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REGULAR ARTICLE

Physical Electronics of Piezoceramic Transducer Systems and their Dependence on the Character of the Electrical Excitation of the Systems

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Three types of electrical excitation were considered: frequency-independent, frequency-dependent, and mixed forms of electrical voltage. It was shown that the physical causes of such dependence are the conditions of coupling between the fields and processes accompanying sound radiation by location devices, as well as the presence of mechanical and electrical strengths of physical fields in transducer systems. Based on systems of differential equations, for systems with transducers having circular polarization, analytical expressions were obtained for the differential equations describing the sound fields of location systems under coupling conditions for each type of electrical excitation. Numerical experiment results are presented and analyzed. It was established that among the given coupling conditions, only those related to the formation of acoustic fields are dependent on the character of the electrical excitation of the location devices. The advantages and disadvantages of each type of electrical excitation were identified, based on their relationship to the mechanical and electrical strengths of the transducer systems.

Keywords: Piezoceramic transducer systems, Character of electrical excitation, Coupling conditions, Dependence of excitation and coupling conditions.

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1. INTRODUCTION

Acoustic location devices composed of piezoceramic electroacoustic transducer systems are characterized by a number of specific features. These features are related to the performance of two functions by the location devices – the function of energy conversion and the function of its shaping in the surrounding spaces [1].

The distinctive feature of the energy conversion process in piezoceramic transducers is the interconnection of three physical fields involved in this process: electrical, mechanical, and acoustic [2]. The process of spatial energy shaping also has its own peculiarities, physically determined by the presence of multiple radiation and reflection of sound waves in space [3]. This multiplicity determines the acoustic coupling of fields formed by individual transducers of the system or their structural elements. Finally, the presence of an acoustic field in the processes of both energy conversion and its spatial shaping is the physical cause of the third feature – the interconnection of the processes of energy conversion and shaping.

These features determine the conditions for the coupling of physical fields and processes during the operation of acoustic location devices [4-9]. Their influence on the physical electronics of piezoceramic transducer systems is also natural. Let us pay attention to one more physical feature of piezoceramic transducer systems. As already noted, their functioning is associated with the interaction of three fields of different physical nature – electrical, mechanical, and acoustic. Of course, the designs of location devices must have a certain resistance to the action of each of these fields [7]. In turn, these resistances depend on the nature of the electrical excitation of the piezoceramic transducer systems of these location devices.

Thus, the physical electronics of piezoceramic electroacoustic transducer systems depends on the conditions of field and process coupling, the levels of electrical and mechanical strength of system structures, and the nature of their electrical excitation.

The purpose of this work is to study the dependence of the physical electronics of piezoceramic transducer systems on the nature of their electrical excitation un-der conditions of field and process coupling, taking into account the strength characteristics of system structures.

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2. PROBLEM STATEMENT

In mathematical terms, taking into account the conditions of field and process coupling in piezoceramic transducer systems during sound radiation and reception by acoustic location devices consists in the joint solution of systems of differential equations describing the propagation of sound waves in the elastic media surrounding the location device, the electrostatic vibrations of the transducers, and the state of the piezoceramics from which the transducers are made [6, 7].

For piezoceramic electroacoustic transducer systems designed as cylinders with circular polarization, these equations take the following form [8]:

- Helmholtz wave equation

$$\Delta\Phi^s + k_{is}^2\Phi^s = 0, s = 1, \ldots, N \quad (1)$$

where Φ^s – potential velocity of the s-th radiator, $k_s = 2\pi/\lambda_{is}$ – wave number of the s-th radiator ($i = 1$, 2 – external and internal environment, respectively), Δ – Laplace operator.

equation of electromechanical oscillations of the s-th cylinder in a vacuum in cylindrical coordinates

$$\begin{cases} (1+\beta^s)\frac{\partial^2 u^s}{\partial\varphi_s^2} + \frac{\partial w^s}{\partial\varphi_s} - \beta^s\frac{\partial^3 w^s}{\partial\varphi_s^3} = \alpha^s\gamma^s\frac{\partial^2 u^s}{\partial t^2}, \\ -\frac{\partial u^s}{\partial\varphi_s} + \beta\left(\frac{\partial^3 u^s}{\partial\varphi_s^3} - \frac{\partial^4 w^s}{\partial\varphi_s^4}\right) - w^s + \frac{e_{33}^{(s)}r_{0s}}{C_{33}^{E(s)}}E_\varphi^{0s} + \\ \frac{\alpha^s}{h_s}q_r^{(s)} = \alpha^s\gamma^s\frac{\partial^2 w^s}{\partial t^2}, \\ s = 1, \ldots, N \end{cases} \quad (2)$$

