UNDERWATER ELECTROACOUSTIC TRANSDUCERS

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1. INTRODUCTION

The research institute 'Morphyspribor' (that means Marine Physical Equipment) is a leading firm in Russia in the field of underwater acoustics. In May month of this year the Institute will celebrate its fiftieth anniversary. 'Morphyspribor' has been established with a purpose to develop and manufacture sonar equipment for Navy, including active and passive sonars, which provide mine detection, underwater communication, intercept of sonar signals, safety navigation, mapping the underwater environment, and also for stationary systems designed to protect the vital littoral facilities. This paper presents the results obtained in the field of the development and production of underwater electroacoustic transducers - key units in sonar design.

2. RING ELECTROACOUSTIC TRANSDUCERS

Ring transducers driven in circumferential mode are incorporated in the arrays of various configurations for active sonars or vertical linear arrays, omnidirectional in the plane perpendicular the axis of the transducers, and also for research work as free flooded transducers with wide frequency band.

In active sonars for steering the main lobe and avoiding the side lobes close in dimensions to the main one the distance between the centers of near-by transducers and hence the diameter of ring transducers at resonant frequency should be about half of wavelength of sound in water, Smaryshev [1], Smaryshev, Dobrovolsky [2]. At the same time for a LZT ring this diameter is two thirds of wavelength in water. Thus the task to design a transducer with lowered resonance dimension was introduced. It was found that the ring with periodic structure could be the mostly efficient in this case, as piezoceramic staves are partly replaced by staves made from passive material with density more or elastic module less than density and elastic module of piezoceramic.

The relationship of resonant frequency of the latter transducer with the staves of low resonance dimension ϖ_0 to the resonant frequency ω of piezoceramic transducer is defined by formula:

$$F = \frac{\varpi_0}{\omega}[1-\beta(1-\frac{\rho_S}{\rho_C})]^{-\frac{1}{2}}[1-\beta(1-\frac{Y_C}{Y_S})]^{-\frac{1}{2}} \qquad (1)$$

where ρ_c, ρ_s, Y_c, Y_s - densities and elastic modulus of piezoceramic and passive material; β - relative volume of passive staves ($0 \leq \beta \leq 1$).

As it follows from (1), varying the parameters and amount of the passive material it is possible to lower the resonant frequency of the transducer without increasing its diameter. Furthermore, it is obvious that

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using the passive staves with high density will not yield to decreasing the resonant frequency to the great extent as the material with density exceeding the density of LZT more than three times does not really exist. However, the effective mass of passive staves might be increased expanding the staves inside the ring.

The investigations revealed that it was inexpedient to expand the high-density staves into the ring. Firstly, the transducer mass is increased that is not desirable, secondly, the expanding staves concentrate mechanical stresses and lower the dynamic durability of the ring. Thus, the passive staves with low elastic modulus have been selected as the most suitable as the transducer mass does not increase while dynamical stresses are lowered, although we lose in effective coupling coefficient. Nevertheless, we do not lose significantly in acoustic power as we use effective LZT ceramic providing some reserve in electric voltage.

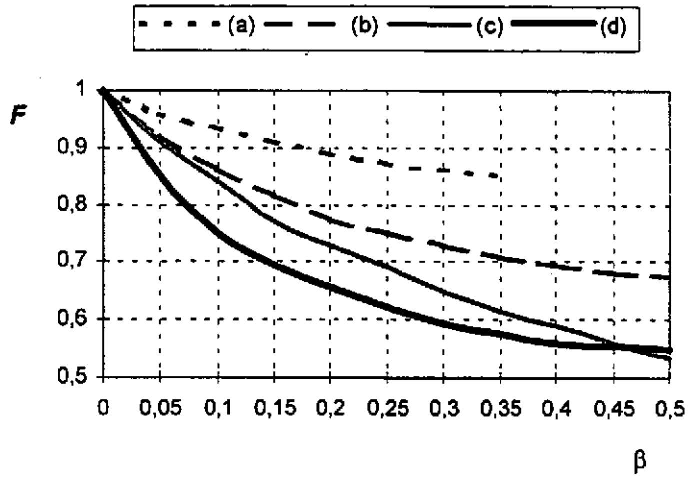

Fig. 1. Relationship between relative lowering of resonance frequency (F) and relative volume (β)
a) fiberglass; b) perforated steel; c) lead; d) designed by 'Morphyspribor'

Selection of proper material for the staves is the greatest difficulty while designing the ring transducers with elastic staves. Relative lowering of resonance frequency versus relative volume of passive staves is depicted in Fig. 1. It is seen that the material obtained in our Institute is the most efficient.

