American Journal of Earth Science and Engineering
2018; 1(3): 166-173
http://www.aascit.org/journal/ajese

American Association for Science and Technology

Geophones for Recording Acoustic Waves in Water

Askold Belyakov

Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, Moscow, Russia

Email address

askbel32@gmail.com

Citation

Askold Belyakov. Geophones for Recording Acoustic Waves in Water. *American Journal of Earth Science and Engineering*. Vol. 1, No. 3, 2018, pp. 166-173.

Received: April 25, 2018; **Accepted**: May 17, 2018; **Published**: June 8, 2018

Abstract: In the modern concept, the geophone is an electrodynamic converter. The geophone has a mechanical resonance at frequency f0. In practice, a characteristic area is used after resonance with a linear frequency dependence (f1) limited to a frequency of 110-120 Hz. The amplitude-frequency characteristic of a piezoelectric transducer has a quadratic dependence of the amplitude on the frequency (f2). But the disadvantage of the piezoelectric transducer is its high impedance, which requires the mandatory use of a preamplifier with a high input impedance. The current requirements for increasing the resolution of seismic exploration of oil and gas by amplitude and frequency have served as a pretext for developing a new geophone converter similar to an electrodynamic geophone, but which uses a section before mechanical resonance with a cubic amplitude-frequency dependence (f3) as the performance characteristic. This allowed solving the problems inherent in traditional geophones, namely: expand the range of recorded frequencies from 1 to 1000 Hz, increasing the upper limit of the frequency of received signals to 1 (5) kHz. In parentheses, the calculated data for the fifth generation geophone are given. The new transducer was developed on the basis of the magnetoelastic effect in a ferromagnet with a crystalline structure (iron-aluminum alloy), which allowed the construction of a vector sensor with a single inertial mass and three electric windings. Modern hydrophones use mainly piezoelectric effects of crystalline and ceramic materials with high sensitivity to pressure. But the large output impedance of the piezoelectric transducer requires a special preamplifier with a high input impedance. The hydrophone, unlike a geophone with an inert mass, is a scalar device. To determine the direction of arrival of the acoustic signal, and this is one of the main tasks of the device, it is necessary to create special antennas of large dimensions. With the use of a new transducer, a hydrophone with an inertial system can be constructed that will measure three components of the wave velocity vector (pressure gradient) of the acoustic wave in water.

Keywords: Geophone, Hydrophone, Scalar Measurement, Vector Measurement, High Resolution, Vibrating Speed, Gradient Pressure

1. Introduction

New type geophones that were designed to control seismic processes and were tested in the 1990 earthquake forecast program in Parkfield, California, USA [1] attracted interest from representatives of the Central Geophysical Expedition of the USSR Minneftegazprom (CGE). Therefore, in the same 1990, a three-component fourth-generation geophone MAS-3C with an electromechanical clamp was tested in a special, dry, well-cemented measuring well at a depth of 730 m. Test signals in the form of a sweep signal were excited from the surface by a seismic vibrator with a force of 30 tons. Signals of 13 seconds were used. Their initial and final frequencies were: 23-138 Hz, 40-160 Hz and 60-180 Hz. For comparison, geophones SV-5+SV-5 were used. Registration was carried out by the American seismic survey station DFS-4. Vertical components of the recorded seismic signal were compared. The test results are shown in figure 1.

It should be noted that the sensitivity of the standard geophone to the seismic signal (trace "a") ends at a frequency of 116 Hz, and the magnetoelastic geophone registers the signal in the entire range of radiated frequencies (trace "b"). And yet, on the vibrograms at the beginning and at the end, in the absence of an artificial signal, one can clearly see that the level of the micro seismic background in a conventional geophone is several times higher than for a new magnetoelastic geophone. Encouraged by the results of the tests, the CGE in 1994 obtained RF patent No. 2013792 [2] for a single-component magnetoelastic seismometer for seismic exploration.

