LOW-FREQUENCY, LOW-NOISE MOLECULAR-ELECTRONIC HYDROPHONE FOR OFFSHORE AND TRANZIT ZONE SEISMIC EXPLORATION

Dmitry Zaitsev [1], Egor Egorov [1], Maxim Ryzhkov [1], Grigory Velichko [2], Prof. Vladimir Gulenko [3]

[1] Moscow Institute of Physics and Technology, **Russian Federation**
[2] Yuzhmorgeologiya **JSC**, **Russian Federation**
[3] Kuban State University, **Russian Federation**

ABSTRACT

The study presents the results of the development of low-noise broadband hydrophone based on molecular electronic technology (MET) for mineral exploration systems in transit zones and on the shelf to depths of about 100 meters. The study investigates amplitude-frequency response (AFR), self-noise, dynamic range, and stability of sensor characteristics. The paper provides the results of experimental studies of prototypes in a laboratory and natural conditions in the Kara sea, including a comparison with hydrophones cable telemetry system ARAM ARIES II based on bottom receivers PZ dual sensor GS-PV-1S. The prototypes of MET hydrophones demonstrated a low level of self-noise—below the Wenz model in the low-frequency region up to 48 dB concerning 1 μPa/√Hz—the possibility of obtaining qualitatively new seismic information in the low-frequency region, a good signal-to-noise ratio, a wide dynamic range, and linearity of response. The research shows that the characteristics of the MET hydrophone signals in the main frequency band (from 1 to 300 Hz) are not inferior to the characteristics of the reference sensor signals.

Keywords: transit zones, offshore, hydrophone, mineral exploration systems, low-noise, high sensitivity, molecular electronics

INTRODUCTION

The complex objects of exploration include transit zones, in which the use of a simple combination of standard methods and means for land and sea seismic exploration is not always possible. This implies, in particular, the desire of seismic survey customers to use seismic data recording tools with the widest possible band of the signal recorded, primary sensing elements with high linearity of measurements and high channel identity. The increasing interest in the use of stationary high-precision measurement systems for prospecting and exploration of minerals in transit zones and on the shelf requires the use of high-resolution equipment, in particular, hydrophones with a low level of self-noise and a wide band of signal registration.

The application of a new type of low-frequency hydrophones based on molecular electronic technology looks promising for these tasks [1]. The schematic diagram of such devices is presented in detail in [2]. The diagram contains a key structural element, i.e. an electrochemical liquid MET transducer, the physical basis of which is presented in [3, 4] and in the patent [5]. The use of products based on MET technology for seismic exploration on the shelf and in transit zones in recent years has become increasingly important and promising because sensors based on MET demonstrate high technical parameters and have a relatively low cost [6, 7]. Among the key features of the technology and products based on this technology have a low level of self-noise [8], a wide dynamic range [9], and high sensitivity, especially in the low frequency range up to hundredths of Hz [10], as well as simplicity and reliability of the design [11].

THEORETICAL MODEL

An experimental sample of the hydrophone is presented in Figure 1. The hydrophone consists of 2 flanges securing the converting electrode assembly 1 between the elastic membranes 3, forming a channel bounded by membranes in which an electrically conductive liquid can flow. The electrode unit forms a pressure drop in the system due to the hydrodynamic resistance and converts the liquid flow into an electric current on the electrodes of the unit. To form negative feedback, a magnet (4) is glued to the upper membrane in the center, and an electromagnetic coil (5) is placed in a special cover (6) that is installed and fixed on the upper flange (2). The geometric dimensions of the cover and the electromagnetic coil were selected so that the magnet could move freely inside the coil both under the influence of the Lorentz force and under the influence of inertia. If the cover (6) is sealed, the system begins to feel pressure variations acting on the open membrane. Thus, the cover is necessary for compensation of static external pressure.

