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Characteristics of a compact hydroacoustic transducer with high power density in transmission and reception modes

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The use of reversible compact low-frequency transducers in hydroacoustic repeaters designed for use at distances of up to several tens of kilometers allows reducing the mass and dimensions of such devices. The paper presents the results of electroacoustic measurements of a compact transducer with a complex shape of an all-metal case both in the emission and reception modes of hydroacoustic signals. The acoustic power emitted by such a transducer exceeds 38 W for quasi-harmonic signals and reaches 12 W for complex pulse signals. The voltage amplitude at the output of the transducer operating in the reception mode is at a level of about 1500 mV in the operating frequency band and 200–400 mV outside its operating band, which is several times higher than the indicators of existing reversible hydrophones at similar values of the received sound pressure.

Keywords: hydroacoustics, underwater sonar communication, piezoelectric transducer, hydroacoustic emitter, hydroacoustic repeater, reversible hydrophone, electroacoustics.

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Introduction

A specific feature of hydroacoustic measurements in marine conditions is their dependence on positioning errors of the measuring system components, which, along with the effect of environmental parameter fluctuations on sound propagation, reduces measurement accuracy. The use of transponders (responder beacons) that emit the same or a predetermined signal after registration reduces positioning errors and the dependence on environmental parameter variations. Responder beacons have become widespread in navigation [1], including that of unmanned vessels [2], the control of autonomous underwater vehicles, and telemetry data transmission, as well as for marking underwater equipment to facilitate search operations [3], and in other hydroacoustic applications.

Such devices are subject to mutually exclusive requirements of increasing autonomous operation duration and emitted signal energy. To meet these requirements, the device must incorporate a radiator with high efficiency along with an energy-efficient driving circuit. Therefore, the development of radiators with small wave dimensions and high specific power [4] is one of the urgent tasks of engineering support for hydroacoustic measurements.

Compact 3D LF radiator – a high specific power transducer

Compact low-frequency transducers are typically defined as those satisfying the relation $\lambda > 2\pi D$ (λ is the sound wavelength, and D is the characteristic dimension of the radiator), given

that $D < 0.5$ m and the fundamental resonance frequency does not exceed 2 kHz. Given the small wave dimensions of the radiating surface, compact low-frequency transducers usually exhibit low efficiency and a narrow operating frequency bandwidth. To achieve higher efficiency and increase the sound pressure level generated by the radiator, technical solutions are employed that are primarily aimed at increasing the vibration amplitude and the radiating surface area. A successful example of a compromise between the radiated acoustic power, efficiency, operating frequency bandwidth, and fundamental resonance frequency is the 3D LF radiator – a flextensional hydroacoustic transducer with an all-metal body of complex geometry [5].

The compact 3D LF radiator described in [6], measuring 96×130 (diameter×length) mm and weighing less than 1.5 kg with a structural volume of 735 cm³, has its fundamental resonance in the range up to 2 kHz and a relative operating frequency bandwidth of 25–30 %, which allows it to radiate up to 40 W of acoustic power using CW and LFM signals (more than 2.0 kPa of effective sound pressure value reduced to 1 m). For complex signals, the acoustic power radiated by such a radiator reaches 12 W. Fig. 1a shows the radiated acoustic power for pulsed phase-modulated signals with a crest factor up to 1.6, a duty cycle close to 100%, and an effective value of the driving voltage applied to the radiator of about 700 V (Fig. 1b).

