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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

DEVELOPMENT AND RESEARCH OF DIFFERENTIAL PIEZOELECTRIC TRANSDUCERS

Specialty	3337.01.–Information - measurement and control systems
Field of science:	Technology science

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GENERAL CHARACTERISTICS OF WORK

The relevance of the topic and the state of knowledge. When developing Differential Piezoelectric Converters (DPEC), in order to meet the high requirements for accuracy and quality of work, it is necessary to carry out design and research, targeted measures to create completely new types of these converters. The main research work in this area should be directed to the search and finding of new design solutions that increase their strength and performance, simplify design designs, reduce cost. In addition, such metrological characteristics as linearity and sufficiently high rigidity of the static characteristic, a wide measurement range in the frequency domain with stable dynamic sensitivity should be provided. Based on the above, we can definitely say that the topic of the dissertation work is undoubtedly modern and has scientific and technical relevance.

Abroad, as well as in the CIS countries, many researchers and scientists have carried out quite extensive research work on the problems of improving the efficiency of DPEC. Among them are the works of Y.B. Kadimov, R.G. Dzhakupov, T.B. Gurbanov, F. Tappert, G. Agraval, V. G. Alekseeva, G. Ayu House and many others. The result of the enormous work of the above-mentioned and other researchers is the proposed variety of design options for piezoelectric converters to determine the parameters of mechanical movements of objects, which have been used with various successes in various technical and technological systems, and some are still used today. However, even despite such an extensive consideration of the multidimensional problems of synthesis and design of DPEC, such important issues and methods as the study of the influence of the factor of piezoelectric sensing elements on the rigidity of static characteristics, methods for determining the coefficients of the characteristic equation of the transfer function in order to obtain transients tuned to the technical optimum, as well as minimizing linearly varying errors of DPEC are rather poorly covered in these works and works, with serial connection of sensitive elements. On the other hand, modern strict operational requirements for the accuracy, speed and informativeness of the DPEC clearly determine the relevance of the above issues in the development of the DPEC

The object of and subject research. The object of research is piezoelectric sensors and converters of mechanical motion parameters, with sensitive elements connected by a differential circuit. The subject of research is methods and methods that ensure the finding of new, perfect structural designs, improving the accuracy and quality of their work.

Purpose and objectives of the research. The main purpose of the research is to develop completely new differential piezoelectric converters that provide high accuracy in determining the parameters of mechanical motion and the study of their metrological characteristics.

To achieve this goal , the following main issues have been identified and resolved:

● Justification of increasing the efficiency of the process of measuring and determining the parameters of mechanical motion of moving objects, analysis of electromechanical parameters of differential piezoelectric converters;

● Development of piezoelectric converters with completely new designs based on differential connection of sensitive elements;

• Investigation of static and dynamic characteristics that determine the main metrological indicators of differential piezoelectric converters, including the influence of the Q factor of sensitive elements on the static characteristic, ensuring stable dynamic sensitivity based on the developed mathematical models.;

● Development of algorithms for digital processing of output voltage with a trigger principle;

● Construction of a model and minimization of linear errors of a differential piezoelectric converter.

Research methods. In order to successfully solve the tasks, the methods of theoretical foundations of electrical engineering, electrical measurements, information technology, mathematical and computer modeling, automatic control were used. Numerical calculations, development of computer models and their simulation are performed in the MATLAB software environment.

The main provisions of the defense. The main provisions of the defense are as follows:

●Scientific and technical justification of the need to improve the efficiency of the use of differential piezoelectric converters in measuring and control systems of mechanical motion of moving objects;

● Development of piezoelectric transducers with completely new structural designs in order to more accurately determine the parameters of the movement of objects.•

● Mathematical model of static characteristics and the study of the influence on its Q factor of sensitive elements;

● Mathematical dynamic model and provision of stable dynamic sensitivity over the entire operating range in the frequency domain

● Mathematical model of differential piezoelectric converter errors and error minimization;

Development of algorithms for digital processing of the output voltage with a trigger trailer, in order to determine the parameters of the movement of objects.

Scientific innovations. The main scientific innovations in the dissertation are as follows:

1. A new method of designing perfect differential piezoelectric converters **[1-8, 14]**;
2. Mathematical static model of a piezoelectric converter with a series-differential circuit for connecting sensitive elements **[9, 12, 13, 17];**
3. A dynamic model of a piezoelectric converter with a series-differential circuit for connecting sensitive elements based on an operator substitution circuit.**[11];**
4. Mathematical formulas determining the dependence of the dynamic sensitivity of the differential converter on the physical and geometric parameters of piezo-sensitive elements. **[10, 15, 16]**.

