SHIFTING THE OPERATING FREQUENCY OF THE PIEZOCERAMIC ELECTROACOUSTIC TRANSDUCER LANGEVIN TYPE USING PASSIVE COOLING METHODS

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ABSTRACT

The object of research: the shift of resonant frequency of the piezoceramic electroacoustic transducer Langevin type depending on the shape of the back plate.

Investigated problem: the relationship between changes in shape of back plate of the Langevin type transducer with the resonant frequency of the oscillating system. Search quantitative contribution to shift the resonant frequency of each of the modifications: shape, diameter, thickness, weight of back plate.

The main scientific results: vibration modes of a transducer with a back plate with horizontal and vertical radiator ribs were obtained. The graphs of the shift resonant frequency depending on the change in the diameter and thickness of the back tail with vertical radiator ribs are presented. It is established, that the change in the thickness and diameter of the back plate of the transducer effects on resonance frequency much less than the change in mass.

The area of practical use of the research results: designing piezoceramic electroacoustic transducer with passive cooling method.

Innovative technological product: guidelines for choosing the shape changes back plates of the Langevin type transducer for decreasing heating temperature, with keeping resonant frequency.

Scope of the innovative technological product: scope of application of the Langevin type transducer: underwater acoustics, ultrasonic technological equipment, ultrasonic engine, piezotransformer, medical equipment, rock drilling devices.

1. Introduction

1. 1. The object of research

The object of research is the shift of resonance frequency of a piezoceramic electroacoustic transducer (PET) of the Langevin type depending on the shape of the back plate.

1. 2. Problem description

During operation, PETs are heated. To reduce the heating temperature of the transducer, passive and active cooling methods are used. One of the passive ways to reduce the heating temperature is to change the shape of the back plate, to the one that has a large heat sink area [1, 2]. It was assumed, that the shape of the back mass does not change the resonant frequency of the system. Most valuable are temperature reduction options that, in addition to efficient cooling, are also making the smallest changes in the transducer characteristics and design. To select the most correct back plate, it is necessary to confirm the constancy of the resonant frequency of the oscillating system. To select the most correct back plate, it is necessary to confirm the constancy of the resonant frequency of the oscillating system.

1. 3. Suggested solution to the problem

To quickly select a method for changing the back plate, it is necessary to have a concept of the quantitative shift of the resonant frequency of the transducer depending on the different changes.

There are similar studies of the shifting in the resonant frequency depending on the shape of the emitting plate [3, 4]. The addition of the helical slot structure to the radiating plate has previously been investigated and it was concluded, that the number and size of the slots affect the vibration amplitude and resonance frequencies [5]. Also, the changes in the emitting and back plate together was studied [6]. Thus, there are insufficient data on the influence of the size, mass, and shape of the back plate on the resonance frequency shift. The described problem can be solved by analyzing different options for changing the shape of the back plate and their effect on the resonant frequency of the oscillating system.

The aim of the research is to determine what affects the shifting of the resonant frequency more – the shape, mass of the back plate or its geometric dimensions.

2. Materials and Methods

A piezoceramic electroacoustic transducer of the rod (Langevin) type (**Fig. 1**) is investigated, consisting of: two passive mass (tail and emitting mass), an active element, a sealing washer, which are tightened with a bolt.

