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To cite this article: B Ch Ee *et al* 2019 *J. Phys.: Conf. Ser.* **1352** 012015

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On the reducing of the acoustic signal length from the piezoelectric transducers of the sea ice monitoring systems

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Abstract. The solution of navigation problems the ice situation problems in the Arctic region need to study the acoustic parameters and local reflective properties of ice in real conditions. Information about the local sea ice acoustic properties essentially helps to solve the problems of statistical forecasting of reflective and scattering properties of ice cover. The successful solution of these problems mostly depends on the metrological parameters of the probing signals emitted by the primary piezoelectric transducers. This means, that to increase the resolution of the control and measuring equipment it is better to radiate and to receive short acoustic pulses. The article presents the results of analysis the pulse mode of operation of cylindrical piezoelectric transducers designed to measure the velocity of sound in sea ice. To reduce the length of acoustic pulses, an inductive-resistive load is connected to the electrical input of the radiator. The length and the amplitude of the emitted acoustic pulse were estimated using equivalent circuits of piezoelectric transducers and a spectral method based on the Fourier transforms. The optimal parameters of the electrical circuit, ensuring the minimum length of the acoustic pulses are calculated. The technique of possible measurements is described. The results are presented in the most general form, making possible to use them within different frequency ranges.

1. Introduction

Oil and gas resources of the sea shelf according to various data exceed half of the global resources [1]. At the same time, the most part of them falls on the Arctic shelf. Therefore, the development of deposits of the Arctic shelf requires the solution of numerous complex problems [2, 3]. Simultaneously with the increase in resource extraction in the Arctic region, the volume of Maritime transport is also increasing. At the same time, sea ice makes the major problem for any shelf activity. Ice affects all kinds of works on the surface of the sea. The presence of sea ice can force changes in the schedule or even a complete cessation of work. Oil and gas activities in winter require a thorough knowledge of data on strength, mobility, and the general morphology of ice. The main characteristic features include: seasonal evolution; composition (annual or long-term ice after summer melting); concentration of these different types; types of ice formations (ice fields, hummocks, layered ice); speed of their movement; properties associated with mechanical strength.

Studies of the strength (elastic and unelastic) characteristics of sea ice for navigation purposes have been carried out for a long time and in large volumes. Data on these items have been collected, apparently, since the early 30s of the XX century [4]. The objects of such studies are the elastic moduli and Poisson's ratio, which in most cases are determined on ice samples by static methods (by measuring strain under different types of load). However, timely coverage of the ice situation is possible using the sonar methods [5]. However, when using sonar navigation devices, sound reflections from the ice boundary essentially impact on the propagation of acoustic waves in the seas, most of the time covered by ice. In this regard, there is a need to study the acoustic parameters and local reflective properties of ice in natural conditions. Knowledge



of local acoustic characteristics of sea ice makes it much easier to solve the problems of statistical forecasting of the reflective and scattering properties of the ice cover.

Currently, the following methods for studying the acoustic parameters of ice are known: seismic, resonant, pulse ultrasonic [4]. The most widely used is the pulse method to measure the velocity of sound over the time of run of an ultrasonic pulse over a known distance in the ice between the radiator and the receiver. The method of such full-scale measurements is presented, for example, in [4]. A chain of radiators located vertically 50 cm from each other was frozen into the ice. Radiators were thick-walled cylinders made of PZT piezoceramics bonded on the circumference of the individual prisms. The application of electric voltage across the electrodes caused radial (normal) and azimuthal (tangential) displacements of the radiating surface. Such an oscillating radiator, being frozen into the ice, well excited both longitudinal and transverse vibrations in the ice. The signal was radiated by one transducer of choice, depending on which horizon of the ice cover at the moment the velocity of elastic waves was measured. The oscillations were taken by a spherical piezoceramic hydrophone immersed in a shaft vertically drilled in the ice at some distance from the radiator, filled with non-freezing liquid (antifreeze, kerosene). The hydrophone was plunged into a depth corresponding to the depth of the selected radiation. At the curved boundary of the mine, shear waves propagating in the ice transformed into longitudinal sound waves in the liquid filling the mine and were received by a hydrophone. Thus, the hydrophone received both pulses of longitudinal waves and those corresponding to shear waves propagating in the ice.

