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REGULAR ARTICLE

Mechanical Dynamic Properties of a Piezo Transducer in the Presence of an Active Acoustic Screen

O.V. Bogdanov[1,*], A.V. Derepa[2,†], O.H. Leiko[1,‡], S.V. Kurdiuk[3,§]

[1] *National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", 03056, Kyiv, Ukraine*
[2] *The Central Scientific Research Institute of Armament and Military Equipment of the Armed Forces of Ukraine, 03049 Kyiv, Ukraine*
[3] *National University «Odessa Maritime Academy», 65052, Odessa, Ukraine*

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To create opportunities for operational control of the parameters of acoustic location devices, it is proposed to make their acoustic screens in the form of electroelastic systems. For devices with cylindrical piezoceramic screens, the method of coupled fields in multi-coupled regions is defined: analytical relations for mechanical fields of location devices, which take into account the mutual connections of electric, mechanical and acoustic fields in the process of energy conversion; acoustic interaction of device elements in the process of forming this energy and mutual connection between these processes. A wide numerical experiment was carried out and its results were analysed in relation to the operational management of the mechanical parameters of location devices. A number of interesting frequency regularities are established, and their physical justification is given.

Keywords: Dynamic properties, Active acoustic screen Mechanical fields.

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1. INTRODUCTION

Sound location systems must determine the azimuth of the desired object [1, 2]. This can be achieved only if these systems have one-way spatial selectivity. The latter is achieved due to the fact that an acoustic screen is included in the location system [3, 4]. In most cases, this screen is passive. Along with high efficiency, passive screens have a number of significant disadvantages [5, 6]. The main ones are the significant dependence of their acoustic properties on the action of external factors and the inability to control screen parameters during their operation. In the first case, this forces the search for original ways of building acoustic screen structures, for example, in the form of gratings made of elastic metal shells [5] and their application [7-10]. In the second case, it becomes a serious obstacle in the construction of multifunctional location systems [1], in which there is a need to control their electroacoustic characteristics, including by changing the parameters of acoustic screens. The idea of using active methods of controlling screens is related to their construction in the form of electromechanical oscillating systems. This makes it possible [11-14] to have an electrical side in the structure of the screen, which allows you to quickly control the parameters of the oscillating system by changing the amplitude, phase and frequency of the electrical signal exciting it.

When performing an active screen in the form of an electromechanical, for example, piezoceramic oscillating system, the processes of energy transformation and its formation in the surrounding spaces begin to operate in it. At the same time, in the process of energy conversion in the active screen, electric, mechanical, and acoustic fields interact [10, 15, 16]. The formation of acoustic energy is accompanied by the appearance of a multiple process of radiation and re-reflection of scattered sound waves, both by elements of the screen and by elements of the grid in which it is used. This determines the acoustic interaction in the space of fields that are radiated and scattered. And since the acoustic fields act in both processes of energy transformation and its formation by the screen, a third type of interaction arises – a mutual connection between these processes.

This study aims to elucidate the impact of the proposed active screen on the dynamic properties of the mechanical field of adjacent piezoelectric transducers, considering all aforementioned interactions.

2. STATEMENT OF THE PROBLEM AND ITS SOLUTION

Consider the acoustic location device, the cross section of the physical model of which is shown in **Fig. 1**. The device consists of a cylindrical acoustic screen 1 and a cylindrical piezo transducer 2. Their longitudinal axes are parallel and placed at a distance of l. Acoustic screen 1 is made in the form of a p/c (piezoceramic) shell with an average radius r_1 and thickness d_1. The shell can be

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[*] Correspondence e-mail: oleksiib@gmail.com
[†] derepaan@i.ua
[‡] log40413-ames@lll.kpi.ua
[§] serega15507@ukr.net