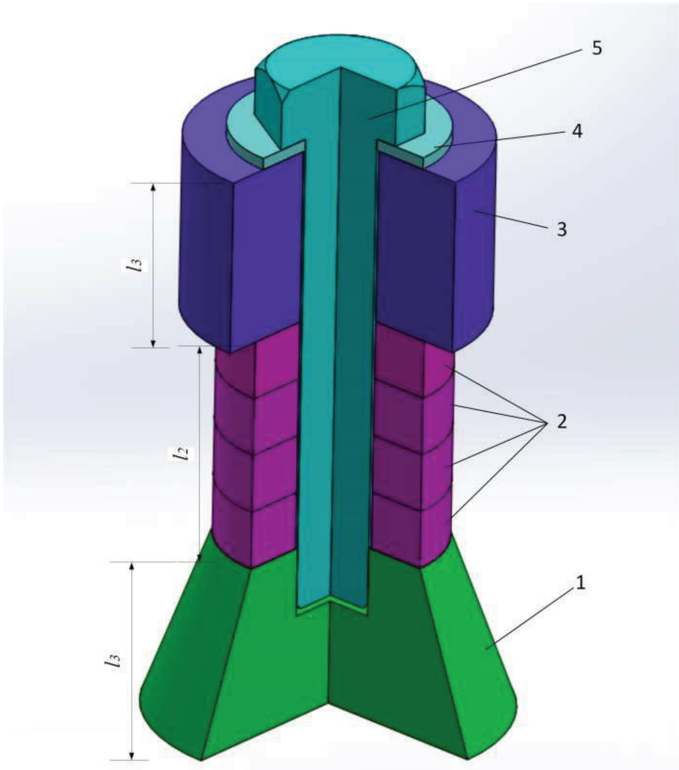


Fig. 1. Model of a piezoceramic electroacoustic transducer of the Langevin type:
1 – emitting plate; 2 – active element; 3 – back plate; 4 – washer; 5 – bolt

Emitting plate 1 is made of AMg – 6 aluminum alloy, in the form of a truncated cone with a large diameter of 60 mm, a smaller diameter of 38 mm, and a thickness of 30 mm with a recess for tightening bolt 5. Back plate 3, washer 4, bolt are made of AISI 1020 steel. The outer diameter of the cylindrical back plate is 50 mm, the inner diameter is 17 mm, and the thickness of the plate is 30 mm. A M16 tie bolt, 82 mm long is get into the radiating plate at 10 mm and sealed with a washer 36 mm in diameter, 2 mm thickness. Active element 4 – is 4 rings of APC-840 piezoelectric ceramics, 38 mm in diameter, 17 mm in inner diameter, 10 mm thickness each. The transducer works in air. Note that these parameters are not related to a specific transducer, but carry the collective characteristics of the most used Langevin-type transducer.

2. 2. Determination of the resonant frequency of the transducer by the analytical method

To determine the resonant frequency of the system with an analytical method, it is necessary to solve the transcendental equation. To determine the resonance frequency f_r of a three-component oscillatory system, a graphical method was used. Relation (1) connects the resonant frequencies and geometrical dimensions through the wave dimensions of the passive mass and the active element [7].

$$\frac{\rho_1 c_1 S_1}{\rho_2 c_2 S_2}\,\mathrm{tg}\left(\frac{2\pi l_1}{\lambda_1}\right)\cdot\frac{\rho_3 c_3 S_3}{\rho_2 c_2 S_2}\,\mathrm{tg}\left(\frac{2\pi l_3}{\lambda_3}\right)\mathrm{tg}\left(\frac{2\pi l_2}{\lambda_2}\right)=$$
$$=\frac{\rho_1 c_1 S_1}{\rho_2 c_2 S_2}\,\mathrm{tg}\left(\frac{2\pi l_1}{\lambda_1}\right)+\frac{\rho_3 c_3 S_3}{\rho_2 c_2 S_2}\,\mathrm{tg}\left(\frac{2\pi l_3}{\lambda_3}\right)+\mathrm{tg}\left(\frac{2\pi l_2}{\lambda_2}\right), \tag{1}$$

where $S_{1,2,3}$ – are the cross-sectional areas of the emitting pad, active element, back plate; $\rho_{1,2,3}$ – density of materials; $c_{1,2,3}$ – speed of sound in materials; $\lambda_{1,2,3}$ – wavelength in materials; l_1 – length (thickness) of the emitting plate; l_2 – length (thickness) of the active element, l_3 – length(thickness) of the back plate. For the cross-sectional area of the radiating plate, the cross-sectional area along the centerline of the truncated cone is taken.

According to relation (1), the resonant frequency of the transducer is f_r=15,581 Hz.