Theoretical and practical significance. The proposed method of developing completely new design designs for creating digital-analog differential piezoelectric converters for obtaining primary ormation about the motion parameters of moving objects is also applicable for converters with sensitive elements of a different type. The technique proposed for the compilation of mathematical models of static and dynamic sensitivity and methods for adjusting the transition process to the technical optimum by changing the ficio-geometric parameters of the sensing elements, as well as for the compilation of static errors and their minimization can be applied to other types of electromechanical converters

Approbation of the work and publication of the main scientific results. The dissertation work was carried out at the Azerbaijan Technical University (AzTU). 17 papers have been published on the topic of the dissertation, including 6 scientific reports related to the materials of scientific conferences of ApNE professors and teaching staff in 2004 -2011, 2 author's certificates, 9 scientific articles.

The dissertation work was performed at a fairly high level using a modern computer modeling program like MATLAB. The results obtained from the simulation of the developed computer models confirm the reliability of the theoretical studies carried out

Structure and scope of the dissertation. According to the content, the dissertation work consists of an introduction, four chapters, the results obtained and the list of sources used, by volume (excluding the list of sources used) - 161 pages, including 28 figures, diagrams and tables (220058 characters), including an introduction -5 pages (8640 characters), I chapter 34 pages (48132 characters), II chapter 36 pages (43 379 characters), III chapter 45 pages (67089 characters), IV chapter 41 pages (52818 characters). The volume of the abstract itself (in Azerbaijani) consists of 28013 characters.

BRIEF CONTENT OF THE DISSERTATION

The **introduction** shows the relevance of research, issues to be studied, the object and subject of research, the main provisions to be defended by the author were defined and touched upon their scientific novelty and practical significance, extensive information has been provided on publications, approbation and structure of dissertation work.

The first chapter describes the results of the theoretical substantiation of the design of differential piezoelectric transducers (DPET), which provide useful information about the linear and angular displacement of objects and allow to obtain the required accuracy and stability of this information. Thus, the design of the power junctions of these transducers was substantiated, and the functional dependencies between the non-electrical input and electrical output parameters of the transducers were determined.

Figure 1, which is an object of study. The structural scheme of a spherical piezoelectric element, one of the typical examples of DPET, is given and consists of the following: spherically shaped piezoelectric sensitive element (1), cylindrical spring (3) and rods (4), guide supports between them (2), balls connected to conical ends (5), variable profile handles attached to the grooves' seat (6), fixing nuts (7), shoulder holding the rods by hanging (8), constructive axis of the transmitter (9), eccentric shape on the surface (11) from the front body(10) of the transmitter to which it is opened, the cylindrical spring (12) which ensures that the axis of the transmitter is compressed to its front body, and the cover of the transmitter (13). The measurement of the mechanical parameter is connected to the moving object by means of a transmitter axis.

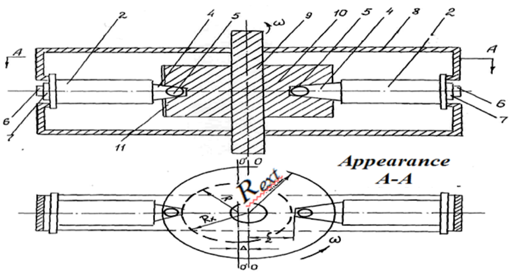

Fig. 1. Structural scheme of a spherical piezoelectric element, which is one of the typical examples of DPET

Through this axis, the rotational motion is transmitted to the grooves through the shoulder and moves circularly along the inner profile of the eccentricity relative to the body with a piezoelectric sensitive element (PSE) placed inside the grooves, a rod and a ball at the end. In this case, one of the piezo-sensitive elements in the shoulders works to compress and the other to release, creating signals of different polarity voltages, respectively, according to the outputs.

In DPET, the sequence of transducing of displacements into a signal is characterized as follows:

$$X_n \to X_p \to \varphi_p \to F_{np} \to X_ş \to \varphi_ş \to U_c , \qquad (1)$$

Here, X_n – displacement of the slide relative to the body; X_p – displacements of Γ-form supports relative to slide; φ_p – angle of Γ-form supports; F_{np} – Static compressive(traction) force of cylindrical springs; $X_ş$ – linear displacement of rods; $\varphi_ş$ –angular displacement of rods; U_{ac} output voltage of the transformers.

