INCREASING THE WORKING SPEED DURING WIRE DRAWING BY ULTRASONIC ACTIVATION OF THE DIE

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The basic process investigated in this research is that of obtaining wires by wire-drawing technology, which consists of successively passing a semi-finished wire through a sequence of dies until the desired final diameter is obtained. The phenomena that can still be studied in this process and improved is that of reducing the friction between two parts that are in relative motion named also "ultrasonic lubrication". The article presents the design and calculation of the ultrasonic transducer used to activate the drawing die, the FEM to determine the optimal vibration frequencies and vibration modes used in activation of the die to increase the working speed.

Keywords: piezoceramic, materials, ultrasonic, die, wire drawing

1. Introduction

Piezoceramic materials are currently used in a series of very important industrial and scientific fields that include elements of high intelligence and innovation. Thus, we can find such structures, and the notion of structure is well used here because these materials include several elements, in areas such: industrial automation; high precision engineering and mechanics; aviation and space activities; automobile industry; industrial automation; advanced medicine; telecommunications; consumer goods industry. In all these industries, electrical energy is usually transformed into mechanical energy by using various types of electrical transducers [1,2,3,4]. Very interesting applications can be found, for example, in the use of ultrasound in the phenomenon of ultrasonic cavitation [5,6,7,8,9] used in medical cleaning installations, for example, or air filtration systems. Another example of the very successful use of ultrasound is that in the construction of ultrasonic motors [10,11,12,13]. These systems transform electrical energy into "traveling wave" vibratory waves to obtain high-precision translational or rotational movements that cannot be influenced by electric or magnetic fields, for example. In addition to all these applications of ultrasound, the reduction of the coefficient of friction between two surfaces that are in relative motion relative to

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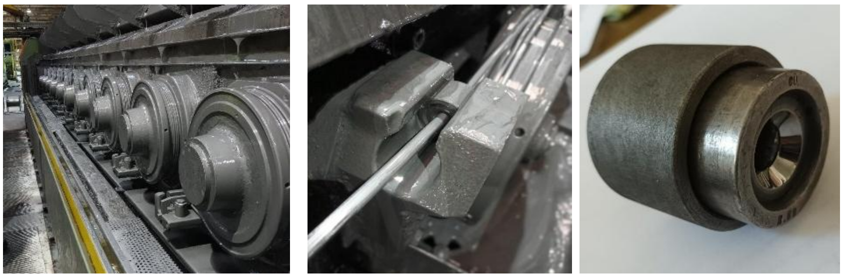
each other is also distinguished. The evaluation of friction reduction and frictionless stress in ultrasonic vibration forming process was studied also by Jul L. [16]. The phenomenon has been studied also from the point of view of ultrasonic motors by

H. Storck, end all [14]. Thomas Sednaoui &all [15] studied using an experimental stand the variation of the friction coefficient depending on the vibration amplitude and found a substantial reduction from the value of 1.6 to the value of 0.4 µm if the vibration amplitude increases from 0.5 µm to 3.5 µm. at a frequency f = 25 KHz. The experiments were carried out in the case of palpating with the finger a plate that oscillates in the ultrasonic field. Pham, T.M.; Twiefel, J studied in [16] the reduction of the friction coefficient at the contact between an elastomer and a metal.

Wire drawing represents a processes for obtaining semi-finished products through plastic deformation, in which the metal material under the action of a drawing force is forced to pass through a calibrated hole of a tool, which is smaller than the initial section of the material. If the traction force is provided by a drum or roller, on which the deformed material is wrapped, the process is called drawing; if the traction force is exerted by a machine body with rectilinear movement, and the deformed products (bars or pipes) are obtained straight, the process is called pulling. To obtain the wires, drawing machines are used (Fig. 1a), which are made up of several dies (Fig. 1 b,c) that ensure a gradual reduction of the diameter of the semi-finished product until the final, desired.



a. b. c.