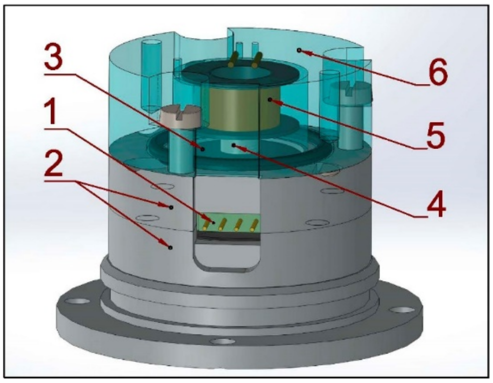


Figure 1 - Experimental sample of molecular electron hydrophone. 1- electrode assembly (EA); 2 - upper and lower flanges; 3 - rubber membrane; 4 - permanent magnet; 5 - electromagnetic coil; 6 - cover.

Full amplitude-frequency response of the hydrophone consists of two parts. The mechanical part converts the pressure drop of the measured wave into the electrolyte flow through the transducer and the electrochemical one converts the liquid flow to the signal current of the hydrophone. The electrochemical part of the AFR is well studied [12], whereas it is the mechanical part that determines the possibility of using molecular electronic technology to measure the wave field of pressures in the medium. The study [2] provides the mathematical model of AFR of the mechanical system of molecular electronic hydrophone ($W_{mech}(\omega)$).

$$|W_{mech}(\omega)| = \frac{1}{\sqrt{\left(\frac{p_0 s_{эф} s_{м}}{V_0 M}\frac{1}{\omega} - \omega\right)^2 + \left(\frac{s_{эф} s_{м} R_h}{M}\right)^2}} \frac{s_{эф} s_{м}}{M} \qquad (1)$$

where p_0 is the external static pressure (in the absence of perturbation); $s_{м}$ is the area of the membranes; $s_{эф}$ is the effective area of the electrode assembly; M is the mass of the electrolyte in the vessel; V_0 is the volume of the medium under the cap (6) in the absence of perturbation; R_h is the coefficient of hydrodynamic resistance to the flow of liquid through the electrode assembly; ω is the cyclic frequency of external pressure fluctuations.

Let's try to change the size of the electrode assembly ($s_{эф}$) and study what happens to the transfer function at different external parameters, Figure 2.

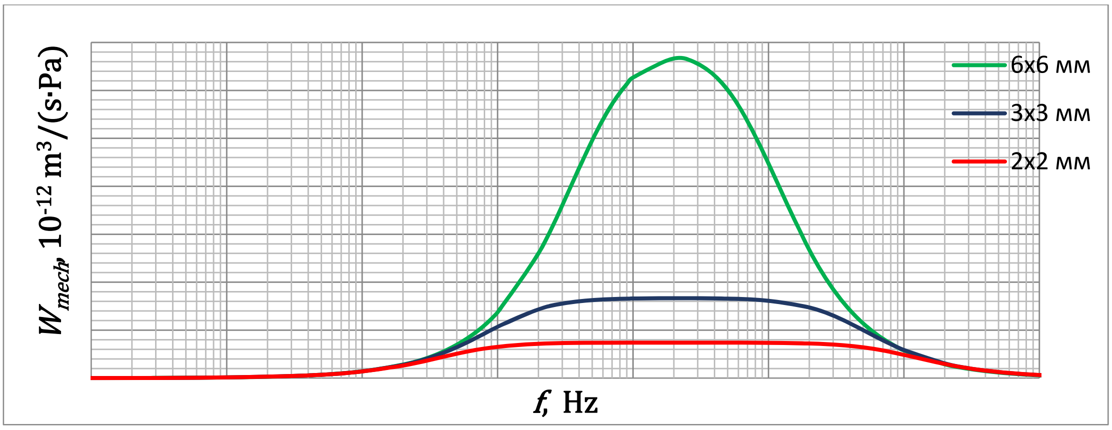


Figure 2. Frequency response of the mechanical subsystem for different areas of the EA channel at p = 3 bar.; p_0V_0= 1 bar · sm^3.

The results indicate that in order to expand the band of the transmission characteristics of the mechanical subsystem of the hydrophone, the size of the converting element should be reduced.

