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Appliance of mechanical energy converting elements to condition monitoring

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Introduction

The theory of a conversion model of the mechanical energy into the electrical one is based on the Lagrange equations of the second order describing elastic oscillations of inspected mechanical systems, on the equations of the conversion effect and on the equations of dissipation or withdrawal of the converted electrical energy. It means that the whole electromechanical system consists of three sub-systems: mechanical, conversional and electrical. A general model was developed by author [1,2] enables us to analyze the parameters of the converted energy according to different parameters assigned by both physical and mechanical properties of the inspected system and disturbances. This model also allows us to optimize the parameters of converting and withdrawing the converted electrical energy from the sub-systems taking into account the reason of the conversion process. By seeking to convert the maximum sensitivity of the autonomous inspection unit to some defects of the mechanical system (crack, loosening fixture, change of the vibration frequency spectrum, etc.) considering the imposed constraints, it is possible to obtain an optimal conversion of a sub-system of the whole system mentioned above. The theoretical investigation and numerical experiments with models allowed us to create the diagnostic devices for constructive elements in rotor systems [3, 4] and others applications.

Mathematical model

For creation of the energy conversion model and its investigation a finite elements method was used (when analyzing mechanical sub-system and mechanical energy converting sub-system), also the method of matrix algebra (when analyzing the equivalent electric scheme of energy conversion sub-system and loading sub-system).

According to requirements of the finite element method the following system of equations was used:

$$\begin{cases}\mathbf{M}\ddot{\overline{q}}+\mathbf{H}\dot{\overline{q}}+\mathbf{K}\overline{q}+\mathbf{T}\overline{\Phi}=\overline{F}\\ \mathbf{T}^{T}\,\overline{q}+\mathbf{S}\overline{\Phi}=\overline{Q}\end{cases}. \tag{1}$$

Here K, M, H, T, S are the structural matrices of stiffness, mass, damping, electrical elasticity and capacity respectively; $\overline{Q}$ and $\overline{F}$ are the vectors of nodal point charges and forces respectively.

A general mathematical model of the abstract mechanical system which is shown in Fig. 1 and having conversion and dissipation (or withdrawal of the converted electrical energy) sub-systems was obtained in the following form [2]:

$$\begin{cases}\left(\mathbf{K}-\omega^{2}\mathbf{M}\right)\overline{q}_{s}-\mathbf{H}\omega\overline{q}_{l}+\mathbf{T}\overline{\Phi}_{s}=\overline{F}\\ \left(\mathbf{K}-\omega^{2}\mathbf{M}\right)\overline{q}_{l}-\mathbf{H}\omega\overline{q}_{s}+\mathbf{T}\overline{\Phi}_{l}=0\\ \mathbf{T}^{T}\,\overline{q}_{s}-\mathbf{S}\overline{\Phi}_{s}-\overline{Q}_{s_1}=0\\ \mathbf{T}^{T}\,\overline{q}_{l}-\mathbf{S}\overline{\Phi}_{l}-\overline{Q}_{l_1}=0\\ \left(\dfrac{C_0+C_1}{C_1C_0}-\omega^{2}L_1\right)\overline{Q}_{l_1}-R_1\omega\overline{Q}_{s_1}+\dfrac{1}{C_0}\overline{Q}_{l_2}-\overline{\Phi}_{l}=0\\ \left(\dfrac{C_0+C_1}{C_1C_0}-\omega^{2}L_1\right)\overline{Q}_{s_2}-R_1\omega\overline{Q}_{l_1}-\dfrac{1}{C_0}\overline{Q}_{s_2}-\overline{\Phi}_{s}=0\\ \left(\dfrac{C_0+C_2}{C_2C_0}-\omega^{2}L_2\right)\overline{Q}_{l_2}-R_2\omega\overline{Q}_{s_2}+\dfrac{1}{C_0}\overline{Q}_{l_1}=0\\ \left(\dfrac{C_0+C_2}{C_2C_0}-\omega^{2}L_2\right)\overline{Q}_{s_2}-R_2\omega\overline{Q}_{l_2}-\dfrac{1}{C_0}\overline{Q}_{s_1}=0\end{cases} \tag{2}$$