where $u^{(s)}$, $w^{(s)}$ – circumferential and radial components of the displacement vector of the mid-surface points of the s-th radiator; $\beta^s = h_s^2/12r_{0s}^2\left(1 + {e_{33}^s}^2/C_{33}^{E(s)}\varepsilon_{33}^{s(s)}\right)$, $\alpha^s = r_{0s}^2/C_{33}^{E(s)}$ – for circular polarization; $q_r^{(s)}$ – external load of the s-th radiator; $C_{11}^{E(s)}, \varepsilon_{33}^{s(s)}, e_{31}^s$ – elastic modulus at zero electric field, dielectric permittivity at zero strain, and the piezoelectric constant of the material of the s-th radiator, respectively; γ^s – material density; E_φ^{0s} – electric field strength in the material of the s-th radiator for circular polarization.

forced electrostatic equations

$$\vec{E}^{(s)} = -grad\,\psi^{(s)}; div\,\vec{D}^{(s)} = 0, s = 1, \ldots, N \quad (3)$$

where $\vec{E}^{(s)}$ and $\vec{D}^{(s)}$ – vectors of electric field intensity and induction of the s-th radiator; $\psi^{(s)}$ – excitation voltage.

Analysis of the system of differential equations (1 – 3) shows that the electronic physics of the acoustic location device is determined by equations (1 – 3) of this system under conditions of coupling and the presence of restrictions on electrical and mechanical strength.

When analyzing these equations, it becomes evident that the unknowns may include the radial $w^{(s)}$ and circular $u^{(s)}$ mechanical displacements (vibrational velocities $\dot{w}$ and $\dot{u}$), the electric field intensity E_φ (excitation voltages ψ), or both w and E_φ simultaneously. It all depends on how the strength levels of the location device transducer structures are defined and controlled.

Let us consider three practically interesting options related to the nature of electrical excitation of location device transducers.

The first one is related to the excitation of transducers by frequency-independent voltage. In this case, the electrical strength of the transducers of the location device is controlled by setting the excitation voltage values, and the system of differential equations has the form (1 – 3). Thus, the desired values are mechanical displacements (vibrational velocities).

The second option is related to the fact that expressions (2) specify the displacements w and u (vibrational velocities $\dot{w}$ and $\dot{u}$), while the desired values are the voltages E_φ^s (voltages ψ_s) of the electrical excitation of the transducers of the location device. In this option, it is desirable to make all transducers oscillate with the same radial oscillation velocity $\dot{w}$. This velocity can be selected at the maximum permissible level $\dot{w}$ in terms of the permissible values of mechanical stresses in the piezoceramics of the transducers. Then the differential equations take the form:

$$\Delta\Phi^s + k_{is}^2\Phi^s = 0, s = 1, \ldots, N \quad (4)$$

$$\frac{e_{33}^s r_0^s}{C_{33}^{E(s)}}E_\varphi^s + \frac{\alpha^s}{h^s}q_r^s = (1 - \alpha^s\gamma^s\omega^2)w^s, s = 1, \ldots, N \quad (5)$$

$$\vec{E}^s = -grad\,\psi^s; div\,\vec{D}^{(s)} = 0, s = 1, \ldots, N \quad (6)$$

In this case, the mechanical strength of the transducers of the location device is controlled by setting identical and known values of mechanical displacements (vibrational velocities), and the system of differential equations has the form (4 – 6). Thus, the desired values are the electrical excitation voltages.

In order to reduce the dependence of sound radiation on the mechanical and electrical strength levels of transducer structures, it is possible to introduce mixed electrical excitation of transducer systems. It consists of the following. On a part of the transducers of the system, $s = 1, \ldots, N_1$, we set a certain frequency-independent excitation voltage. We also set the condition that the vibration speeds of all converters in the system are equal to each other. Then, in differential equations (1 – 3), the excitation voltages of all other converters in the system, $s = N_1, \ldots, N$, and the vibration speeds of the converters themselves become unknown.

