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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

STUDY OF MULTIFUNCTIONAL PIEZOELECTRIC TRANSDUCERS FOR VIBRATING DEVICES

Specialty: 3340.01– Electrotechnical systems and complexes

Field of sciences: Technical sciences

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INTRODUCTION

Relevance and the development of the topic. One of the methods for determining the technical condition of operated and designed electrical equipment is the analysis and measurement of their vibration and temperature parameters. This method is the determination of changes in parameters as a result of the interaction of the movement dynamics and strength of the processed parts, joints, and the making and management of appropriate technical decisions. It is known that frictional forces between the tool and the workpiece create a significant temperature gradient in the machining zone, which leads to overheating of the tool, changes in durability and working properties, including machine tool vibration. Dynamic temperature changes, heat resistance, and other processes for operating stability maximize the reliability and durability of the tool. Measuring the vibration process allows the measurement of parameters generated in electrical machines and robots. As a result, the dynamic system ensures the wear modes, minimal impact inclination, and vibration are controlled in accordance with accepted standards for the purpose of further control.

Vibration diagnostics allows for monitoring the development of mechanical defects in the mechanical systems, identifies some electrical and mechanical defects of actuators and tools and reveals inefficient points reliability and accuracy of processing modes. Solving this problem can be easily and effectively implemenfed using vibration analysis and monitoring techniques.

Any processing equipment contains moving or rotating electrotechnical, electromechanical devices that creates mechanical vibrations, leading to premature equipment failure, increased tool wear, and a decrease in the quality of manufactured parts.

Recording and analyzing selection parameters related to the vibration level allows you to determine the current technical condition of all equipment and its conditions, as well as diagnose various defects and identify potential problems.

Solving the problem of optimal synthesis of piezoelectric transducers and transducers for various degrees of vibrations, technical systems and complexes for the purpose of recording and analyzing the selection parameters, improving the overall dimensions, electrical, technical, constructive and operational parameters of these devices, and developing new high-precision models is an urgent scientific and technical issue.

Summarizing the above, it can be said that currently, vibration monitoring systems and their widespread application in 3D printers and modern high-precision areas, as well as improving the electrical, technical, structural and operational parameters and characteristics of these devices, are important and relevant both from a scientific point of view and for industrial sectors.

Object and subject of research. The object of research in the dissertation is new electromechatron based electrotechnical systems based on piezoelectric transducers in vibrating electrical and electromechanical devices, and the subject is vibration monitoring systems.

The purpose and objectives of the study. The purpose of the dissertation is to create and develop models of new multifunctional converters and new generation 3D printer systems to improve their characteristics based on the study of technical, structural, and operational parameters, taking into account nonlinear indicators in vibrating electrotechnical devices.

Research methods. The dissertation work used, the dynamic analysis method, the theory of piezoelectricity, differential equation theory, Laplace transforms, nonlinear electrical theory, graph method, etc.

The main provisions put on defense. The main provisions put forward for defense are as follows:

1. Construction of the operating mechanism of piezoelectric converts with descriptive physical models;
2. Synthesis of a new model of piezoelectric transducers for vibration control as a result of the conducted analyses;
3. Determination and computer analysis of the dependence of the changes caused by the influence of mechanical vibrations on the voltage at the output of the piezoelectric transducer according to the operating modes of the prepared transducer;
4. Design of control and experimental models of the proposed

piezoelectric transducer and 3D printer;

Scientific novelty of the research. The scientific innovations obtained in the dissertation work allow for the improvement of the electrical, technical, constructive and operational parameters and characteristics of piezoelectric transducers that control vibrations in electrotechnical devices and a new 3D printer with their application, and consist of the following:

1. Based on electromechanical analogy, an equivalent circuit has been developed that reflects the physical principles of the actions of piezoelectric transducers, taking into account the nonlinearity and losses during frictional contact between the piezoelectric element and the system.
2. The transition processes in piezoelectric transducers were studied taking into account various complex boundary conditions.
3. The proposed mathematical model investigated wave processes in piezoelectric elements used for piezoelectric transducers under various boundary conditions and proposed a model taking into account losses.
4. A mathematical model for constructing a system for determining the "point-to-point" transition speed of the printing nozzle of the presented 3D printer has been proposed. Reliability indicators were determined based on the Markov graph of the 3D printer.
5. A complex of technical hardware and software has been created that allows for real-time monitoring of equipment vibration, spectral analysis of vibration, and recording of the signal for analysis.

Theoretical and practical significance of the study. The issues of synthesis of multifunctional piezoelectric transducers for vibrating devices were studied, and the possibility of their use in electrotechnical systems that perform vibration status, diagnostics, and control was experimentally tested. A 3D printer model was created based on the proposed methods.

Author's personal contribution. The results of the dissertation work were obtained personally by the author. The application of the main scientific results was carried out with the participation of the author.

Implementation and application of the results of the work.

The scientific and experimental results obtained during the research and synthesis of multifunctional piezoelectric transducers for vibrating devices can be used when conducting vibrodiagnostics of technological equipment in an industrial enterprise. At the same time, the scientific and methodological innovations of the dissertation work were widely used in the scientific research and teaching process conducted at the "Energy" department of the "Engineering" faculty of the Sumgayit State University, as well as in the compilation of methodological works and textbooks. The application of the obtained results in the above-mentioned educational institution was approved by the relevant act.

Approval of the dissertation. The main scientific, theoretical and practical results obtained in the dissertation work were reported and discussed at the international and republican conferences, symposiums and seminars:

-“I International Scientific Conference of Young Researchers” dedicated to the 90th anniversary of the birth of the National Leader of the Azerbaijani people Heydar Aliyev, April 25-26, 2013, Baku, Azerbaijan;

-Azerbaijan Technical University: Materials of the international scientific and technical conference on the modern state and development prospects of information and communication technologies, November 23-25, Baku 2015;

- X International Scientific and Practical Conference of Young Scientists. Current Problems of Science and Technology - 2017 Collection of materials from the UFA conference. Publishing house "Oil and Gas Business" 2017;

-Modern means of communication materials of the XII International Scientific and Technical Conference October 19-20, 2017 Minck, Republic of Belarus;

-Materials of the International Scientific Conference on Actual Problems of Applied Physics and Energy, May 24-25, Sumgayit, 2018;

- Modern means of communication materials of the XIII International scientific and technical conference October 18-19, 2018 Minsk, Republic of Belarus;

- Instrumentation and automated electric drive in the fuel and energy complex and housing and communal services: Proceedings of the IV National Scientific and Practical Conference December 6-7, 2018 Kazan, KGEU;