Fig. 1. The process of obtaining wires by drawing; (a) wire drawing machine; (b) positioning a die on the wire drawing machine; (c) wire drawing die

2. Design of the ultrasonic transducer to activate the drawing die

2.1 Analytical dimensional design of the ultrasonic transducer

The analytical calculation to realize the dimensional design of the main elements of the piezoceramic transducer represents a very important stage in the realization of the entire ultrasonic assembly. To calculate and size the ultrasonic system, according to [17,18] in the first stage, the initial data necessary to solve the equations describing the vibrational behavior of piezoceramic materials are entered, namely [19]: material permittivity - $\varepsilon_0 = 9.69\,E11$[F/m], resonance frequency - f_0 = 35000 Hz, resonance pulsation - $\omega_0 = 2\pi f_0 = 21.9 \cdot 10^4$, particle displacement - ξ= $0.5\cdot10^{-7}$ m, input electrical power - Pin = 1500 W, acoustic intensity [20,21] - $I_a = \frac{Z_c\cdot(2\cdot\pi\cdot f_0)^2\cdot\xi^2}{2}$ = $4.8\cdot 10^6$ W/m^2, where Z_c – acoustic impedance; f_0 – resonance frequency; ξ - particle displacement, Z_c = 80 kRayl, the acousto-mechanical efficiency [35,36] - η_{am} = 0.8, the electromechanical coupling factor - [37,38] – ζ = 0.75, the electroacoustic efficiency [22] - ηea = 0.95, piezoceramic material density $\rho = 7.8 \cdot 10^3$ [Kg/m^3], piezoceramic material Young modulus $Y = 5.1 \cdot 10^{10}$ [N/m^2], piezoceramic material Poisson coefficient ν = 0.25, the relative permittivity at 1 Hz - $\varepsilon_{rp} = 2600$, loss angle - δp = 0.73 deg ; tg (δp) = 0.0127, piezoelectric constant $k_p = 390 \cdot 10^{-12}$ [m/V], steel Young modulus - $Y = 200 \cdot E9$ [N/m^2], steel density - $\rho = 7.8 \cdot 10^3$ [Kg/m^3], steel Poisson coefficient ν = 0.3, aluminium density - $\rho = 7.8 \cdot 10^3$ [Kg/m^3], aluminium Poisson coefficient - ν = 0.33.

Using the input data presented previously, the dimensions of the transducer composed of a passive element (the reflector) and an active element, made of steel and aluminum, were calculated. It was calculated as follows:

- ultrasound propagation speed through piezoceramic elements - vp, with formula:

$$s_p = \sqrt{\frac{E_p(1-\nu_p)}{\rho_p(1+\nu_p)(1-2\nu_p)}} = 2801 \text{ m/s}, \quad (1)$$

where: E_p is the modulus of elasticity of the material; ν – Poisson's ratio.

Using the same formula, the speed of ultrasound propagation through the aluminum amplifier area S_{Al} = 6148 m/s and through the steel area S_{St} = 5952 m/s resulted. The wavelength λp of ultrasound through the same elements. For the piezoceramic material this is:

$$\lambda_p = \frac{s_p}{f_0} = 80 \text{ mm}; \quad (2)$$

For aluminum and steel cylinders respectively, the wavelengths are λ_{Al}= 297 mm and for the steel one λ_{St} = 307 mm. The axial dimensions of the main components made of piezoceramic material, aluminum and steel of the ultrasonic transducer according to the longitudinal direction of propagation of ultrasonic vibrations in $\lambda_p/4$ are, according to relation, for the piezoceramic elements:

$$l_p = \frac{l_p}{4} = 20 \text{ mm}. \quad (3)$$

As can be seen from figure 2, the block of piezoceramic elements is 20 mm long. For the aluminum portion of the transducer amplifier the resulting length is l_{Al} = 74.25 mm and for the steel portion l_{St} = 76 mm. To determine the radius of the piezoceramic active element, the radiation area of the active element must be calculated. This must be correlated with the input power, P_{in} = 3000 W and with the required acoustic intensity and is calculated:

$$A_p = \frac{P_{in}}{I_a \cdot \eta_{ea}} = 781 \cdot 10^{-6}\ m^2 \quad (4)$$

- the radius of the resulting piezoceramic active element (for the circular section), is r_p:

$$r_p = \sqrt{\frac{A_p}{\pi}} = 15.7\ mm \quad (5)$$

- the effective electroacoustic efficiency of the transducer of the compound transducer is [30,31]:
- the force developed by the active element [30,31]:

$$F_p = k_p \cdot U_p \cdot \frac{A_p \cdot Y_p \cdot \eta_{e\,ar}}{d_p} = 685\ N \quad (6)$$

where:

$$U_p = \frac{\sqrt{\alpha_0 \cdot Z_p \cdot P_{in} \cdot \eta_{ea}}}{\eta_{am} \cdot n_p} = 6.5 \cdot 10^2\ V \quad (7)$$

where $\alpha_0 = 0.85$, $n_p = 2.23\ N/V$ is the electromagnetic transformation coefficient. If the effective electroacoustic efficiency of the transducer is $\eta_{e\,ar} = 0.8$ the actual mechanical energy is of the form [17,18]:

$$W_m = \frac{1}{2}\left(F_p^2 \cdot C_m\right) = 0.31 \cdot 10^{-3}\ Ws \quad (8)$$

where C_m = 1.36 nF is the real electrical capacitance of the active element.

- the electrical energy consumed is calculated with the relationship [17,18]:

$$W_e = \frac{1}{2}\left(U_p^2 \cdot C_p\right) = 0.272 \cdot 10^{-3}\ Ws \quad (9)$$

Where C_p = 1.16 nF is the electrical capacitance of the active element.

Calculation elements for the ultrasonic energy concentrator are:

- length of ultrasonic energy concentrator:

$$L = \frac{n \cdot c}{2 \cdot f_0}\sqrt{1 + \left[\frac{ln(N)}{\pi \cdot n}\right]} = 104\ mm \quad (10)$$

where: f_0 = 35000 Hz; n = 1; N = 5.

- nodal points x_{nod} are calculated with the relation [30,31]:

$$X_{nod} = \frac{L}{n \cdot \pi} arc\ tg \left(\frac{\ln N}{n \cdot \pi} + n_1 \cdot \pi \right) = 42 \text{ mm} \quad (11)$$

$$X_{nod} = \frac{L}{n \cdot \pi} arc\ tg \left(\frac{\ln N}{n \cdot \pi} + n_1 \cdot \pi \right) = 42 \text{ mm} \quad (12)$$

Considering the constructive possibilities regarding the choice of piezoceramic elements, the radius of the available piezoceramic element is r_p = 17.5 mm. This radius was used for the construction of the piezoceramic transducer instead of radius = 15.7 mm resulted from theoretical calculation. One of the most important elements of the ultrasonic transducer system is represented by the ultrasound concentrator. It has the role of concentrating the energy of the ultrasonic vibrations and sending it to the area of interest. As can be seen in figure 1, a concentrator consisting of three cylindrical zones was designed with a total length of 104 mm as resulted from calculations and experience of the authors in this domanin. Figure 2 presents the overall scheme of the ultrasonic system used to activate the molds used for wire drawing. Here they were noted as follows: 1 – the ultrasonic reflector; 2 – the four piezoceramic discs; 3 – the ultrasonic amplifier (the aluminum part); 4 – the ultrasonic amplifier (steel part); 5 – nodal flange; 6 – the ultrasonic concentrator. To determine the optimal working frequencies of the ultrasonic system and to greatly reduce the time required for the experiment regarding the determination of the frequency at which the vibration amplitude is maximum, the finite element method can be used. This method, implemented through the ANSYS software, within the performance of a modal analysis, determines the free, natural vibration frequencies of the ultrasonic system. The analysis was carried out using two types of discretization elements, namely SOLID98 for the discretization of piezoelectric elements and Solid187 for the discretization of elements made of aluminum and steel. The material properties used to characterize the piezoceramic material are: ET,1,SOLID98,1; MP,DENS,1,7500; MP,PERX,1,804.6; MP,PERZ,1,659.7, TB,PIEZ,1; TBDATA,16,10.5; TBDATA,14,10.5; TBDATA,3,-4.1; TBDATA,6,-4.1; TBDATA,9,14.1, TB,ANEL,1; TBDATA,16,3.0E10; TBDATA,19,2.6E10; TBDATA,21,2.6E10.