The error in this measurement method is mainly determined by the error of measuring the time of the acoustic pulse propagation in ice. To increase the resolution of the apparatus, it seems good to carry out these measurements using the pulse mode of the transducers. In this case, the duration of the acoustic signals should be the minimum possible, i.e. it should not exceed only a few half-cycles of oscillations. Using the mode of radiation-receiving short signals will improve the most important characteristics of the apparatus. This caused the authors' interest to the problem of studying the possibility of reducing the duration of an acoustic signal emitted by piezocylinder.

2. Theoretical analysis

In some previous authors' works [6], the problems related to the study of the influence of corrective electrical circuits on the duration and amplitude of the radiated signals in the application to the problems of non-destructive ultrasonic testing were considered. The possibility of reducing the acoustic pulse duration emitted by piezoelectric plate transducers, depending on the method of connecting them to the inductive-resistive circuits was studied. The possibilities of reducing the duration of the probing signal for all possible combinations of connection of R - and L -elements with each other, as well as for different methods of connecting the RL -circuit to the transducer are considered. The parameters of the circuits, allowing to receive the short signal, were studied as well as the effects of circuits on the amplitudes of the pulses. The problem was solved both for the case of an ideal voltage source (assuming that its internal resistance is equal to zero) and in the most general formulation (for an arbitrary value of the internal resistance of the source). Issues of relevance for the purposes of hydroacoustics were considered in [7,8]. Thus, in [7] a similar study of acoustic signals emitted by a spherical piezoceramic transducer, the inner cavity of which is filled with liquid (to work in deep water), and an RL circuit is connected to the electrical input, was carried out. In [8] the pulse mode of operation of a cylindrical radiator filled with various liquids was studied.

It is of interest to continue these studies, for example, for the case of connection of an electric inductive-resistive correcting circuit to a cylindrical radiator in order to study the possibilities of reducing the duration of the emitted acoustic signal. This paper contains some results obtained in the course of this study. It should be noted that the presented results can probably be used to measure the velocity of sound in sea ice using the method [4] with some modifications. For example, we propose to facilitate the extraction of the radiator system after the measurements, not to freeze piezocylindrical transducers into ice, but to lower them into a mine similar to the one in which the hydrophone is placed. It can also be filled with non-freezing liquid, in which the dependence of the sound velocity on temperature is well studied. Thus, the measurement scheme is an immersion version of the study, widely

used in the practice of non-destructive ultrasonic testing. Evaluation showed, that the parameters of such a liquid can be similar to those of water. Using the proposed method of determining the duration of the emitted acoustic signals, it is not difficult to specify the calculation results for the case of any other (actually used) liquid.

We study the influence of the electrical circuit parameters on the duration of acoustic pulses for different relative thicknesses and heights of the cylinders. As a result, it is necessary to determine the optimal parameters of electrical circuits, at which the pulse duration will be minimal, and to obtain specific estimations of the pulse parameters. Figure 1 schematically shows the considered piezoceramic cylindrical radiator. The active material is PZT piezoelectric ceramics. The electric excitation pulse has the form $U(t)$. The figure shows: R_m , H and δ – average radius, height and thickness of the cylinder wall.

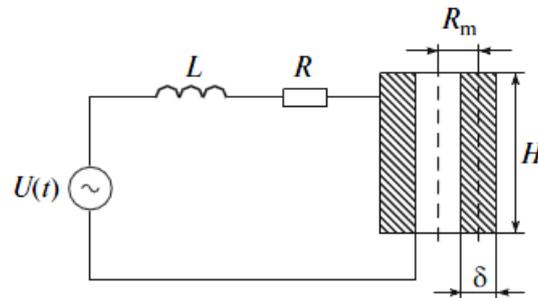


Figure 1. Statement of the problem.

The parameters are: $\alpha = \delta/R_m$ and $A = H/2R_m$. They characterize the relative size of the radiator. It is well known that the radiation resistance of the piezoelectric transducer can be written as

$$Z_S = (\rho c)_w S_1 (x + jy) \quad (1)$$

where $(\rho c)_w$ – specific acoustic impedance of the liquid medium into which the radiation is produced; x and y – active and reactive components depending on frequency (dimensionless). We assume that the radiating surface of the considered radiator is S_1 .

We assume that the considered piezoceramic radiator is a cylinder having rigid ends. Frequency dependences on the parameters x and y , corresponding to different values of A , are presented in [9].