At the same time the selection of static parameters of piezoelectric transducers for measuring the linear and angular displacements of objects were considered in I Chapter and main criteria for measuring displacement parameters of static and non-static managing object were defined while making PET designing.

Chapter II identifies the design features of new variants of DPET with differential circuit, as well as the design features of new differential and sensitive structural variable accelerometer with analog output vibration **[1-8, 14]**;.

The novelty and advantages of the developed new design options are confirmed by the received author's certificates. In one of their new design variants, the connection points of the first and second flat metal springs of the inertial bodies are located in mutually opposite directions.

When a relative linear acceleration is formed, one of these inertial masses, separating from the exciter, increases, and the second, approaching it, reduces the air gap. This leads to bending of metal springs, as well as piezoelectric elements. As a result, the values of the stresses on the electrodes of the elements, which are proportional to the value of the relative acceleration, also change (Fig. 2).

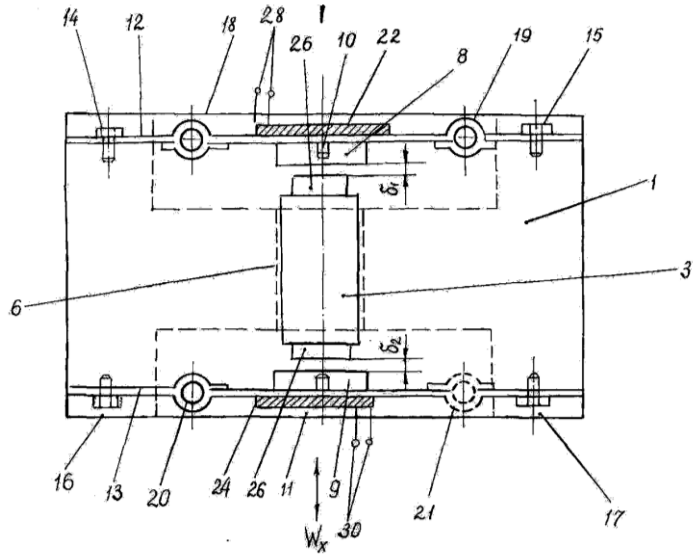

Fig 2. The basic design scheme of the vibration DPET.
1-housing; 2,3-elements of the converter; 4,5-ltverstiya; 6-cental hole; 7-exciter; δ - air gap; 8, 9-identical inertial masses; 14, 15, 16, 17-connecting holes; 12 13-flat metal springs; 18, 19, 20, 21 - metal springs of cylindrical shape; 22, 23, 24, 25-piezoelectric elements; 26-rod; 27, 28, 29, 30, 31 –electrical leads;

So that it is possible to increase the sensitivity and thereby increase the amplitude of mechanical vibrations due to the presence of a direct connection of piezoelectric elements and flat metal layers.

The new type of DPET variants have an analog output in the form of a constant voltage and may be measured in micro-shifts in range of $\pm(10^{-5}g \div 15g)$ and $\pm(0{,}01g \div 300g)$ relatively high value range.

In this case, the sensitivity and measuring range of the designed accelerometers are one step higher than the known accelerometers, and the additive error of the new DPET variants is compensated by their differential implementation. The main goal in the development of such DPETs was to increase their measurement sensitivity and measurement accuracy. To achieve this, the kinetic energy of the inertial mass oscillating under the influence of periodic feeding voltage was used.

At the same time differential vibrational piezoelectric transducers of micro-movements and deformations were studied and algorithms for digital processing of the output signal of the differential PET were developed and the operation algorithm of the collector was determined by the following difference equation:

:

$$N_{\Omega}[n+1] = N_{\Omega}[n] + N_S[n] \qquad (2)$$

here, $N_{\Omega}[n]$- output code of tact signal of register in front of entry moment of $[n+1]$ impulse.

When developing algorithms for digital processing of DPET output signals, the main goal was to: 1) the ability to determine the position, speed and acceleration of the object with the help of only one converter; 2) the developed algorithms of digital processing should ensure the prevention of the formation of additional methodological errors.

