Forming a short acoustic signal to study the underwater environment

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Abstract. Piezoelectric transducers (PET) are widely used as emitters and receivers of acoustic signals to solve a great number of problems related to the study of the World Ocean. Providing the ability to operate the PET in the mode of short-sounding pulse radiation allows increasing the resolution of the remote sensing equipment of the aquatic environment. At the same time, a number of tasks require the use of non-directional emitters, for example, in the form of a thin-walled sphere. It is of interest to study the possibility of obtaining a short probing signal at the output of this type of PET. The paper considers the pulse mode of operation of a non-directional thin-walled spherical emitter excited by a short electrical signal. The research is based on the application of the method of equivalent circuits of the PET and the Fourier spectral method. The durations and amplitudes of the probing pulses emitted by the PEP are estimated. The results obtained may be applied to the design of equipment for underwater research.

1. Introduction
The study of various media, materials and products can be carried out by various methods, which are based on different physical principles. At the same time, acoustic methods for studying different physical media have become widespread. In this sense, the marine environment is no exception.

In this regard, the creation of hydroacoustic means for studying the World Ocean is given the most serious attention in our country and abroad. Developers of equipment designed for underwater research are constantly work to improve the characteristics of this equipment. For example, in location problems, the solution becomes possible by reducing the duration of the probing acoustic pulses emitted by the PET into the external environment (water). Indeed, the operation of the PET in the mode of radiation/reception of short signals allows one to increase the accuracy of determining the location of the object, as well as to improve the resolution of the radiating system. In other words, the creation of conditions that allow
piezoelectric transducers to work in pulse mode is one of the main ways to solve a number of most important problems of hydroacoustics (searching targets, classification, solving problems of underwater positioning, navigation, etc.).

We must note that in many cases, the reduction of the length of the probing pulses is achieved by the same technical means that are used to expand the bandwidth of the PET. Probably, this circumstance is the reason that sometimes it is necessary to realize the fact of existing two tasks, completely different in their physical essence – the creation of a broadband PET and the study its pulse mode. The first problem is the result of the analysis of the continuous mode of operation of the transducer, and this result can be extended to the case of emission/reception of long pulse signals. The second problem can be solved only by using special methods that allow us to study the shape of the signals at the output of the PET [1-7]. Among the methods of expanding the bandwidth of transducers and, accordingly, reducing the length of the radiated pulse, the most popular are the following: mechanical damping, the quarter-wave matching layers and the link of $R-L$ circuits to the electrical side of the PET [2, 8–12]. The first of these methods has not found practical application in hydroacoustics due to the lack of materials that can effectively absorb signals at frequencies used in underwater research. Matching quarter-wave layers are widely used. Their disadvantages include the need to maintain high accuracy of their manufacture in order to achieve the identity of the parameters of the PET. The method of connecting $R-L$ circuits to the electrical side of the PET has been less studied. In a number of previous papers [11, 12], the authors studied the pulse mode of various transducers and the parameters of $R-L$ circuits connected to the electrical side of the PET were investigated. These data allow getting the minimum length of the radiated acoustic pulse. Thus, in [11], the possibility of reducing the length of probing pulses with serial and parallel versions of connecting serial and parallel $R-L$ circuits to a plate-type PET was studied. The operation of a thin-walled piezocylinder with an inductive-resistive circuit connected to it was investigated in [12].

It should be noted that in relation to the problems of underwater acoustics not requiring the usage of directional radiators, the use of a spherical thin-walled converter sometimes might be promising. The pulse mode of such a PET was studied in [12], where a sphere with a liquid filling of the inner cavity was considered (to increase the depth of the transducer operation). As a special case, the paper also studies not filled sphere. It is of interest to continue these studies and consider the pulse mode of a spherical radiator with an $R-L$ circuit to study the possibility of further reducing the length of the radiated pulse. This paper presents the results of these studies.

2. The problem formulation

The statement of the problem one can see in figure 1. Transducer–radiator has the form of the thin-walled sphere of the PZT–type piezoceramics. The transducer radiates to the water. An inductive-resistive circuit is connected to the electrical input of the radiator. The figure shows the following symbols: $U(t)$ – exciting electrical pulse; $R_m$ – average radius of the sphere, $\delta$ – wall thickness. We introduce the parameter $\alpha$, which characterizes the relative wall thickness of the sphere: $\alpha = \delta/R_m$.

The problem is to find the shape of the probing signal emitted by the transducer (when specifying the type of exciting electric pulse).

Let $C_0$ be the electrical capacitance of a mechanically braked piezoelectric transducer. The inductance $L$ and the natural capacitance $C_0$ of the piezoelectric element form a contour. The resonant frequency $\omega_{el} = 1/\sqrt{LC_0}$ of this circuit may be used to characterize the inductance $L$. The resistance $R$ can be characterized by the parameter $Q = \omega_{el}L/R$. This parameter has the sense of $Q$-factor. We also introduce a parameter $n = \omega_{el}/\omega_0$ that characterizes the setting of the electric circuit $LC_0$.