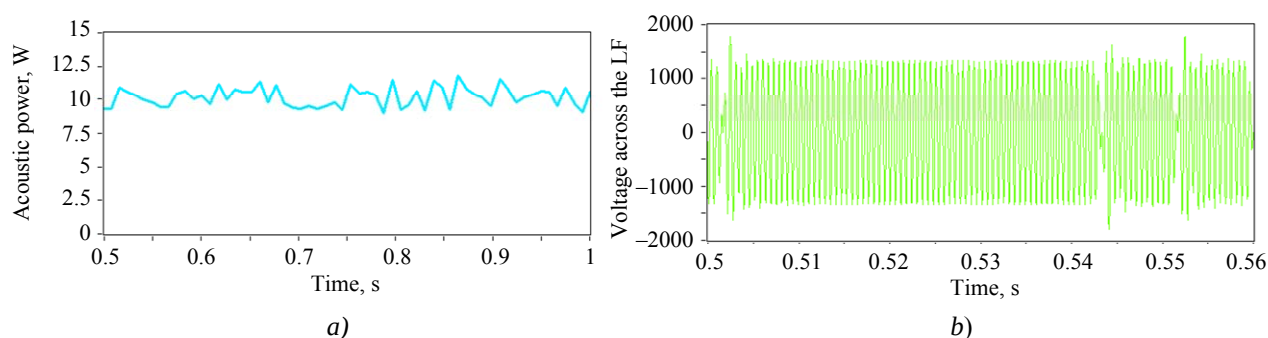


Fig. 1. Radiated acoustic power and driving voltage of the 3D LF radiator for complex pulsed signals with a small off-period

The acoustic radiation power for complex signals is lower than that for quasi-continuous quasi-harmonic signals, because during rapid changes in the signal phase, the 3D LF radiator, being an oscillatory system with a high Q-factor, requires some time to reach the maximum amplitude mode. Fig. 1b shows that the driving voltage amplitude at certain moments during carrier frequency phase changes reaches 1800 V. The difference in the levels of radiated acoustic power for continuous and complex signals directly depends on the information transmission rate [7], since the number of transmitted alphabet elements determines the number of switchings of the transducer's oscillatory system per unit time, and accordingly, the total duration of radiation at maximum power.

The radiated acoustic power of commercially available responder beacons and hydroacoustic modems amounts to 10–20 W for distances ranging from several thousand meters to several tens of kilometers. For example, the maximum acoustic power level of the Evo Logics

S2CR 12/24 hydroacoustic modem is 57 W in the frequency band of 13–24 kHz, while for information transmission at a rate of up to 9.2 kbit/s over a distance of 6 km, the device radiates up to 15 W of acoustic power. A similar operating range of the transponder can be ensured when using the compact 3D LF radiator in the frequency range up to 2 kHz, taking into account the lower attenuation over such distances with an increase in the wavelength of the emitted sound [8]. Taking into account the experimental data (see Fig. 1), the average level of acoustic power radiated by such a 3D LF radiator for complex signals can be increased to 15–20 W, which, combined with high efficiency (over 60 %), allows the use of such transducers in autonomous systems [9].

Measuring the characteristics of the compact 3D LF radiator as a receiver

The voltage sensitivity of the transducer operating as a receiver is determined by

comparing it with the sensitivity of a reference radiator reduced to 1 m:

$$\xi = \frac{U_h L_h}{\gamma_h(f) U_{LFR}^h}, \quad (1)$$

where L_h is the distance from the measuring hydrophone to the reference LF radiator, U_h is the voltage at the measuring hydrophone, $\gamma_h(f)$ is the sensitivity of the measuring hydrophone, U_{LFR}^h is the excitation signal voltage at the reference radiator with a similar dependence recorded using the 3D LF radiator operating as a receiver. Normalizing this dependence by the ratio of distances from the reference LF radiator to the receivers and the sensitivity of the measuring hydrophone yields the frequency dependence of the transducer's receiving voltage sensitivity:

$$\gamma_{3DLFR} = \gamma_h(f) \frac{U_{3DLFR} L_{3DLFR}}{U_h L_h} [\text{V/Pa}], \quad (2)$$

where L_{3DLFR} is the distance from the receiver (3D LF radiator) to the reference radiator, U_{3DLFR} is the voltage at the 3D LF radiator. It should be noted that, in order to reduce the influence of hardware errors during measurements, identical amplitudes of excitation voltages are set at the reference radiator when recording the sound pressure by the reference measuring hydrophone and the 3D LF radiator, which eliminates the need to account for the ratio of these quantities on the right-hand side of formula (2). According to some studies [10, 11], the reciprocity coefficient, equal to the ratio of the transducer's transmitting voltage sensitivity to its receiving voltage sensitivity, does not depend on the design but is determined by the radiation and reception conditions and the properties of the acoustic medium. However, in practice, in-situ measurements are necessary to estimate the reciprocity coefficient precisely because of the transducer's structural design and the conditions of radiation and reception.

