, and partly accumulated in the facility as a result of various wear processes occurring during the operation of machines and devices. The advancement of these wear processes determines the quality of functioning of each object and determines its technical condition (Eickhoff, 1980).

The internal dissipation of ND energy is due to (Ni): surface and volumetric fatigue, friction including fretting, erosion in the particle stream, corrosion of all kinds, and high temperature flow and high load creep. All these processes make up the total energy added to the ED. The amount of this energy, or better, the dissipation intensity, i.e. the ND power, depends on the operating time of the object θand on the external dissipation power V(q). Therefore, the following dependencies (Bishop, Gladwell, Michaelson, 1980) are correct:

$$N_D = (1-\eta)N_i \text{ - additional power} \tag{7}$$

and the advancement of consumption proportional to the internal dissipation energy of the system, the maximum value of which is limited by the relationship:

$$Z(\Theta) \approx E_D(\Theta, V(\Theta, ...)) \le E_{Db} \tag{8}$$

where: E $_{\mathrm{Db}}$ - limit value of added energy just before machine failure.

In this case, with continuous use, changes in consumption Z (q) » ND (...) q £ E $_{\mathrm{Db}}$, proportional to energy changes, for $0 \le \Theta \le \Theta_b$ give a linear model of destruction.

By analyzing the process of the formation and life of an object, it is possible to easily determine what the energy (power) of dissipation E $_D$ depends on:

$E_D(\Theta, V(\Theta), K, W, R, N)$ - for repairable objects (9)

where: Q- lifetime of the object,
V(Q) - power of residual processes (temperature, vibrations - increasing the intensity (power) of dissipation (wear);
K - quality of construction,
W - quality (level) of manufacturing,
R - intensity of traffic loads,
N - quality of repairs and technical services.

Thus, the model of evolution of the machine destruction symptom can be defined as:

$$S(\Theta) = S_0\left(1 - \Theta/\Theta_b\right)^{-1/\gamma}, \ S_0 = V_0^{1/\gamma} \qquad 0 \le \Theta \le \Theta_b, \ \gamma > 0 \tag{10}$$

and in general:

$$S(\Theta) = \frac{S_0(K, W, R, N)}{\left(1 - \Theta/\Theta_b(K, W, R, N)\right)^{1/\gamma}} \tag{11}$$

where: K - construction level,
W - manufacturing technology,
R - movement, loads,
N - repairs.

The conclusions from the observation of real objects, which lead to the description of the object destruction model in the form of a differential equation, are as follows (Bishop, Gladwell, Michaelson, 1980):

- residual processes control the intensity of wear: $E_D(\Theta, V(\Theta), \ldots)$;
- the increase in the power of residual processes occurs as a result of the increase in lost energy:

$$dV(\Theta) = \beta dE_D(\Theta, V(\Theta), \ldots);$$

- the total energy of destruction (dissipation) for each object is limited:

$$0 \le E_D(\Theta) \le E_{Db};$$

Without going into further details of the presented model of object destruction (Bendat, Piersol, 1996; Cempel, 2000), the considerations so far can be summarized in the form of general statements that inspire further improvement of the model, especially in terms of the possible optimization of diagnostic activities. And yes:

* considering simple experimental relations of diagnostics and tribology, in which the relation is correct: $V(\Theta) \approx Z(\Theta) = E_D(\ldots)$ it was possible to develop a model of machine destruction:

$$V(\Theta) = V_0 (1 - \Theta / \Theta_b)^{-1}; \tag{12}$$

* this model has important constructional implications V_0 (K, W, R, N), operational

Θ_b (K, W, R, N) and diagnostic: such S = f(V) by g= min.;

* energy measure of destruction D, depending on the type of process, is a quotient of times or cycles:

$$D = \sum \frac{\Theta_I}{\Theta_b(\sigma_i)}, \quad D = \sum n_i / N_b(\sigma_i) \tag{13}$$

* the obtained model of destruction is a generalized symptom model of destruction from the time domain into a given measure of destruction:

$$S(D) = S_0(K, W, R, N)(1 - D)^{-1/\gamma} \tag{14}$$

* it is possible to generalize the machine destruction model to the production system and technology reproduction.