-E3S Web Conf., 124 03004 DOI:International Scientific and Technical Confe-rence SES-Kazan State Power Engineering University Peter The Great Saint Petersburg Polytechnik University. Kazan 18-20 September, 2019

-Instrumentation and automated electric drive in the fuel and energy complex and housing and communal services: materials. V National scientific-practical conf. Kazan December 12-13, 2019 Kazan State Economic University;

-Materials of the Republican scientific conference on the topic "Personality, Society, State: Modern Approaches to Mutual Relations" December 6-7, 2019 Mingachevir State University;

- "Current Issues of Applied Physics and Energy" II International Scientific Conference Sumgayit State University, Kazan State Power Engineering University November 12-13, 2020;

- II Mezhdu-napodnaya scientific-practice conference of Pckovcko Gocudapctvennogo University "Community innovations in technology and production", October 28-29, 2021, Pckov,

-International Scientific Forum on Computer and Engineering Sciences WFCES, Almaty, 2021 October 12-13, 2021

- Informatics, management and artificial intelligence thesis of the ninth International Scientific and Technical Conference on May 11-13, 2022. Kharkov, etc.

-Current issues of applied physics and energy III International scientific conference Sumgayit State University Kazan State Energy University, 2022, October 27-28;

-Energy efficiency and green energy technologies. Proceedings of the Republican scientific and technical conference, 2022, December 14-16;

- Towards Industry 5.0 Selected Papers from ISPR2022, Lecture Notes in Mechanical Engineering. Springer Nature, 2022, 6-8 october;

- Advanced Mathematical Models & Applications Jomard Publishing, 2024;

Publication of the results of the work. On the results of the dissertation work, 8 articles were published in prestigious scientific journals, 15 theses (6 conference materials) were published in materials of international and republican conferences, and 3 patents were obtained.

The organization where the dissertation work was performed. The dissertation work was completed at the Sumgayit State University.

Structure and scope of work. The dissertation work consists of 148 pages of A4-format computer text, including an introduction, 4 chapters, conclusions, a list of used literature, and appendices. It includes 64 figures, 12 tables, and a list of used literature with 147 titles. The introduction of the dissertation consists of computer text in A4 format, 10474 characters (6 pages), Chapter 1 46492 characters (36 pages), Chapter 2 25520 characters (22 pages), Chapter 3 28333 characters (30 pages), Chapter 4 36888 characters (33 pages), conclusion 1486 characters (1 page), and list of used literature 23939 characters (15 pages). The number of marks in the dissertation is 175705.

MAIN CONTENT OF THE RESEARCH

The introduction substantiates the relevance of the dissertation topic, explains the purpose and main objectives of the research conducted, and presents the scientific novelty of the work and the practical significance of the results obtained.

Information was provided on the application of the obtained results, suggestions and recommendations in the educational process and in production.

The first chapter provides a critical overview of various types of transducers, including piezoelectric transducers, for improving the output parameters of modern electrotechnical devices and systems, electronics, and high-precision modern electromechatronic systems, and an analysis of piezoelectric transducers is conducted.

In this field in Azerbaijan, professor R.G. Jagubov, professor N. Farzana, and professor T. Gurbanov created piezoelectric transducers for various purposes.

Regardless of their application in various junctions of electrical systems and complexes, namely piezoelectric motors and actuators, piezoelectric motion converters, protective devices, converters for various purposes, a large number of various filters, measuring instruments, their application in new modern systems in accordance with the operating modes and conditions of each field is expedient, and the analysis of piezoelectric converters shows that in modern electrical engineering, nanotechnology, biomedicine and many other fields the relevance of the research and application sought is justified.

In this chapter, a new piezoelectric transducer is proposed for measuring small and large mechanical displacements, vibrations, and processes before damage, making technical decisions according to the obtained parameters as a result of the measurement, and controlling the system accordingly. The physical model of piezoelectric displacement transducers is considered for converting mechanical oscillations into electrical oscillations according to the amplitude of vibrations and controlling the system accordingly.

During the operation of the piezoelectric transducer, the mechanical interaction between the piezoelectric and the electrical device and the free movement, that is, the frictional contact determines the smoothing properties and the effect of the transducer on the piezoelectric may vary at different intervals $0 \le t \le T/2$ və $T/2 \le t \le T$. The signals received in the indicated periods are nonlinear processes and various theories are used to solve the problem. When the device is not working, there is no mechanical connection between the rheostat and the device, and in this case, the signal level at the input corresponds to the case of I=0. Based on the above, a general structural diagram reflecting the working principle of a piezoelectric transducer is shown in Figure 1.

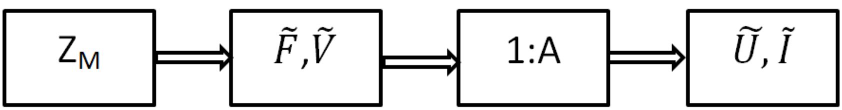

Figure 1. General block diagram illustrating the operation of a rheoelectric converter

Here Z_m -is the mechanical resistance, F -is the exciting force generated at the mechanical output, *V* -is the speed of oscillations (vibrations) at the location of the piezoelectric element electrodes, *A*- is the transformation coefficient of the system that converts mechanical energy into electrical energy, *U, I* -are the voltage and current obtained at the output according to the amplitude and speed of vibration.

To calculate the basic characteristics of *r* piezoelectric motion transducers, various methods can be used, taking into account the nonlinearity of the frictional contact. On of the methods is the harmonic linearization method. To study the dynamics of piezoelectric converters depending on the application area, an equivalent circuit was developed using the harmonic linearization method, which allows studying the piezoelectric converter of a complex configuration of the piezoelectric and the device, as well as taking into account the nonlinear interactions and losses of piezoelectric converters.

In the second chapter a new model of program-controlled piezoelectric transducers for vibration control is developed. Depending on the application areas and the design of the devices, piezoelectric transducers use monopiezoelement of various shapes. These elements are implemented by the ability to measure rapidly changing quantities, the conversion of mechanical oscillations into electrical charges with high accuracy, and the determination of the time of conversion of mechanical voltage into electrical charges with high accuracy (10^{-4} – 10^{-6} and higher).

Taking into account the above-mentioned advantages, we propose a control system consisting of new piezoelectric converters and its operating principle, which is intended for application in various types of vibration control devices (Figure 2).