The equivalent circuit of the cylindrical piezoelectric transducer is shown in figure 2. It is assumed that this radiator has a small wall thickness and oscillates at zero mode. The figure introduced notations: M – the mass of the piezoelectric ceramics; C_M – mechanical flexibility of the radially oscillating shorted cylindrical element; C_0 and K_U – capacity of the clamped mechanical radiator and coefficient of electromechanical transformation. Elements R and L refer to the elements of the inductive-resistive circuit connected to the cylindrical transducer.

The capacitance of the mechanically clamped radiator C_0 and the inductance L form an LC circuit. Let ω_{el} – its resonant frequency. Then $\omega_{el} = 1/\sqrt{LC_0}$. We introduce the parameter Q as follows: $Q = \omega_{el}L/R$. This will allow us to characterize the resistance R . It is worth noting that Q makes sense of Q -factor. The value of the coefficient of electromechanical transformation, included in the number of designations of the parameters presented in the scheme, is determined by the expression:

$$K_U = \left(\frac{2\pi d_{31}}{s_{11}^E} \right) H \quad (2)$$

Here d_{31} – piezomodule; s_{11}^E – element of the flexibility matrix at the constant strength E of the electric field.

Mass $M = \rho_{\text{cer}} S_1 \delta$; ρ_{cer} – piezoceramics; $S_1 = 2\pi R_m H$ – radiating surface area of the cylinder.

Mechanical flexibility $C_M = \frac{s_{11}^E R_m}{2\pi H \delta}$.

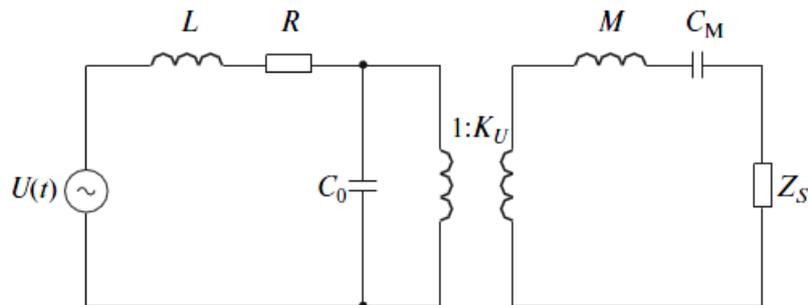


Figure 2. Equivalent electric circuit of the cylindrical transducer.

The main frequency of radial oscillations $\omega_0 = \frac{1}{\sqrt{MC_M}} = \frac{c_1}{R_m}$, where $c_1 = \frac{1}{\sqrt{\rho_{\text{cer}} s_{11}^E}}$. The resonance condition can be written as $k_0 R_m = 1$, where $k_0 = \omega_0 / c_1$ – wave number in the piezoelectric ceramics at the resonance frequency. Resistance of radiation Z_S is the function from $(k_w R)$, where $k_w = \omega / c_w$ – wave number in water. We introduce the dimensionless (relative) frequency: $\gamma = \omega / \omega_0$. We also denote $b = c_1 / c_w$. Then for the components of the radiation resistance we can obtain

$$x(k_w R) = x(b\gamma); \quad y(k_w R) = y(b\gamma) \quad (3)$$

The mechanical resistance of the cylinder taking into account the radiation resistance can be written in the form

$$Z_{\text{mech}} = jz_{\text{cer}} S_1 \alpha \left(\gamma - \frac{1}{\gamma} \right) + z_w S_1 (x(b\gamma) + jy(b\gamma)) \quad (4)$$

where z_{cer} and z_w – are the specific acoustic impedances of piezoelectric ceramics and water, respectively.

The capacitance C_0 is determined by the following expression: $C_0 = \frac{\epsilon_0 \epsilon_{33}^{u_1} S_1}{R_m \alpha}$; where $\epsilon_{33}^{u_1} = \epsilon_{33}^\sigma (1 - k_{31}^2)$. Here ϵ_0 – electrical constant, k_{31} – coefficient of electromechanical coupling of the piezoceramics, ϵ_{33}^σ – dielectric constant at the constant mechanical stress.

The setting of the electric circuit can be characterized by the parameter $n = \omega_{\text{el}} / \omega_0$.

