Experimental Study and Theoretical Simulation of Transient Processes in Piezoelectric Transducers

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***Abstract*— Pulse mode operation of the radiation-reception system, consisting of two immersed piezoelectric plates was studied. The radiating transducer was excited by electrical signals of complex shape, a combination of exciting and compensating pulses. The amplitudes of the compensating half-periods were pre-calculated using the mathematical algorithm developed in the previous authors' works. It was shown that the use of complex waveforms can significantly reduce the length of the signal at the output of the receiver in comparison with the case when the radiator is excited by one half frequency cycle of the of thickness vibrations of the piezoelectric plate. The experimental results are in good agreement with those obtained by the finite element simulation using COMSOL Multiphysics modeling environment.**

Key words*— *radiation-receiving system; система излучения-приема; piezoelectric transducer; finite element method (FEM); transitional processes

I. Introduction

Different characteristics of nondestructive testing systems are improved simultaneously with the improvement of the quality of controlled products. Concerning the acoustical systems of nondestructive testing, this causes to improve the metrological characteristics of the sensitive elements, i.e. acoustic transducers. For the purposes of acoustic nondestructive testing, piezoelectric transducers (PET) are the most suitable [1]. The theoretical basics of these transducers are considered in the scientific and technical literature in details [2–5]. In this study, the authors theoretically (using the finite element method) and experimentally considered the problem of obtaining a short acoustic signal at the output of narrow-band plate PET in ultrasonic immersion radiation–receiving systems (fig. 1). The need of obtain a short acoustic signal is especially important for echolocation problems. For these problems the following parameters are especially important: resolution, the value of the dead zone, the accuracy of the coordinates of the detected defects.

Using the method of successive reflections (d'Alembert method) it is possible to determine the complex shape of exciting signals to essentially reduce of the length of the output receiver signal. The application of this method for this problem is described in the previous works of the authors [6–8].

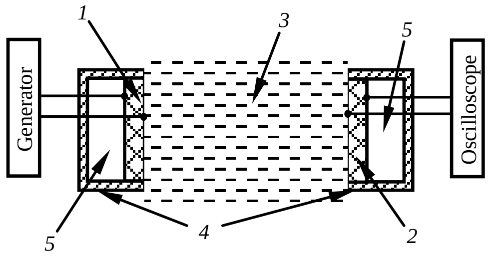

Fig. 1. Experimental setup

To determine the degree of reduction of its length we compared it with the signal at the output of the receiver, when the radiator was excited by the one half-cycle electric pulse of the frequency of thickness oscillations of the piezoelectric plate.

II. Experimental study of the emitting-receiving system

Experimental studies were carried out using a laboratory setup, that is shown in fig. 1. The setup included radiating *1* and receiving *2* piezoelectric transducers (two identical piezoelectric plates fabricated of the piezoceramics PZT-19). The emitter was excited with a special form signal generator Tabor Electronics WW2572A. The output signal from the receiver was analyzed using an oscilloscope LECROY WaweAce 101. The electrical signals generated by the generator and fixed by the oscilloscope were processed digitally on a computer. Glycerin *3* was used as an immersion liquid, which eliminated the possibility of the electrical short. The parameters of piezoceramic plates: main frequency – 1 MHz, diameter – 20 mm, thickness – 1.25 mm. The rear sides of the plates placed in the cases *4* were loaded onto the air *5* [9].

The described radiation-receiving system had the ability to adjust the distance between the working faces of piezoelectric plates. This distance during the experimental measurements was equal to 108 mm. The alignment of the system was achieved by determining the position of piezoelectric transducers, where the maximum signal was observed at the output of the receiver in continuous radiation mode.