The second problem while using the ring transducers in multielement arrays is to meet the desired electroacoustic specifications and beam patterns. It is solved using the acoustic baffles designed and manufactured in our Institute, Glazanov [3].

The ring transducers often called as free-flooded broad band transducers are used in the exploration of the World Ocean. The parameters of single free-flooded transducers are well known, Shenderov [4]. The performance of an array of such transducers was firstly described in the paper of McMahon [5]. This problem was studied in the Institute for several years and a lot of results mostly experimental was obtained. The lowest operating frequency is reached at the given number of transducers when the latter ones are arranged coaxially without the gaps. The resonant frequency of this array versus the wavelength of an array is depicted in Fig. 2.

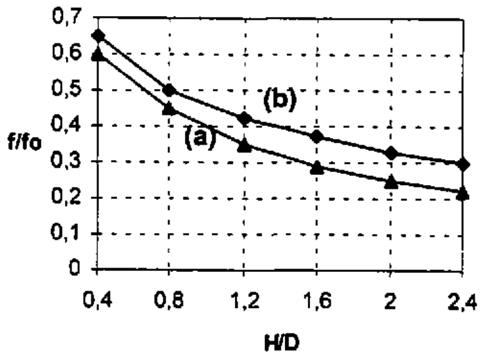

Fig. 2. Relationship between relative resonance and relative height of the array

(a) — calculated curve
(b) — experimental curve
f - resonance frequency in water
f_o — resonance frequency in air
H — height of array
D — diameter of transducer

The situation changes radically once a little gap is introduced between the neighboring transducers. The resonant frequency of the array grows up and comes close to resonant frequency of a single free-flooded transducer. A number of ring transducers designed and manufactured in 'Morphyspribor' is shown in Fig. 3. Their parameters measured in condition of 'free-flooded' rings are seen in Table 1. All transducers are similar in design but differ in dimensions, frequency band and electric power. Transducer GI-0.5 is used in a vertical linear array of a stationary sonar system protecting the economic zone. Transducer GI-1.0 is used mainly for research of the World Ocean, but might also work in sonar arrays. It is one of the most reliable transducers.

Table 1. Parameters of underwater transducers

Model, type	Frequency range, kHz	Resonant frequency, kHz	Max input electric power, kW	Max operating depth, m	Dimensions, mm	Mass, kg
GI-0.5 Ring	0.45...2	0.56	18	not limited	Ø1000 h=220	180
GI-1.0 Ring	1.0...4.0	1.25	6.3	not limited	Ø410 h=230	50
GI-2.0 Ring	1.4...5.5	1.9	1.2	not limited	Ø300 h=140	7.5
GI-6.0 Ring	3.0...8.0	6.5	0.8	not limited	Ø200 h=122	15
GI-3.0 Tonpilz	2.6...5	3.2	1.4	300	(215x215) l=410	35
GI-3.5 Tonpilz	3...6	3.7	280	400	(160x160) l=280	16
GI-7 Tonpilz	2.5...8.2	6	0.24	400	100x100 l=290	8

A lot of nine such transducers was tested on experimental range at Ladoga lake under full power for 2.4 $\cdot 10^8$ cycles, one unit was tested in anechoic vessel under full power and operating depth for 7.2 $\cdot 10^8$ cycles. Transducer GI-2 with wide frequency band is used for communication.

