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SOFTWARE SERVICE FOR DETERMINING THE PARAMETERS AND CHARACTERISTICS OF THIN PIEZOELECTRIC DISK

Disk piezoelectric devices are widely used in elements of information systems. The multiplicity and variety of practical applications of disk transducers naturally stimulate theoretical research, the purpose of which is to predict the characteristics and technical parameters of piezoeletronic devices created on their basis. The forecast is based on a mathematical model, which is the main result of a theoretical description of a real device.

The purpose of the study is to develop a service for determining the parameters and characteristics of a thin piezoelectric disk that oscillates radially.

The scientific novelty of the work lies in the development of the software service in the MATLAB programming language for determining the parameters and characteristics of a thin piezoelectric disk that oscillates radially, which allows to determine with high accuracy and adequacy the frequency dependence of electric impedance modulus, which allows to determine the frequencies of electromechanical resonance and anti-resonance of a thin piezoelectric disk.

The practical significance of the capabilities of the developed model, as well as the software tool for its implementation, lies in the experimentally confirmed results of the calculation of the main parameters of the piezoelectric disk transducer, which confirm the high accuracy and efficiency of such modeling, for the possibility of integration in information and measurement systems.

Keywords: *piezoelectric disk element, physical processes, electrical impedance, oscillations, program service.*

Introduction. One of the most important issues that arise for the management of modern infrastructure is the need for timely and effective diagnostics of the state of its components. An insufficient level of diagnostics can lead to the need for costly repairs or emergency or even dangerous situations [1].

At the same time, ultrasonic diagnostics is one of the most effective methods for assessing the state of urban infrastructure [2]. To ensure sufficient quality of such diagnostics, it is necessary to develop and implement high-precision and reliable ultrasonic sensors. One of the key elements of such a sensor is a piezoelectric element designed to convert a mechanical energy into an electrical signal. However, the use of ultrasonic piezoceramic sensors as the main elements of a diagnostic device is currently limited by the poor knowledge of the influence of the operating parameters of these sensors on the accuracy and reliability of the diagnostic process [3].

Disk piezoelectric devices are widely used in elements of information systems [4-8]. Disks with sectorial surface electrodeposition are practically the main element of many microelectromechanical structures [9]. The multiplicity and variety of practical applications of disk transducers naturally stimulate theoretical research, the purpose of which is to predict the characteristics and technical parameters of piezoelectronic devices created on their basis.

At the same time, the use of mathematical modeling for the development of new ultrasonic diagnostic technologies can solve this problem and establish adequate patterns of the influence of operating parameters of such sensors on the accuracy and reliability of the diagnostic process.

The forecast is based on a mathematical model, which is the main result of a theoretical description of a real device. The practical significance of a mathematical model adequate to a real object is obvious. As a result of studying the mathematical model of a real device, it is possi-

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ble to determine a set of geometric, physical, mechanical and electrical parameters of a real object, which ensures the implementation of technical indicators of a functional element of piezoelectronics, due to the technical problem. This significantly reduces the time and cost of developing new functional elements of piezoelectronics. The cost of saved resources is the commercial price of the mathematical model.

The ultimate goal of mathematical modeling of the physical state of oscillating piezoceramic elements is a qualitative and quantitative description of the characteristics and parameters of electric and elastic fields existing in them. It is quite clear that obtaining meaningful and reliable quantitative estimates of the parameters of the physical state of piezoelectric (piezoceramic) elements is not possible without reliable data on the values of physical and mechanical constants of materials [10].

Thus, it is necessary to build a consistent method for determining the material constants of piezoceramics, which delivers reliable values of at least three moduli of elasticity, two elements of the matrix of piezoelectric modules and one element of the permittivity matrix [11].

Purpose and objectives of the research. Thus, *the purpose* of the study is to develop a service for determining the parameters and characteristics of a thin piezoelectric disk that oscillates radially.

To achieve this aim, it is necessary to solve the following objectives:

- Development of the "IPed" software service.
- Description of the main modes of operation of the developed software service.
- Experimental tests of the "IPed" software service.
- Analysis of the results of using the software service.