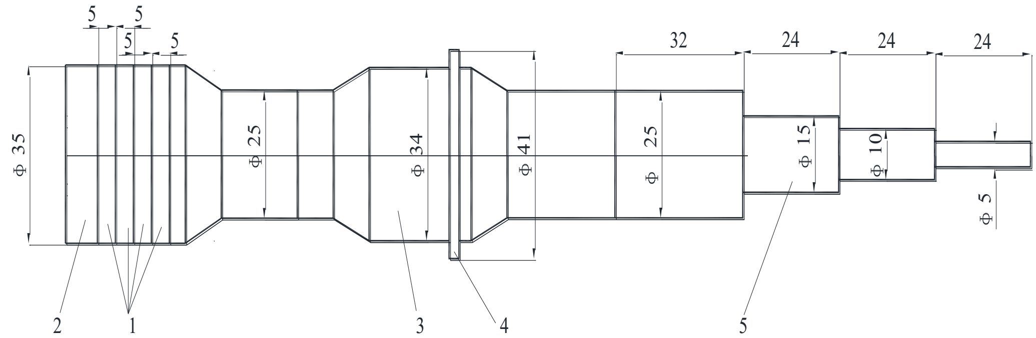
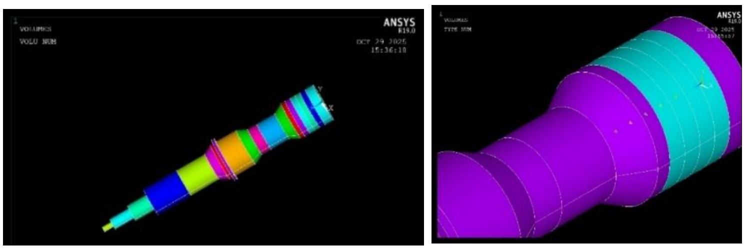


Fig. 2. Ultrasonic transducer design

For aluminum and steel, properties such as Young's modulus, Poisson's ratio and density are already well known. The analytical mathematical calculation presented above was made considering the vibration frequency of 35 KHz. From these calculations the length of the concentrator resulted, finally the entire assembly of the acoustic system used to activate the die used for drawing, being presented in Figure 1. Next, starting from this drawing, the 3D model was made in the Ansys software presented in Figure 3 a while Figure 3 b presents the application of the potential difference on the surfaces of the piezoceramic plates. To determine the free vibration frequencies, a modal analysis was performed that calculated two vibration modes close to the vibration frequency of 35000Hz, namely, the first of them at the frequency f = 33990 Hz and the second at the frequency f = 36000 Hz.



a. b.

Fig. 3. Ultrasonic system modeling; (a) geometrical model of the ultrasonic system used in modeling; (a) geometrical model of the ultrasonic system used in ultrasonic activation of the die; (b) view of application of the electric potential difference

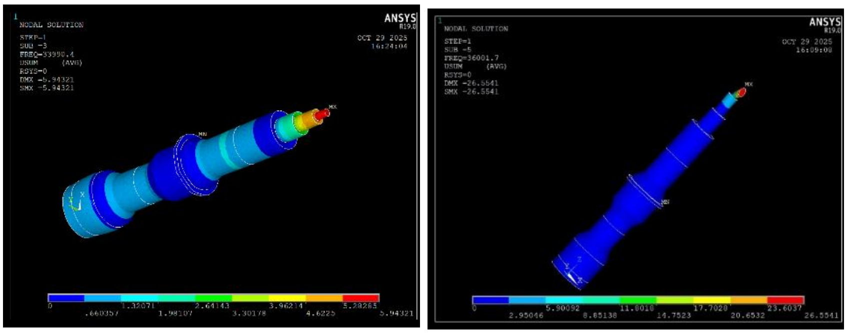
This small difference can be explained by the fact that in the construction of the ultrasonic transducer system, the calculations resulted in a diameter of the piezoceramic elements d = 15.7 mm and due to the constructive possibilities the real diameter is 17.5 mm. On the other hand, small errors can also arise from the configuration of the transducer fixing system in the nodal flange area or, finally, errors due to the differences between the theoretical properties of the piezoceramic material and its real properties.