It should be noted, that the same result of the analytical calculation of the resonant frequency PET was obtained using the more compact relation (2), given in [8, 9].

$$\frac{\omega l_2}{c_2}+\mathrm{arctg}\left(\frac{\rho_1 S_1 c_1}{\rho_2 S_2 c_2}\,\mathrm{tg}\frac{\omega l_1}{c_1}\right)+\mathrm{arctg}\left(\frac{\rho_3 S_3 c_3}{\rho_2 S_2 c_2}\,\mathrm{tg}\frac{\omega l_3}{c_3}\right)=\pi, \tag{2}$$

where ω – circular frequency of mechanical resonance of the piezoelectric emitter.

2. 3. Determination of the resonant frequency of the transducer using computer simulation

For the experiment, the simulation of the resonant frequency of the system in the SolidWorks Simulation software was chosen. The type of research is Modal analysis (or Frequency analysis), it determines natural frequencies and modes of vibration, assuming that the body is not subject to external excitation and there is no damping [10].

a) Simplified transducer model.

To confirm the comparability of the calculation and simulation results, it is necessary to compare the resonant frequency of the transducer, obtained by modeling in the SolidWorks software with the calculated analytical method. In this case, the most approximate version of the simplified transducer to the analytical design model is taken. For this, only the most structurally important elements are taken into account: the emitting plat, the active element, the back plat, with holes for the tightening bolt.

The deformation graph with longitudinal vibrations is shown in **Fig. 2**. Note that the values on the color legend in the results of the displacement of the modal analysis do not have a quantitative meaning, they can be estimated only relatively for the studied points in one vibration mode.

The figure shows the uniformity of displacements in the longitudinal direction, thereby confirming the correctness of the selected vibration mode. The maximum relative displacement on the emitting plate is 1.939/0.191=10.15, on the back plate 0.943/0.191=4. The back heavy plate is displacement less than the emitting light plate. The natural frequency of this construction f_{SW1}=15.2 kHz, weight 836.11 grams.

b) Modeling the natural vibration frequency of a transducer with a tightening element

When a tightening bolt and a sealing washer are added to the transducer model **(Fig. 3),** the resonant frequency of the system increases to f_{SW2}=16.3 kHz, and the total weight became 1022.19 grams.

Adding housing is often necessary during operation of the ultrasonic transducer. The housing is attached to the oscillating system through an elastic decoupling and does not affect the operating frequency of the transducer. The housing has only a damping effect on the oscillating system, reducing its Q-factor. Since neither excitation nor damping is modeled in the software used, the effect of the housing on the resonant frequency is not taken into account.