Materials and methods. Let's consider a disk (Figure 1), the thickness α of which is many times smaller than the radius R. The surfaces of the disk $z = 0$ and $z = \alpha$ (z is the coordinate axis of the cylindrical coordinate system ρ, φ, z, the origin of which coincides with the center of the lower surface of the disk) are electroded – covered with a thin (no more than 10 μm) layer of silver. An electric potential $U_0 e^{i\omega t}$ is applied to the top surface $z = \alpha$ (U_0 is the amplitude of the value of the electric potential; $i = \sqrt{-1}$; ω is the circular frequency; t is the time). The bottom electroded surface $z = 0$ is grounded, that is, it has zero potential.

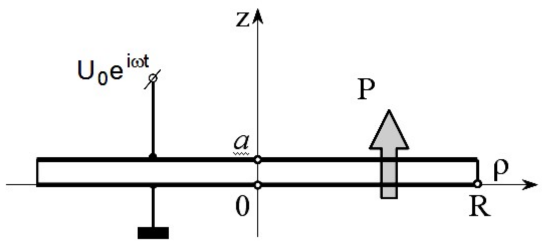

Figure 1. Calculation diagram of an oscillating piezoceramic disk

The electric potential difference applied to the disk creates an electric field in its volume, which displaces the ions of the disk from their equilibrium position. As a result of harmonically changing deformation of the disk in time, polarization charges arise in it. The resulting electric charge $Qe^{i\omega t}$ on the surface $z = \alpha$ with its electric field forms an electric current $I e^{i\omega t}$ in the conductor, which connects the surface $z = \alpha$ with the output of the electric generator. At any moment of time, $I e^{i\omega t} = -\partial Q/\partial t = -i\omega Q e^{i\omega t}$, that is, the amplitudes of the current and electric charge on the surface $z = \alpha$ are connected by a linear relationship $I = -i\omega Q$.

It is obvious that the electrical impedance $Z_{el}(\omega)$ of the oscillating disk must obey Ohm's law for a section of the circle, from which it follows that

$$Z_{el}(\omega) = \frac{U_0}{I} = -\frac{U_0}{i\omega Q}. \qquad (1)$$

Medium frequencies will be called the frequency range in which the scale unit of spatial heterogeneity of the stress-strain state (length of the elastic wave) becomes proportional to the radius of the piezoceramic disk.

The research [12] gives the calculation of the electrical impedance of an oscillating disk, which can be written in the following form:

$$Z_{el}(\omega) = \frac{1}{i\omega C_\partial^*} F^{(*)}(\omega), \qquad (2)$$

where

$$F^{(*)}(\omega) = \frac{\lambda R J_0(\lambda R) - (1-k) J_1(\lambda R)}{\lambda R J_0(\lambda R) - (1 - k - 2K_{31}^2) J_1(\lambda R)}; \qquad (3)$$

$K_{31}^2 = (e_{31}^*)^2 / (c_{11}\chi_{33}^*)$ is the square of the coefficient of electromechanical coupling of pie-

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zoceramics in the regime of radial oscillations of a disk polarized along the thickness; $C_{\partial}^{*} = \pi R^{2} \chi_{33}^{*} / \alpha$ is a dynamic electric capacity of the piezoceramic disk for the mode of planar oscillations, i.e. electric capacity in the mid-frequency range; $\chi_{33}^{*} = \chi_{33}^{\varepsilon}\left(1 + \Delta\chi_{33}^{*}\right)$ is the dielectric constant for the mode of planar oscillations; additive $\Delta\chi_{33}^{*} = e_{33}^{2} / \left(\chi_{33}^{\varepsilon} c_{33}^{E}\right)$ [12].

Research results. The program is designed to determine the parameters and characteristics of a thin piezoelectric disk that oscillates radially, in particular, the frequency dependence of the electric impedance module, which allows to determine the frequencies of electromechanical resonance and anti-resonance of a thin piezoelectric disk.

The algorithm of the developed service is shown in Figure 2.