At the same time, the model of the mechanical system is associated with the self-noise of the hydrophone, which also undergoes changes depending on the variations for the size of the assembly, the rigidity of the system, etc. Summarizing the data presented in [2] model, we can suppose that the spectral density of the total self-noise of the hydrophone (excluding the noise of electronics, which sets the operating voltage of the converter and converts the difference cathode current from the EA to the output voltage) is obtained by adding three components responsible for various physical mechanisms: thermal noise, noise due to the appearance of convective flows and noise due to the heterogeneity of the liquid flow conversion into current in different areas of the electrode assembly (geometric noise), the spectral power density of such noise can be represented as:

$$< p^2 >_\omega = 2kTR_h + \frac{4kT}{R_h|W_{mech}|^2}\alpha + \frac{K(\omega, s_{эл})}{|W_{mech}|^2|W_{el-ch}|^2} \qquad (2)$$

where ω is the cyclic frequency, R_h is the hydrodynamic resistance of the system, k is the Boltzmann's constant, T is absolute temperature, W_{mech} is the mechanical part of the transfer function of the hydrophone, α is the dimensionless coefficient, W_{el-ch} is the electrochemical part of the transfer function of the hydrophone, $K(\omega, s_{эл})$ is the numerical coefficient characterizing the convection, $s_{эф}$ is the surface area of the electrodes.

Let's compare the theoretical models of noise depending on the parameters of the mechanical system of the hydrophone and the physical nature of the noise mechanism, Figures 3 and 4 (on the horizontal axis - external pressure variation frequency in Hz, and on the vertical axis - spectral noise density expressed in units of equivalent pressure, in dB relative to 1 $\mu Pa^2/Hz$. For the electrode assembly 6x6 mm, the value of the hydrodynamic resistance is ~ $3 \cdot 10^9$ N·sec/m^5, whereas for the assembly 2x2 mm it is $27 \cdot 10^9$ N·sec/m^5

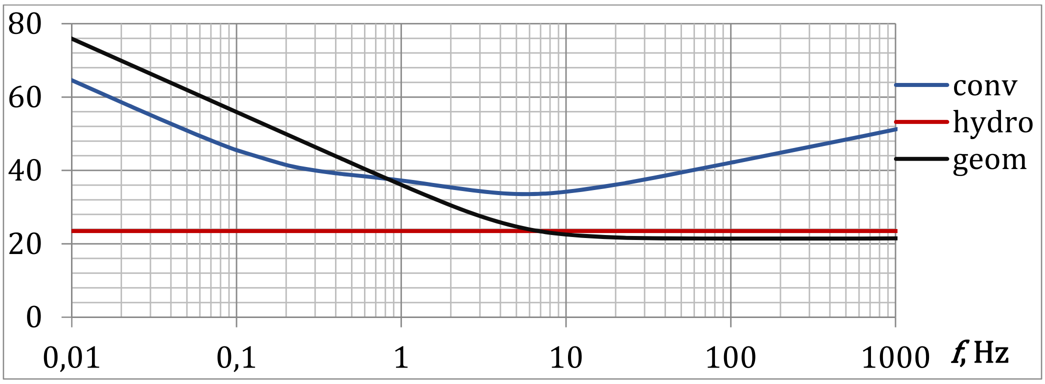


Figure 3. Comparison of spectral noise densities of different nature for the 2x2 mm sensor at p = 3 bar.; p_0V_0= 1 bar · sm^3