The determination of the transmitting and receiving electroacoustic characteristics was carried out in open water at a depth range ranging from 5 to 70 m. The transducer, mounted on an acoustic pole 3 m long, 1 m from the reference

hydrophone and 2 m from the reference radiator, was submerged using a rig structurally connecting the reference radiator, the 3D LF radiator, and the hydrophone (Fig. 2).



Fig. 2. Rig for measuring the electroacoustic characteristics of the 3D LF radiator

For measurements and data recording, NI 9215 ADC and NI 9263 DAC modules were used together with a National Instruments NI cRIO-9031 chassis, a G61N hydrophone, and a Probe Master 4241A differential voltage probe. A Bicon opposed-piston type LF radiator (acoustic monopole) [4] was employed as the reference. In accordance with the measurement procedure [12], the emitted signal, current, voltage at the reference radiator, as well as the voltage from the hydrophone and the 3D LF radiator were synchronously recorded using a data acquisition system based on LabView 2015.

The sensitivity characteristics of the compact 3D LF radiator as a receiver of hydroacoustic signals exceed those of the hydrophone. The frequency dependence of the voltage acquired from the 3D LF radiator operating in the receiving mode practically coincides with its transmitting voltage sensitivity characteristic [6]. The slight difference in the frequency maxima of the characteristics obtained for reception and transmission is related to the difference in the types of resonance phenomena in the oscillatory system of the 3D LF radiator transducer and does not exceed the range of instrumental errors of electroacoustic measurements. Fig. 3 shows the frequency dependences of the output voltage of the 3D LF radiator in the receiving mode on the wave dimension kr , where k is the wave number, r is the equivalent radius of the radiator, defined as the radius of a sphere with a volume equal to the water volume displaced by the 3D LF radiator structure.

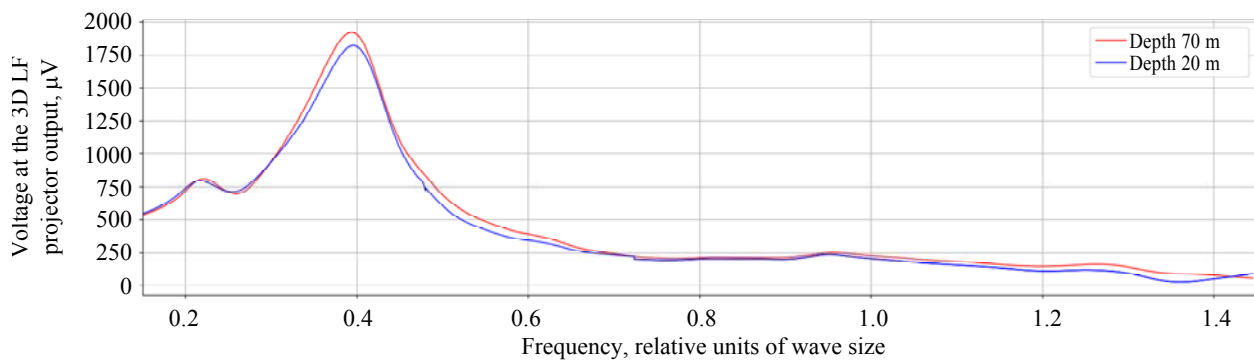


Fig. 3. Output voltage of the compact 3D LF radiator placed at a depth of 20 and 70 m when used as a receiving hydrophone

Due to the special geometry of the 3D LF radiator body, its sensitivity curves as a receiver remain virtually unchanged in a depth range down to 100 m. Considering the characteristics of the compact 3D LF radiator when operating on reception, which are comparable with the parameters of commercially produced hydrophones (e.g., G61N, G3301, ZET 311, etc.), the application of such a transducer as part of a transponder [13] is fully justified.

Using the compact 3D LF radiator as part of a transponder

The high mechanical transformation coefficient of the compact 3D LF radiator and the developed surface of its body provide, outside its operating frequency band, a sensitivity 5–10 times greater compared to reversible hydrophones. For most reversible hydrophones, for example, ZETLAB ZET 351 (manufactured by Electronic Technologies and Metrological Systems), the maximum acoustic radiation power is less than 1.0 W (receiving sensitivity 160 $\mu\text{V}/\text{Pa}$, operating frequency band from 3 to 2500 Hz). Thus, the 3D LF radiator as a hydroacoustic receiver will enable a half-duplex operating mode of the transponder, where the

emission of a response signal at a different frequency is performed with a delay relative to the incoming transmission. Combining the receiver and radiator in a single device reduces the dimensions of the hydroacoustic beacon operating in such a mode and using the 3D LF radiator in the frequency band outside its fundamental resonance.