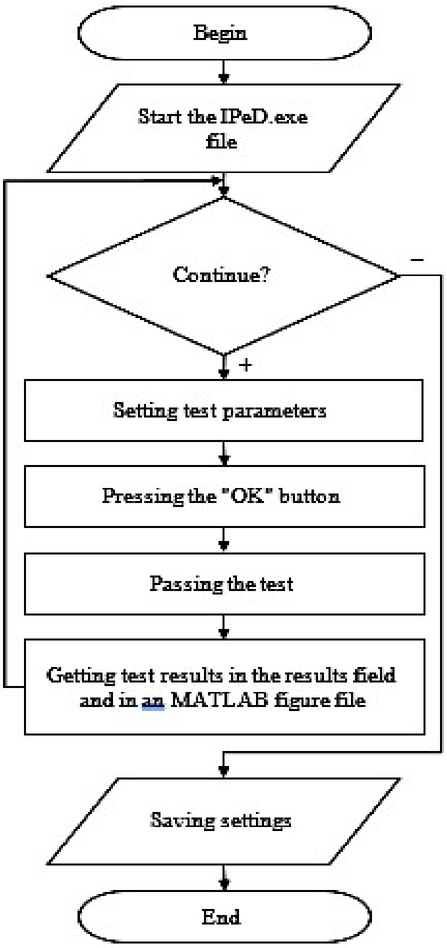

Figure 2. Algorithm of the "IPeD" software service

The developed software is implemented in the MATLAB programming language (Figure 3).

The user communicates with the computer through a graphical visualization interface.

To install the program, the user must run the IPeD_web.exe program installation file and go through the program installation process (Figure 4).

In the future, to work with the program installed on the computer, the following steps are performed:

1. To start the program, you need to run the IPeD.exe file.

2. In the program interface (Figure 5, *a*), the user must specify the input parameters of the piezoelectric disk:

- the radius of the piezoelectric disc *R*, m;
- the thickness of the piezoelectric disk *a*, m (for a thin disk, the condition *a/R* << 1 must be fulfilled);
- quality factor of piezoceramics *Q*;
- density of piezoceramic material *r*0, kg/m^3;
- modules of elasticity c11e, c12e and c33e, Pa (when describing the radial oscillations of a piezoceramic disk polarized along the thickness, knowledge of the material constants, namely the modules of elasticity c11e, c12e, c13e and c33e, is required. Comparing the results of measuring the elastic modules c12e and c13e, it can be seen that they differ from each other by an amount that rarely exceeds the level of 0.3-0.5% of the nominal value. Therefore, the estimation of the numerical values of the modulus of elasticity can be carried out under the assumption that c12e = c13e);
- piezoelectric modules e33 and e31, C/m^2;
- dielectric constant x0, $8{,}85 \cdot 10^{-12}$ F/m.

Press the button «Ok».

An example of the program interface with entered input data is shown in Figure 5, *b*.

3. The program automatically opens the "Figure 1" window (Figure 6), where a graph of the dependence of the electrical impedance [Ohm] of the piezoelectric disk on the relative frequency value is displayed.

The calculation results can be saved in a *.fig file by clicking "File" → "Save as".