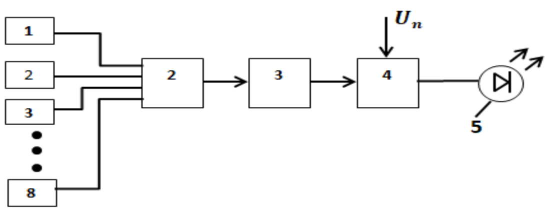

Figure 2. General structural diagram of piezoelectric transducers.

In Figure 2, the control system consists of 8 rheostats - 1, a boost adder - 2, a voltage converter - 3, a comparison circuit - 4, and a check light-emitting diode - 5.

The presented model of the piezoelectric converter device, assembled using 8 circular shaped piezoelectric converter, is shown in Figure 3.

The presented piezoelectric converter device works as follows. During the vibration of the parts to which the device is connected in various machines designed for vibration, mechanical oscillations are directly converted into electrical voltage as a result of the piezoeffect in the piezoelectric plates attached to it.

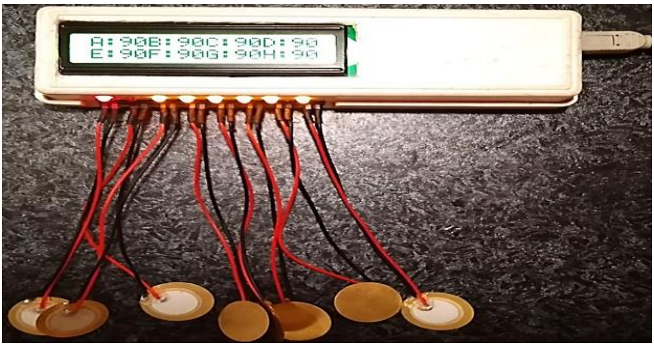

Figure 3. Schematic diagram of a new piezoelectric converter device that records vibrations.

The level of the alternating voltage received at its output is low and is fed to the input of the adder of the converter amplifier. These voltages are combined and amplified in the adder amplifier built into the operational amplifier. The amplified voltage at the output of the adder is fed to the input of the voltage converter. The variable voltage is converted to a constant voltage in the converter. The voltage level at the output of the voltage converter corresponds to the average value of the signals coming from all the converters located on the board.

This voltage is fed into the comparison circuit, and the voltage U_e is applied to the second input of this circuit. The level of voltages must be appropriate to the level of vibration present in the device.

When the vibration level exceeds the voltage allowed at the output during the comparison period, voltage is generated to ignite the light-emitting diode, indicating that there are changes in the quality performance of the part being manufactured or soldered. The recorded processes can be monitored by a computer connected to the output of the comparison circuit and the voltage can be controlled to normalize the process based on a program written to the computer.

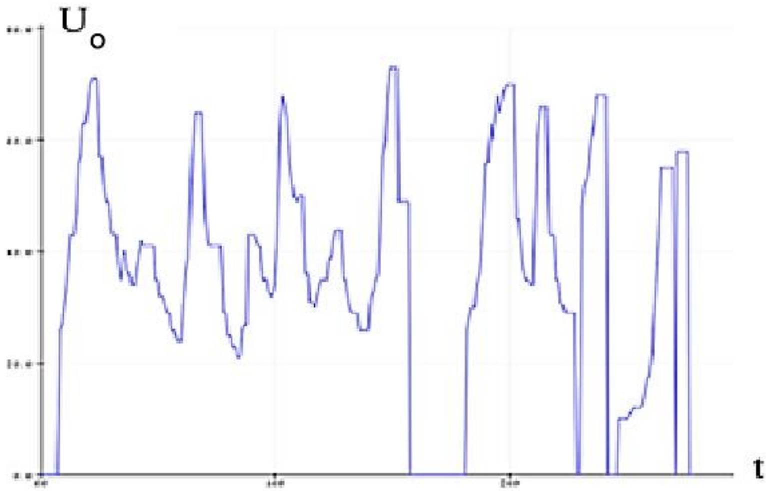

Figure 4. Dependence curve of voltage changes at the output of the comparison circuit as a result of mechanical impact.

In Figure 4, the voltage changes at the output of the comparator circuit as a result of mechanical impact are reflected, and the changes include vibration changes as a result of the influence of mechanical oscillations.

Here, the level of the signal coming from the output of the piezoelectric converter is compared with the level of the initial "reference" signal of the machine, and here we consider two cases:

-the level of the signal entering the output of the piezoelectric converter is the same as the level of the initial “standard” signal $(u_o = u_s)$, where u_c, is the amplitude of the signal at the output of the transducer, and u_s is the level of the initial “standard” signal, which indicates a normal state under the conditions;

- he level of the signal coming from the output of the piezoelectric converter is greater than the level of the “standard” signal $(u_f > u_e)$. In this case, there may be errors in the working process of the redundant device and inaccuracies in the dimensions of the manufactured element, and in this case, the system operation is stopped (Figure 5).

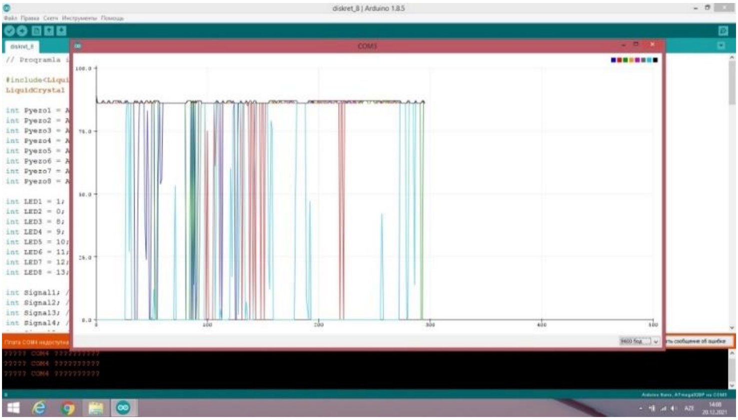

Figure 5. Computer graph of the voltage at the output of a piezoelectric transducer during vibration

Thus, the system is constantly under automatic control. The accuracy of the system's operation is determined by comparing the amplitude value of the reference voltage with the voltage corresponding to the amplitude of the vibration during operation.

The entire work process, in accordance with the specified operating conditions, can be monitored remotely via computer or directly next to the system. Here, the electrical control scheme of the piezoelectric converter is designed, its technical characteristics are determined, and at the same time, the sequence of compiling the control program via the Arduino element is presented. Thus, the transducer, which is presented in accordance with fuzzy effects, accurately reflects all the results on the screen, and a system sensitive to external physical effects, vibrations, and physical changes in the input signal is created.