After some algebraic transformations, for the electric inductive-resistive circuit, that is used to correct the radiated signal, we can obtain:

$$R = \frac{1}{nQ} \frac{1}{\omega_0 C_0}; \quad j\omega L = j \left(\frac{\gamma}{n^2} \right) \frac{1}{\omega_0 C_0} \quad (5)$$

Recalculate the equivalent circuit (fig. 2) to its electrical side (see fig. 3). The mechanical resistance is given by the following expression:

$$Z_{\text{inc}} = \frac{Z_{\text{mech}}}{K_U^2} \quad (6)$$

Figure 3 contains the parallel connection C_0 and Z_{inc} . This suggests that $Z = \frac{Z_{\text{inc}}}{1 + j\omega C_0 Z_{\text{inc}}}$.

The expression for the input electric impedance of a cylinder with a connected electrical circuit is:

$$Z_{\text{input}} = R + j\omega L + Z = \frac{1}{\omega_0 C_0} \left[\frac{1}{nQ} + j \frac{\gamma}{n^2} + \frac{\omega_0 C_0 Z_{\text{inc}}}{1 + j\omega C_0 Z_{\text{inc}}} \right] \quad (7)$$

Then the total current through the transducer is:

$$I = \frac{U}{Z_{\text{input}}} = \frac{U \omega_0 C_0}{\frac{1}{nQ} + j \frac{\gamma}{n^2} + \frac{Z_{\text{inc}} \omega_0 C_0}{1 + j\omega C_0 Z_{\text{inc}}}} \quad (8)$$

From the diagram shown in figure 3, it is seen that the currents I_C and I_{load} are the terms that make up the current I .

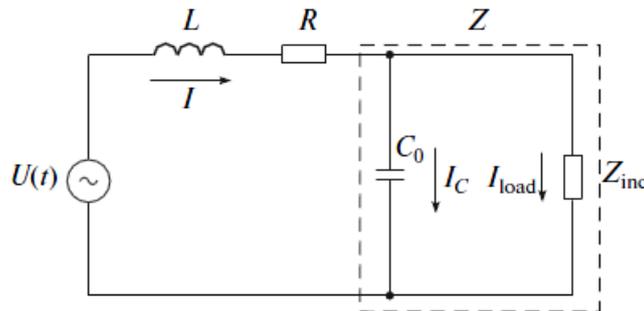


Figure 3. Electric circuit analog of the cylindrical transducer after being reduced to its electric part.

To find the current I_{load} we shall use the expression for the transmission coefficient $K = \frac{I_{\text{load}}}{I} = \frac{Z_C}{Z_C + Z_{\text{inc}}}$. Here Z_C is the resistance arising from the existence of the capacity C_0 . In addition, we note that $\frac{K_U^2}{\omega_0 C_0} = k_{31}^2 \alpha Z_{\text{cer}}$, with $Z_{\text{cer}} = z_{\text{cer}} S_1$.

Then, after some mathematical transformations, taking into account the expressions that define I , K , Z_C and Z_{inc} , one can obtain

$$I_{\text{load}} = U \frac{K_U^2}{A(\gamma) k_{31}^2 \alpha Z_{\text{cer}} + B(\gamma) Z_{\text{mech}}} \quad (9)$$

with $A = \frac{1}{nQ} + j \frac{\gamma}{n^2}$, $B = 1 + j\gamma A$.

On the surface of the cylinder the expression for the oscillatory velocity has the form:

$$v = \frac{I_{\text{load}}}{K_U} = \left(\frac{UK_U}{Z_{\text{cer}}} \right) \frac{1}{A(\gamma) \alpha k_{31}^2 + B(\gamma) z'_{\text{mech}}} \quad (10)$$

with $z'_{\text{mech}} = \frac{Z_{\text{mech}}}{Z_{\text{cer}}} = j\alpha \left(\gamma - \frac{1}{\gamma} \right) + \left(\frac{z_w}{z_{\text{cer}}} \right) (x(b\gamma) + jy(b\gamma))$.

Let us now consider the pulse mode of the transducer under consideration. To do this, we shall use a spectral method based on Fourier transforms. We introduce the dimensionless time as follows:

$T = \frac{t}{(T_0/2)}$. Here t – normal (physical) time, and T_0 – the period of oscillation of the radiator at the

frequency ω_0 .