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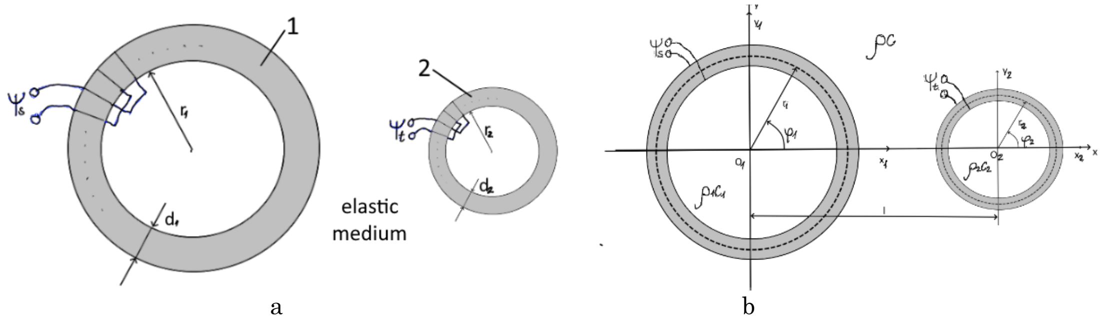


a b

Fig. 1 – Acoustic location device a) – physical model; b) – calculation model

continuous or sectioned. Its internal cavity can be vacuumed, filled with gas or liquid. Shell 1 is excited by the electrical voltage Ψ_e .

Piezo transducer 2 is a continuous or sectioned structure with an average radius r_2 and thickness d_2, vacuumed, filled with gas or liquid. Transducer 2 is excited by the electrical voltage Ψ_n. The location device is placed in an elastic environment.

The calculation model (**Fig. 1**b) is a system of parallel circular cylinders placed in the general Cartesian coordinate system $0xyz$. Local Cartesian and circular cylindrical coordinate systems are associated with each of the cylinders.

As it was shown above, the physical feature of the acoustic location device is the presence of three types of interactions during its operation – two types of interactions of physical fields during the implementation of energy transformation and formation processes and one type of interaction of these processes themselves.

Mathematically, these interactions of physical fields and processes can be taken into account by jointly solving the system of the following differential equations:

- the Helmoltz equation, which describes the movement of media inside the screen and the emitter and outside them:

$$\Delta\Phi_{ns} + k_{ns}\Phi_{ns} = 0, \quad s = 1,2;\ n = 1,2;$$

- equation of motion of the thin p/c shells of the screen and the emitter with circular polarisation (for sectional versions) in displacements:

$$\left.\begin{aligned}
&(1+\beta_s)\frac{\partial^2 u_s}{\partial\varphi_s^2} + \frac{\partial w_s}{\partial\varphi_s} - \beta_s\frac{\partial^2 w_s}{\partial\varphi_s^2} = d_s\gamma_s\frac{\partial^2 u_s}{\partial t^2},\\
&-\frac{\partial u_s}{\partial\varphi_s} + \beta_s\left(\frac{\partial^3 u_s}{\partial\varphi_s^3} - \frac{\partial^4 w_s}{\partial\varphi_s^4}\right) - w_s + \frac{e_{33s}}{C_{33s}^E}r_{0s}E_s + \frac{\alpha_s}{h_s}q_{rs} = \alpha_s\gamma_s\frac{\partial^2 w_s}{\partial t^2},
\end{aligned}\right. \quad s = 1,2;$$

- equations of forced electrostatics for piezoceramics:

$$\vec{E}_s = -grad\psi_s,\ div\vec{D}_s = 0, \quad s = 1,2.$$

Here Δ – the Laplace operator; Φ_{ns} – speed potential of the s - th element of the location system (inside $n = 1$ and outside $n = 2$); k_{ns} – wave numbers of media (k_{1s} inside and k outside the element); u_s and w_s – circumferential and radial components of the vector of displacements of the points of the middle surface of the shell of the s -th element; $\beta_s = \frac{h_s^2}{12r_{0s}^2}\left(1 + \frac{e_{33s}^2}{C_{33s}^E\varepsilon_{33s}^D}\right)$; $\alpha_s = \frac{r_{0s}^2}{C_{33s}^E}$; q_{rs} – external load of the s -th element; C_{33s}^E , ε_{33s}^D , e_{33s} , γ_s – respectively, the modulus of elasticity at zero electric stress, the dielectric constant at zero strain, the piezo constant, and the density of the material of the s -th p/c shell.