Then the differential equations are given as follows:

$$\Delta\Phi^s + k_{is}^2\Phi^s = 0, s = 1, \ldots, N \quad (7)$$

$$\begin{cases} (1 - \alpha^s\gamma^s\omega^2)w^s\frac{\alpha^s}{h^s}q_r^s = -\frac{e_{33}^s r_0^s}{C_{33}^{E(s)}}E_\varphi^s, s = 1, \ldots, N_1 \\ -(1 - \alpha^s\gamma^s\omega^2)w + \frac{e_{33}^s r_0^s}{C_{33}^{E(s)}}E_\varphi^s + \frac{\alpha^s}{h^s}q_r^s = 0, s = N_1, \ldots, N \end{cases} \quad (8)$$

$$\vec{E}^s = -grad\,\psi^s; div\,\vec{D}^{(s)} = 0, s = 1, \ldots, N \quad (9)$$

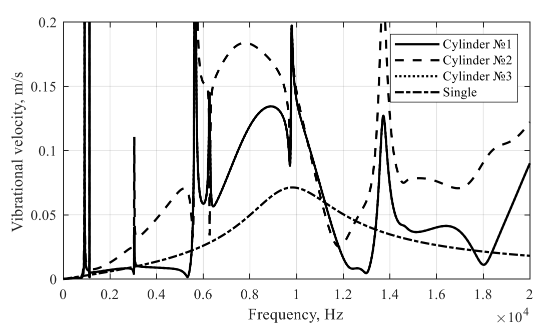
In this case, the mechanical strength of the location device transducers is controlled by applying identical mechanical displacements (vibration speeds) and setting known and frequency-independent excitation voltages on part of the system transducers, $s = 1, \ldots, N_1$. Under the formulated conditions $w = w^s$, $s = 1, \ldots, N$ and $E_{\varphi}^{s} = const$, $s = 1, \ldots, N_1$, the system of differential equations takes the form (7 – 9). Thus, the desired values are the mechanical displacements w on all transducers of the system and the excitation voltages on their part, $s = N_1, \ldots, N$.

This procedure is repeated until the electrical strength of the system reaches the required values.

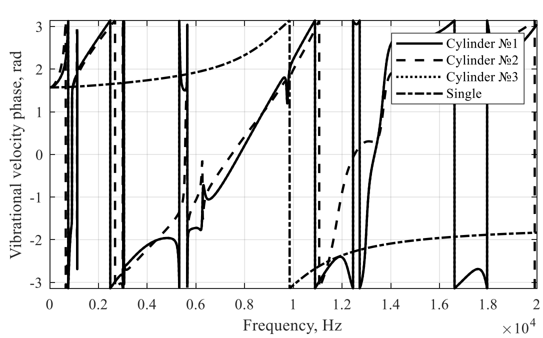
3. NUMERICAL EXPERIMENT RESULTS

Here we present the results of numerical experiments demonstrating the changes occurring in the mechanical and electrical fields of a system of piezoceramic transducers, considering the conditions of coupling and applying the three considered options for their electrical excitation.

Fig. 1 shows the frequency dependencies of amplitudes (a) and phases (b) of vibration velocities on the surface of transducers when they are excited by a frequency-independent electric voltage, as presented in [10]. The flat transducer system under consideration consists of three identical circular cylindrical piezoceramic shells with an average radius $r_0 = 0{,}068$ m and a thickness $h = 0{,}008$ m. The distance between the axes of adjacent shells was 0.147 m. The shells were made of piezoceramic composition CTBS-3 with parameters $\gamma = 7210$ (kg/m^3), $d_{33} = 286$ Kl/N, $C_{33}^{\varepsilon} = 13{,}6\,\frac{N}{m^2}$, $\varepsilon/\varepsilon_0 = 1280$. The excitation voltage was $\psi = 220$ V.



a



b

Fig. 1 – Frequency dependencies of amplitude (a) and phase (b) of cylindrical transducers in a transducer system and without it