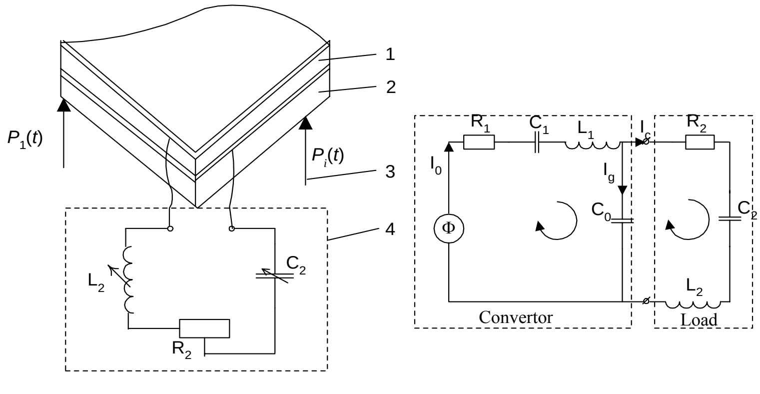

Fig. 1. **Simple abstract mechanical vibration system (a): 1-conversion sub-system; 2-mechanical sub-system; 3-excitation; 4-electric load. Equivalent circuit diagram of a conversion and load sub-systems (b)**

Where **M**, **H**, **K**, **T**, **S** are the general mass, damping, stiffness, electroelasticity, capacity matrices of the system, respectively; $\overline{q}_s, \overline{q}_l, \overline{Q}_s, \overline{Q}_l, \overline{\Phi}_s, \overline{\Phi}_l$ - vector components in the general system of coordinate: $\overline{q} = \overline{q}_l \cos\omega t + \overline{q}_s \sin\omega t$ – vector of a generalized displacement; $\overline{Q} = \overline{Q}_l \cos\omega t + \overline{Q}_s Q_S \sin\omega t$ – vector of the electric charge with corresponding indexes $\overline{Q_1}$ for the converter and $\overline{Q_2}$ for the load; $\overline{\Phi} = \overline{\Phi}_l \cos\omega t + \overline{\Phi}_s \sin\omega t$ – vector of E.M.F.; $\overline{F}$ - vector of the excitation force.

Numerical analysis of a mathematical model

From the given set of equations it is evident that the number of unknowns is equal to the number of equations, the equations being linear, and their solution can be found by using numerical methods. Let us consider some qualitative and quantitative characteristics of the conversion process from mechanical energy into the electrical one when a piezoelectric converter electrically charged and mechanically excited is a rectangular piezoceramic plate supported as a cantilever and has the following parameters: $l = 6{,}0 \cdot 10^{-2}$ m; $b = 2{,}0 \cdot 10^{-2}$ m; $h = 4{,}0 \cdot 10^{-3}$ m; $\rho = 6500$ kg/m^3; $\eta^S_{33} = 9{,}35 \cdot 10^{-9}$ F/m; $e_{31} = 1{,}51$ C/m^2; $C^e = 5{,}2 \cdot 10^9$ N/m^2.

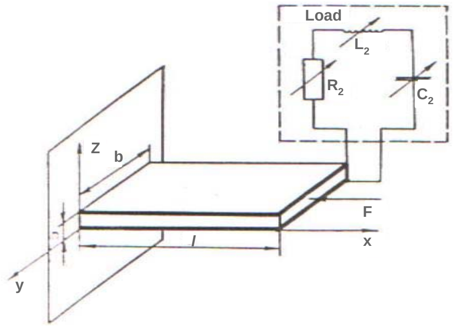

Fig. 2. **Scheme of electromechanical system with a piezoelectric converter and electric load used for calculation and experiments**

The design and calculations allow us to investigate the amplitude – phase frequency responses of the system, dependencies of the converter efficiency change on the load parameters, dependencies of the electric parameter change on the changing excitation conditions and characteristics of the mechanical sub-system.