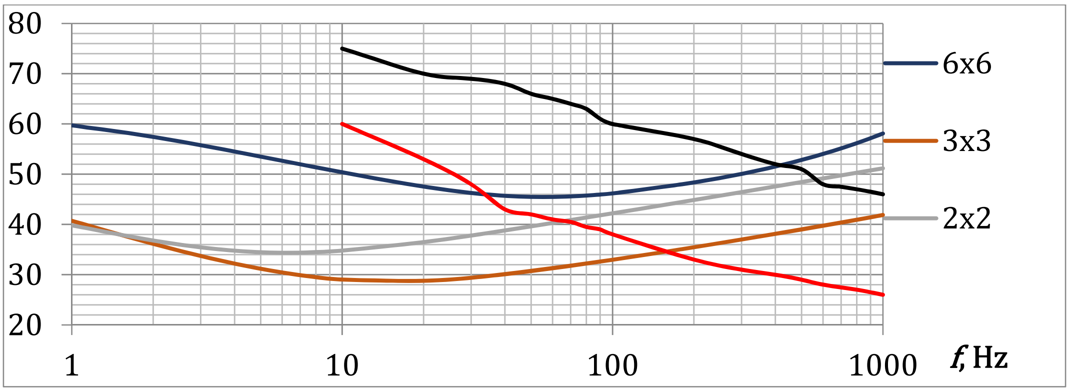


Figure 4. Total noise spectral density for sensors with 6x6, 3x3, 2x2 mm channels at p = 3 bar.; p_0V_0= 1 bar · sm^3

Our detailed study of the regularities observed in the model shows that at frequencies below a few tenths of Hertz the main contribution to the noise of the sensor is geometric noise, and starting with the frequencies ~ 1 Hz – convective noise; whereas the hydrodynamic noise for all the studied configurations is so small that even for the size of 2x2 mm, a further increase in the hydrodynamic resistance is allowed several times without losing the generality of the results. Note that in the frequency range 1 – 1000 Hz, the total noise does not exceed 60 dB for all 3 types of sensors. Moreover, the all spectral noise densities at low frequencies are less than the same in the Wenz model.

EXPERIMENTAL VERIFICATION OF THE MODELS

In accordance with the modified mathematical models and the proposed design optimization options, experimental laboratory testing of the amplitude-frequency response and the noise parameters was carried out. For this purpose, hydrophones with different areas of the transforming cell were collected, tests were carried out for hydrophones with cell sizes of 6x6 mm, 3x3 mm and 2x2 mm. The frequency response study was carried out on a special stand. The value of absolute sensitivity is fixed in relation to the reference piezoelectric hydrophone, such as ZETLab BC-311 [13]. The test results are provided in Figure 6 that presents the total transfer function of the hydrophone without frequency correction, removed from the first gain stage, according to the scheme similar to that of used in [2].

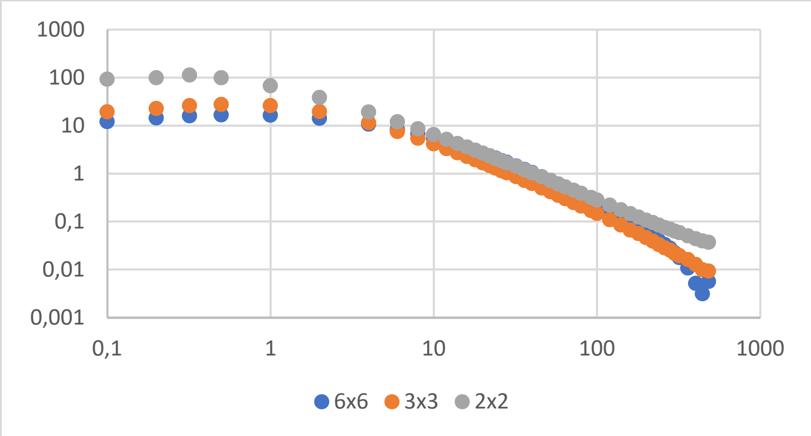
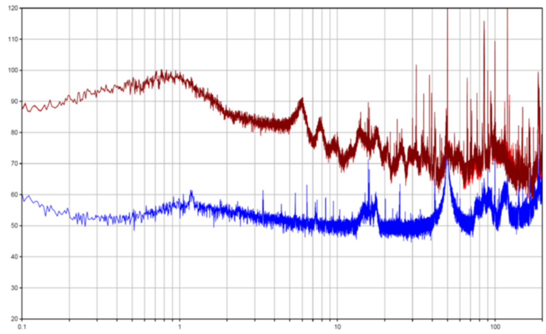


Figure 6 – Voltage values in the first stage of current-to-voltage conversion of preliminary experimental samples of molecular-electronic hydrophones with different cell size. (Blue – 6x6 mm, orange – 3x3 mm, gray 2x2 mm, on the abscissa axis – Hz, on the ordinate axis – relative units)

Figure 6 shows that the predictions of the mathematical model as a whole are performed, so, in particular, there is a predicted expansion of the working band of the hydrophone with a large value of hydrodynamic resistance (less one $s_{эф}$). This is evidenced by the decrease in the order of decline in the overall sensitivity at low and high frequencies in Figure 6 for the assemblies with a smaller area.