According to the developed algorithms of digital processing, the expressions for forming digital codes of the angle of rotation, angular velocity and angular acceleration of a moving object, respectively, are as follows:

$$N_{\theta} = f_0 \frac{\theta}{\omega_R} \; ; \quad N_{\Omega} = K_N \frac{\Omega}{\omega_R} \; ; \qquad N_{\varepsilon} \approx \frac{2\pi}{\omega_R{}^2} \varepsilon \qquad (3)$$

Here, ω_R -is the clock frequency of digital processing algorithms that operate on the principle of triggers (in other words, the frequency of synchro pulses) and which is determined depending on the value of the resonant frequency DPET- $\omega_R=2KN\pi f_0$; K- is the calculated value of the proportionality coefficient; N - is the coding coefficient; f_0 - is the resonant frequency DPET.; $\theta, \Omega, \varepsilon$- is the angle of rotation, angular velocity and angular acceleration of the moving object, respectively,

The **third chapter** substantiates the need for a differential bridge circuit in which the sensitive elements are connected in series to ensure the linearity of the output signal of the resonant differential PET. Analytical expression was obtained to determine the functional relationship between the input and output parameters of the generated DPET, static characteristics (SCH) were constructed and determined that the characteristic line around the resonant frequency, analytical expression of static errors of the furnace was determined on the basis of a sequential differential bridge scheme, ways to reduce static error within the accepted conditions are shown.

Depending on the initial state of DPET, both PSEs with differential coupling are compressed with the same force and the sequence of transducing of the angle of rotation to the output voltage occurs according to the scheme in Fig 3

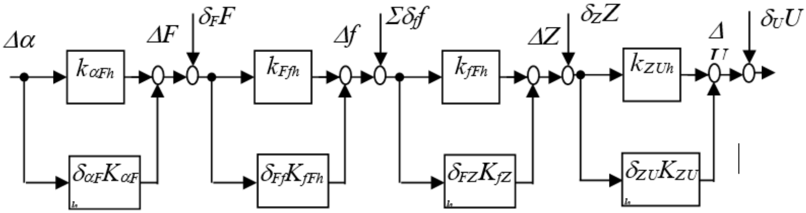

Fig.3 Structural scheme of formation of measurement errors of DPET

Here: α-the measured angle of rotation; ΔF-the change in the compression force of the piezoelectric sensing element; Δf- the frequency offset from the resonance frequency of the piezoelectric sensing element; $\Delta Z(j\omega)$ - the change in the resistance of the reactive nature of the piezoelectric sensing element; $U_Ç$ - the output voltage of the bridge electrical circuit; $K_{a\Delta F}$- the conversion coefficient "angle of rotation – change in force"; $K_{\Delta Ff}$-- the conversion coefficient "change in force-frequency offset"; $K_{f\Delta Z}$- the conversion coefficient "frequency offset–change in resistance"; $K_{\Delta ZU}$-conversion coefficient "resistance change-voltage change”; $\delta_{\alpha Fh}, \delta_{Ffh}, \delta_{fzh}, \delta_{zuh}$ -errors of the corresponding transformations; $\delta_f ;\delta_Z ;\delta_F$ δ_U -errors of the corresponding output signals from external influences.

It is revealed that the static characteristic of the DPET, which determines the dependence of the voltage change on the measured angle of rotation, is linear, only if the Q factor of the piezoelectric sensor is constant, otherwise it is not linear/

The analytical expression of the static errors of the DPET connected to the series differential bridge circuit was determined, the minimization of the static error was solved within the accepted conditions. Static errors were made only in the direction of the tool and the determination of fixed errors. Errors were identified under the following conditions:

1. If the error changes linear, the following expression can be written:

$$A_d = A_h(1+\delta_n) \tag{4}$$

δ_A - the relative error factor of parameter A

2. Because the relative error is a small parameter.:

$$\prod_{i=1}^{n} \delta_i = 0;\ n \geq 2 \tag{5}$$

Tool errors shown in the block diagram of the output voltage transducing when measuring the angle of rotation:

$$y = k \cdot \gamma = K_h(1+\delta_k) \cdot x$$

(6)

according to this expression, the fixed errors are determined regardless of the transducing of the input signal.