The oscillatory velocity at the output of the radiator is determined by the following expression (the problem is solved with an accuracy of up to a constant multiplier):

$$v(T) = \operatorname{Re} \int_0^{\infty} U(\gamma) v(\gamma) e^{j\gamma\pi T} d\gamma \quad (11)$$

where $U(\gamma)$ – spectral function of the pulse exciting the radiator. Let it be a signal in the form of half of the period of the sine wave at the natural frequency of the transducer:

$$U(t) = \begin{cases} U_m \sin \omega_0 t, & \text{for } 0 \leq t \leq T_0/2 \\ 0, & \text{for } t < 0 \text{ and } t > T_0/2 \end{cases} \quad (12)$$

Its spectral function (taking into account dimensionless variables) will be written in the following form:

$$U(\gamma) = \frac{\cos\left(\gamma \frac{\pi}{2}\right)}{1 - \gamma^2} e^{-j\gamma \frac{\pi}{2}} \quad (13)$$

3. Results of calculation

The calculations of the shape of the acoustic pulse emitted by piezocylinder with corrective inductive-resistive circuit were carried out using the above mathematical algorithm. The piezoelectric ceramics of PZT-type was chosen as piezoactive material. The duration of the signal at the output of the radiator was estimated in accordance with the criterion of -20 dB. Recall that the duration of the acoustic pulse was determined using the dimensionless time-the number of half-cycles of oscillations at the main frequency of the cylinder radial oscillations.

Table 1. Optimal values of n and Q for different A , α , τ_p and v_{\max} .

A	α	In the presence of the RL circuit with the optimal parameters		In the absence of the RL circuit
2.5	0.15	$n_{\text{opt}} = 1.25$	$\tau_p = 4.3$	$\tau_p = 5.2$
		$Q_{\text{opt}} = 1.5$	$v_{\max} = 11.6$	$v_{\max} = 9.1$
	0.25	$n_{\text{opt}} = 1.1$	$\tau_p = 5.3$	$\tau_p = 7$
		$Q_{\text{opt}} = 1.5$	$v_{\max} = 7.9$	$v_{\max} = 6.8$
0.5	0.15	$n_{\text{opt}} = 1$	$\tau_p = 6.8$	$\tau_p = 12$
		$Q_{\text{opt}} = 1.5$	$v_{\max} = 12$	$v_{\max} = 10.2$
	0.25	$n_{\text{opt}} = 0.95$	$\tau_p = 6.6$	$\tau_p = 15.8$
		$Q_{\text{opt}} = 2$	$v_{\max} = 9.12$	$v_{\max} = 7.5$

Calculations were carried out for the cases: $A = 2.5$ (relatively “long” cylinder) and $A = 0.5$ (corresponds to the “short” cylinder). Parameter α , used to specify the relative wall thickness, was chosen $\alpha = 0.15$ and $\alpha = 0.25$. Such choice allowed to consider that the cylinder is rather thin-walled.

First, in the course of the calculations, approximate ranges of the parameters n and Q were established, allowing to achieve a significant reduction in the duration of the emitted signals. These values were then adjusted. The result was the determination of pairs n and Q , allowing to obtain the minimum duration of acoustic pulses. The table shows the values of n and Q , as well as the durations τ_p and maximum amplitudes v_{\max} (in conventional units, which is explained by the solution of the problem up to a constant factor) of the received signals. For comparison, the parameters of signals for the absence of inductive-resistive correcting circuit at the electrical input of the transducer are presented.

Based on the calculation and theoretical work done, it can be confidently argued that the correctly selected parameters of the circuit allow to achieve a reduction in the duration of the signal emitted by the transducer. The relative decrease in the duration is more pronounced in cases of using shorter cylinders and thicker walls. For example, as it follows from the table, for the case of $A = 2.5$ and $\alpha = 0.15$ the duration can be reduced by 1.2 times. If $A = 0.5$ and $\alpha = 0.15$, the positive effect is 1.76 times, and at $\alpha = 0.25 - 2.39$ times.