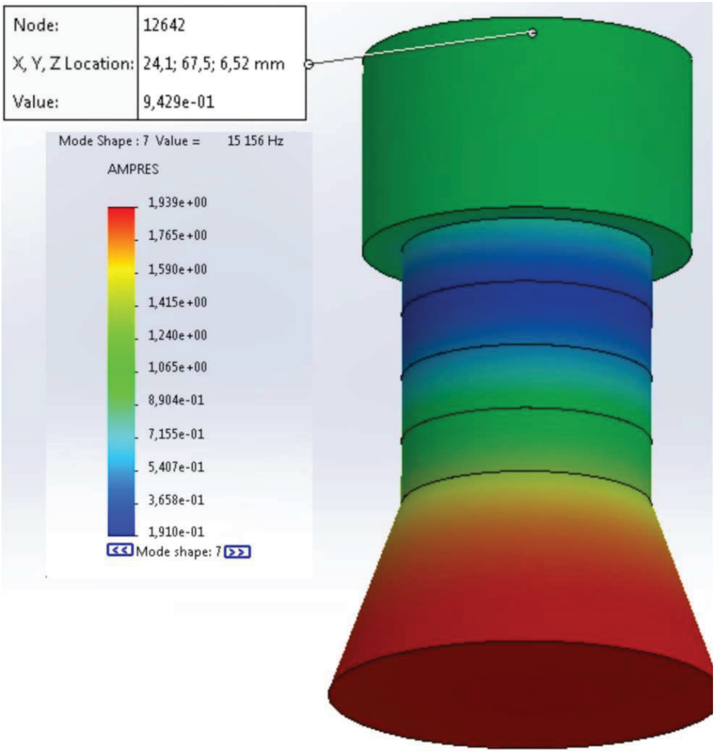


Fig. 2. Frequency analysis of the transducer

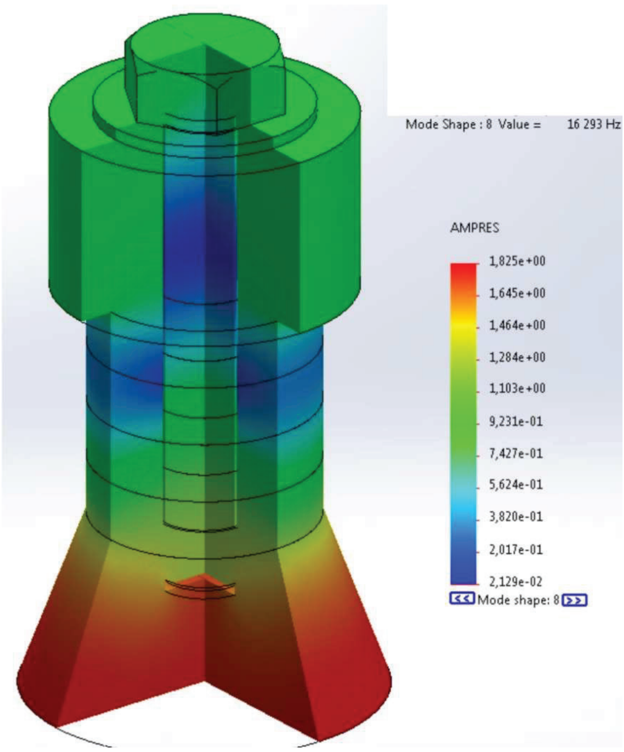


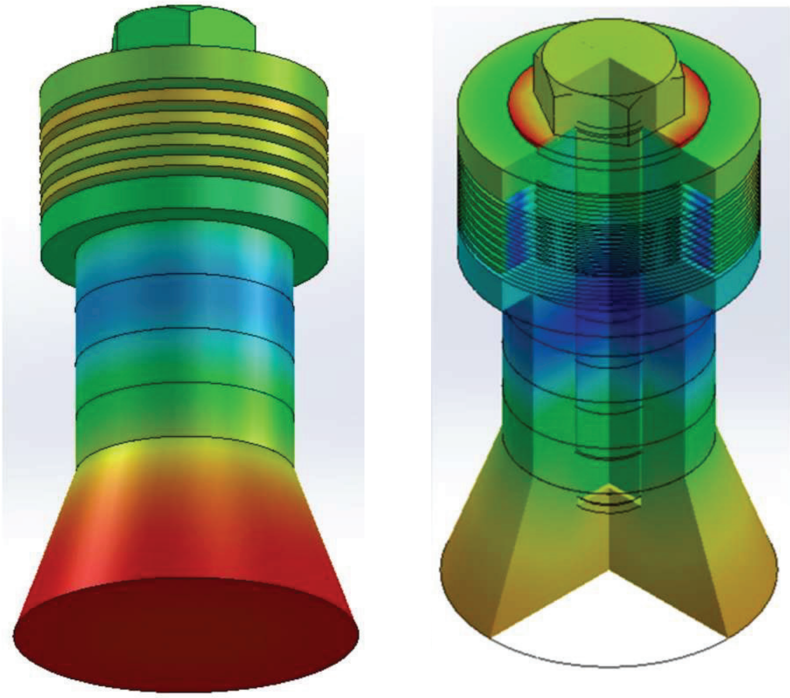
Fig. 3. Model of a transducer with a tightening element

3. Results

Determination of the shift of resonant frequency of the transducer depending on the shape of back plate by simulation.

1) Changing the shape of the back plate for a plate with horizontal radiator ribs.