This allows us with a help of a numerical experiment to investigate and theoretically validate the possibilities of converted energy usage in different condition monitoring and diagnostics instruments.

The results of the experiment are presented in Fig. 3 and 4.

The parameters of converted energy also reflect alternation of excitation conditions or characteristics of the mechanical sub-system. For example, while increasing the exciting force value, the relative change of voltage in the active resistance R_2 of the load increases according to the linear rule, also the electrical power (Fig. 5, curves 4 and 5 respectively). In the same graph there is presented the dependence of the relative change of resistance voltage drop versus the excitation frequency, in turn sensitivity depends on the load active resistance (1, 2, 3 curves).

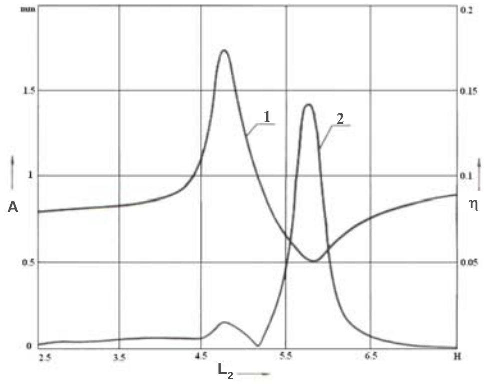

Fig. 3. **The dependency of free end piezoelectric plate displacement amplitude (1st curve) and energy conversion efficiency factor (2nd curve) to reactive load parameter L₂**

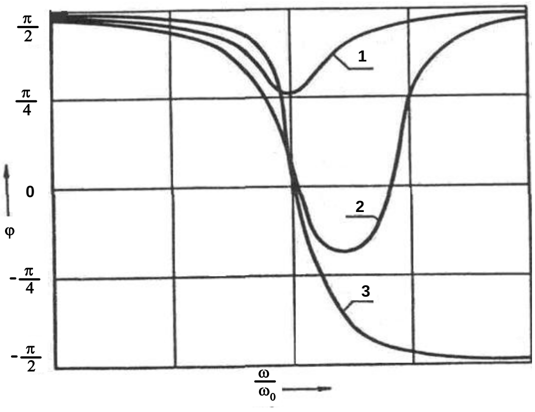

Fig. 4. **Phase frequency responses: 1 – mechanical sub-system; 2 – sub-system of converter; 3 – sub-system of load**

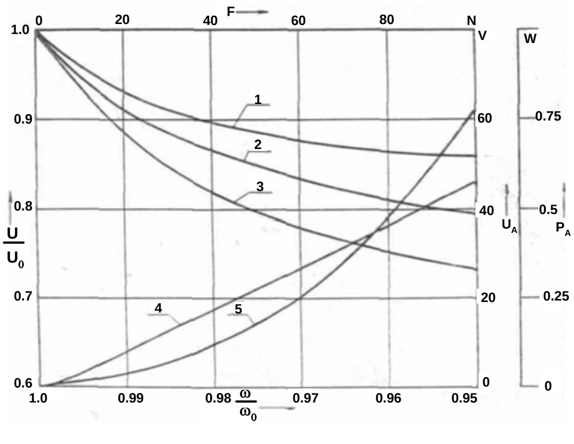

Fig. 5. **The voltage (curves 1-4) and the power (curve 5) change in the load, depending on the frequency (ω_0 – resonance frequency). Curves: 1- R_2 = 500Ω; 2 - R_2=1000Ω; 3 — R_3 = 1 500Ω**.

The dependencies presented in the Fig. 5 may be used for the monitoring and diagnostics of constructions, attaching indicators to the load measurement. The biggest sensitivity in this case was obtained when the resonance frequencies of mechanical construction oscillation and electric oscillation in load circuit coincide. The experiments with generating oscillations in the mechanical sub-system on its resonance frequency using vibration shaker showed that the amplitude of the plate free end and the mechanical energy conversion efficiency factor curves (see Fig. 6) are similar (they alternate according similar regularity) to the curves, which were obtained from calculations (Fig. 3). This fact confirms, that mathematical model properly describes the mechanism of energy conversion.