$$y = y_d + \delta_y y_d = y_d(1+\delta_y) \tag{7}$$

In expressions (4-7) $K_{\alpha Fh}, K_{Ffh}, K_{fzh}$, K_{uzh} -the calculated values of the corresponding coefficients; $\delta_{\alpha Fh}, \delta_{Ffh}, \delta_{fzh}, \delta_{zuh}$ -the values of the errors formed from the appropriate transformations ; $\delta_f ;\delta_Z ;\delta_F$ and δ_U - the relative errors of the corresponding vhldlv formed under the influence of the external environment. According to the block diagram shown in the figure, an expression for the output voltage value is found:

$$\Delta U = \Delta U_n(\alpha)\left[1 + (\delta_{\alpha F} + \delta_{Ff} + \delta_{fZ} + \delta_{ZU}) + \right. \\ \left. + \ (\delta_f + \delta_Z + \delta_F + \delta_U)\right] . \quad (8)$$

Here:

$$\Delta U_n(\alpha) = K_{\alpha Fh} \cdot K_{Ffhn} \cdot K_{fZn} \cdot K_{ZUh} \cdot \Delta\alpha \quad (9)$$

is calculated value of the output voltage change.

The following criteria are defined for the minimum allowable error: if the bridge connected to the inverter is in balance, inclination of the resistance of its sensitive element according to the accuracy class to which the bridge belongs, the output voltage during which the value is greater than the inclination, to define signal $\delta_U \Delta U$ the parameters of the bridge circuit of the converter were minimized.

The following conditions were adopted when minimizing errors. The internal resistance of the food source is infinitely small- $R_d=0$, and load resistance, infinite big - $Z_{yuk} \to \infty$ the relative values of the resistances with respect to the first arm of the bridge - $m = Z_2 / Z_{10}$; $n = Z_3 / Z_{10}$ are integers, with the scattering forces of the maximum values of the currents passing through the resistors – $I^2_i Z_i \leq P_{id}$ it was determined that the maximum value of sensitivity should be equal to a quarter of the supply voltage.

The resulting mathematical expression of the static characteristic DPEC:

$$U = 0.25 U_0 \left[1 - - \sqrt{\frac{1 + Q_0^2 (1 - Q_\alpha \Delta\alpha)^2 (Q_\alpha \Delta\alpha)^2}{\left(1 + \frac{ES}{ES - Q_\alpha \Delta\alpha}\right)^2}} \right], \quad (10)$$

$$Q_\alpha = \frac{v k_y r}{ES \sin\varphi} . \quad (11)$$

Here U_0 - the supply voltage of the electrical bridge circuit to which the piezoelectric sensing elements are connected; Q_0 - the Q factor of the piezoelectric sensing elements; E- the Young's modulus; S – the active area of the piezoelectric sensing element ($S = ab$, a, b - length and width, respectively); φ - the angle of inclination of the excenter profile, the converter design; ν - the Poisson's ratio; k_y - the coefficient of conversion of the angle of rotation to linear displacements, determined by the design of the converter r - - the distance between the axes of the piezoelectric sensor element and the converter itself, determined by the design of the device. $\Delta\alpha$ - the measured angle of rotation.

In order to influence the shape of the static characteristic of the structural errors, as well as the errors of the angle of rotation itself, the dimensions of the sensitive element *a*, *b*, the center distance *r*, the angle of rotation $-\Delta\alpha$ are presented as: $r = r_0 + \Delta r$; $a = a_0 + \Delta a$; $b = b_0 + \Delta b$; $\Delta\alpha = \Delta\alpha_0 + \Delta_\alpha$. In these expressions: $a_0, b_0, r_0, \Delta\alpha_0$ - the calculated values, Δa ,Δb ,Δr ,Δ_α -the known errors of the corresponding parameters, ($\Delta a = a_0\delta_a$; $\Delta b = b_0\delta_b$; $\Delta r = r_0\delta_r$; $\Delta_\alpha = \Delta\alpha\delta_\alpha$),Need to define the dependency:

$$\Delta U = f(a_0, b_0, r_0, \Delta\alpha_0, \Delta a, \Delta b, \Delta r, \Delta_\alpha) \qquad (12)$$

Using equations (10), (11) and the rules for performing arithmetic operations with infinitesimal numbers, an expression is found that defines the dependence (12) **[18]**:

$$\Delta u = 1 - \sqrt{\frac{1 + Q_0^2 (C_0)^2 (1 + \delta_r + \delta_\alpha)^2 \left(2 - D_0 \frac{1 + \delta_r + \delta_\alpha}{1 + \delta_a + \delta_b} \right)^2}{1 + Q_0^2 (C_0)^2 (2 - D_0)^2}} .$$

(13)

Here:

$$C_0 = \frac{\nu k_y r_0}{\sin\varphi} r_0 \Delta\alpha_0 , \; D_0 = \frac{\nu k_y}{E \sin\varphi} \frac{r_0 \Delta\alpha_0}{S_0} .$$

A computer model of expression (13) is compiled in the MATLABSimulink software environment using the following data:: U_0 =12V; Q_0 =12; E =767; a =0.02 m; b=0.015 m ; φ =8^0 ; ν =0.34; k_y =0.45; r =0.12 m; $\Delta\alpha$ = (0-360); δ_a=0.002; δ_b=0.003; δ_r=0.025; δ_α=0.032, model simulation performed.