This chapter also uses Arduino nano elements to create a multi-pot piezoelectric transducer, a control program is designed, and a computer screen image of the period, amplitude level, and frequency changes of electrical signals corresponding to the effects of vibration changes at the transducer output is obtained.

The third chapter considers the issues of constructing a mathematical model of wave processes in piezoelectric converters with fixed parameters. For this, an equivalent circuit has been designed according to the operating mode of piezoelectric converters.

The transition process in piezoelectric converters has been studied under various complex boundary conditions, using the D'Alembert method, the voltage and current at any point on the piezoelectric element. The Laplas transformation was applied to obtain the recurrence relations for each of the individual waves corresponding to the working state of the piezoelement.

The advantages of the obtained models are that they allow the study of the characteristics of their rotors in a compact form, for example, the numerical calculation of the local wave process and its continuity. A mathematical model has been proposed for studying wave processes in piezoelectric converters under certain conditions in elements located at the ends of *n*-channel lines. The working principle of piezoelectric converters is based on the direct and inverse piezoelectric effect, which is the effect of the piezoelectric element vibrating longitudinally and transversely along its length.

In the study of micropiezoelectric converters with fixed parameters, mathematical methods based on the Fourier method and the Laplas transform with the orator method were applied.

The transition processes in resistance-loaded piezoelectric converters can be described by the generalized equivalent circuit of lossless piezoelectric converters loaded with resistance r when connected to the used voltage source $e(t)$ and vice versa, where L_0 and C_0 - can be taken as the inductance and capacitance per unit length of the piezoelectric element, respectively (R_0, G_0– resistance and capacitance in lossless piezoelectric converters are equal to zero).

In this chapter, an equivalent circuit of resistively loaded piezoelectric converters is constructed, and the following boundary conditions are adopted in accordance with the working principle to establish a mathematical model of wave processes in piezoelectric converters based on the equivalent circuit:

Initial boundary conditions

$$(x=0)\ ,u(0,t)=e(t) \tag{1}$$

Express the voltage in terms of incident and reflected waves[1]:

$$u(x,t)=u'(x,t)+u''(x,t) \tag{2}$$

$0 \le t \le \dfrac{l}{c}$ let's take a look at the interval (c – wave speed), until the falling wave reaches its end $u''(x,t)=0$ when it is,

$$u(x,t)=u'(x,t)=e(t-\frac{x}{c}),\quad (0 \le t \le \frac{l}{c}) \tag{3}$$

$t=\dfrac{l}{c}$ the incident wave reaches the end point of the piezoelectric. The following boundary condition:

$$u(l,t)=ri(l,t) \tag{4}$$

it's easy. Expressing the current and voltage in the form of incident and reflected waves:

$$u'(l,t)+u''(l,t)=r\left[i'(l,t)-i''(l,t)\right] \tag{5}$$

Lossless piezoelements:

$$i'(l,t)=\frac{u'(x,t)}{\rho},\qquad i''(x,t)=\frac{u''(x,t)}{\rho} \tag{6}$$

here ρ - wave resistance $\rho=\sqrt{\dfrac{L_0}{C_0}}$.

Substituting formulas (6) and (5), we get:

$$u''(l,t)=\frac{r-\rho}{r+\rho}u'(l,t)=k\cdot u'(l,t) \tag{7}$$

$$i''(l,t)=ki'(l,t) \tag{8}$$

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[1] В.Л.Бидерман Теория механических колебаний. Москва 1980.стр.405

here κ – is the reflection coefficient: $k = \frac{r - \rho}{r + \rho}$.

The reflected wave $(x = 0)$ is delayed by time $\tau = \frac{2l}{c}$ relative to the incident wave. Taking this into account, we can write the recurrence relation of formulas (3) and (7) we have considered:

$$u'(0,t) = e(t) - ku'_н(t - \tau) \tag{9}$$

Time immeasurable:

$$t = (n + \varepsilon) \cdot \tau \tag{10}$$

here $n-$ integer $n = 1,2,3,...,$ $\varepsilon \in [0,1]$:

$$\bar{u}'_н(n + \varepsilon) = \bar{e}(n + \varepsilon) - ku'_н(n - 1 + \varepsilon) \tag{11}$$

Applying the Laplassa discrete transform (LDT) to this expression, we obtain the following equation for the voltage at the origin of the line in the reflected field[2]:

$$U_H^{*'}(q,\varepsilon) = E^*(q,\varepsilon) - k \cdot e^{-q} U_H^{*'}(q,\varepsilon),$$

or

$$U_H^{*'}(q,\varepsilon) = \frac{E^*(q,\varepsilon)}{1 + ke^{-q}} \tag{12}$$

Analogously, then for the reflected wave according to the boundary condition (5)

$$U_k^{*''}(q,\varepsilon) = \frac{kE^*(q,\varepsilon)}{1 + ke^{-q}} \tag{13}$$

we get.

Considering (12) and (13) for any point of the piezoelectric element, we obtain the following expressions for the voltage and current:

$$U^*(q,\varepsilon) = U_H^{*'}(q,\varepsilon - \gamma) + e^{-q} U_k^{*''}(q,\varepsilon + \gamma - 0{,}5), \quad \gamma \le \varepsilon < 0{,}5 - \gamma \tag{14}$$

[2] Stewart, James. *Calculus : Early Transcendentals 2022-06-10* 7th ed., Brooks/Cole, Cengage Learning, 2012. Chapter 14: Partial Derivatives. p. 908.

$$I^*(q,\varepsilon) = \frac{1}{\rho}\cdot\left[U_H^{*'}(q,\varepsilon-\gamma) - U_k^{*''}(q,\varepsilon+\gamma-0{,}5)\right],$$
$$0{,}5-\gamma < \varepsilon \le 1 \; u \; \varepsilon \ge \gamma$$

if

$$I(q,\varepsilon) = \frac{1}{\rho}\left[U_H^{*'}(q,\varepsilon-\gamma) - e^{-q}U_k^{*''}(q,\varepsilon+\gamma-0{,}5)\right], \qquad (15)$$
$$\gamma \le \varepsilon < 0{,}5-\gamma$$

For example, let's look at how a piezoelement connects to a fixed source $e(t) \equiv E$ when its end is open $(k=1)$ and its end is short $(k=-1)$.