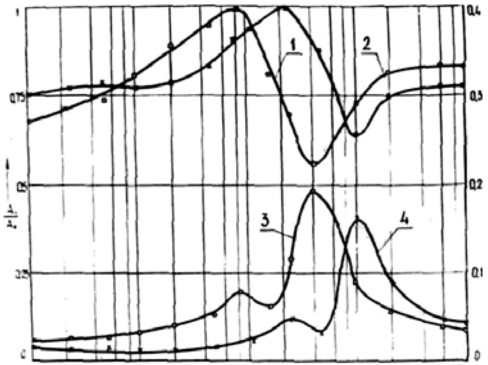

Fig. 6. **Experimental dependencies of piezoelectric plate free end relative amplitude $\frac{A}{A_0}$ (1, 2 curves) and alternation of energy conversion efficiency coefficient η to full electric resistance value Z of the load**

The numerical analysis of the mathematical model has indicated that such defects of the structural element as crack, loosing fixture, change of the vibration parameters, etc. are obtained. Built-in inspection is available practically when the power of a separate spectral component of the vibration is not less than 0,12 W. Fig. 7 represents the dependencies of the variation of the voltage decrease value on the active resistance of the load. The plots help to determinate the start 24 min and the end 34 min of the development of a crack, the start of self-unscrewing of a fastening screw of a structural element after 10 min and the increase in the exciting vibration level after 32 min.

Using the optimization of the parameters of the general model (but not the mechanical sub-system parameters), it is possible to simulate the process of the energy conversion with the best set of the parameters of the attached passive load and to evaluate the possibilities and advantages of using the converted energy in terms of diagnostics and monitoring [2].

In general, spectrum of construction vibrations is quite complicated, though in most practical cases it has typical several predominant frequency components, so with the help of piezoelectric converters, fixing them in the places of concentration of mechanical system potential energy and attaching electrodes to the adjusted filters, monitoring of predominated spectral frequencies may be performed and according to changes the decisions about inspected system technical state may by made. The example of such a solution is presented in Fig. 8

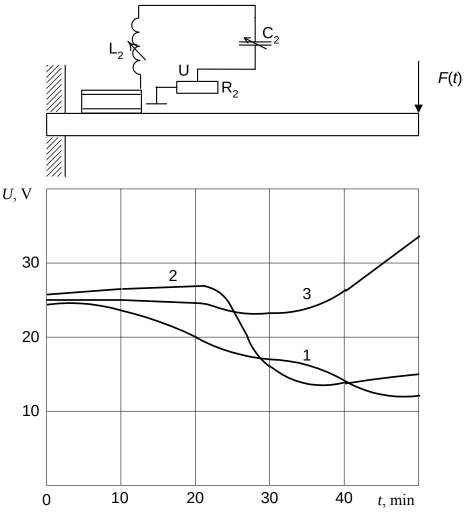

Fig. 7. **Dependencies of the change of the resistance voltage drop value on the active resistance of the load with the appearance of defects. Curves: 1 - formation of fatigue crack; 2 - when changing of fastening conditions; 3 - when increasing exciting forces**

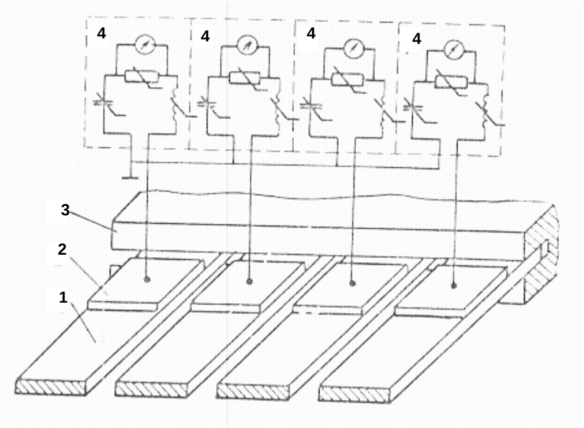

Fig. 8. **Scheme of the built-in inspection of construction, using mechanical energy conversion into electrical one: 1 - cantilever beam with the resonance frequency ω_i; 2 – piezoelectric plate or film; 3 – inspected construction**

Theoretical investigations and experiments made allowed to develop a number of devices for built-in inspection, a few of them are presented below.