Fig. 4 shows a transducer with a back plate with horizontal radiator ribs, outer diameter 54 mm, inner diameter 17 mm, with maintaining the mass of 411.42 grams (**Fig. 4, *a*)** and 414.82 grams (**Fig. 4, *b*).**



a *b*

Fig. 4. Transducer with a back plate: *a* – with horizontal radiator ribs; *b* – horizontal radiator thin and thick ribs

As a result, a resonant frequency of 16112 Hz was obtained, but in **Fig. 4** we see that the ribs are displaced unevenly. It was previously assumed, that such a change in the shape of the back cover does not affect the resonant frequency [2]. With an increase in the number of ribs (**Fig. 3, *b*),** respectively, the thickness of each smaller, the resonant frequency of the system is 16732 Hz, and it also does not vibrate as a whole system.

Simulated the transducer with a similar change in the back plate, but with the keeping of the initial overall dimensions – the result is also unsatisfactory. The frequency has increased by almost 8 %, and the ribs are still displacing unevenly.

2) Changing the shape of the back plate for a plate with vertical radiator ribs.

Fig. 5 shows a transducer with a back plate, outer diameter 53 mm, inner diameter 17 mm. Weight 410.4 grams, selected as close as possible to the original.

As a result, a resonant frequency of 16290 Hz is obtained in the longitudinal vibration mode, which practically coincides in the resonant frequency of the transducer without changing the shape of the back plate.

In addition, more than nine variants of the back plate are analyzed with the same weight and thickness. And the increase in the area of the plate is achieved by changing only the outer diameter of the plate and the depth of the ribs. The resonant frequency is shifted by no more than 0.1 %.

3) Changing the shape of the back plate for a plate with vertical radiator ribs, keeping initial dimension size.

The transducer with vertical radiator ribs on the plate, with the same outer size of the back plate as the original version is simulated. The size of the back plate is: diameter 50 mm, thickness 30 mm, depth of the fins – 4 mm.

As a result, the resonance frequency of the oscillating system is 16701 Hz, while the mass of the pad is 348.35 grams. Leaving the diameter and thickness of the back plate unchanged, this addition of ribs reduced the weight of the back pad by 15.4 %. This led to increase the frequency by 2.5 %.

Further, a more detailed study is performed. Which parameter – the outer diameter, thickness or mass of the back plate with vertical ribs – makes a greater impact on the resonant frequency of the system.

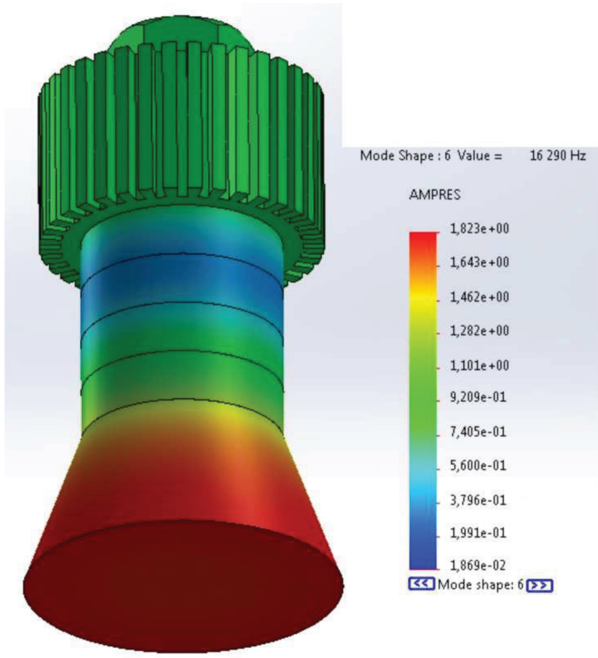


Fig. 5. Transducer with a back plate with vertical radiator ribs, with maintaining the initial mass

Fig. 6 shows the relationship between the resonant frequency of the longitudinal vibration of the transducer by changing the diameter of the back plate (from the initial 50 mm up to 60 mm), with the depth of the slots changes accordingly.