It was found that in the range of measuring the angle of rotation 0-360^0, the static characteristic has a relatively higher error, about 0.5-0.6%, than in the middle part of the range: 0.08-0.1 %

In **Chapter IV**, in order to study the dynamic characteristics of a differential bridge circuit with a resonant nature connected in series with a piezo-sensitive element, the operator's calculation method was applied to the electrical circuit and a bridge replacement circuit was built (Figure 4).

A description of the load current was found using the method of contour currents, a computer study was conducted on the basis of the obtained expressions and the transition processes of the bridge system were studied.

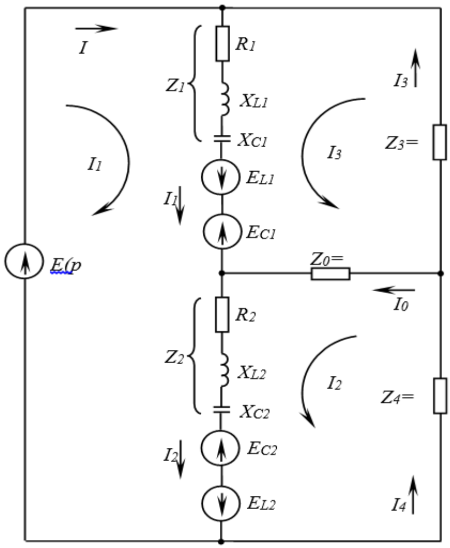

Fig 4. Operator replacing cheme of DPEC

$$I_0(p) = \frac{\Delta_2 - \Delta_3}{\Delta} = E_{11}\frac{a_1 s^3 + b_1 s^2 + c_1 s}{as^4 + bs^3 + cs^2 + ds + e} +$$
$$+ E_{22}\frac{a_2 s^3 + b_2 s^2 + c_2 s}{as^4 + bs^3 + cs^2 + ds + e} - E_{33}\frac{a_3 s^3 + b_3 s^2 + c_3 s}{as^4 + bs^3 + cs^2 + ds + e}$$
(14)

Here, the coefficients included in the last expression are calculated as follows:

$$\begin{cases} a_1 = 2R_0\left(L_1C_1C_2 - L_2C_1C_2\right) + R_4L_1C_1C_2 - R_3L_2C_1C_2 \\ b_1 = 2R_0\left(R_1C_1C_2 - R_2C_1C_2\right) + +R_4R_1C_1C_2 - R_3R_2C_1C_2 \\ c_1 = 2R_0\left(C_2 - C_1\right) + R_4C_2 - R_3C_1 \end{cases}$$
;

$$\begin{cases} a = (4R_0 + R_3 + R_4)L_1L_2C_1C_2 \\ b = (4R_0 + R_3 + R_4)\left(L_1C_1C_2R_2 + L_2C_1C_2R_1\right) + \\ \quad + \left[\left(R_3 + R_4\right)R_0 + R_3R_4\right]\left(L_1C_1C_2 + L_2C_1C_2\right) \end{cases}$$

$$\begin{cases} a_3 = \left(2R_0 + R_4\right)\left(L_1C_1C_2 + L_2C_1C_2\right) \\ b_3 = \left(2R_0 + R_4\right)\left(R_1C_1C_2 + R_2C_1C_2\right) \\ c_3 = \left(2R_0 + R_4\right)\left(C_2 + C_1\right) \end{cases}$$