Built-in inspection

Cracks occurring in the elements of rotating mechanical constructions emit high frequency signals. These signals, however, are often masked by other noises or are too weak to be reliably registered by measurement systems. Thus such defects in, for example, turbine blades are found only when the vibrations increase, due to increases in the misbalance of rotating constructions. The evaluation of these processes using built-in autonomous devices capable of converting the vibration energy into electrical energy makes it possible to determine the technical state of such systems. A mathematical model of high frequency vibrations like described above may be used. Such the model describes the elastic oscillations of the mechanical sub-system in the zone of the element being inspected, the conversion of the oscillation energy into the electric energy, and the process by which an electric voltage and its changes are transmitted from the rotating element (rotor) to the stationary base (stator), where the load is read by a voltage indicator or other measurement instrument. The modeling enables development of a device for built-in inspection of cracks in the rotating element of the turbine. A schematic drawing of the device is shown in Fig. 9.

Applying appropriate measurement technologies, a series of experiments were carried out which confirmed the suppositions made at the initial stages and the predicted results. As it can be seen from Fig. 9 c, a crack in the rotor blade of a high speed turbine was registered for more than 20 s (in experiments 80% of the turbine blade was then broken off near the base). It was possible to be achieve only because a device highly sensitive to high frequency tension waves had been fixed at the side of a possible defect and there were no intermediate elements, creating noise (transmitters and amplifiers, etc.) and also because optimal geometric and electrical parameters were chosen when developing the model.

The effectiveness of the described method is especially high when used in rocket and aircraft turbines operating under high loads for which the exploitation resources are strictly limited and there are especially high reliability requirements.

The converted energy also can be used to decrease the vibroactivity of a mechanical system and for vibration level monitoring goals. As example a damping device could be mentioned, which was designed for decrease of vibration of rotating shafts and rotors (Fig. 10) operating through the critical speed. Damping of vibrations in the device proceeds through friction between components and through oscillation energy conversion to electrical with a help of bimorph piezoelectric plates, and in result this energy goes to an electric load. While measuring the voltage drops in the resistance, vibration level may be controlled.

It is purposeful to use piezoelectric converters in devices, which can be applied in active vibration and acoustical noise compensation of various constructions, for example, covers of power machines (Fig. 11). In this case compensation efficiency may be inspected.

Usually such devices are complex and expensive. Using two plates, mounted on both sides of the cover with different directions of converters polarization allows applying one of them as a transducer and a filter, and another one as a phase inverter and vibration exciter. The design of the mentioned devices may be simplified, so, reliability and durability increase. The filtration of the signal from the first piezoelectric plate is performed by choosing the most optimal configuration of the external electrode and this enables to distinguish the required frequency of vibration spectrum, separate a high frequency noise and control the vibration of the cover.

Analysis of autonomic devices and also application of theoretical and experimental investigations allows foreseeing following trends of usage of vibration energy conversion to electrical one:

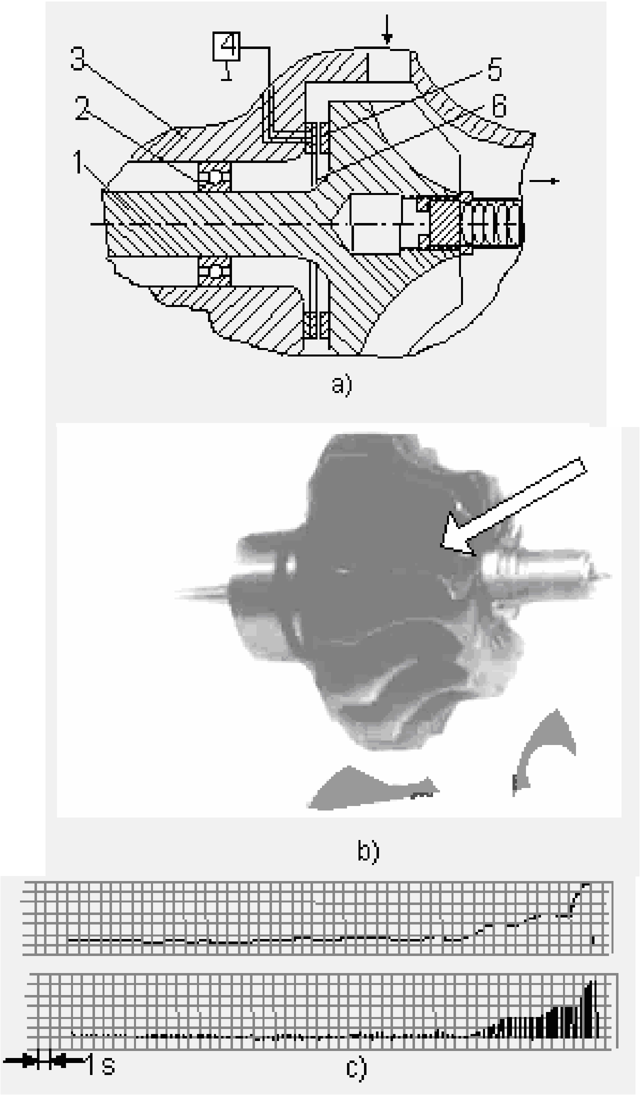

Fig. 9. **A device for monitoring cracks in a turbine (a): 1-rotor; 2-bearing; 3-stator; 4-indicator; 5- piezoelectric plate; 6-metal ring dielectrically fastened to the stator. The rotor with several blades torn away (b). The signals (peak values and intensity) of a rotor had measured during experiment time (c)**

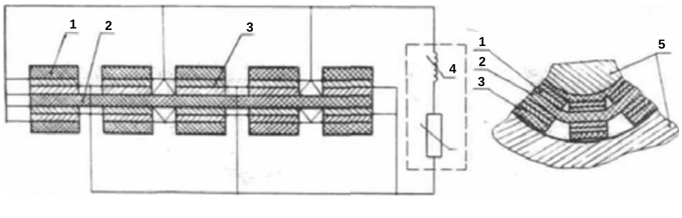

Fig. 10. **Scheme of vibration damping device of rotating shafts and rotors, operating through the critical speed: 1 – damping sections, 2 – rubber base, 3 piezopolymeric bimorph plates, 4 – electric load, 5 – damped construction**

1. Vibrodiagnostics of technical state of machinery construction on the ground of converted energy parameters.
2. Decrease of vibroactivity and stabilization of vibrations of mechanical systems both by applying converted energy for creation of compensating vibrations.

3. Usage of the converted energy as secondary source of energy.

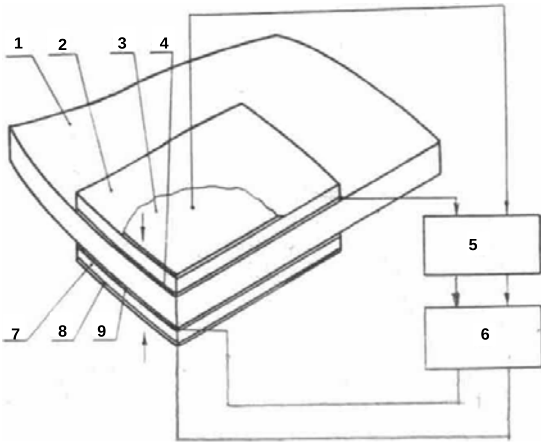

Fig. 11. **The scheme of device for vibration or acoustical noise level control of electric machine cover and active compensation of these processes: 1 – part of cover, 2 and 7 – piezoelectric elements, 3, 4, 8 ir 9 – external and internal electrods of piezoelements, 5 – attenuator, 6 – amplifier (the polarization voltage of piezoelectric plate is shown by arrows)**

Successful realization of previously described trends requires solution of several tasks, related to selection and optimization of parameters of converters, position, and subdivision of frequency components and also presentation of processed energy, to be easily used further. Some of these problems are solved by R. Bansevičius [5, 6] to observe polymerization processes, for monitoring of composite construction [7] and other applications of built-in inspection.