The measurement of self-noise was performed by the method of cross-correlation provided in [3]. The studied devices with the size of electrodes 3x3 mm were placed in the pool, the axes of sensitivity of hydrophones were directed coaxially. To record the signals, a 24-bit NDAS-8226 data acquisition system was used [14], with a sampling rate of 1 kHz. To analyze the noise characteristics, the signal of the samples was taken for a long time (~10 h) in the absence of external influences and at a constant ambient temperature. Figure 7 shows the result of our self-noise measurement. Red and light red–power spectral densities were recorded with molecular-electronic hydrophones No. 1 and No. 2. One can see a high degree of signal correlation. Blue is the spectral density of the hydrophone self-noise, calculated in accordance with the formula 15 from [3]. The units are similar to Figures 3 and 4 of the theoretical model. Figure 7 shows that compared to the prototype from [2] that used a 6x6 mm assembly, the level of basic noise was reduced by more than 25 dB in a frequency range of 1-100 Hz and even surpassed the Wenz model [15] in the lowest part of the spectrum. As predicted in the theoretical model achieved self- noise level is below 60 dB, and for the best recording it was possible to reach a level of 48 dB in the bandwidth 5-80 Hz.



Red and dark red – noise signal of two hydrophones, blue – uncorrelated noise
Figure 7 - Power spectral density of the basic noise of hydrophones

FIELD TESTS

Offshore field trials of the experimental hydrophones were performed in the southwestern part of the Kara sea waters of the South Kara shelf during the period from August to September 2018. For experiments, hydrophone prototypes were fixed coaxially with reference sensors – two-component GS-PV-1S of ARAM ARIES II system. Research studies were carried out according to the scheme in Figure 8.

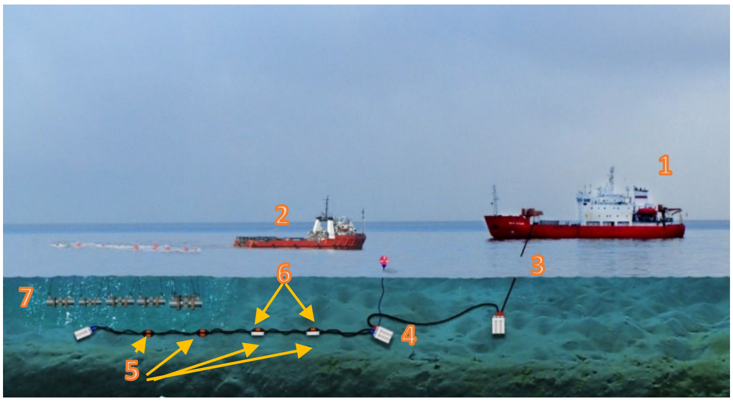


Figure 8 Scheme of excitation of elastic oscillations with data recording. 1 – registrar vessel, 2 - source vessel, 3 - seismic braid, 4 - the RAM and TAR (float) modules, 5 – dual sensors (GS-PV-1S), 6 – experimental hydrophones, 7 – a group of shallow pneumatic sources, of 720 inches volume [3]

Figure 9 shows the normalized signals of the reference and the test hydrophones in one of the field records (offset shot-receiver = 550 m). The figure shows the qualitative compliance of the data for the test hydrophone. Figure 10 shows the normalized seismic records of hydrophones for several traces, low-frequency disturbances those not recorded by the reference sensor are clearly visible for the MET hydrophone.