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The emitter was excited by an electric signal of a complex shape, calculated by the d'Alembert method on the basis of the algorithm described in [6, 7]. The forms of these signals are given in Fig. 2. Abscissa axis is for the dimensionless time, which is defined as $T = t/(T_0/2)$, where t – physical (true) time, T_0 – the period of oscillations at the antiresonance frequency of the plate. The ordinate axes are for the electric voltage u/u_1 normalized to the amplitude u_1 of the exciting half-period. Fig. 2*a* shows the electric signal consisting of only one (exciting) half-period of the sine wave supplied to the emitter. Figs 2*b–f* show the electrical pulses of complicated forms, exciting the radiating plate. They contain exciting and compensating half-periods. The amplitudes of the exciting half-periods, due to the accepted normalization, are always equal to 1, and the amplitudes of the compensating half-periods are: 0.926 (Fig. 2*b*); –0.852 (Fig. 2*c*); 0.789 (Fig. 2*d*); –0.726 (Fig. 2*e*); 0.672 (Fig. 2*f*).

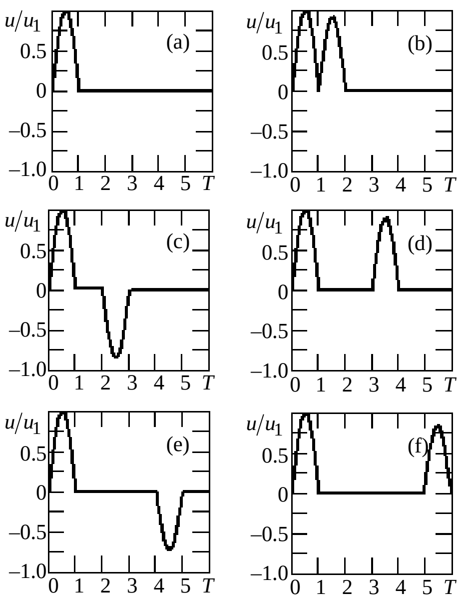

Fig. 2. Forms of electrical signals exciting the radiating piezoelectric plate

The shapes of electrical signals at the output of the radiation-receiving system, depending on the signals at the input of the emitter, are given below in comparison with the results of the solution of the problem by the finite element method.

III. The solution of the problem by finite element method

The application of d'Alembert method allowed to obtain the estimated values of the required amplitudes of the exciting and compensating half-periods of the signal supplied to the emitter. This problem was solved for one-dimensional piezoelectric plate. Traditionally, it was taken, that its thickness was small compared to the size of the aperture. However, in real cases it is necessary to take into account the limited size of the piezoelectric plate transducer. In these cases, the model becomes more complex, and the analytical solution becomes more difficult. It is more convenient to use numerical calculation methods, such as finite element method (FEM), boundary element method (BEM), spectral element method (SEM), finite difference method (FDM) etc. We used the finite element method of the COMSOL Multiphysics modeling environment with customized user modules Structural Mechanics, Acoustics и Electrostatics.

A. *Theoretical background*

Electrical and mechanical phenomena in the radiation-reception system (mechanical strain u, mechanical stress σ, electrical field strength E, and electrical displacement D) can be described on the basis of the fundamental equations of direct and reverse piezoelectric effect:

$$\left.\begin{aligned} u_i &= s_{ij}^{E}\sigma_j + d_{im}E_m \\ D_m &= d_{mi}\sigma_i + \varepsilon_{mk}^{\sigma}E_k \end{aligned}\right\}$$

where s_{ij}^{E} is the mechanical compliance of the material measured at zero electric field (E = 0), $\varepsilon_{mk}^{\sigma}$ is the dielectric permittivity measured at zero mechanical stress (σ = 0), and d_{mi} represents the piezoelectric coupling effect.

At the same time, the process of acoustic wave propagation is described by the wave equation:

$$\frac{1}{c}\frac{d^2p}{dt^2} = \nabla(-\nabla p), \tag{1}$$

where p – sound pressure in liquid, ∇ – Hamiltonian, c – sound speed in the liquid.

The transfer of mechanical displacements and stresses from the emitting piezoelectric element to the medium and from the medium to the receiving piezoelectric element is described by the boundary condition: continuity of the normal component of the acceleration at the interface:

$$\mathbf{n}(-\nabla p) = \mathbf{n}\frac{d^2\xi}{dt^2}$$

where $\mathbf{n}$ – the normal to the interface, ξ – mechanical displacement.