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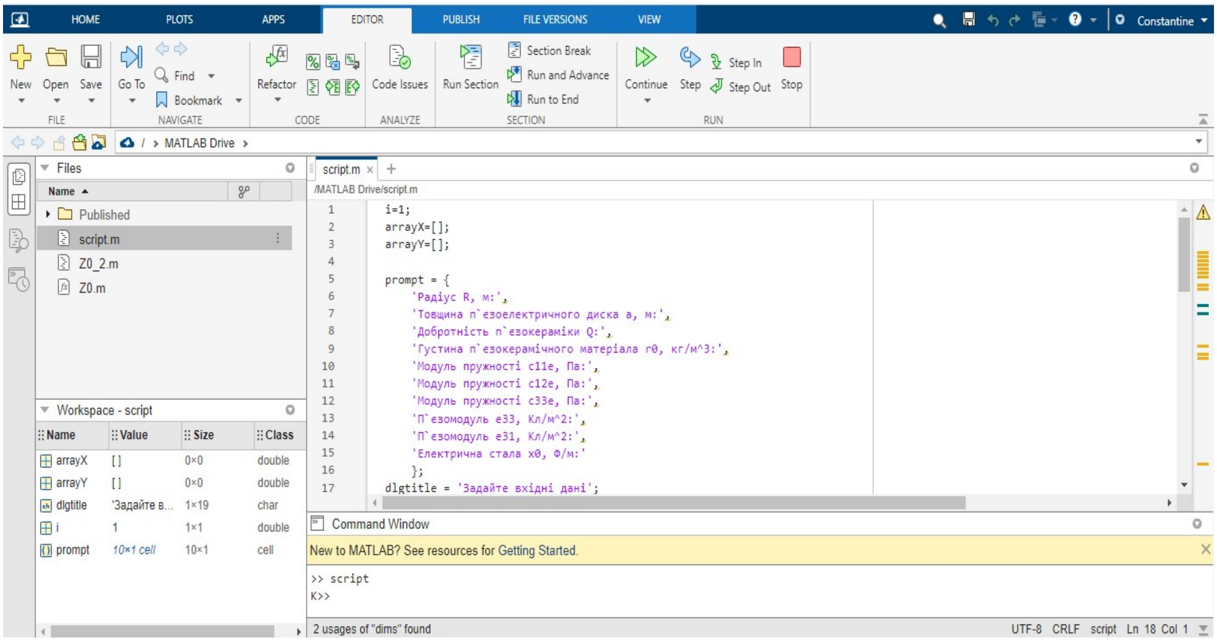

Figure 3. Fragment of a listing of a mathematical problem

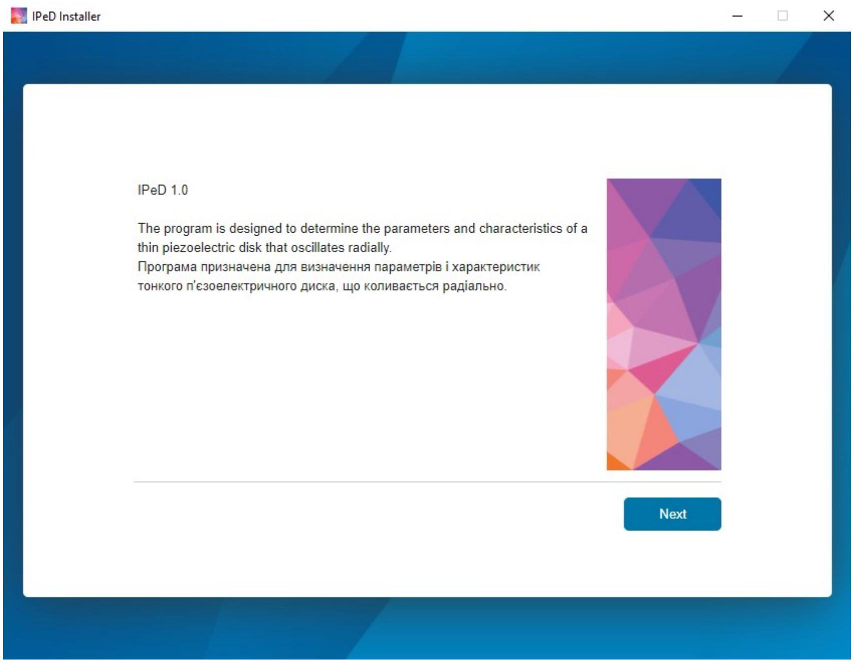

Figure 4. Program installation process

The method of experimental determination of the electrical impedance of a piezoceramic disk is considered in [13]. The scheme for conducting experimental research is shown in Figure 7.

Massive disks were used for experimental research. At the same time, the effects associated with the attached mass, which occurs in the process of soldering conductors to the electroded surfaces [14] of the disk, are minimized.