In the previous paper of the authors [12], an algorithm for determining the shape of the probing pulse emitted by the transducer in the form of a thin-walled piezocylinder was developed and described in detail. This technique can also be applied to a thin-walled spherical radiator. There is no need to describe it again. Note only that to state the signal at the output of the PET, the method of
equivalent circuits of piezotransducers and the Fourier spectral method are used. The shape of the exciting electrical signal was assumed the following:

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

that is, in the form of a half-period of a sine wave at the resonance frequency \( \omega_0 \) of the sphere. While solving the problem, dimensionless (relative) variables were used for the better generality, namely: dimensionless frequency \( \gamma = \omega_0/\omega_0 \) and dimensionless time \( T = t/(T_0/2) \), where: \( t \) – usual time, and \( T_0 \) – period of oscillation of the transducer at its own frequency \( \omega_0 \).

Having determined, in accordance with [12], the frequency dependence \( v(\gamma) \) of the oscillatory velocity at the output of the transducer, it is possible (up to a constant) to determine the dependence of the oscillatory velocity on time in the radiated probing signal:

\[ v(T) = \text{Re} \int_0^\infty U(\gamma) v(\gamma) e^{i\gamma T} d\gamma, \]

where \( U(\gamma) \) – spectral density of the exciting electric pulse.

The usage of above these allowed us to make a theoretical investigation of the form of acoustic signals emitted by a spherical transducer with an electric \( R-L \) circuit. The length of the acoustic probing signals was determined in accordance with the criterion (-20) dB.

3. Calculation and results

The following are some results of numerical studies. They consisted of a significant amount of the calculations for different values of parameter \( \alpha \) and were carried out by brute force method and consisted of determining the values of parameters \( n \) and \( Q \), in which it is possible to obtain the probing signal of minimal length. The pairs of values \( n \) and \( Q \) that allow achieving this goal were taken as optimal. The range of variation of the parameter \( \alpha \) was chosen according to the requirements of the thinness of the sphere, which corresponds to the lower and upper limits: \( \alpha = 0.01 \) and \( \alpha = 0.2 \), accordingly.

In the course of the computational study, it was found that the presence of the \( R-L \) circuit actually contributes to reducing the durations of the probing signals in the case when \( \alpha > (0.06 \pm 0.07) \). This is illustrated in figure 2. It contains several types of probing acoustic signals for the absence of an \( R-L \) circuit (figure 2(a), (b)) and its presence at optimally calculated values of the parameters \( n \) and \( Q \) (figure 2(c), (d)). In this case, figs. 2(a, b) are for \( \alpha = 0.1 \), and figs. 2(c, d) are for \( \alpha = 0.2 \). If we compare in pairs figure 2(a) and figure 2(c), also figure 2(b) and figure 2(d), we can see, that the use of an \( R-L \) circuit with optimally defined parameters \( n \) and \( Q \), allows to obtain signal reduction of 1.25 times (from \( \tau_p = 5 \) up to \( \tau_p = 4 \)). For the case \( \alpha = 0.2 \), the electrical correction is more effective (from \( \tau_p = 9.8 \) up to \( \tau_p = 6 \), i.e. approximately 1.6 times). It is also interesting to note that the presence of an electrical load does not distort the shape of the probing signal. This can be observed from the data shown in figure 2.

The table 1 shows some results of the calculated work on the study of the positive effect of an electric correction circuit with optimally defined parameters \( n \) and \( Q \) (they are shown in the table 1) on the duration \( \tau_p \) and maximum amplitude \( v_{\text{max}} \) of the probing signals. We must note, that the parameter \( v_{\text{max}} \) is dimensionless and proportional to the vibrational velocity in the emitted signal. This is because the problem was solved up to a constant factor. The range of changes in the relative wall...
thickness of the sphere shown in the table 1 is very wide – from $\alpha = 0.05$ up to $\alpha = 0.20$. It follows from the above data, that the electrical loading of the spherical transducer may cause a certain reduction in the duration of the probing signals in comparison with the case of its absence.

Table 1. Basic parameters of probing signals for cases of a transducer without a circuit and with a calculated optimal circuit

| $\alpha$ | In the presence of the $R$–$L$ circuit with the optimal parameters | In the absence of the $R$–$L$ circuit |
|----------|-------------------------------------------------|---------------------------------|
| 0.05     | $r_{opt} = 2, Q_{opt} = 1.5$ = 3.3 $v_{max} = 1.18$ $\tau_p = 3.3$ | $v_{max} = 0.94$ |
| 0.10     | $r_{opt} = 0.65, Q_{opt} = 1.2$ $v_{max} = 0.85$ $\tau_p = 4$ | $v_{max} = 1.44$ |
| 0.15     | $r_{opt} = 1, Q_{opt} = 1.5$ $v_{max} = 1.86$ $\tau_p = 5.2$ | $v_{max} = 1.70$ |
| 0.20     | $r_{opt} = 1, Q_{opt} = 1.5$ $v_{max} = 2.0$ $\tau_p = 6$ | $v_{max} = 1.85$ |

We noted that during the calculation study, that within the range of values $\alpha > (0.06–0.07)$ the positive effect of the electric loading is absent.
4. Conclusion
The paper describes the pulsed radiation of short signals of a spherical piezoelectric transducer to the water. It was shown the possibility of reducing the length of radiated signals using the electrical correcting $R$–$L$ circuit with optimal parameters connected to the transducer. The parameters of the $R$–$L$ circuit were obtained for a wide range of values of the relative wall thicknesses of the piezoceramic sphere. Comparatively estimated of the probing pulse durations and amplitudes in the presence and absence of a correction circuit.

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