The model of destruction of the energy transforming system presented here can be used to describe changes in the dynamic state of both the entire object and its individual subassemblies and parts (Bendat, Piersol, 1996; Cempel, 1989). In the simplest terms, the energy model of a single element can be presented in the following form (Fig. 1):

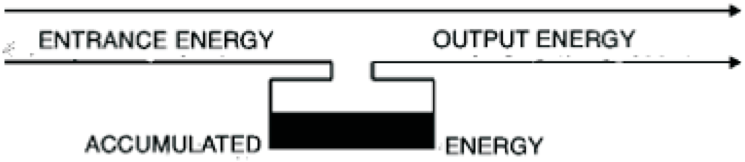

Fig. 1. The energy model of single element

Source: Augustyn, Żółtowski, 1999. Model of energy flow and accumulation of a single element

By determining such individual models for partial excitations in the facility and then adding them up for the entire facility, an evolutionary model is obtained that clearly describes changes in the condition symptoms under variable loads.

Building models of object operation process

There are two ways to create a mathematical model of the research object for the operation of technical objects:

- based on experimental research (experimental method). This way of creating a mathematical model is adopted if the theoretical basis is unknown or the phenomena in the research object are particularly complex;
- based on a theoretical analysis of phenomena related to the object (theoretical method).

Experimental method

The scheme of the process of creating a mathematical model of the research object primarily concerns the creation of a qualitative model of the object (Morrison, 1996), which is defined by the relation:

$$F_z(x_1, x_2, \ldots, x_m, y_1, y_2, \ldots, y_n, c_1, c_2, \ldots, c_s, z_1, z_2, \ldots, z_k) \qquad (15)$$

$x_1, x_2, \ldots, x_m$ – input quantities (control quantities, independent quantities , investigated factors), the values of which can be selected to create an experiment plan;

$y_1, y_2, \ldots, y_n$ – output quantities (decision quantities , result quantities, dependent quantities, result factors), the values of which are the results of measurements depending on the input values set in the experiment plan;

$c_1, c_2, \ldots, c_s$ – constant values, whose values are deliberately not changed during experimental research;

$z_1, z_2, \ldots, z_k$ - disturbing quantities (interfering factors) that are either known and measurable but deliberately omitted, or known but not measurable, or unknown and their influence on the experiment result is accidental.

Having a qualitative model of the research object, one should (Żółtowski, Niziński, 2010):

1) develop an experiment plan,
2) realize experiences,
3) perform a statistical and substantive analysis of the results of the experiments,

4) strive using the function of the research object of the form:

$$y=F(x_1, x_2, \ldots, x_i), \tag{16}$$

being only an approximation function to create a mathematical model of the system.

The function of the research object can be determined as a dependence approximating the measurement results and it can remain as such and be used, for example, for optimization and control. The function of the research object can become a mathematical model after transformations that logically illustrate the theoretical cause-and-effect relationships inherent in the research objects. This function can only be considered as its mathematical model after its logical compliance with the physical, chemical and other laws governing the real object, which in practice comes down to giving a physical interpretation to the coefficients of the models.

The model created in this way meets not only the cognitive purpose of the research, presenting new information in an unambiguous and condensed form - a mathematical function, but above all it can be used in practice. However, some disadvantages of the model created through experimental research should be borne in mind, e.g.:

- often the model reflects only a random statistical correlation, and not a real cause-and-effect relationship;
- the model cannot be extrapolated beyond the experimental test conditions;
- the model as a mathematical function may be subject to admissibly formal transformations, which may be in contradiction with the physical meaning of these procedures.