The procedure for the simultaneous solution of the given system of differential equations by the method of coupled fields in multi-connected domains is similar to that described in [9].

As a result of solving the formulated problem by the described method, we have a reduction of the system of differential equations to an infinite system of linear algebraic equations of the form:

$$\begin{cases}
-B_{sv}J_v'(k_{1s}r_{1s}) + ic_{1s}w_{sv} = 0;\\
icw_{sv} - \left[A_{sv}H_v'^{(1)}(kr_s) + \sum\limits_{\substack{q=1\\q\neq v}}^{2}\sum\limits_m A_{qv}J_m'(k_{1s}r_1)H_{v-m}^{(1)}(kl)e^{i(v-m)\varphi_{qs}}\right] = 0;\\
R_{sv}w_{sv} + \frac{\alpha_s}{h_s}i\omega\rho\left[A_{sv}H_v^{(1)}(kr_s) + \sum\limits_{\substack{q=1\\q\neq v}}^{2}\sum\limits_m A_{qv}J_m(k_{1s}r_1)H_{v-m}^{(1)}(kl)e^{i(v-m)\varphi_{qs}}\right] -\\
-\frac{\alpha_s}{h_s}i\omega\rho_s B_{sv}J_v(k_{1s}r_{1s}) = -\frac{e_{33s}}{C_{33s}^E}\frac{M_s\psi_{0s}}{2\pi}\int\limits_0^{2\pi}e^{iv\varphi_s}d\varphi_s;
\end{cases} \quad (1)$$

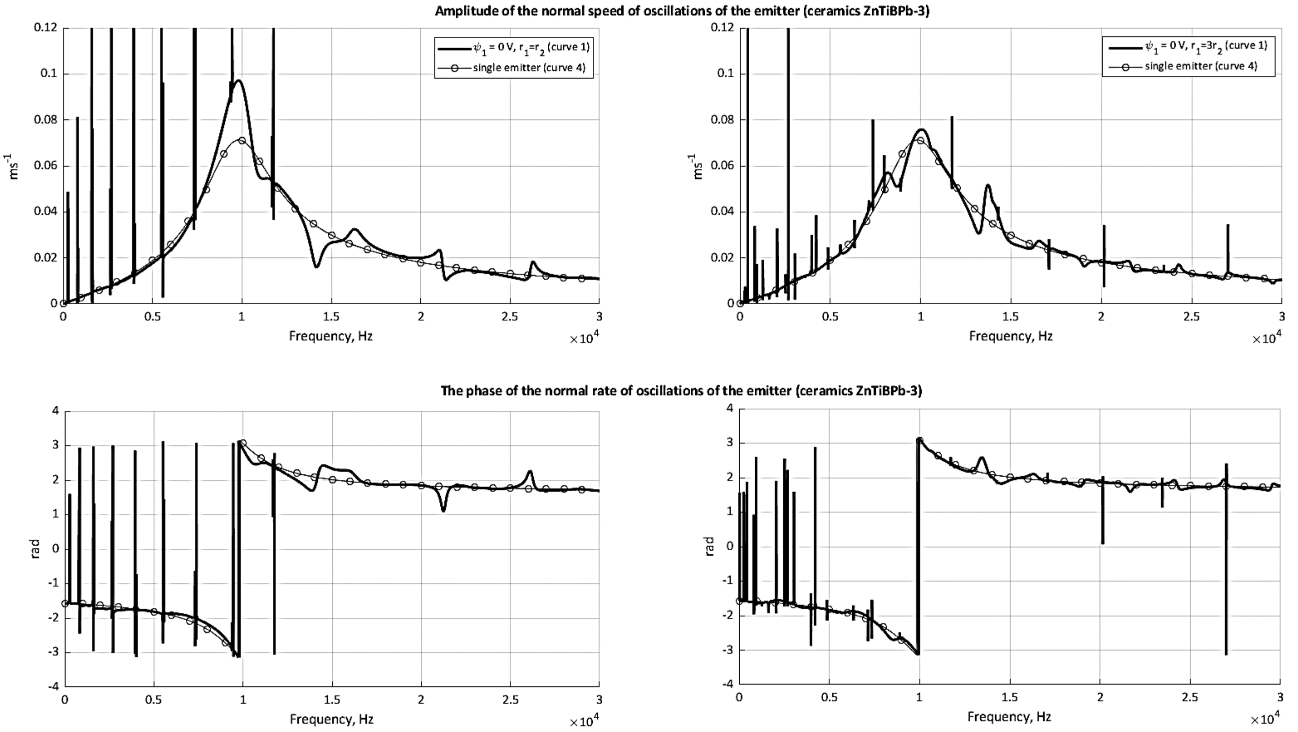
$$R_{sv} = \frac{v^2\left(1+\beta_s v^2\right)^2 - \left(1+\beta_s v^4 - \alpha_s\gamma_s\omega^2\right)\left(v^2+\beta_s v^2 - \alpha_s\gamma_s\omega^2\right)}{v^2\left(1+\beta_s\right) - \alpha_s\gamma_s\omega^2}$$