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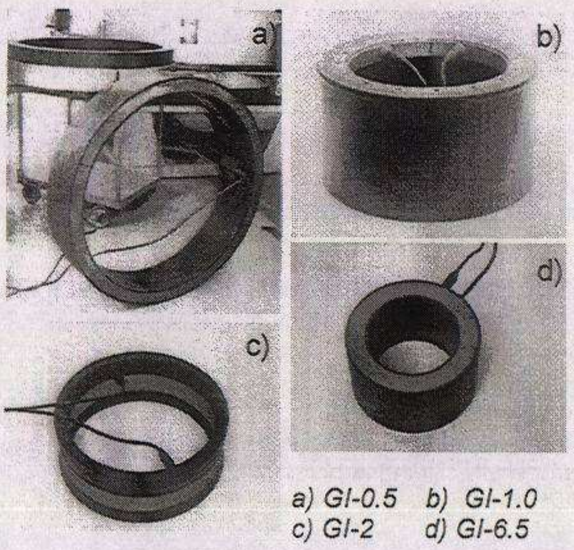

At first sight the design of a ring transducer is quite simple: its only ceramic ring reinforced by fiberglass layers and coated by epoxy resin, but a lot of problems were to be solved to make the design efficient and reliable. Firstly, it was so called scale factor. Projector Gi-0.5 contains two ceramic rings cemented at the butts and each ring consists of three hundred ceramic staves and electrodes. The cementing of such ring requires high-skilled workers and special facilities.

Secondly, with such a great amount of staves and wrapping glass fibre layers over them there is certain danger of electric break-down between the positive and negative electrodes of the staves.

Fig. 3 Underwater ring transducers

Finally the wrong choice of the thickness of epoxy resin and rubber coating layers especially at the butt-ends of the ring may lead to sufficient grows of shear losses in these layers and as the result to lowered efficiency or reliability of the transducer.

3. LONGITUDINAL ROD TRANSDUCERS

For acoustical arrays with certain beam patterns operating in the frequency bands from several to hundred kiloherz were designed and widely used the longitudinal rod transducers. It was followed by many problems which were solved, for instance,
— increasing of the acoustical output and efficiency of the projectors;
— extending of the frequency band;
— improving of shock resistance and durability;
— increasing of the opearting depth;
— lowering of significant interaction between the individual projectors in the arrays.
To increase the output of the projectors research work has been carried out concerning the strengthening of piezoelements, revealing and eliminating the concentration of mechanical stresses in the designs, selection and testing rigid and durable materials for reinforcing element. The alloyed steel has been chosen as a construction material. Reinforcing element — the center bolt was made without threaded connections.

To extend the frequency band the traditional tonpilz design has been thoroughly studied. It was found out that the bandwidth of 30÷40% could be available by increasing the mechanical transformation, optimizing the dimensions of the basic design of transducer element, and proper selection of material for front and rear masses.

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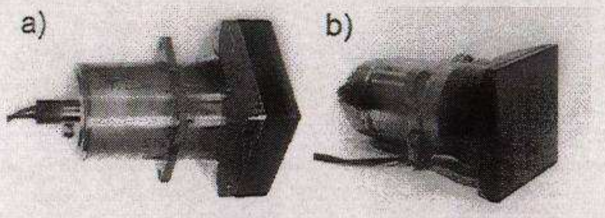


Fig. 4. Underwater tonpilz transducers
a) GI-3.0 b) GI-3.5

It is known that it is necessary to fill dielectric liquid into the inner enclosure of the transducer operating at the depths deeper than 1000 m. Many efforts were spent to minimize the influence of liquid volumetric resonances on the parameters of the transducers. When the wavelength dimensions are small and the transducers are mounted close to each other in multielement steering arrays, interaction between the transducers is of great importance especially for determining the operating mode of transducers and matching transducers with multichannel electric power amplifiers. All these problems have been solved in a course of designing and manufacturing the transducer prototypes. Some of them are shown in Fig.4 and Table 1.

The first two transducers are designed in traditional manner: light-weight and extended in width front piston, stack of LZT piezoelements, and heavy rear mass. Active element of the transducer is inserted in the metallic housing and sealed by O-ring of rubber mounted between the housing and front piston. These designs are based on results of previous investigations. The tonpilz transducer GI-7 is of certain interest, as its frequency band is much wider that the band of commonly used transducers. It is achieved owing to special matching layers and higher modes of vibration.