2.3 Displacement calculation of the ultrasonic system using FEM at f = 33990 Hz.

Using the finite element method, the ultrasonic transducer displacements for the two vibration frequencies determined by modal analysis are presented below. Since the energy concentrator peak is the zone that comes in contact with the drawing die, attention will be focused on it. Thus, Figure 4 presents for these two vibration frequencies how they vibrate by presenting the USUM displacements. Figure 4 a present the transducer deformation at frequency f = 33990 Hz for which it can be observed how the design of the entire system led to obtaining oscillations only in the free part of the ultrasonic concentrator where their value is around the USUM = 6 μm value. In the rest of the ultrasonic transducer the amplitude of the oscillations is very small, close to zero. What is noteworthy is the fact that the free end of concentrator oscillates only along the OZ axis which can be useful in achieving the "ultrasonic lubrication" phenomenon necessary to reduce the friction forces during wire drawing. Figure 4 b presents the transducer deformation corresponding to frequency f = 36000 Hz. And this time, only the free end of the ultrasonic concentrator oscillates, but these are bending oscillations around the OX axis. Considering the way in which the drawing takes place, this vibration mode is also considered useful. In the same way, it can be observed that throughout the volume of the transducer the calculated displacements are almost zero, which is very useful considering the fact that in the nodal flange area it is necessary that the amplitude of the oscillations be zero or extremely small. From the point of view of the amplitude of the oscillations, for the frequency f= 36000 Hz, these are approximately USUM = 26 μm which can constitute a much better efficiency of the ultrasonic system.

2.4 Mechanical stress stress calculation of the ultrasonic transducer using FEM at f = 33990 Hz.

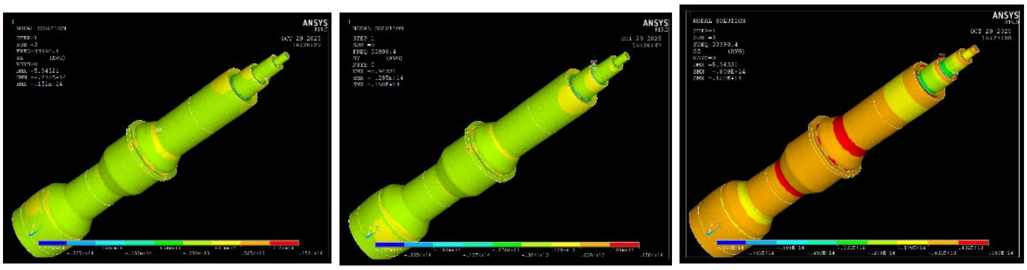
For the two vibration frequencies that can be used in practical experiments to reduce the friction coefficient in drawing, it is very important to analyze the state of mechanical stresses that occur during the operation of the ultrasonic system, since this system must operate for a long time on drawing machines.



a. b.

Fig. 4. Modal analyse of the ultrasonic system: (a) vibration mode at f = 33990 Hz; (b) vibration mode at f = 36000 Hz.

The interest zone for observation is the piezoceramic elements and the nodal flange. This is important because for a long time of use, the piezoceramic elements can be destroyed and, also for a long time, high stresses can damage the fixation of the system in the nodal flange area. For the frequency f = 33990 Hz, figure 5 presents the calculation of the mechanical stresses related to the three orthogonal axis.



a. b. c.

Fig. 5. Mechanical stress calculation at frequency f = 33990 Hz. (a) OX axis; (b) OY axis; (c) OZ axis

From the analysis of the images in Figure 3, Table 1 presents the mechanical stress values in the two areas studied, and it can be seen that they have very similar and not dangerous values even at the maximum level.

Table 1

Stress values on the Ox, Oy and Oz axis for the frequency f = 33390 Hz.

Studied zone	SX [N/m^2]	SY [N/m^2]	SZ [N/m^2]
Nodal flange	-0.38 E13 – 0.93 E12	-0.38 E13 – 0.1 E13	-0.63 E13 – 0.43 E13
Piezoceramic elementes	-0.38 E13 – 0.93 E12	-0.38 E13 – 0.1 E13	-0.63 E13 – 0.43 E13

3. Experiments regarding friction force reduction during drawing in an ultrasonic field

A pneumatic experimental stand was used to conduct experiments on reducing the friction coefficient by ultrasonic activation of the wire drawing die. In this way, the wire was drawn through the inside of the die. In this sense it is known that Pneumatic actuators remain a compact, safe and cost-effective solution for many automation and research tasks. The experimental stand described here is designed to collect high-resolution data from pneumatic cylinders, evaluate performance (speed, flow, pressure), study wear effects, and enable predictive maintenance using edge computing, time-series databases and dashboarding. The experiments on obtaining metal wires through the ultrasonic wire drawing process were carried out using the stand presented in Figure 6. Cylinder 1, driven and controlled by pneumatic system 2, pulls piston 3 to which semi-finished wire 4.