For operation in full-duplex mode, due to the high voltage amplitude at the radiator, in order to avoid damage to the receiving path of the transponder, it is necessary to use filters with isolation between bands of about 120 dB. Such a characteristic can be implemented based on an active filter model [14] consisting of several stages on operational amplifiers (Fig. 4).

Due to the limitations of the existing component base in terms of maximum input voltage levels, ensuring the operation of the transponder in full-duplex mode involves replacing the integrated circuits of the first stages of the separation filter with circuits made of discrete components having the required dielectric strength. Thus, taking into account the parameters of existing high-voltage transistors (such as 2SC5411, IHW30N160R5XKSA1, or 2T839A/IM), the implementation of a filter with isolation between bands of at least 120 dB appears technically feasible.

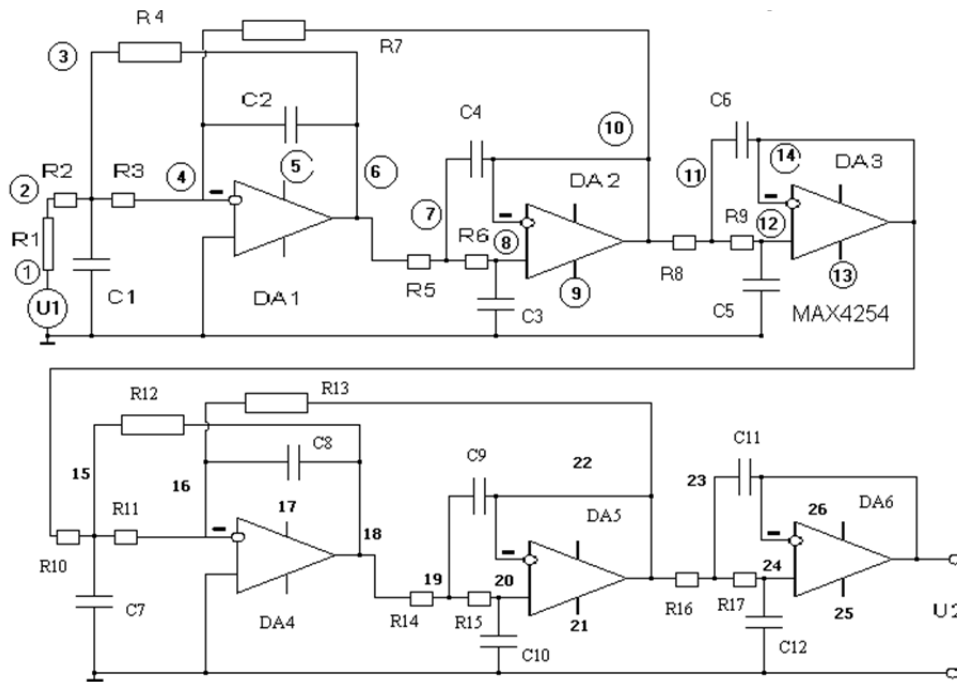


Fig. 4. Circuit of an active 12th-order polynomial filter with a roll-off slope of more than 120 dB per octave

Influence of depth on radiator characteristics

The electroacoustic characteristics of a radiator depend on many factors, in particular, on the external hydrostatic pressure. Due to the special geometry of the 3D LF radiator body, the stiffness of its oscillatory system remains practically unchanged in the depth range of 10–70 m. However, with an increase in immersion depth, the radiator body undergoes some

deformation under the influence of external hydrostatic pressure. As the shell deflection decreases, the Q-factor of the transducer drops slightly and its resonance frequency f_0 decreases, causing an increase in the frequency response bandwidth from 16 % (of f_0) at a depth of 10 m to 20–24 % at 70 m. The drift of f_0 is less than 2.5 % per 100 m (Fig. 5), which is lower than the values for traditional flextensional radiators of similar size with a force-driven design [15].