In system (1) A_{sv} and B_{sv} – are the unknown coefficients of decomposition of acoustic fields into series by cylindrical wave functions on the outside and inside, respectively, of the s - th element; the first derivative of the function is marked with a dash; J_v and $H_v^{(1)}$ the traditional notation of the Bessel and Hankel functions.

Let us consider some dynamic properties of the location device that are interesting for practice, depending on the nature of the electrical excitation of its acoustic screen. As the parameter studied, we take the frequency dependence of the amplitude and phase of the oscillating speed of the external medium on the surface of the transducer from the side opposite to the acoustic screen. We will determine the dynamic behaviour of this parameter depending on the size of the screen, the amplitude, and phase of its electrical excitation relative to the converter.

3. RESULTS OF THE NUMERICAL EXPERIMENT AND THEIR DISCUSSION

Calculations were performed according to expressions (1) and $\vec{v} = -\mathrm{grad}\,\Phi$, where the value of the speed potential $\Phi_1\left(r_2,\varphi_2\right)$ was taken from the work [9] N of the series and was determined by the formula $N = \{2ra\} + 10$. That ensured the fulfillment of the conjugation conditions of the boundary conditions of the problem with an error of less than 7 % [10], where a is the radius of the largest of the two cylinders. Quantitative estimates of the frequency dependences of the amplitudes and phases of the oscillating speed near the surface of the transducer were performed for two cases. The first case corresponds to an active screen with dimensions similar to those of the transducer. In the second case, the converter remains unchanged and the screen increases three times. At the same time, the distances between the converter surfaces and the screen remain unchanged. The number of piezoceramic prisms in both variants of active screens is chosen in such a way that the intensity of the electric field in the piezoceramic prisms of the screen in both variants is unchanged.



a b

Fig. 2 – Frequency dependences of the oscillating speed of the transducer at $\psi_1 = 0\,\mathrm{V}$: a) $r_1 = r_2$, b) $r_1 = 3r_2$