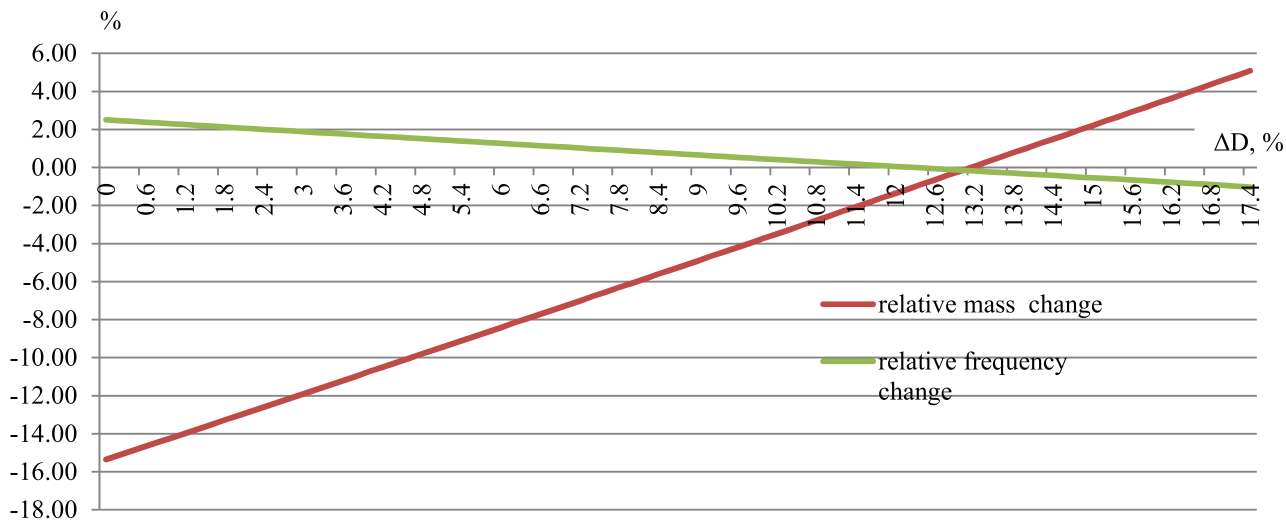


Fig. 6. Graph of relative changes in frequency, mass, diameter of the back plate (abscissa axis – relative diameter, ordinate axis – percent)

Fig. 7 shows the relationship between the resonant frequency of the longitudinal vibration of the transducer by changing the thickness of the back plate (from the initial 30 mm up to 38.5 mm).

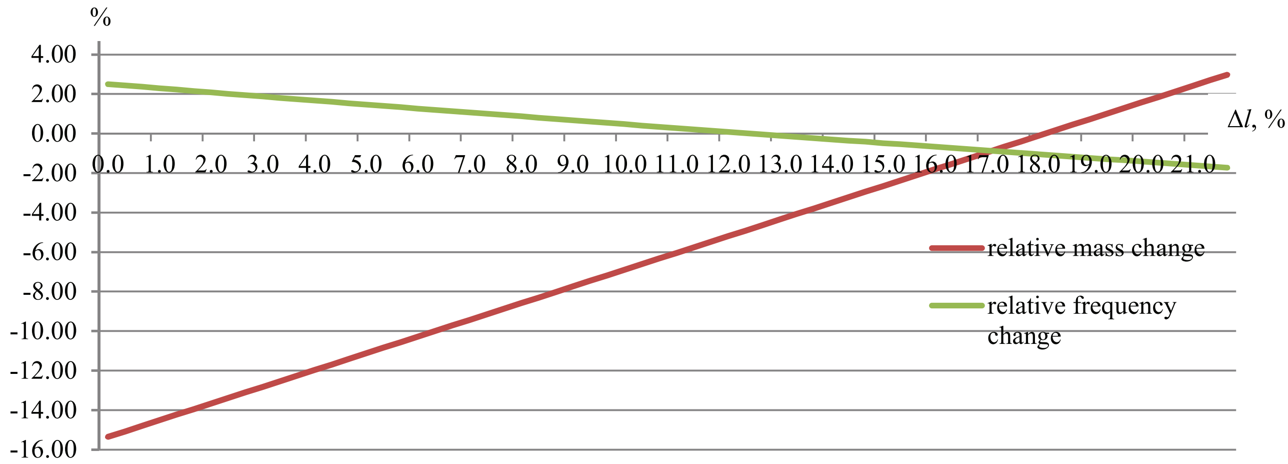


Fig. 7. Graph of relative changes in frequency, mass, thickness of the back plate (abscissa axis – relative thickness, ordinate axis–- percent)