4. HIGH FREQUENCY TRANSDUCERS (20-500 KHZ)

The relatively small dimensions at wavelengths from 0.5 to 50 λ are the main property of high frequency transducer. When the frequency increases the dimensions are becoming small but at the same time the sound attenuation grows considerably. That is why when designing high frequency transducers the compromise must be found between contradicting requirements of maximum radiating power and small dimensions of radiating surfaces limited by the beam width. Small dimensions of high frequency transducers and accordingly very small tolerances on the accuracy of manufacturing including the control of configuration results in nonordinary technical solutions. Hence, it leads to higher requirements for acoustic pressure and acoustic power.

Usually the high frequency transducers are designed as half wave rods with bandwidth up to 15%. In the frequency range from 10 to 60 kHz they are made of piezoelectric stack and reinforced by centre bolt similar to low frequency transducers. To separate the transducer and the array is difficult at high frequencies, so the transducers are cemented to the joint plate that radiates the acoustical signal. Otherwise acoustical signals are radiated and received through sound transparent membrane or polymer coating while the transducers are mechanically decoupled. High frequency transducers operate at the depths from 100 to 6000 m.

5. HYDROPHONES

'Morphyspribor' commonly uses two types of the transducers as hydrophones: cylindrical and flexural disk transducers. Two versions of cylindrical hydrophones are shown in Fig 5 and Table 2. Hydrophone GF-20 (Fig. 5a) consists of six elementary piezoceramic cylinders arranged coaxially and coated in rubber boot. It operates at the depths up to 1000 m in a wide frequency range. Hydrophone GF-16 has the similar design. The only difference compared to the previous model is the dielectric liquid filling the internal enclosure. The operating depth of this hydrophone is 6000 m. Flexural disk transducer GF-5 (Fig 5b) may be considered as an example of deep-water reliable and durable hydrophone. The piezoeramic disks are fully sealed in titanium casing.

a) b) c)

Fig. 5. Hydrophones
a) cylindrical hydrophone GF-20; b) flexural disk hydrophone GF-5;
c) joint group of flexural disk hydrophones GF-10A with rear baffle

Table. 2. Hydrophones

Model, type	Frequency range, kHz	Receiving sensitivity, dB re.1 V/μPa	Capacity, nF	Max operating depth, м	Dimensions, mm	Mass, kg
GF-20 Cylinder	0.01...20	-183	2.5	1000	Ø45 l=176	0.6
GF-16 Cylinder	0.35...16	-200	52	6000	Ø28 l=640	0.8
GF-5 Disk	0.01...5.0	-190	35	1500	Ø93 l=36	0.7
GF-10A 4-channel Disk	0.01...10	-182	6.5	400	100x100 l=30	0.5

The above hydrophones may be used as individual units or components of multielement arrays of various configurations. It often recommended to unite individual hydrophones in groups with common casing in multielement array. Fig. 5c demonstrates the example of such joint group, that consists of four disk flexural hydrophones sealed in epoxy resin covering. Multi-lead cable ensures the electric connection of each channel.

6. ACOUSTIC BAFFLES

Integral part of the underwater electroacoustic transducers is passive sound release element — acoustic baffle. In passive sonar it takes part in both forming the beampatterns and increasing signal-to-noise ratio. In active sonar it provides increasing of the efficiency in preset spatial sector. In many cases pressure release elements with increased compliance are used as a part of a baffle, so the characteristics of the baffle may depend on hydrostatic pressure. 'Morphyspribor' commonly prefer the baffles of the following types, some of them being of own design and manufacture.

a) b) c)