In the calculations, it was assumed: piezoceramics of the composition ZnTiBPb-3 with density $\gamma = 7210\,\dfrac{\mathrm{kg}}{\mathrm{m}^3}$, piezo constant $e_{33} = d_{33}C_{33}^E$, where is the piezo modulus $d_{33} = 286\cdot 10^{-12}\,\dfrac{\mathrm{C}}{\mathrm{N}}$, dielectric constant $\varepsilon_{33}^D = 1280\cdot 8.85\cdot 10^{-12}\,\dfrac{\mathrm{F}}{\mathrm{m}}$ and modulus of elasticity $C_{33}^E = 136\cdot 10^{10}\,\dfrac{\mathrm{N}}{\mathrm{m}^2}$; average radii of piezoceramic shells: to the transducer $r_2 = 0.068\,\mathrm{m}$ at thickness $h_2 = 0.008\,\mathrm{m}$, number of prisms $M_2 = 48$ and screen (first version) $r_1 = 0.068\,\mathrm{m}$ at thickness $h_1 = 0.008\,\mathrm{m}$, number of prisms

$M_1 = 48$, screen (second version) $r_1 = 0.204\,\mathrm{m}$ at thickness $h_1 = 0.008\,\mathrm{m}$, number of prisms $M_1 = 144$; electric excitation voltages at zero mode of oscillations $\psi_2 = 200\,\mathrm{V}$ and $\psi_1 = \{0; 200\}\,\mathrm{V}$ with a phase shift between ψ_1 and ψ_2 $\varphi = \{0^\circ; 90^\circ; 180^\circ\}$; the distance between the surfaces of the emitter and screen shells was assumed to be equal $3\,\mathrm{mm}$. The inner cavities of both shells were taken vacuumed ($\rho_1 c_1 = 0$), the external environment is water ($\rho c = 1.5 \cdot 10^6 \dfrac{\mathrm{kg}}{\mathrm{m}^2\mathrm{s}}$). The results of the alculations are given per unit height of the shells and are partially set out in a

b

Fig. 2 – Fig. 4. At the same time, curves 1-3 describe the oscillating velocities at the corresponding phase shifts, and curve 4 gives an understanding of the frequency behaviour of the oscillating speed of the external medium on the surface of a single converter (without a screen).