When measuring the electrical impedance $Z_{el}(\omega)$, the disk was suspended in the air on thin threads in order to avoid mechanical contact with other objects.

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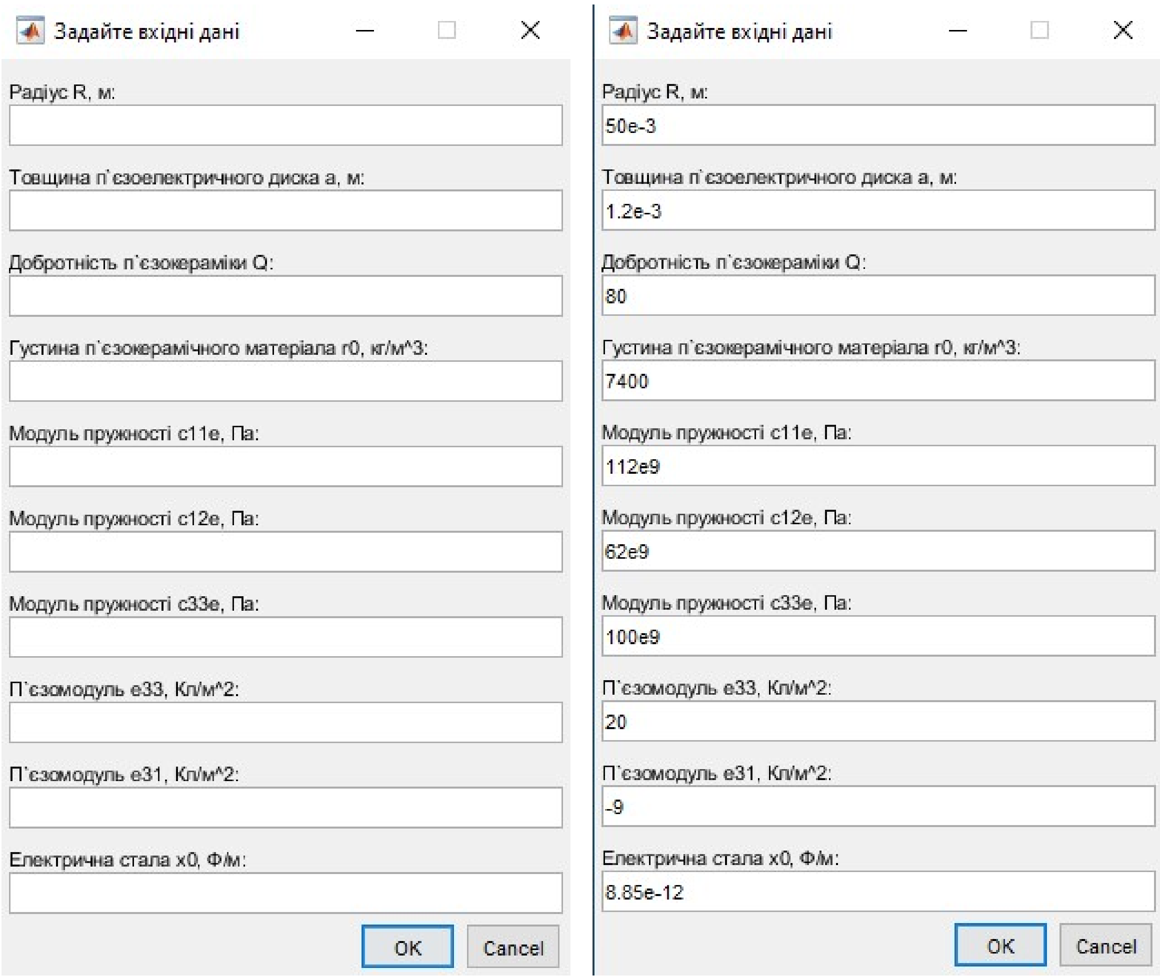

Figure 5. IPeD program interface (*a*) and program interface with entered input data (*b*)