In this case

$$E^*(q,\varepsilon) = \frac{E\cdot e^q}{e^q-1} \qquad (16)$$

Using formula (16), we can write expression (12) as follows:

$$U_H^{*'}(q,\varepsilon) = E\cdot\frac{e^q}{(e^q-1)(1+ke^{-q})} \qquad (17)$$

The original matches this expression:

$$u_H'(n+\varepsilon) = E\cdot\left[1-k+k^2-k^3+\ldots+(-1)^n k^n\right] \qquad (18)$$

Taking into account expression (13), (16) is obtained as follows:

$$U_k^*(q,\varepsilon) = E\cdot\frac{k\cdot e^q}{E(e^q-1)\cdot(1+k\cdot e^{-q})} \qquad (19)$$

The original matches this expression:

$$u_k''(n+\varepsilon) = kE\cdot\left[1-k+k^2-k^3+\ldots+(-1)^{n-1}k^{n-1}\right] = E\left[k-k^2+k^3+\ldots+(-1)^{n-1}k^n\right] \qquad (20)$$

According to expression (14), for the starting point of the rhizoelement

$$u(n,\varepsilon) = E\cdot[1-k+k+k^2-k^2+k^3+\ldots+(-1)^n k^n+(-1)^{n-1}k^n] = E \qquad (21)$$

For the points at the end of the piezoelectric element:

$$u(n,\varepsilon) = E\cdot\left[1-k+k+k^2-k^2+\ldots+(-1)^{n-1}k^{n-1}+(-1)^{n-2}k^{n-1}+(-1)^{nj}k^n\right] = E\left[1-(-1)^n k^n\right] \qquad (22)$$

will be.

It can be seen from expression (19) that in the final open state, when $u_k = 0$ is n, it is an odd number, when $(k = 1)$ is n, it is an even number, and when $u_k = 2E$ is n (Figure 6).

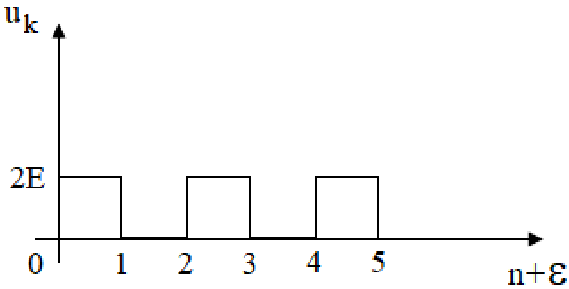

Figure 6. Voltage dependence at the open end of the piezoelement

In the final dark state, it can be seen from expression (19) that $u_k = 0$ is (in the absence of vibration).

It can be seen from expression (15) that the starting points of the moving line are as follows:

$$i(n,\varepsilon) = \frac{E}{\rho} \cdot \left[1 - k - k + k^2 + k^2 - (-1)^n k^n - (-1)^n k^n\right] = \frac{E}{\rho} \cdot \left[1 - 2(k - k^2 + (-1)^n k^n\right] \quad (23)$$

And at the end of the point:

$$i(n,\varepsilon) = \frac{E}{\rho} \cdot [1 - k - k + k^2 + k^2 + \ldots + (-1)^{n-1} k^{(n-1)} - (-1)^{n-2} k^{n-1} + (-1)^n k^n =$$

$$= \frac{E}{\rho} \cdot \{1 - 2[k - k^2 + \ldots + (-1)^{n-1} k^{n-1}] + (-1)^n k^n \quad (24)$$

it's easy.

In this chapter, based on the equivalent circuit of a piezoelectric transducer loaded with R, L, C elements, we have constructed a descriptive expression for the reflected wave at the end and a description and graph of the voltage at an arbitrary point of the piezoelectric element.

At the same time, a mathematical model of the breakdown of the cylindrical piezoelectric element of the proposed linear piezoelectric motor during long-term operation has been established.

Thus, the piezoelectric element of a linear micropiezoelectric motor is structurally cylindrical and consists of electrodes that feed longitudinal waves separately along the circumference and height of the cylinder. The design of a cylindrical piezoelectric element consists of electrodes that create oscillations transversely along the circumference of the cylinder and longitudinally along its height. Electrodes of the same name are connected together and connected to a high resonant frequency power source. The resonant frequency of the food source must match the resonant frequency of the mechanical vibrations.

The working principle of the mentioned linear micropiezoelectric motor is achieved as a result of the combined effect of both oscillations. As a result, as a result of both mechanical oscillations (height and width), the same points of the cylindrical piezoelectric element are excited by two types of oscillations simultaneously. The study of the operating characteristics of the cylindrical piezoelectric element of a linear micropiezoelectric motor operating on the aforementioned principle, including its long-term operation, is a very relevant issue for piezoelectric motors.

As it can be seen if two oscillations are used in both cases, including excitation with longitudinal waves along the height of the cylinder, the amplitude of transverse mechanical oscillations increases by 2-3 times. However, depending on the working process, the mechanical stresses caused by tension and torsion in the cylindrical piezoelements used in piezoelectric motors change their value and direction. Therefore, the period of stress caused by external forces whose value changes depending on time is called stress.

Experience shows that piezoelectric elements whose strength is not impaired during the initial period of loading may fail when the number of loading cycles reaches a certain value, i.e. the strength of the piezoelectric element depends on the number of operating cycles.

The strength limit of piezoelectric elements operating under the influence of repeatedly changing mechanical stresses is much smaller than the strength limit when the stresses do not change. The essence of their breakdown as a result of long-term operation under the influence of such stresses is as follows:

- With a long-term change of voltages, the crystals located on the edges of the cracks begin to disintegrate, and the resulting cracks deepen inward;
- Under the influence of periodic stresses, the crystals on the cracks rub against each other and that surface becomes smooth. As a result of the gradual growth of the cracks, the cross-sectional area decreases and, in connection with this, the value of the stress gradually increases, when the value of the stress reaches a dangerous level, the piezoelement suddenly stops;
- The phenomenon of fatigue-induced degradation depends on the structure of molecules and crystals of the piezoelement. Therefore, the assumption that the geometrical volume of the piezoelement is completely filled (the assumption of the integrity of piezoelements) cannot be used in the interpretation of fatigue strength, etc.

The issue of calculating the breakdown of piezoceramic piezoelectric elements, which are subjected to torsional deformation as a result of the influence of periodically varying stresses, as a result of long-term operation, is considered one of the relevant issues in the design of piezomotors. The development of modern technologies requires the consideration of new factors (causes) in these matters. One of the main factors here is the damage of piezoelectric elements from long-term operation, that is, the occurrence and accumulation of defects of various nature.