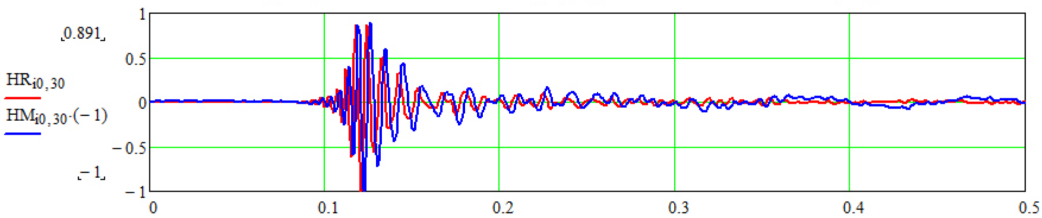


Figure 9. Standardized hydrophone signals in the experiment, blue – MET hydrophone, red – reference hydrophone

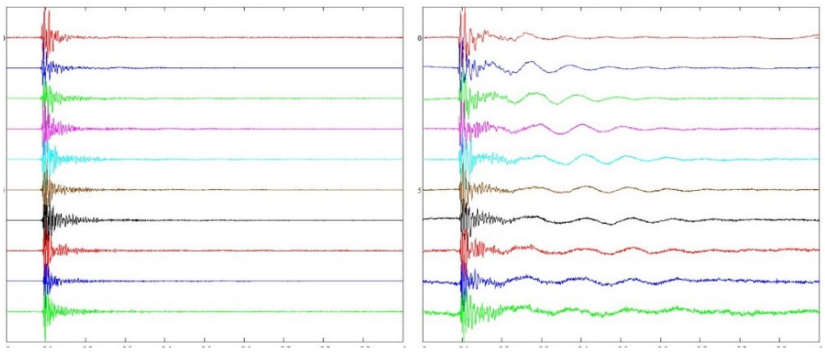


Figure 10. Normalized seismic records of hydrophones (several traces)

More clearly observed features are seen on the signal spectra, Figure 11, where in the low-frequency region of the MET hydrophone demonstrates a significantly greater amplitude of the recorded signals, giving qualitatively new information for geophysicists.

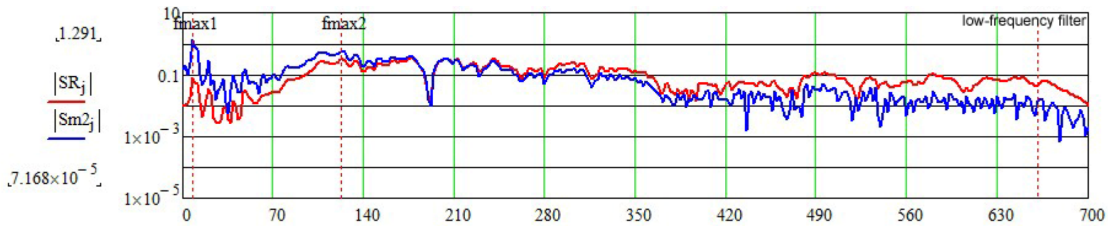


Figure 11. Comparison of hydrophone spectra, blue – MET hydrophone, red – reference hydrophone

CONCLUSION

The presented mathematical models and the verified experimental data demonstrate that in order to increase the sensitivity and expand the frequency and dynamic ranges of the mechanical hydrophone system, it is necessary to reduce the total area of the electrode conversion unit from a standard size of 6x6 mm to a size of 2x2 mm or less. At the same time, the proposed technical solution leads to a decrease in the usual dimensions and the weight of the hydrophone. It significantly reduces the inertial mass of the electrolyte, and allows the molecular electronic hydrophone to reach the level of its self-noise, about 0.03 mPa, in the units of the applied pressure. It also leads to expand the working band of the hydrophone towards low frequencies up to 0.01 Hz, and towards high to 500 Hz. Preliminary tests demonstrate that the average sensitivity of the experimental sample of the molecular hydrophone is 2.5-3 times higher than the nominal sensitivity of the reference hydrophone, equal to 10.2 mV/mbar in accordance with the technical description. The analysis of the amplitude spectra shows a very high level of amplitudes and signal-to-noise ratios. At the same time, the boundary frequencies of the bandwidth of the molecular hydrophone in all the experiments are noted at a frequency below 1 Hz and about 300 Hz for the upper frequency. Preliminary experiments demonstrate a significant superiority in sensitivity and a possibility to obtain qualitatively new seismic information in the low-frequency region of the spectrum.

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