For the numerical solution of the differential equation (1), in addition to the boundary conditions, it is necessary to determine the initial conditions. They are: zero pressure $p = 0,\ \frac{\partial p}{\partial t} = 0$ and zero displacement $\xi = 0,\ \frac{\partial \xi}{\partial t} = 0$ in the material at the initial time.

B. *Model specifications*

The geometry of the model created in COMSOL Multiphysics completely corresponds to the experimental one. Fig. 3 shows this geometry. The ordinate axis coincides with the axis connecting the centers of the radiating and the receiving piezoelectric plates. The abscissa axis is the radius (r) of this axisymmetric model. The radiating piezoceramic plate *1* is loaded on one side to the glycerin and is excited by an electric pulse of a complex form (Fig. 2). The generated acoustic pulse, after passing through the glycerin layer *3*, comes to the receiving piezoceramic plate *2*. The piezoelectric plates are rigidly fixed at the edges. The carrier frequency of the electric exciting pulses was 1 MHz, Частота электрических импульсов возбуждения равна 1 MHz, the thickness of the piezoceramic plates – 1.25 mm, the diameter – 20 mm. Piezoelectric elements are coaxially located at a distance 108 mm from each other. The material of the piezoelectric elements – piezoelectric ceramics PZT-19 [10].

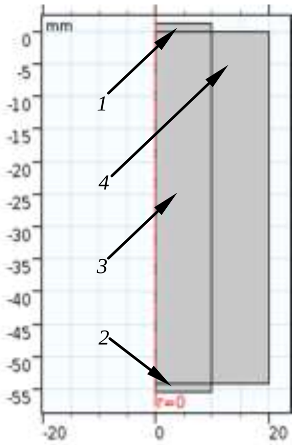

Fig. 3. The studied geometrical area in COMSOL Multiphysics environment

The finite element method is only applicable for finite geometric size models. Divergence of the ultrasonic beam, causes possible reflections from the boundaries of the glycerine layer *3*. The calculation model uses a perfectly matched layer *4* to avoid re-reflections. This layer omits without reflection waves falling into it from other zones and does not reflect them back [11].

The area subject to study was divided into sub-areas *dx*, according to the following criterion $dx = \lambda/16$, where λ – is the wavelength in glycerin. Time step *dt* was selected according to the criterion Courant–Friedrichs–Lewy (CFL), which is a necessary condition for the stability of the numerical solution of the differential equation [12]. For the two-dimensional case, this criterion is as follows:

$$c_x \frac{dt}{dx} + c_y \frac{dt}{dy} < \mathrm{CFL}\,, \tag{2}$$

where c_x, c_y – speeds of sound in glycerin along the coordinate axes *x* and *y* correspondingly; *dx, dy* – steps along coordinate axes *x* and *y*. Since glycerin is a linearly isotropic material, then $dx = dy$, $c_x = c_y = c$, $\mathrm{CFL} = 1$. Then the equation (2) can be rewritten as follows $2c\frac{dt}{dx} \le 1$ или $dt \le \frac{dx}{2c}$.

As a result, considering that $dx = \lambda/16$, and $c = \lambda f$, where *f* – emitter excitation frequency, the time step selection criterion takes the form $dt \le 1/(32f)$.

IV. Comparison of Experimental Data with the Simulation Results

In [9] the estimated shapes of the electrical signals at the output of the receiver obtained using the method of d'Alembert, are compared with the experimental data. Now is also of interest to compare the experimental data with the results of finite element simulation. As the characteristics for comparison, as in [9], we shall use a voltage at the reception plates surfaces. The results of the present work in combination with the data presented in [9] can be useful to those, who are involved in the design of piezoelectric transducers intended for solving problems in applied acoustics.