Prior analysis of uncertainty evaluation in built-in channel vibration measurements

Science and industry increasingly requires that the quality of a measurement be stated by an assessment of the measurement uncertainty. While modelling measuring system and optimizing its parameters, it may be necessary to make prior uncertainty evaluation model, at the same time evaluating influence factors. The first requirement when starting uncertainty analysis here is to identify the model functions $Y = f(X_1, X_2, ..., X_N)$ where Y is the measurand determined from N input quantities $X_1, X_2, ..., X_N$ through the functional relationship f. Analyzing the complex system, depicted in Fig. 1, two parts were excluded. The first part consists of conversion and mechanical sub-systems, which generate the voltage U_1.

$$U_1 = K_p \cdot \delta\,, \tag{3}$$

where U_1 is the voltage, generated by conversion sub-system; K_p is the coefficient, which depends on the characteristics of piezoplate; δ is the deformation in a piezoplate.

The load sub-system is defined by

$$U_{out} = I_2 \cdot R_2\,, \tag{4}$$

where

$$I_2 = \frac{U_1 \dfrac{1}{\omega C_0 z_{11}}}{\sqrt{\left(r_{22} + r_{11}\dfrac{x_{12}^2}{z_{11}^2}\right)^2 + \left(x_{22} - x_{11}\dfrac{x_{12}^2}{z_{11}^2}\right)^2}}\,. \tag{5}$$

The variables in this equation z_{11}, z_{22}, r_{11}, r_{22}, x_{11}, x_{22} can be found using system of equations:

$$\begin{cases} z_{11} = R_1 + R_2\dfrac{x_{12}^2}{z_{22}^2} + j\left(\omega L_1 - \dfrac{1}{\omega C_1} - \dfrac{1}{\omega C_0} - \dfrac{x_{12}^2}{z_{22}^2}\right) \\ z_{22} = R_2 + R_1\dfrac{x_{12}^2}{z_{11}^2} + j\left(\omega L_2 - \dfrac{1}{\omega C_2} - \dfrac{1}{\omega C_0} - \dfrac{x_{12}^2}{z_{11}^2}\right) \end{cases},$$

$$\begin{cases} r_{11} = R_1 + r_{22}\dfrac{x_{12}^2}{z_{22}^2} \\ r_{22} = R_2 + r_{11}\dfrac{x_{12}^2}{z_{11}^2} \end{cases},$$

$$\begin{cases} x_{11} = \omega L_1 - \dfrac{1}{\omega C_1} - \dfrac{1}{\omega C_0} - x_{22}\dfrac{x_{12}^2}{z_{22}^2} \\ x_{22} = \omega L_2 - \dfrac{1}{\omega C_2} - \dfrac{1}{\omega C_0} - x_{11}\dfrac{x_{12}^2}{z_{11}^2} \end{cases},$$

where C_0, C_1, C_2 – capacities of electric circuits; L_1, L_2 – inductivities of electronic circuits; R_1, R_2 – active resistances of electric circuits.

The characteristic of the technical state of mechanical system here is the variable U_{out}. It depends on the voltage which is induced by piezoplate U_1. The influence factors affect its components: piezoelectric factor and deformation of piezoplate. So, Fig. 12 depicts the influence factors, which should be taken into account while analyzing uncertainty of the vibration measurement with built-in device.

Particular mechanical systems and built-in devices have different specific characteristics and the mentioned influence factors differently affect the measurand. Besides, the vibration is determined using the measured output voltage, and thus here comes additional uncertainty contribution when applying the relationship between output voltage and vibration characteristics required to make decision about current state of mechanical system.