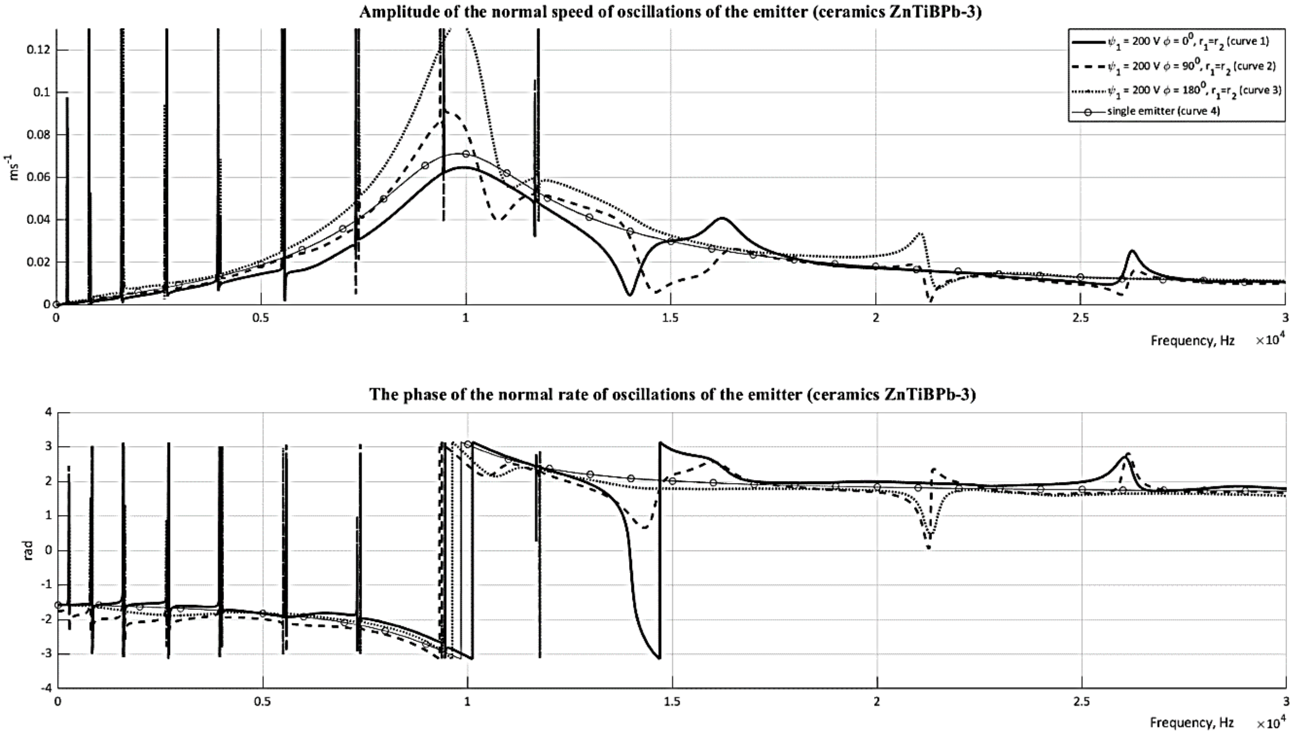


Fig. 3 – Frequency dependences of the oscillating speed of the transducer at $\psi_1 = 200\,\mathrm{V}$: and $r_1 = r_2$

Let's analyze the obtained results. First of all, we note that depending on the electrical excitation, the acoustic screen of the location system has a different physical state. In the absence of an electric voltage supply to it ($\psi_1 = 0$) it turns into a cylindrical body, on which the diffraction of cylindrical sound waves, which are created by an electrically excited transducer, occurs. But both when electrically excited and without it, the acoustic screen remains a piezoceramic device in which: in the process of energy conversion, electric, mechanical and acoustic fields interact; in the process of formation of the acoustic field by the system, the acoustic interaction of the fields of individual elements of the system occurs: the processes of energy transformation and its formation interact with each other.

The analysis of the given curves shows that the frequency dependence of the mechanical field of the piezo transducer in the presence of a piezoceramic screen has a resonant character. In the dependencies presented, it is possible to distinguish three zones. The first (low-frequency) zone covers the frequency range $f < 8\,\mathrm{kHz}$. The second is the resonant zone, named so because it is electrically excited at the frequency of the mechanical resonance of the converter, and includes the frequency range $8\,\mathrm{kHz} \le f < 12\,\mathrm{kHz}$. And, finally, the third (high-frequency) zone extends from $f \ge 12\,\mathrm{kHz}$.

The analysis of the dependences of the low-frequency zone shows that, compared to a single transducer, all types of interaction of fields and processes in the location system lead to a significant increase in the number of mechanical resonances in the system and amplitudes of the transducer's oscillating speeds. At the same time, these amplitudes decrease rapidly with decreasing frequency. Physically, this is due to two factors. First, because the inherent mechanical impedance of both piezo shells in this zone has an elastic character, it increases significantly as the frequency decreases. Secondly, at the same time, the wavelength radii of the shells decrease with a decrease in frequency, which causes a decrease in the radiation impedance of the shells. In this regard, the acoustic interaction of the envelope fields during their formation in the location system and therefore the mutual connection of the energy transformation and formation processes decrease with a decrease in frequency.

The transition to the resonance zone results in a decrease in the number of resonances in the mechanical field, an expansion of the resonance frequency bands, and a certain decrease in the amplitudes of the transducer's oscillating speeds compared to the first zone.