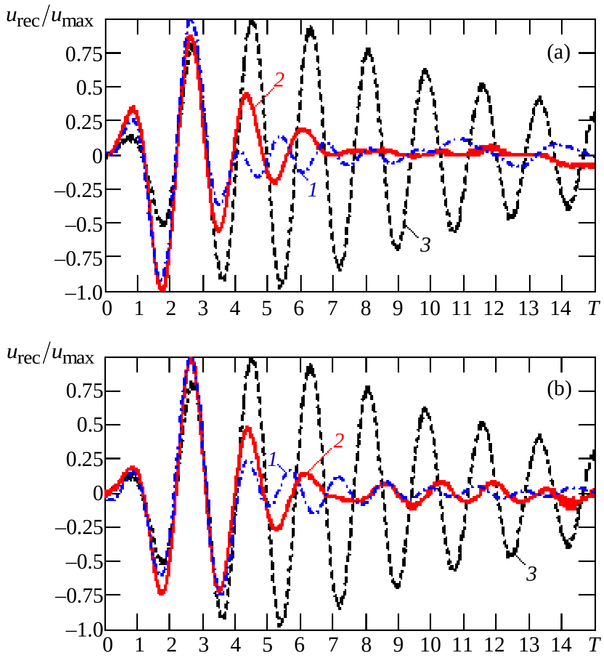

Fig. 4. Shapes of electrical signals at the output of the receiver

Fig. 4 shows some shapes of electrical signals at the output of the receiver. These shapes correspond to the electrical pulses, applied to the emitter, depicted in Fig. 2*a*–*c*. In Fig. 4 curve *1* corresponds to the calculated data obtained by the finite element method and curve *2* – to the experimental data. Fig. 4*a* shows the results when the emitter receives the signal shown in Fig. 2*b* Fig. 4*b* shows the results when the emitting plate is excited by the electrical pulse, shown in Fig. 2*c*. In addition, Fig. 4 contains one more curve – number *3*. It corresponds to the signal, obtained experimentally at the output of the receiver, when an electrical pulse at the emitter, is shown in Fig. 2*a*. All the pulses presented in Fig. 4, are normalized to one, i.e. normalization to the amplitudes of the signal maxima u_{max} for each of the received pulses u_{rec} is carried out. The parameter u_{rec}/u_{max}, obtained as a result of normalization is placed along the ordinate axis. On the *x*–axis is the dimensionless time $T = t/(T_0/2)$, where $T_0 = 1$ µs – the period of the signal at the natural frequency of the plate; *t* – physical (real) time.

Analysis of the curves, presented at Fig. 4, indicates that curves *1* and *2* are very close one to each other. The main parts of the pulses are almost identical, some differences are observed only in the final (“tail”) part of the signal. One can see, that the duration of the signal at the receiver output in the experiment (curve *2*) and in numerical simulation (curve *1*) is greatly reduced in comparison with the signal corresponding to the curve *3*. For example, for the case presented in Fig. 4*a*, it is reduced from 27 to 11 half-cycles (–20 dB from maximum value).

One can note, that the “tails” of the pulses on the curves *1* and *2* have frequency distortion compared to the main (initial) part of the pulses. This can be explained by the influence of the compensating half-period of the signal coming to the emitter.

In [9] a limitless plate was assumed as a model of a piezoelectric element to calculate by d’Alembert method. The obtained calculated results were used as estimates necessary for the analysis of transient processes in a finite-size piezoelectric element by COMSOL Multiphysics. Evidently, that each of the considered methods gives qualitatively and quantitatively results similar to the experiment.

V. CONCLUSION

Thus, the pulse mode of operation of the radiation-reception system consisting of two identical piezoceramic plates is studied numerically and experimentally. Glycerin was chosen as the immersion liquid. It was experimentally confirmed that the excitation of the emitter by a complex electric signal, the shape of which is determined theoretically and numerically, allows to reduce the duration of the signal at the output of the receiver. The duration of the output signals was compared at the excitation of the emitter by different types of signals: by one half-cycle at the natural frequency of the emitter and by the signals of complex shape. It was noted the similarity of both forms of the calculated and experimental signals at the output of the system.

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