Conclusions

The investigations carried out for the development of the mathematical model are premises for making autonomous built-in inspection devices in various technical objects. Moreover, the cheapest and the most reliable version can be obtained by converting the energy of elastic waves into the electric energy.

Nowadays the above given theory is practically applied to vibration diagnosis of crack formation in heavily loaded rotor systems, to the inspection of the processes of vibrational ageing of structures and to the other fields. The obtained results allow us to predict its broad application in the future. The methodology of uncertainty evaluation allows investigate influence factors in project stage and evaluate their interrelation. The uncertainty model for real constructions could be made by using their particular characteristics and analyzing the way influence factors affects the mechanical and conversion sub-systems.

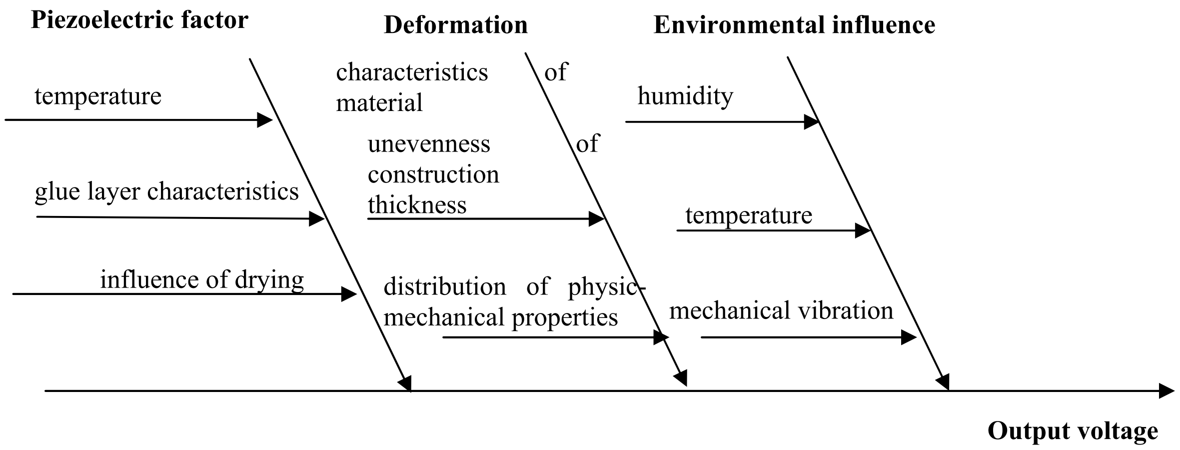

Fig. 12. **The scheme of cause-effect diagram of uncertainty influence factors for vibration measurements with built-in piezoelectric converter**

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V. Volkovas, M. Eidukevičiūtė

Mechaninės energijos keitiklių naudojimas integruotoje kontrolėje

Reziumė

Pasiūlytasis mechaninės energijos keitimo į elektrinę modelis parodo, kad remiantis šiomis technologijomis autonominiai diagnostiniai prietaisai gali būti tobulinami. Šie prietaisai, kurie buvo ištirti teoriškai ir praktiškai, gali būti taikomi integruotoje kontrolėje. Mechaninei vibracinei energijai keisti galima naudoti pjezoelektrines matricas, sujungtas su mechanine sistema. Keitikliai, pagaminti iš pjezokeramikos ar pjezoplėvelės, įdiegti į kontroliuojamus objektus, gali dirbti gana patikimai. Energijos keitimo santykinis tikslumas ir galimybės sprendžiant monitoringo ir diagnostikos problemas gali būti įvertinti modeliuojant bendro modelio dinamiką pagal mechaninės sistemos techninę būklę. Siūlomas konkretus techninės būklės monitoringo ir konstrukcinių elementų įtrūkimo diagnostikos sprendimas skirtingose mechaninėse sistemose. Išnagrinėti veiksniai, darantys įtaką matavimo neapibrėžčiai.

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