The method of dividing complex fractions into simple fractions was used to determine the original of the current in expression (14). In this case, the numerical report of the system was based on the following data using theoretical results:

$$\begin{cases} c = 4(R_0 + R_3 + R_4)\left(L_1C_1 + L_2C_2 + C_1C_2R_1R_2\right) + \\ \quad + \left[\left(R_3 + R_4\right)R_0 + R_3R_4\right]\left(R_1C_1C_2 + R_2C_1C_2\right) \\ d = 4(R_0 + R_3 + R_4)\left(R_1C_1 + R_2C_2\right) + \\ \quad + \left[\left(R_3 + R_4\right)R_0 + R_3R_4\right]\left(C_1 + C_2\right) \\ e = 4(R_0 + R_3 + R_4) \end{cases}$$

$$\begin{cases} E_p = E_0\,\omega/\left(s^2+\omega^2\right); E_{L1} = LI_1(0\_); E_{L2} = LI_2(0\_); \\ E_{C1} = U_{C1}(0\_)/s; E_{C1} = U_{C2}(0)/s \end{cases}$$

In this case, the numerical report of the system was based on the following data using theoretical results:

$R_0 = 5\cdot10^6 Om; R_1 = 7\cdot10^6 Om; R_2 = 5\cdot10^6 Om;$

$R_3 = 11\cdot10^6 Om; R_4 = 8\cdot10^6 Om; C_1 = 16\cdot10^{-9}\Phi;$

$C_2 = 46\cdot10^{-9}\Phi; L_1 = 3\cdot10^{-3} hn; L_2 = 2\cdot10^{-3} Hn;$

$E_0 = 15V, LI_1(0\_) = 8V; LI_2(0\_) = 10V; U_{c1}(0) = 3V;$

$U_{c2}(0\_) = 5V; f = 2*10^5 Hs;$

After the necessary calculations, the following values are taken for the coefficients of the expression (14):

$$\begin{cases} a = 4.4\cdot10^{-24}; b = 3.8\cdot10^{-13}; c = 41\cdot10^{-4}; d = 6.6\cdot10^{-5} \\ a_1 = 8{,}8\cdot10^{-12}; b_1 = 2{,}2\cdot10^{-3}; c_1 = 4.9\cdot10^{-4}; a_2 = 7.7\cdot10^{-13}; \\ b_2 = 1.8\cdot10^{-5}; c_2 = 1{,}3; a_3 = 6.6\cdot10^{-13}; b_3 = 1.5\cdot10^{-5}; c_3 = 1{,}1 \end{cases}$$

$$\begin{cases} E_{11} = E_0\,\omega/\left(p^2+\omega^2\right) + 18 - 8/p \\ E_{22} = 5/p - 10 \\ E_{33} = 8 - 3/p \end{cases}$$

The expression of the load current of the bridge circuit is descriptive written as follows:

$$I_0(s) = \left[E_0\,\omega/\left(s^2+\omega^2\right) + 18 - 8/s\right]\times$$
$$\times\left[-\frac{1.009}{0.559s+1} + \frac{0.96}{0.073s+1} + \frac{0.049}{0.004s+1}\right] +$$

$$+\left(5/s - 10\right)\left[-\frac{216.3}{0.559s+1} + \frac{212.8}{0.073s+1} + \frac{3.53}{0.004s+1}\right] +$$
$$+\left(8 - 3/s\right)\left[-\frac{1.99}{0.559s+1} - \frac{2.56}{0.073s+1} + \frac{4.56}{0.004s+1}\right] \qquad (16)$$

As a result of numerical calculations, the expression of the original load current was found and the transition processes were established, and it was determined that the output current of the DPEC changes periodically and is approximately linear (24.2A/sec), settling time 1.9-2, 2 m/sec.

The developed DPEC are provided with an extended measurement range with stable dynamic sensitivity. For this purpose, the model "supply voltage –output voltage" was selected for the converter, the transfer function for this model was compiled using a well-known method, the characteristic equation with normalized coefficients was calculated and obtained, and an active second-order filter was applied, and as a result, the unstable area near the resonant frequency was smoothed. [16].

Using the known equations of the parameters of the piezoelectric disk-shaped sensing element substitution circuit

$$C=\frac{8\pi r^2}{(n\pi)^2}\frac{(d_{13})^2}{S_{33}^E}\frac{1}{h};\ R=\rho\frac{(n\pi)^2}{8\pi r^2}\frac{\left(S_{33}^E\right)^2}{(d_{13})^2}h_0;\ C_k=(\varepsilon_{11})^5\pi r^2\frac{1}{h};$$

(here: *r*, *h*- thickness and radius of the piezoelectric sensing element of the disk shape; *ρ*- density; *p*- serial number of the mod; S_{33}^E - elastic viscosity coefficient; d_{13} - pyezomodul).