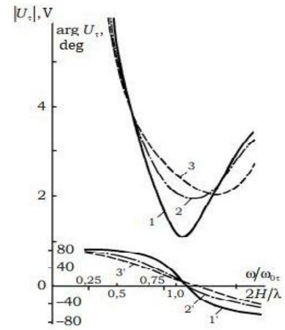
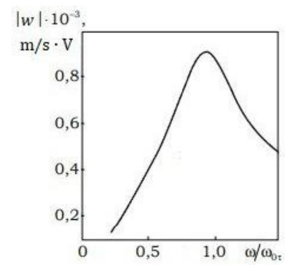
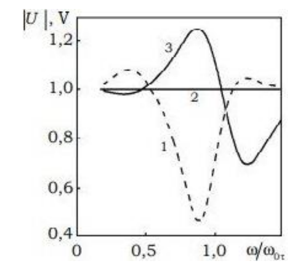


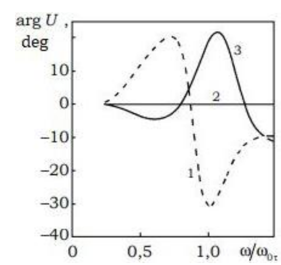
Fig. 2 – Frequency dependence of the modulus (kr.1-3) and phase (1'-3') of the electrical voltage on the electrodes of the first, second and third shells of the transducer system



a



b



c

Fig. 3 – Frequency dependencies of linear system parameters at: a) equal amplitudes w of oscillation velocities of all shells of the transducer system; b) amplitudes of frequency-independent excitation of the second shell; c) phases of frequency-independent excitation of the second shell

Fig. 2 of [8] shows the frequency dependences of the modulus (curves 1 – 3) and phases (curves 1' – 3') of the excitation voltages of the first, second, and third shells of the transducer system. We consider a linear transducer system formed from five identical shells made of the CTBS-3 piezoelectric material.

The height of the system H is related to its average radius R_0 as $H/R_0 = 1{,}67$. The radial components $\dot{w}$ of the vibrational velocities of the shells are the same and equal to $\dot{w} = 0{,}4 \cdot 10^{-3} m/s$. The same calculations can be performed according to expressions (4 – 6) for such a system of five cylindrical transducers.

Fig. 3 [6] presents the frequency characteristics of the transducer system under the following conditions. All transducers in the system have the same vibrational velocity. In the numerical experiment, it was assumed that identical frequency-independent electric voltage is applied to the second and fourth transducer shells. Fig. 3a shows the vibration amplitudes, which are the same for all shells. Fig. 3b and 3c illustrate the amplitudes (b) and phases (c) of the electric voltages required to excite the transducer system. It should be noted that in the case of implementing the transducer system as shells with circular polarization, it is necessary to solve the system of equations (6).

When solving the system of differential equations given in expressions (1) – (3), the number of complex unknowns that were kept when solving the system of algebraic equations varied from 44 to 56. Checking the quality of both boundary conditions and conjugation conditions at the boundaries of the domains showed that the inconsistency of the field components does not exceed 1-5 %.

4. ANALYSIS OF THE RESULTS

Physically, the electronic dependence of piezoceramic transducer systems on the nature of their electrical excitation is caused by the following reasons. As shown above, the conditions of coupling are caused by the peculiarities of two operating processes – energy conversion and its formation in the surrounding environment.

The process of energy conversion depends mainly on the characteristics of the piezoceramic materials from which the transducers of the system are made. Therefore, it is not very productive to affect it using the nature of electrical excitation. The process of energy formation is caused by the reflection and re-reflection of the radiated sound waves. Their acoustic impact de-pends on many factors related to the construction of transducer systems. At the same time, one of the main ones is the nature of electrical excitation. And using this factor, it is possible to partially control the coupling conditions that determine the radiation and reception of sound by piezoceramic transducer systems.

Excitation of the systems by frequency-independent electric voltage creates conditions for maximum influence of the radiated and re-reflected acoustic waves on the formation of acoustic fields of the system under consideration.

This explains (Fig. 1) the appearance of new mechanical resonances of systems in the low-frequency region, an increase in the amplitude of vibrations in a small frequency band, and the need to reduce the radiating power, based on the need to preserve mechanical strength.

The transition to frequency-dependent voltages in the electrical excitation of the systems (Fig. 2) allows creating conditions under which sound waves do not affect the acoustic interaction of transducers in the system. The transducers behave as in systems where their acoustic interaction is absent. At the same time, their vibrational velocities become the same for all elements of the system, and the risk of losing their mechanical strength becomes controlled. This makes it possible to increase the acoustic power emitted by the system. However, the opposite side of such excitation is, first, the need to create certain frequency dependence. Second, the electrical strength of the transducers becomes uncontrollable, especially in frequency regions that are lower and higher than the transducers' natural resonant frequency.