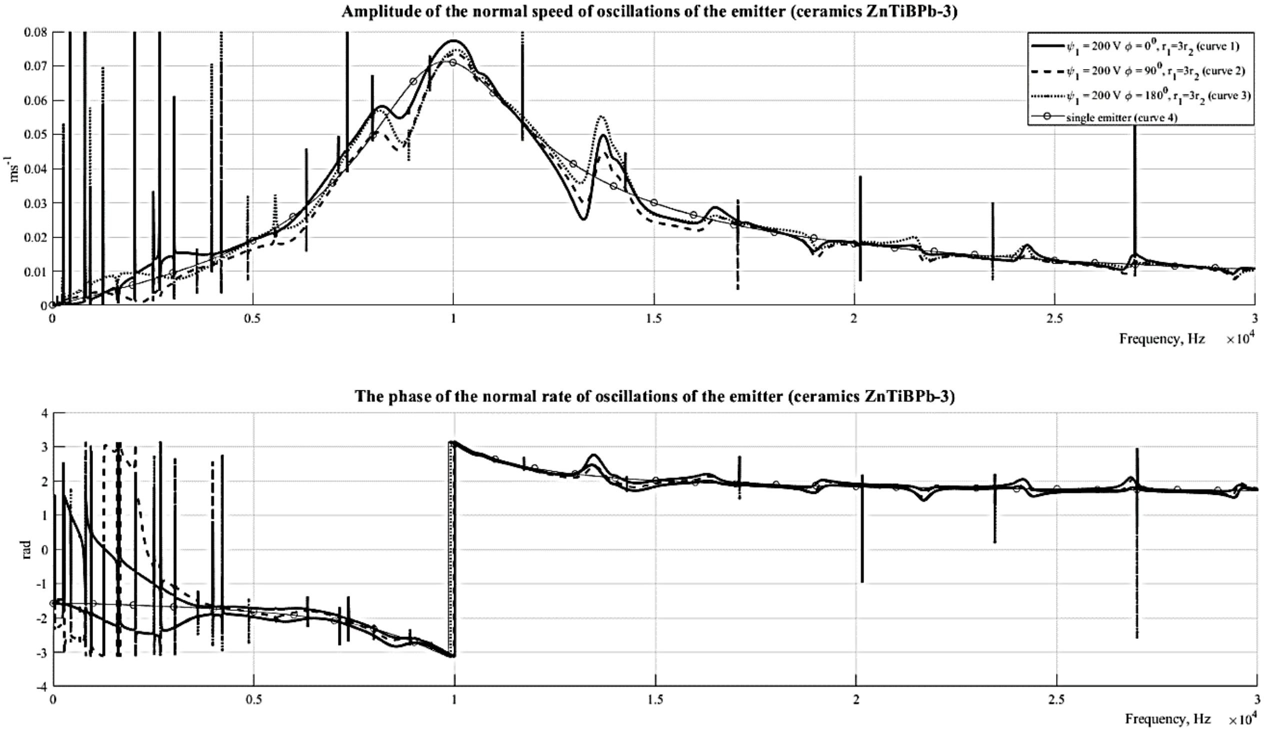


Fig. 4 – Frequency dependences of the oscillating speed of the transducer at $\psi_1 = 200\,\mathrm{V}$ and $r_1 = 3r_2$

Physically, in the second zone, the influence of the reaction of the environment to the excitation of sound waves in it and the acoustic interaction during the formation of energy fields of shells and processes in them increases significantly. This is since in this zone, the mechanical impedances of the shells and their radiation impedances are compared to each other.

At high frequencies in the third zone, the frequency dependences of the mechanical field of the converter are very significantly different from those for the first and second zones. At the same time, the number of mechanical resonances decreases, and the amplitudes of the oscillatory speed resonances differ from the previous two zones by more than an order of magnitude and become comparable to the amplitudes of the oscillatory speed of a single converter. The physical cause of these changes is an increase in the mechanical impedance of the shells and its transition to the inertial region. It is clear from the physical conditions that in the considered cases the resonances of the frequency of the active screen (determined, in particular, by its diameter) and the amplitude with the phase of its electrical excitation act as a control parameter for the mechanical dynamic properties of the location system.

The analysis of the results of the numerical experiment shows the following: the change in the diameters of the piezo shells of the screen and the transducer when piezoceramics of the same composition are used in them is accompanied by significant changes (**Fig. 3** and **Fig. 4**) in the frequency dependence of the mechanical field of the transducer in the location system. At the same time, the amplitudes and phases of the oscillating speed in the low-frequency and resonant zones are the most different. We also pay attention to the fact that the decrease in the main resonance frequency of the screen leads to a decrease in the amplitudes of the oscillatory speed of the transducer, which are smaller in the first and second zones than in the case of a single transducer.