In some publications (Cempel, 1989; Wiśniewski, 1985), the act of determining the structure and parameters of the model is called identification, while the confrontation of the model with real data is called verification. In other words, verification - it is checking whether the model correctly reflects the process of exploitation of technical objects.

Theoretical method

In the theoretical method, four stages of model construction can be distinguished (Cempel, 2000; Wiśniewski, 1985):

- modeling;
- experiment;
- estimation;
- verification.

Methods used for dynamic analysis of objects

The most requirements are related to the sphere of product exploitation. This is understandable when we consider its use as the raison d'être of an object. In this regard, the following can be distinguished:

- durability and reliability requirements,
- requirements related to the effectiveness of use (efficiency, efficiency, costs),
- requirements directly related to use (universality, ease of use, susceptibility to renewal, automation),
- requirements related to the impact on the environment (quiet operation, safety, ergonomics, environmental pollution).

The following methods are used to study the dynamics of objects (Żółtowski, Cempel, 2004):

Vibration methods

Qualitative measures of the dynamic state include various measures defined in terms of time, frequency and amplitudes, which reflect changes in the state of both objects as a whole, as well as their individual elements and parts. The available simple and complex measures of the vibration process are widely used in various methodologies for assessing changes in the state of objects.

Finite element method (FEM)

A characteristic feature of FEM is the modeling and calculation of the dynamic properties of the object and the ability to quickly introduce changes in the support structure and assess their impact on vibrations.

Rigid Finite Element Method (MSES)

Compared to FEM, this method is a simplified method, but much faster and less laborious. It can be used with small computers, giving the designer some insight into the dependencies involved. Its main advantage is the ease of interpretation and calculations. Using the SES method, it is possible to test the impact of certain construction procedures easily qualitatively on the level of generated noise. The developed program makes it possible to compare the level of noise produced by smooth or ribbed plates of the required mass and stiffness. The plate is modeled using rigid finite elements (SES) and elastic-damping elements (EST).

Modal analysis

The purpose of the modal analysis is to stimulate the support to vibrate using a vibrator or hammer and measure the response (vibration acceleration) in many points of the support, which is used to determine the structure of the model and determine its parameters. Model parameters: eigenfrequencies, *damping and eigenvectors* (called vibration modes) are determined during identification in the experiment. A characteristic feature of the modal analysis is the animation of the form of housing vibrations, which allows the optimization of the dynamics of the transmission.

Vibration reproduction using laser interferometry (VPI)

This method enables quick serial checking of machine dynamics by obtaining a color - three-dimensional image of housing vibrations. The measurement is possible thanks to the phenomenon of wave interference, with a laser as the radiation source. The laser beam checks the state of vibration displacements of the housing surface without contact.

Acoustic holography

Acoustic holography deals with the preparation and use of a record of information about the amplitude and phase of coherent radiation reflected from a given object. By using two beams of radiation and using the phenomenon of interference, the state of displacement of the housing surface is obtained, recorded on a hologram.

Conclusions

The considerations presented in this paper concern a modern approach to modeling the dynamic state of objects, using the description and research in the field of identification, with the distinction of various methods and issues directly supporting various ways of shaping the dynamics of machines. The evolutionary dynamic models created in this way should improve the methodology and reasoning in the assessment of the dynamic state, often used for optimization and supporting operational decisions.

It is assumed that in identification tasks, a specific form of the mathematical model is proposed first, and then the values of its parameters are determined. When determining the values of the parameters, one proceeds strictly according to a specific algorithm, observing strict rules of conduct. For typical vibrating engineering systems, the linear model is assumed a priori. It is usually a model of the form, based on knowledge of the structure of the real system, or based on the analysis of the measured response to a specific set of inputs.

Knowledge of the dynamic state and structure of the system makes it possible to describe its behavior and to build prognostic models of the system's behavior as a function of dynamic evolution time, based on the growth model of technical condition symptoms.

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