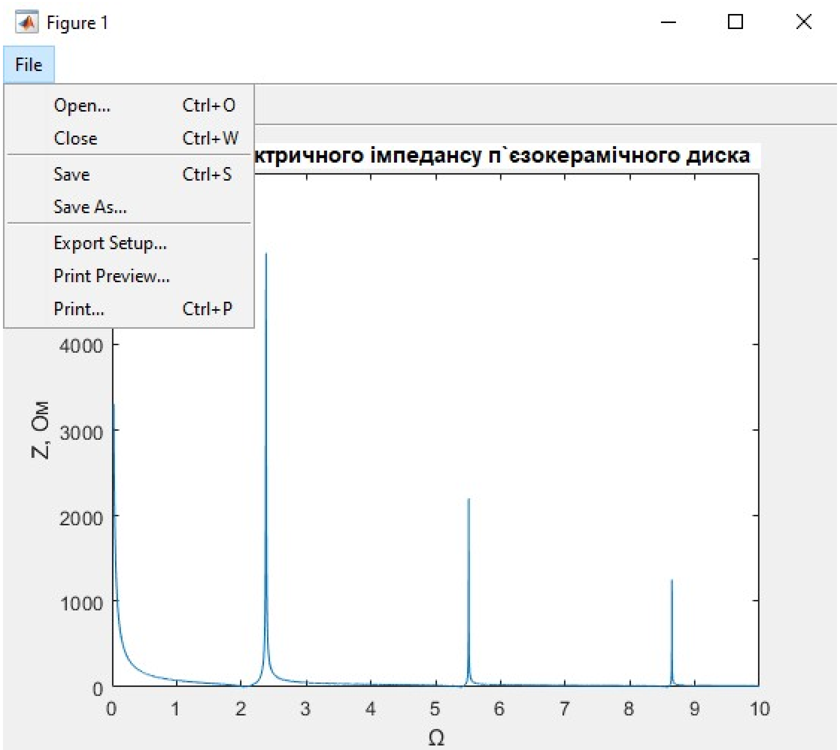

Figure 6. The modulus of the electric impedance of the disk in the area of medium frequencies

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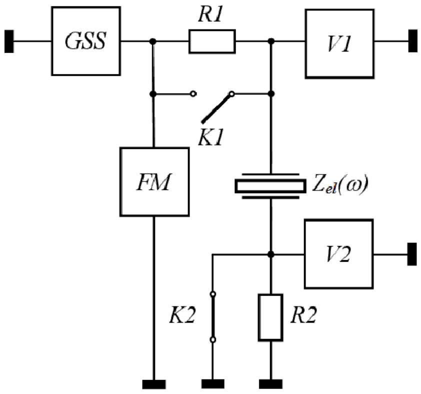

Figure 7. Electrical scheme for measuring the electrical impedance of piezoceramic disk: *GSS* is a generator of sinusoidal signals, *FM* is a frequency meter, *V1* and *V2* are voltmeters, *K1* and *K2* are mechanical keys, *R1* and *R2* are load resistors [14]

For experimental research, a disk piezoelectric element Ø50×1.2 mm made of PZT-type (lead zirconate titanate) ceramics [15] was used.

The results of measuring the electrical impedance of the piezoelectric disk in the medium frequency range are presented in Figure 8.

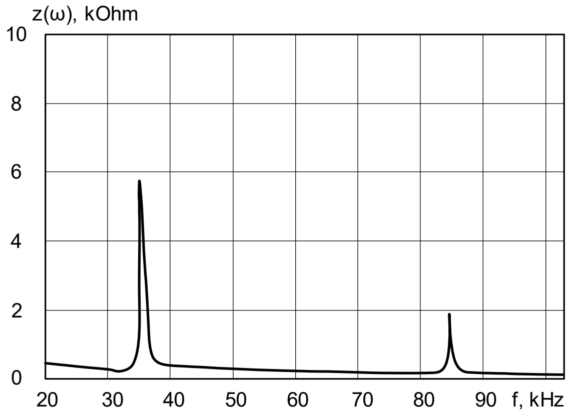

Figure 8. Electrical impedance of a piezoelectric disk in the medium frequency range