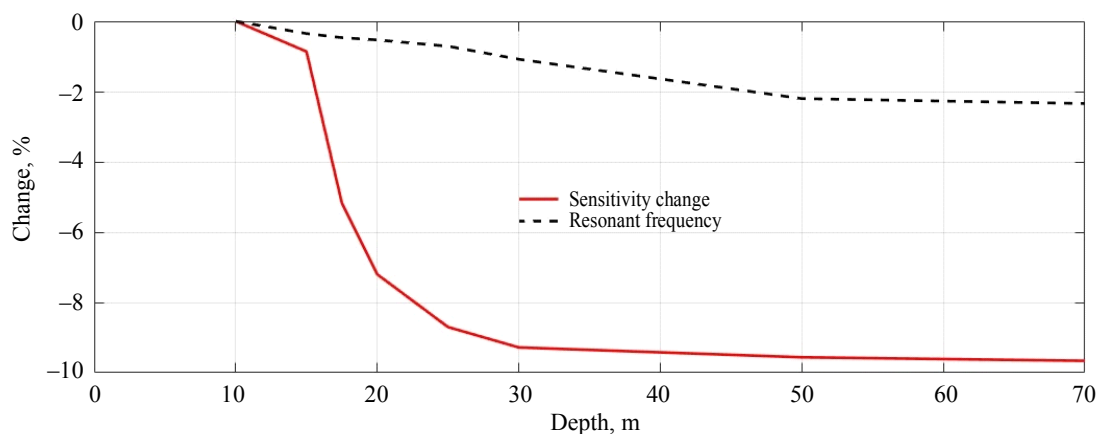


Fig. 5. Dependence of the electroacoustic parameters of the compact 3D LF radiator on depth

In known transducers [16], the fundamental resonance frequency usually increases with depth due to the aggregate increase in the stiffness of the transducer's oscillatory system. Thus, the resonance frequency of a compact LF flextensional radiator of traditional design with a

hydrostatic pressure compensator at 200 m can rise by 10 % or more from f_p at a depth of 30–50 m, increasing with depth by more than 3.5 % per 100 m [17].

The decrease in the 3D LF radiator voltage sensitivity caused by the increase in radiation

resistance with increasing depth amounts to about 5 % per 100 m (Fig. 5), which does not exceed the measurement error. The relative error of voltage measurement in accordance with GOST R 8.736-2011 and the errors of the ADC $\delta_{\text{ADC}} = \pm 1 \%$, hydrophone – $\delta_h = \pm 12 \%$, differential high-voltage probe – $\delta_U = \pm 2 \%$, and measurement of the distance to the radiator – $\delta_L = \pm 0.5 \%$, is determined by the formula

$$\delta_{\gamma_{3D\text{ LFR}}} = \sqrt{\sum_i \delta_i^2}, \quad (3)$$

where δ_i are the relative measurement errors, including the errors of excitation voltage measurement (errors of the differential probe δ_U and ADC δ_{ADC}), errors of voltage measurement at the hydrophone (δ_h and δ_{ADC}), distance from the LF radiator to the hydrophone L , etc. Thus, the resulting sensitivity measurement error is within $\pm 14\text{--}15 \%$ (reception) and $\pm 10\text{--}12 \%$ (transmission).

As can be seen from Fig. 5, the influence of external hydrostatic pressure in the depth range from 20 to 50 m on the radiator parameters is insignificant; however, in some applications it must be taken into account due to the requirements for the developed sound pressure level given the limited energy resources of the driving system.

Conclusion

The 3D LF radiator possesses sufficient dielectric strength, allowing it to radiate complex signals with a crest factor of 1.6 or more at a level of 10–15 W. The unevenness of the frequency response of the compact 3D LF radiator operating

in the receiving mode in the low-frequency range does not play a significant role for an acoustic transponder due to the possibility of frequency correction in the preamplifier, and the reception of signals of a certain type is not associated with requirements for a high degree of linearity of the receiving path's frequency response. The combination of compact dimensions with electroacoustic characteristics, in particular, high specific radiated acoustic power and a wide frequency band for receiving acoustic signals, allows the use of such 3D LF radiators in various hydroacoustic applications: modems, underwater acoustic communication systems, and responder beacons, including those operating in full-duplex mode.

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