The gradual breakdown process that occurs in piezoelectric elements over time is related to their long-term durability. In this regard, the study and investigation of the breakdown process is considered one of the most urgent problems. The strength of piezoelectric elements directly depends on the nature of the breakdown process occurring in the piezoelectric element of piezoelectric motors. Therefore, studying the breakdown process becomes a necessity.

The structure of the piezoelectric element has a significant impact on the dissipation process. For this reason, the dispersion can be complex and unstable. Also, the decomposition process is highly dependent on the influence of external factors. These can be the nature of the loading, the temperature regime, surface effects and other reasons. All these reasons affect the nature of the stress state of the piezoelectric element. This, in turn, causes the breakdown. One type of dissipation is associated with arbitrary types of defects that arise and accumulate in piezoelectric elements, expressed by the term total damage. Such a breakdown is called diffuse breakdown. If the stress is uniform (for example, in tension of a rod), then the damage increases regularly with volume. In the case of a non-uniform stress field, two stages must be distinguished for the analysis of the breakdown process: latent breakdown (incubation period) and overt breakdown stages. In the latent phase of breakdown, microcracks and other defects are formed (in a certain time interval $0 \leq t < t^*$). At the moment $t = t^*$, local breakdown already occurs. Microcracks and other defects scattered around such local breakdown areas merge together to form macrocracks. Microcracks and other defects scattered around such local breakdown areas coalesce to form macrocracks. For example, experiments conducted on the fatigue failure of a piezoelectric element show that in the initial stage of failure, damage accumulates continuously and the damage is of a scattering nature. At the end of this stage, macrocracks form, which develop intensively in the following moments, and the piezoelectric motor is damaged.

Two types of approaches are used to study long-term dispersion problems. The first of these is the criterion approach. This type of approach is based on establishing criteria that determine the long-term degradation process of piezoelectric elements. In constructing such criteria, a stress called "equivalent stress" is used. The criterion approach is more often used in the study of strength for components of the stress tensor that are not time-dependent.

The fourth chapter discusses the creation of a 3D design model of a new 3D printer using piezoelectric transducers, a mathematical model for establishing a system for determining the “point-to-point” transition of the printer's print nozzle, and the construction of a program-controlled stabilization system taking into account vibrations. In this regard, a new generation of 3D printers has been proposed (Figure 7). Figure 7 shows the mechanical structural diagram of the 3D design model of the prepared 3D printer.

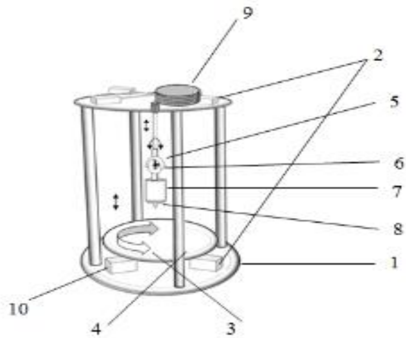

Figure 7. Mechanical construction scheme of the 3D printer model

As can be seen from Figure 9, the 3D printer consists of: 1 - a common support, 2 - fastening elements of the support columns, 3 - a lower platform with the ability to move up and down, 4 - an orthogonal transducer that monitors the displacement of the lower platform with the ability to move and the working body 7, 8 and the quality of the manufactured element and the displacement of the plastic yellow melter, 5 - a crucible, 6 - a plastic yellow melter fixed to the crucible's arms, which rotates 360 degrees in the printer's operating environment. It consists of micromotors capable of moving, 7 - a plastic film melter and 8 - a nozzle (both of which work together), 9 - a roll of plastic film melted by combustion, 10 - an automatic control system that provides program support for the printer and control over the creation of the manufactured element.

The piezoelectric transducers that control the vibration of the 3D printer can be placed at different points on the printer, depending on the degree of vibration. We have created a linear piezoelectric motion transducer to drive the up-down movement of the 7, 8 working bodies and the 3-up-down movement of the lower platform.

It is known that the mechanical structural structure of controlled mechanical devices plays the structural role of a connection for its other mechanical constituent parts. The structural block diagram of the mechanical structure of the 3D printer is shown in Figure 8.

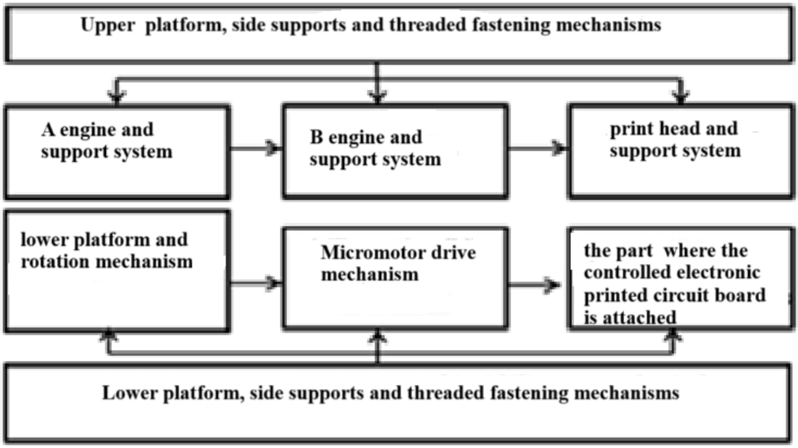

Figure 8. Structural block diagram of the structure of a 3D printer

As can be seen from Figure 8, a 3D printer mainly consists of two parts, mechanical and control-electronic parts. Let's analyze the composition of both parts separately. The mechanical components are divided into two groups according to the upper and lower platforms, each of which, in turn, is composed of individual components.

Considering that, in addition to the mechanical and structural parts, the electronic control circuit, which is of fundamental importance in controlling the device, plays an important role in the preparation of a prototype model of a 3D optical switch, let's analyze their main reporting part.

First, let's look at the structural block diagram of the control circuit used in the presented scheme (Figure 9) according to the working algorithm of the initial model of the 3D printer.