Discussion of results. The value of the electrical impedance module in ohms is plotted on the ordinate axis, and the dimensionless wave number $\Omega = \gamma R = \omega\tau_0$ is plotted on the abscissa axis (Figure 6), where $\tau_0 = R/v$ is the time scale, $v = \sqrt{c_{11}/\rho_0}$ is propagation speed of elastic disturbances in a thin disk. For the above parameter values $v = 3153$ m/s and $\tau_0 = 7.93 \cdot 10^{-6}$ s. A value of $\Omega = 1$ corresponds to a frequency of 20.072 kHz. The calculation of electrical impedance began with $\Omega_0 = 0{,}025$.

It is clearly visible that the electrical impedance of the disk at some frequencies acquires practically zero values (frequency of electromechanical resonance). With a relatively small increase in the frequency of the change in the sign of the stress-strain state, a sharp and very significant increase in the electric impedance modulus of the oscillating disk (frequency of electromechanical anti-resonance) is observed.

When comparing the results of mathematical modelling of the electrical impedance of a piezoelectric disk in the medium frequency range (Figure 6), performed according to expression (2), and the results of experimental measurements shown in Figure 8, it can be seen that the obtained estimate is in good agreement with the true value of the electrical impedance.

Conclusions. An expression for calculating the electrical impedance of an oscillating piezoceramic disk in the mid-frequency range is constructed, where the displacement vector of the material particles of the disk is almost completely determined by the radial component.

The scientific novelty of the work lies in the development of the software service in the MATLAB programming language for determining the parameters and characteristics of a thin piezoelectric disk that oscillates radially, which allows to determine with high accuracy and adequacy the frequency dependence of the electric impedance module, which allows to determine the frequencies of electromechanical resonance and anti-resonance of a thin piezoelectric disk.

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In further research it is planned to model and investigate the process of the occurrence of oscillations in piezoelectric transducers of various shapes.

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ПРОГРАМНИЙ СЕРВІС ДЛЯ ВИЗНАЧЕННЯ ПАРАМЕТРІВ ТА ХАРАКТЕРИСТИК ТОНКОГО П'ЄЗОЕЛЕКТРИЧНОГО ДИСКА

Одним із найважливіших питань, що виникають при управлінні сучасною інфраструктурою, є необхідність вчасної та ефективної діагностики стану її компонентів. Недостатній рівень діагностики може призвести до необхідності дорогих ремонтних робіт або аварійних чи навіть небезпечних ситуацій. Для забезпечення достатньої якості такої діагностики необхідно розроблювати і впроваджувати високоточні та надійні ультразвукові перетворювачі. Дискові п'єзоелектричні пристрої широко використовуються в елементах інформаційних систем. Багатоманітність і різноманітність практичних застосувань дискових перетворювачів закономірно стимулюють теоретичні дослідження, метою яких є прогнозування характеристик і технічних параметрів створених на їх основі п'єзоелектронних пристроїв. Прогноз базується на математичній моделі, яка є основним результатом теоретичного опису реального пристрою.

Метою дослідження є розробка сервісу для визначення параметрів і характеристик тонкого п'єзоелектричного диска, що коливається радіально.

Наукова новизна роботи полягає в розробці програмного сервісу на мові програмування MATLAB для визначення параметрів і характеристик тонкого п'єзоелектричного диска, що коливається радіально, що дозволяє з високою точністю та адекватністю визначати частотну залежність модуля електричного імпедансу, що дозволяє визначати частоти електромеханічного резонансу та антирезонансу тонкого п'єзоелектричного диска.

Практичне значення можливостей розробленої моделі, а також програмного засобу для її реалізації полягає в експериментально підтверджених результатах розрахунку основних параметрів п'єзоелектричного дискового перетворювача, які підтверджують високу точність і ефективність такого моделювання, для можливості інтеграції в інформаційно-вимірювальні системи.

Ключові слова: *п'єзоелектричний дисковий елемент, фізичні процеси, електричний імпеданс, коливання, програмне забезпечення.*

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