Based on reference data: ρ=2686 *kg/m*^{3}; *r* =0.004 *m;* *p=1;* S_{33}^E= *12,77·10*$^{-12}$ *m*^{2}*/N;* d_{13}= *2,31·10*$^{-12}$ *Kl/N* , solutions for the parameters were found *h* and *r*. From the area of found solutions, positive real numbers are selected: *r*=0.00421*m*, h_1=0.002131 *m* ; h_2=0.002122 *m.*

Thus, sensitive elements made of materials with known physical properties must be disk-shaped, with a radius of: *r*=4.21 *mm;* thick *h*=2.131 *mm.* Compression strain obtained during measurement : : Δ *h*=0.002131- 0.002122 = 0. 000009 *m.* Secure range with stable dynamic sensitivity: $f_{öd}$= *0*-1600 *Hs.* Filter transfer function:

$$W(s)_S = \frac{K}{s\left(2RC_1C_2s+(C_1-C_2)\right)\left(2T^2s^2+2\varepsilon_{to}Ts+1\right)}. \quad (17)$$

The logarithmic frequency response and transients are shown in Figures 5 and 6.

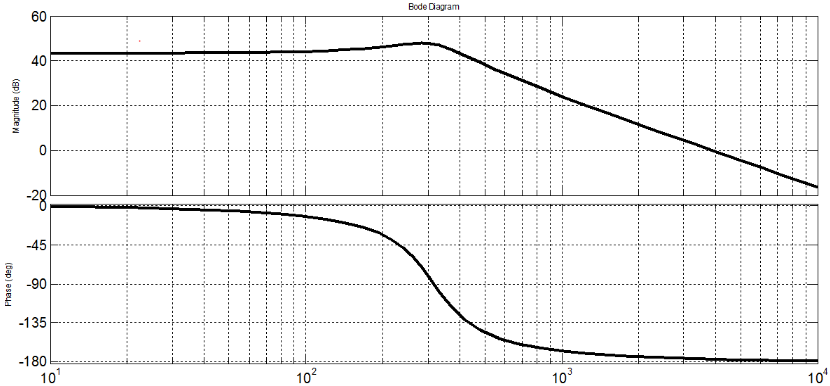

Figure 5. DPET transient with a normalized characteristic and a second-order filter.

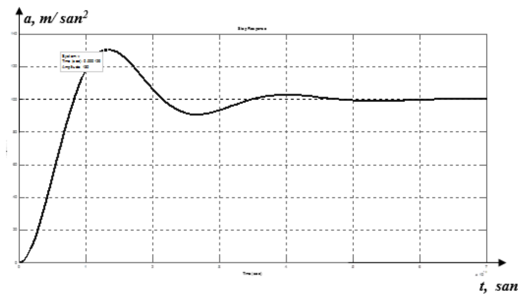

Figure 6. DPET transient with a normalized characteristic and a second-order filter

It was found that under certain conditions it is possible to normalize the coefficients of the characteristic equation of the PET and adjust the measuring range by means of geometric dimensions of piezo-sensitive elements in the form of discs

The main results of the dissertation

1. DPEC has implemented a new design solution and has been found to be relatively simple in design and highly sensitive.

2. The issue of placing DPEC in the bridge measurement scheme has been resolved. Thus, the need for a sequential differential bridge circuit to ensure the linearity of the converter's output signal has been identified.

3. An analytical expression was obtained to determine the functional dependence between the input and output parameters of DPET, its static characteristics were built and it was determined that the characteristic is linear around the resonant frequency only if the quality coefficient of the piezoelectric element remains constant.

4. The analytical expression of the static lines of the DPEC connected to the series differential bridge circuit is determined, the static error minimization is solved within the accepted conditions and it is determined that the maximum value of sensitivity is not more than a quarter of the supply voltage.

5. In order to measure the movement parameters of DPEC and algorithms of digital processing junctions of the output signal were developed.

6. In order to study the dynamic properties of resonant-type DPET in the case of non-zero resonant type of series-connected differential bridge circuit, the switching scheme was applied using the operator calculation method of electric states, computer-based transition studies were studied. It was determined that the settling time of the output current of DPEC is 19-2.2 m/s.

7. Sequentially connected differential bridge circuit Resonant-type parametric PEC switching process depending on the physical parameters of the piezoelectric element, mathematical expressions are obtained that allow it to be adjusted to the technical optimum.

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