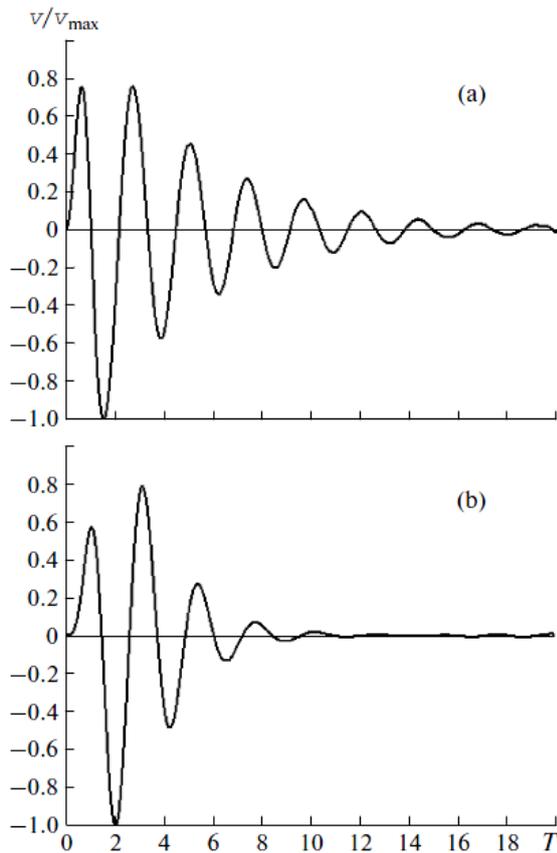


Figure 4. Shape of the emitted acoustic pulse (at $A = 0.5$, and $\alpha = 0.15$) (a) without the correcting circuit and (b) with the optimally adjusted correcting circuit ($n_{\text{opt}} = 1, Q_{\text{opt}} = 1.5$).

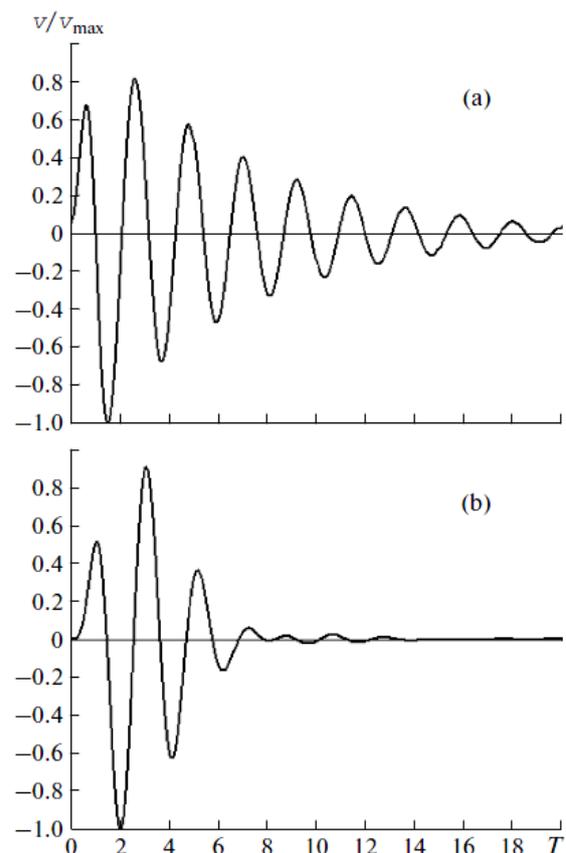


Figure 5. Shape of the emitted acoustic pulse (at $A = 0.5$ and $\alpha = 0.25$) (a) without the correcting circuit and (b) with the optimally adjusted correcting circuit ($n_{\text{opt}} = 0.95, Q_{\text{opt}} = 2$).

An example of the signals emitted by the investigated Converter is the data given in figure 4 and figure 5, where for comparison the pulses of vibrational velocity emitted by a cylinder without an electric circuit are shown (figure 4 (a) and figure 5 (a)) and with a corrective circuit having correctly defined parameters (optimal n and Q). Case shown in figure 4, corresponds to $A = 0.5$ and $\alpha = 0.15$, and in figure 5 – $A = 0.5$ and $\alpha = 0.25$. One can see that the positive effect is evident in both cases.

4. Conclusion

The paper discusses a pulsed mode of operation of piezotransducer, radiating in a liquid medium and having a correcting electric circuit connected to the electrical side of the radiator. The mathematical apparatus based on the theory of equivalent piezoelectric transducer circuits in combination with the Fourier spectral method, which allows to determine the shape of the emitted signals, is presented. The optimal values of the parameters describing the radiating system at which it is possible to obtain the

minimum duration of the signal at the output of the radiator are determined. Cylinders of different relative lengths with different relative wall thicknesses are considered. It is noted that the positive effect of the use of electric corrective circuit is more pronounced for the use of “short” cylinders with thicker walls.

Acknowledgments

The work was carried out under the grant of the President of the Russian Federation for State support of leading Russian scientific schools (SS-4165.2018.8).

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