The operational change of the amplitude and phase of the electrical excitation of the screen also affects the frequency dependence of the mechanical field of the transducer in the system differently. In this case, the main possibilities for controlling the dynamic properties of the mechanical field of the location system are concentrated in the first and second zones. In the absence of electrical excitation of the screen (a

b

Fig. 2), when its piezo shell behaves as an elastic body that scatters sound cylindrical waves created by the transducer, several resonances of the transducer's oscillating speed occur in the low-frequency and resonant zones. In the first zone, they are narrow band, in the second, their resonance bands expand. Amplitudes of resonant oscillations of the converter in the system significantly exceed those for a single emitter.

The introduction of electric excitation of the piezo shell of the acoustic screen into the location system (**Fig. 3** and **Fig. 4**) significantly increases the number of mechanical resonances in the first zone and the amplitude of the oscillating speed in them. In the second zone, the resonant frequency bands expand significantly, and with small screen sizes (**Fig. 3**), the phase shift between the excitation signals of the converter and the screen has a significant impact. Significant changes also occur in the high-frequency zone, especially with large sizes of active screens (**Fig. 4**).

CONCLUSIONS

To create possibilities for the application of active methods of controlling the parameters of acoustic screens as part of acoustic location devices, the construction of screens in the form of electromechanical oscillating systems is proposed. Their feature, when using piezoceramic materials for the transformation and formation of energy, in location devices is the appearance of three types of interaction when the energy of the interaction of electric, mechanical, and acoustic fields is transformed; during its formation in the surrounding elastic environment, acoustic interaction of device elements; interactions between processes of energy transformation and formation. Formulated physical and calculation models of the location device. Analytical expressions for calculating physical fields are obtained considering the defined interactions.

Numerical experiments were performed, and their analysis was carried out to establish the possibilities of operational control of the frequency dependences of the parameters of the mechanical fields of the devices. It is shown that the main resonant frequency of the active screen has the greatest influence on the ability to control the mechanical fields of the devices studied. It was established that precisely when the main resonant frequencies of the screen and the transducer are identical, the frequency dependence of the oscillatory speed of the transducer changes significantly when the amplitudes and phases of the electric excitation of the electro elastic screen change. And such an operational change of the mechanical fields of the transducer takes place in frequency ranges lower than or corresponding to the main resonant frequencies of the screen and the transducer.

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Механіко-динамічні властивості п'єзоперетворювача за наявності активного акустичного екрана

О.В. Богданов[1], А.В. Дерепа[2], О.Г. Лейко[1], С.В. Курдюк[3]

[1] *Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського», 03056, Київ, Україна*
[2] *Центральний науково-дослідний інститут озброєння та військової техніки Збройних Сил України, 03049 Київ, Україна*
[3] *Національний університет «Одеська морська академія», 65052, Одеса, Україна*

Для створення можливостей оперативного керування параметрами акустичних локаційних пристроїв запропоновано їх акустичні екрани виконувати у вигляді електропружних систем. Для пристроїв з циліндричними п'єзокерамічними екранами методо зв'язаних полів в багатозв'язаних областях визначені: аналітичні співвідношення для механічних полів локаційних пристроїв, в яких враховані взаємні зв'язки електричних, механічних й акустичних полів в процесі перетворення енергії; акустична взаємодія елементів пристроїв в процесі формування цієї енергії та взаємний зв'язок між собою цих процесів. Виконано широкий чисельний експеримент і проведено аналіз його результатів відносно оперативного керування механічними параметрами локаційних пристроїв. Встановлено ряд цікавих частотних закономірностей і дано їх фізичне обґрунтування.

Ключові слова: Динамічні властивості, Активний акустичний екран, Механічні поля.