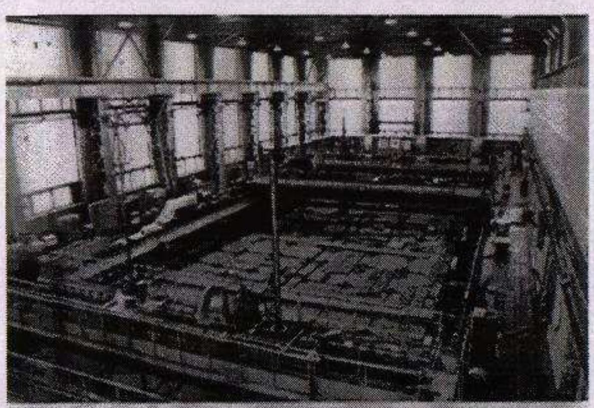
Fig. 6. Acoustic baffles

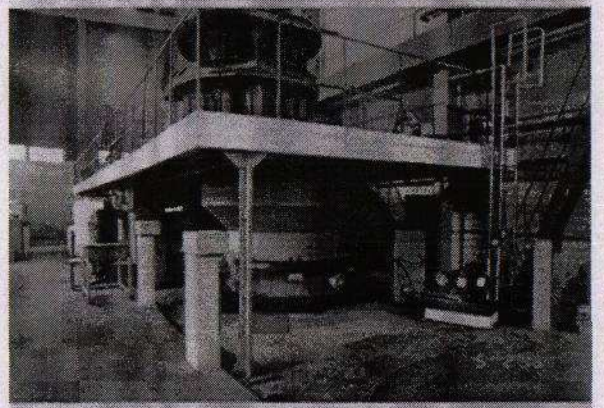
1. Cellular rubber operates to depth of about 250 m in a wide frequency range.
2. Perforated rubber layers sealed with metal plates. They are used to depth of 600 m in a wide frequency range (see Fig. 6a).
3. Rigid foamed polyurethane plastic baffles. They are used as internal baffles for ring transducers to the depth of 1000 m.
4. Double-sided flexural disk made of metal with air volume inside is efficient in vicinity of its own resonance (Fig. 6c). Such baffle is used in multielement arrays to reduce negative interaction between projectors.
5. Metal plates of a quarter wavelength for high frequency transducers at high pressures.
6. Absorbing baffles — rubber with rigid impurities.

7. TECHNICAL SUPPORT BASE FOR TRANSDUCERS DESIGN AND MANUFACTURE

It was already mentioned that the underwater electroacoustic transducers for all types of the sonars in the frequency range from hundreds hz to 500 khz are designed and manufactured by 'Morphyspribor'. Really this activity requires the proper scientific, manufacturing and test support. Such support was developed in a coarse of activity of the Institute and is functioning successfully. The Acoustic Department is engaged in design of arrays and transducers. The Acoustic Department consists of several sectors with qualified personnel concentrated on basic design and evaluation of electroacoustic parameters, providing sealing and durability of the arrays and transducers, static and dynamic testing, and stability against shock and explosive forces.

Manufacturing facility consists of shops for assembling arrays and transducers. The shops are equipped with necessary equipment and attachments for cementing and reinforcing piezoceramic elements, assembling and sealing and also with proper instrumentation to control measurements.





The experimental base includes:

— test tank with dimensions 50x14x10 m, shown in the upper photo. The tank is covered by anechoic coating of rubber wedges on all sides of reservoir and the water surface. It is provided with lifting and rotating mechanisms, electronic apparatus sufficient to perform all the acoustical measurements of arrays and transducers with weight up to 5 tons in the frequency range 1÷200 kHz;

—section of high pressure vessels up (photo in the middle) for testing arrays and transducers under hydraulic pressures up to 270 MPa. One of the tanks is equipped with anechoic covering thus it is possible to measure the electroacoustic parameters of arrays and transducers at the operating depth;

— testing range at Ladoga lake (bottom) supports design engineering tests conducted with arrays and transducers of large dimensions in conditions close to open sea. The range includes the laboratory research vessels, auxiliary ships and coastal facilities.

8. CONCLUSIONS

'Morphyspribor' has generated Russian scientific school of underwater acoustics where professors and doctors of technical science have been working. A lot of monographs, papers, articles, inventions and textbooks have been published during this years, some of them present the results of research in the field of electromechanical transformation, Aronov [6] or engineering methods of evaluating the parameters of underwater electroacoustic transducers, Bogorodsky [7]. Taking into consideration that the Institute is a typical representative of applied science in this country a great deal of its activity is connected to design, development and production of underwater acoustic equipment generally released as production prototypes. Currently they are used by Navy customers and in conversion technology fields.

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