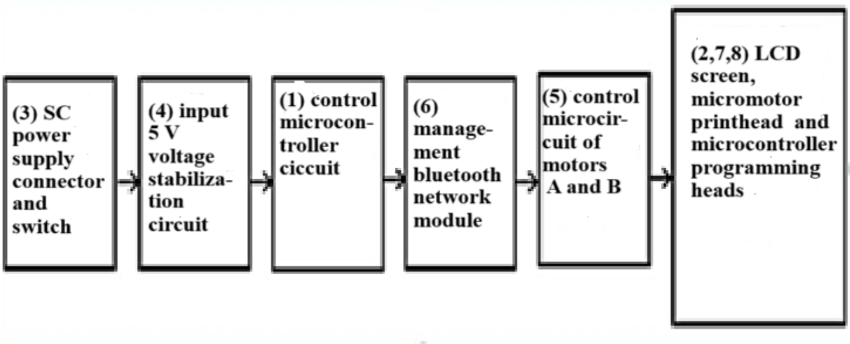

Figure 9. Structural diagram of the 3D printer control circuit

As can be seen from the structural block diagram of the control circuit structure, the circuit can be divided into 7 main groups:

1 – logic control microcontroller circuit; 2,7,8 – monitor, display module, controlled motors, laser and terminal headers for programming the microcontroller; 3, 4 – power supply and voltage stabilizer part; 5 – motor control circuit, 6 – wireless remote control module, 2 – LCD for monitoring, display module and 7 – printhead.

Taking into account the mentioned working principle and the corresponding working algorithms, the communication and control scheme between the blocks of the 3D printer can be shown in the block diagram shown below.

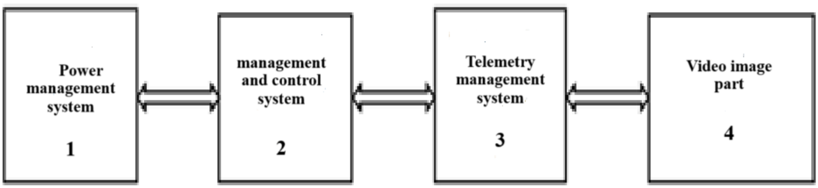

Figure 10. Block diagram of the communication and control structure of a 3D printer

As can be seen from Figure 10, the 1st power management section of the 3D printer contains the 36-42V voltage required by the micromotors (according to the presented rotor), while the other electrically powered parts on the 3D printer are fed with the necessary voltages at the output of the voltage reduction modules. At the same time, if the 3D printer is to be operated remotely (standalone), the printer should be powered by a battery and its rating should be calculated based on the operating time. 2- The motion control part uses an Arduino model with input/output to the ESCs that control all the motors, connected to a 10-channel receiver Arduino MEGA to control the command signals received from the Android operating system in the required format.

In addition to controlling the speed of the 3D printer, ESCs can control the required directions of the current, i.e. forward and backward movement, left and right movement, increasing and decreasing the speed of movement, right and left movement, up and down movement, movement of the lower platform, and circular movement, according to the ESCs output to the appropriate motors.

Additionally, a 3D printer can be equipped with a rotating LED light array on the front to provide a camera view in dark conditions. 3- the telemetry control unit controls the operation of the 3D printer, monitors and measures the level of vibrations coming from the transducers, and displays them on the screen or monitor of the 3D printer. 4 - in the video display section, the screen module located on the 3D provides a visual image of the device being viewed and is also capable of displaying some of the signals input from the converters.

In this chapter, a mathematical model of the proposed 3D printer nozzle's "point-to-point" transition image determination system is established.

The definition of the direction that allows the spatial trajectory of the printhead $x(t)$ to fall within a small neighborhood of the point $x(T) = 0$ is determined using the Euclidean norm of the vector $x(t)$:

$$F = \|x(t)\| = \left[x_1^2(t) + x_2^2(t) + \ldots + x_n^2(t)\right]^{0,5} = (x_T - x)^T (x_T - x)$$

(25)

Here X_T- is the final state of the system. Since the scalar quantity *F* is a positive definite function, its zero means that all X_i coordinates of the state are equal to zero. Therefore, by continuously monitoring *F* in the system, it is possible to determine the position of the *x(t)* trajectory relative to the coordinate origin. The arrival of the 3D printer working body at the coordinate origin is detected by monitoring the Euclidean norm $F = \|x(t)\|$. This occurs when the condition *F=0* is met. When the condition F=0 is met, it becomes *x(t)=0*. Figure 11 shows the nature of the change of the function *F*.

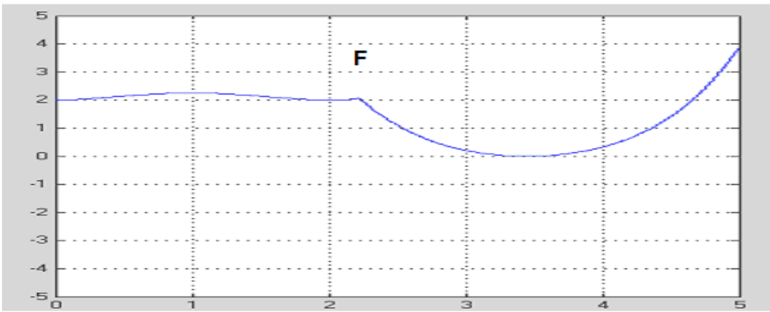

Figure 11. Character of the change of the function.

At the same time, in this chapter, a control scheme for a 3D printer model has been developed based on a mechanical design scheme to determine the reliability indicators of a 3D printer based on the Markov graph (Figure 12).

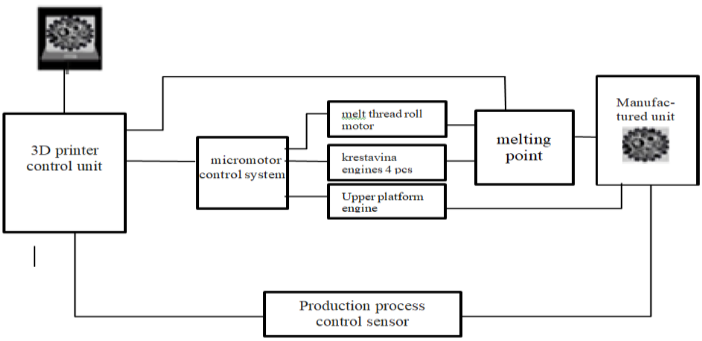

Figure 12. Control scheme of a new generation 3D printer

According to the working principle of a 3D printer, each element has 2 states: either it is working and executing the corresponding commands, or it is in rest mode and waiting for the next commands. For example, the control unit receives a signal at the input. Depending on the signal level, commands are transmitted to the defrosting unit. As can be seen from the 3D printer model's control scheme, each micromotor can move the lower platform in both directions and at different speeds by rotating the gears on its chassis. The base, where the gold platform is mounted, has a circular rotating head that allows the micromotors to freely rotate the platform in both axial directions. An analytical Markov model has been constructed to match the operating conditions of the elements of the proposed new 3D printer.

Based on the operating state of the 3D printer shown in Figure 12, let's construct a Markov graph that reflects the operating principle of the elements of the 3D printer (Figure 13).