The mixed form of electrical excitation of piezoceramic transducer systems makes it possible to control both the mechanical and electrical strength of the systems when radiating acoustic power. It consists in the following. The same vibrational speed is set for all transducers in the system. This allows you to control the mechanical strength of the transducers. Next, one or more transducers in the system are set to a certain electrical voltage. On the other converters of the system, the excitation voltage must be determined. This approach allows you to reduce the excitation voltages to a certain extent and take some control over the electrical strength of the transducers. It can be used until the voltages and electrical strengths are obtained that are acceptable. Fig. 3 [6] shows the results of a numerical experiment for a five-element linear system of converters, which demonstrate a certain effectiveness of this approach to reduce the electrical excitation voltages of transducers.

Each of the proposed approaches to the electrical excitation of piezoceramic transducer systems under coupling conditions has its advantages and disadvantages.

The advantage of electric excitation of systems using frequency-independent voltage is the advanced engineering ways of implementing electric excitation generators [9]. The disadvantages of this approach are the appearance of low-frequency resonances of mechanical vibrations with very large displacement amplitude, which can significantly exceed the mechanical strength of the transducer structure.

The advantage of excitation of the system converters by frequency-dependent electric voltage is that this excitation option takes under control the mechanical strength of the structures of the locating device transducers, since their vibrational speeds are set and have the required level of mechanical strength. The disadvantages are related to two reasons. First, the excitatory electric generators must create frequency-dependent electric voltages, which significantly complicate its technical implementation. Second, there is a significant increase in all excitation voltages, especially in the frequency ranges above and below the fundamental resonance frequency of the transducers.

The mixed electrical excitation of the system's transducers allows for full control of their mechanical strength and partial control of their electrical strength. This is its advantage. The disadvantage is the need to use generators with frequency-dependent electrical voltage for electrical excitation of some transducers.

5. CONCLUSION

The dependence of the physical electronics of piezoceramic electroacoustic transducer systems on the nature of their electrical excitation is studied. It is shown that the necessity of such studies is related to the conditions of fields and processes coupling that occur in the systems of piezoceramic electroacoustic transducers in acoustic location devices, and the presence of mechanical and electrical strengths of physical fields acting in the studied systems. Three approaches to the possible nature of electrical excitation of systems are considered. They include frequency-independent, frequency-dependent, and mixed electrical excitation. The systems of differential equations describing the physical fields created by the location devices corresponding to each of the taken into account variants of electric excitation are presented. An analysis of the coupling conditions is performed and it is shown that only those conditions that correspond to sound waves associated with the processes of sound field formation are related to the nature of the electric excitation. On this basis, the results of calculations corresponding only to each of the proposed variants of electrical excitation of systems are presented. All of them are tied to the levels of mechanical or electrical strength of the transducers used. The advantages and disadvantages of each of the variants of electrical excitation of piezoceramic transducer systems are analyzed.

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Фізична електроніка систем п’єзокерамічних перетворювачів і її залежність від характеру електричного збудження систем

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Розглянуті три варіанти електричного збудження – частотно незалежною, частотно залежною і змішаною формою електричної напруги. Показано, що фізичними причинами появи такої залежності є умови зв’язаності полів і процесів, супроводжуючих випромінювання звуку локаційними засобами, і наявність в системах перетворювачів механічних і електричних міцностей фізичних полів. Виходячи із систем диференційних рівнянь, для систем із перетворювачів з окружною поляризацією для кожного із варіантів електричного збудження отриманні аналітичні вирази для диференційних рівнянь опису звукових полів локаційних систем в умовах зв’язаності. Наведені результати чисельних експериментів і проведено їх аналіз. Встановлено, що із наведених умов зв’язаності тільки умови, пов’язані з формуванням акустичних полів, прив’язані до характеру електричного збудження локаційних засобів. Визначені переваги і недоліки кожного із варіантів електричного збудження, виходячи із зв’язку їх з механічною і електричною міцностями систем перетворювачів.

Ключові слова: Системи п’єзокерамічних перетворювачів, Характер електричного збудження, Умови зв’язаності, Залежність збудження і умов зв’язаності.