1 2 3 4

Fig. 6. Experimental stand for carrying out the wire drawing process in ultrasonic field

The wire passes through the die 5 placed in support 6 (Fig. 7a). A hole is drilled in this support through which the edge of concentrator 7 passes, which concentrates the mechanical energy produced by the ultrasonic transducer 8 that converts the electrical energy received from the ultrasound generator 9 (Fig. 7b) into mechanical energy. To achieve the best possible contact between the tip of the concentrator and the die, a conical bore hole was drilled in it. The working regime, ultrasound generator was self-tuned to the frequency f = 33940 Hz as can be observed from Figure 7b. From Figure 4a which presents the modal analysis of the free vibration modes, mathematically calculated frequency is ft = 33990 Hz. As can be seen, between the two frequencies, the working f_w = 33990 Hz and the one calculated by the finite element method, the difference is very small, namely approximately 0.14%.

Fig. 7. Elements of the experimental stand used in ultrasonic assisted wire drawing process; a. 5 - die for wire drawing process, 6 – 3D printed support of the die, 7 – ultrasonic concentrator, 8 – ultrasonic transducer; b. 9 – ultrasonic generator

The experiments carried out on the effect of the ultrasonic field on the wire drawing process were carried out in four steps. In the first stage, wire drawing was carried out without the lubricating cooling liquid that is currently used industrially. The average wire drawing speed used in this case is v_1 = 43.3 mm/s. Starting from this speed, when applying the lubricating cooling liquid, an average working speed v_{w1} = 51.81 mm/s was obtained. When the ultrasonic system was activated, an increase in the working speed was found according to the values in Table 3. The average speed in this case is thus v_{wU1} = 51.81 mm/sec. Thus, compared to operation without an ultrasonic field, an increase in the working speed by 5.7% is found. A second set of tests was carried out using an average traction speed, without an ultrasonic field, v_{w2} = 95.5 mm/s.

4. Conclusions

The research presented aimed to highlight the effect of the ultrasonic vibration field on the process of obtaining wires by wire drawing but not only [23]. This effect is already known as "ultrasonic lubrication" and consists in reducing the coefficient of friction between two surfaces in the presence of this type of vibration. The novelty of the research is the highlighting of this process during wire drawing under conditions very similar to industrial ones. Information in this field is very limited in the specialized literature. Compared to similar studies in which the phenomenon of "ultrasonic lubrication" was highlighted and in which a much more significant effect was generally found, the present research highlighted increases in working speeds but in smaller proportions. What was found is an increase in the influence of the ultrasonic field as the drawing speed increased. Unfortunately, however, the experiments were carried out up to a working speed of approximately 1 m/sec. In industrial production, the working speeds for wire drawing are approximately 12....13 m/sec.

Table. 3

Presentation of experimental results regarding the increase in drawing speed when applying the ultrasonic field to the aluminum wire drawing die

Test no.	Drawing speed without cooling liquid lubrication [mm/s]	Drawing speed with cooling liquid lubrication [mm/s]	Drawing speed with cooling liquid lubrication with application of ultrasonic field (ultrasonic lubrication) [mm/s]
1		51.81	54.38
2		51.81	54.67
3	43.3	51.81	55.26
4		95.5	104.31
5		95.5	105.9
6		95.5	104.82

The presented article aimed to carry out the entire process of mathematical calculation, design and experimentation of the functioning of an ultrasonic system that aims to increase working speeds in the wire drawing process based on the process of reducing friction forces, known in the specialized literature as "ultrasonic lubrication". For this, an attempt was made to define working conditions as close as possible to those in industrial production. For this purpose, the following were carried out:

- an analytical calculation model of the main characteristics of the ultrasonic system;
- based on this, the geometric design of the ultrasonic system was carried out, which includes the stepped shape of the ultrasonic energy concentrator;
- the geometry thus defined constituted the model for carrying out a modal analysis based on FEM, through which the vibration modes were determined at the working frequencies found by the mathematical method; following this analysis, it was found that one of the two vibration frequencies, namely f = 33900 Hz, is very close to the vibration frequency of the piezoceramic elements used in the analytical calculation, f = 35000 Hz. The mathematical model aimed to determine the amplitude of vibrations and the state of stress as long-term operation of the ultrasonic system is necessary;
- on drawing under the action of the ultrasonic field at the vibration frequency f = 33940Hz, also very close to that determined by FEM, namely f = 33900 Hz;

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