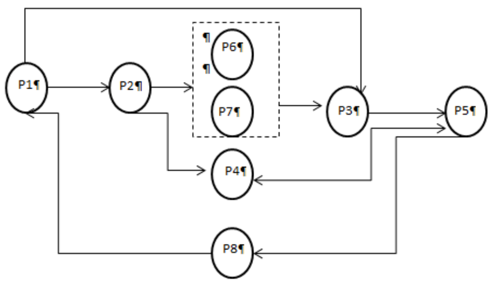

Figure 13. Markov cycle characterizing the operation process of a 3D printer

Considering the above, we combine the melting coil motor and the crosshead motor in one block, since they receive commands from the engine control unit and transmit them to the melting mechanism, and we will denote it as P_6. According to Figure 13.

$$\frac{dP_1(t)}{dt} = \lambda_8 P_8(t) - P_1(t)(\lambda_2 + \lambda_3) \quad (26)$$

$$\frac{dP_2}{dt} = \lambda_1 P_1(t) - P_2(t)(\lambda_4 + \lambda_6) \quad (27)$$

$$\frac{dP_3}{dt} = \lambda_6 P_6(t) + \lambda_1 P_1(t) - \lambda_5 P_3(t) \tag{28}$$

$$\frac{dP_4}{dt} = \lambda_2 P_2(t) - \lambda_5 P_4(t) \tag{29}$$

$$\frac{dP_5}{dt} = \lambda_3 P_3(t) + \lambda_4 P_4(t) - \lambda_8 P_5(t) \tag{30}$$

$$\frac{dP_6}{dt} = \lambda_2 P_2(t) - \lambda_3 P_6(t) \tag{31}$$

$$\frac{dP_8}{dt} = \lambda_5 P_5(t) - \lambda_1 P_8(t) \tag{32}$$

will be. Here $P_i(t), \lambda_i \quad i = 1,2,3,4,5,6,7,8$- it is possible that the corresponding rejection elements will work without rejection. For simplicity, we can write $P_6(t) = 1 - e^{-\lambda_6 t}$.

Then, from expression (31), we determine $P_2(t)$:

$$P_2(t) = \frac{\lambda_6 - \lambda_3}{\lambda_2} e^{-\lambda_6 t} + \frac{\lambda_3}{\lambda_2} \tag{33}$$

Taking the last expression into account in equation (27) we determine $P_1(t)$:

$$P_1(t) = \frac{\lambda_4(\lambda_6 - \lambda_3)}{\lambda_1 \lambda_2} e^{-\lambda_6 t} + \frac{\lambda_3(\lambda_4 + \lambda_6)}{\lambda_1 \lambda_2} \tag{34}$$

From equation (26) we determine $P_8(t)$:

$$P_8(t) = \frac{\lambda_4(\lambda_6 - \lambda_3)(\lambda_2 + \lambda_3 - \lambda_6)}{\lambda_1 \lambda_2 \lambda_8} e^{-\lambda_6 t} + \frac{\lambda_3(\lambda_4 + \lambda_6)(\lambda_2 + \lambda_3)}{\lambda_1 \lambda_2 \lambda_8} \tag{35}$$

Let us consider expression (33) in equation (29) and solve the first-order simple linear differential equation with the initial condition:

$$P_4(t)|_{t=0} = 1$$

After some elementary transformations, we get:

$$P_4(t) = \left(1 + \frac{\lambda_6 - \lambda_3}{\lambda_5 - \lambda_6} + \frac{\lambda_3}{\lambda_5}\right) e^{-\lambda_5 t} - \frac{\lambda_6 - \lambda_3}{\lambda_5 - \lambda_6} e^{-\lambda_6 t} - \frac{\lambda_3}{\lambda_5} \tag{36}$$

We define $P_3(t)$ and $P_5(t)$ in the same way:

$$P_3(t) = \left(1 + \frac{\lambda_6(\lambda_4 - \lambda_2) - \lambda_3 \lambda_4}{\lambda_2(\lambda_5 - \lambda_6)} + \frac{\lambda_6(\lambda_2 + \lambda_3) + \lambda_3 \lambda_4}{\lambda_2 \lambda_5}\right) e^{-\lambda_5 t} -$$

$$-\frac{\lambda_6(\lambda_4-\lambda_2)-\lambda_3\lambda_4}{\lambda_2(\lambda_5-\lambda_6)}e^{-\lambda_6 t}-\frac{\lambda_6(\lambda_2+\lambda_3)+\lambda_3\lambda_4}{\lambda_2\lambda_5} \quad (37)$$

$$P_5(t)=\frac{\lambda_4(\lambda_6-\lambda_3)(\lambda_2+\lambda_3-\lambda_6)(1-\lambda_6)}{\lambda_1\lambda_2\lambda_5\lambda_8}e^{-\lambda_6 t}+\frac{\lambda_3(\lambda_4+\lambda_6)(\lambda_2+\lambda_3)}{\lambda_2\lambda_5\lambda_8} \quad (38)$$

The report was received on the same day as the search.

RESULT

1. Based on electromechanical analogy, an equivalent circuit has been developed that reflects the physical principles of piezoelectric transducers, taking into account the nonlinearity and losses during frictional contact between the piezoelectric element and the system.

2. The transient processes of piezoelectric transducers were studied taking into account various complex boundary conditions. Using the D'Alembert method, a model of incident and reflected waves with current and voltage at any point of the piezoelectric element was obtained, and recurrent expressions for the mentioned waves were obtained using discrete Laplace transforms.

3. The proposed mathematical model was used to study wave processes in piezoelectric elements used for piezoelectric transducers under various boundary conditions and methods for applying it, taking into account losses, were proposed.

4. Based on the proposed model and methods, a new 3D printer model was created, issues of synthesis of multifunctional piezoelectric transducers for the presented printer and other vibration devices were studied, and the quality and speed indicators increased by approximately 10%.

5. An electrical circuit for controlling the proposed 3D printer was developed, a block diagram of the operating algorithm was drawn up, and the electronic components were analyzed.

6. A mathematical model for constructing an optimal stabilization system for the fast operation of the presented 3D printer has been proposed.

7. Reliability indicators of the presented 3D printer have been determined based on the Markov graph.

8. A hardware and software complex has been created that allows monitoring equipment vibration in dynamic mode, performing spectral analysis of vibration, and recording the signal for subsequent analysis.

The main results of the dissertation work were explained in the following scientific articles:

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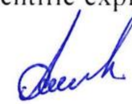

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