To compensate for the mass of the oscillating system by increasing the diameter of the back plate (**Fig. 6**), it is necessary to increase it by 13.2 %. In this case, the frequency decreased by 0.18 %.

To compensate for the mass of the oscillating system by increasing the thickness of the back plate (**Fig. 7**), it is necessary to increase it by almost 18 %. In this case, the frequency decreased by (0.12–0.16) %. But it should also be taken into account, that with an increase in the thickness of the plate, the total length of the transducer increased due to the material with high elastic modulus (in relation to aluminum). This increases the hardness of the entire transducer and the vibration amplitude should be reduced.

4. Discussion

A phenomenon that ribs does not vibrate as a whole system (**Fig.4.**) is explained by the fact that longitudinal vibrations are investigated. And the horizontal ribs vibrate at a separate frequency, creating an additional shift in the resonant frequency of the entire system. To use this change in the shape of the plate, it is necessary to greatly reduce the depth of the ribs, or use other modes of vibration. Another problem solution is to change the location of the ribs, for example to vertical ribs (**Fig. 5**.). Due to this one changing, the system is oscillating correctly. But another problem arises, how to correctly change the shape of the back plate – keeping size or mass of the plate. In the next subsection, it proved that by keeping the mass of the plate unchanged (**Fig. 5**.) and the following research, stated in text form), it is possible to achieve the exact resonant frequency.

Previously, the change in the position of piezoceramic rings relative to the nodal section was experimentally investigated, while maintaining the total thickness of the transducer. That is, the thickness of both plates of the bidirectional transducer was interchanged. The results showed a significant decrease in the amplitude of oscillations and a shift of the resonant frequency up to 10 % [11]. Also in [12] it was investigated, that the it is possible to change the back plate, the position and length of the bolt and to change the emitting plate that the resonant frequencies of all seven transducers were equal to the initial frequency. But previously, such a detail study of the change in the dimensions of the back plate has not applied. Through careful analysis of the outer diameter (**Fig. 6.**) and thickness (**Fig. 7**) change of the back plate, we have a concept about the quantitative shift of the resonant frequency depending on these parameters.

Note, that presented changes to the back plate are effective in reducing the maximum heating temperatures of the converter by increasing the surface area of the heat sink. Therefore, in order to select the most appropriate change in the shape of the back plate, the shape should be selected based on the permissible shifting of the resonant frequency and the maximum increase in the surface area.

The article does not investigate the resonant frequency with the use of pre-stressed by a bolt, which may also be an idea for further research.

Also ways of further studies on this theme are very extensive. Since the topic of displacement of the resonant frequency of the Langevin type transducer due to the change in the shape of the back plate is directly related to a heating decrease of the transducer. Therefore, other changes are possible, for example, cylindrical cooling ribs or plate with slots of various shapes.

5. Conclusions

The horizontal radiator ribs on the back plate are not suitable for the longitudinal mode of the Langevin type transducers.

With the addition of radiator ribs at the back plate and keeping the initiation dimensions of the back plate, the mass of the system decreases, which leads to the resonance frequency increase.

If exact stability of the resonant frequency is required, changes to the back plate due to the overall dimensions should be made. With a permissible deviation of the resonant frequency of no more than 0.1 %, a change in mass is possible by no more than 0.3 %.

It is established, that a change in the thickness and diameter of the back plate of the piezoceramic electroacoustic transducer Langevin type affects its resonance frequency much less than mass changing.

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