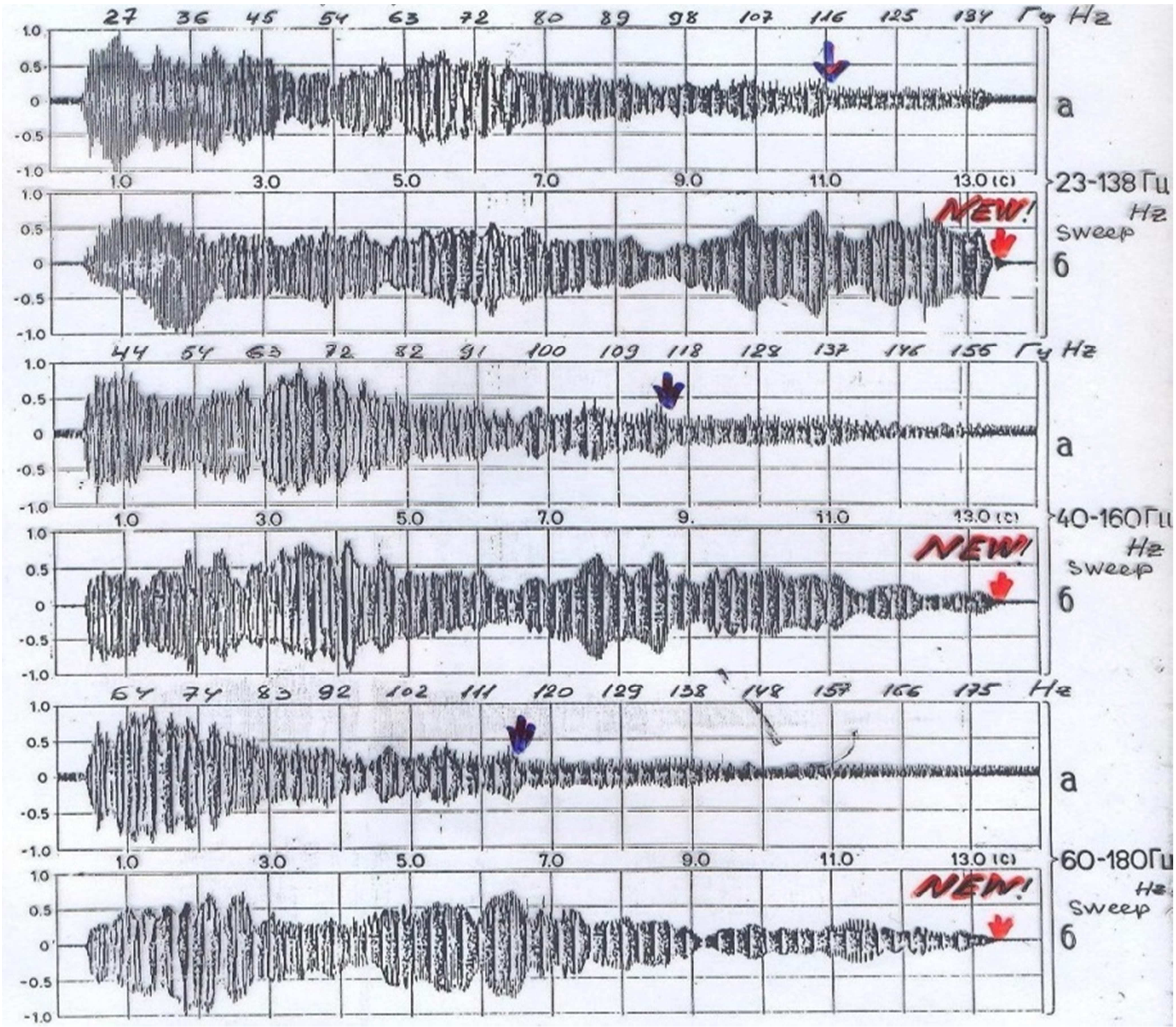

Figure 1. *Photo of the original field recording of DFS-4.*

The fourth-generation magnetoelastic geophone in its parameters (frequency range 1-1000 Hz) overlapped the requirements of both seismology and high-resolution seismic surveys, but studies of 2016-2017 showed that a recording system with a sampling rate of 10-100 kHz per channel detects acoustic tracks in the earth's crust with frequencies of 5 kHz or more [3]. A fourth-generation geophone is capable of detecting signals with frequencies above the frequency of mechanical resonance, but the algorithm for their automatic amplitude estimation after resonance should change because after resonance the amplitude-frequency dependence becomes non-cubic rather than linear. For seismic measurements of the expansion of the frequency band of more than 1000 Hz is not relevant.

The use of magnetoelastic receivers in seismic prospecting of minerals opens up great prospects. Modern seismic prospecting is forced to use a limited frequency range up to 120 Hz. This limitation is related to the design features of seismic electrodynamics geophones and significantly reduces the resolution of seismic prospecting. However, the problems of separating oil and gas reservoirs of small sizes (less than hundreds of meters) and with a capacity of about a dozen meters, the investigation of which requires an improvement in resolving power, are becoming increasingly common. This is easily achievable if the bandwidth of the received signals is extended to 250 ÷ 500 Hz and recorded with a magnetoelastic receiver. This is especially true in the production of seismic exploration of deposits on the shelves. Preliminary tests of the receivers were carried out successfully. For the reflected wave method, simple and inexpensive one-component magnetoelastic receivers are the most promising. According to the results of experimental studies conducted by the CGE in 1990, it was established that one surface magnetoelastic device can replace a group of electrodynamics geophones.

Figure 2 shows simplified amplitude-frequency characteristics of some seismic instruments popular in the mid-1980s. The horizontal axis shows the frequency in Hertz, and on the vertical axis - the offset in meters, with the output voltage for all devices - 1 μV. Blue, seismometers and geophones are indicated, green - accelerometers, gravimeters and tiltmeters, and red - a new magnetoelastic surface geophone that confidently covers the frequency range 0.1-1000 Hz and amplitude range 10^{-3}-10^{-15} m (240 dB). When using modern amplifiers with input noise of less than 0.1 μV, the amplitude range of the new device expands to 260 dB. There are no fundamental limitations to the expansion of these limits.

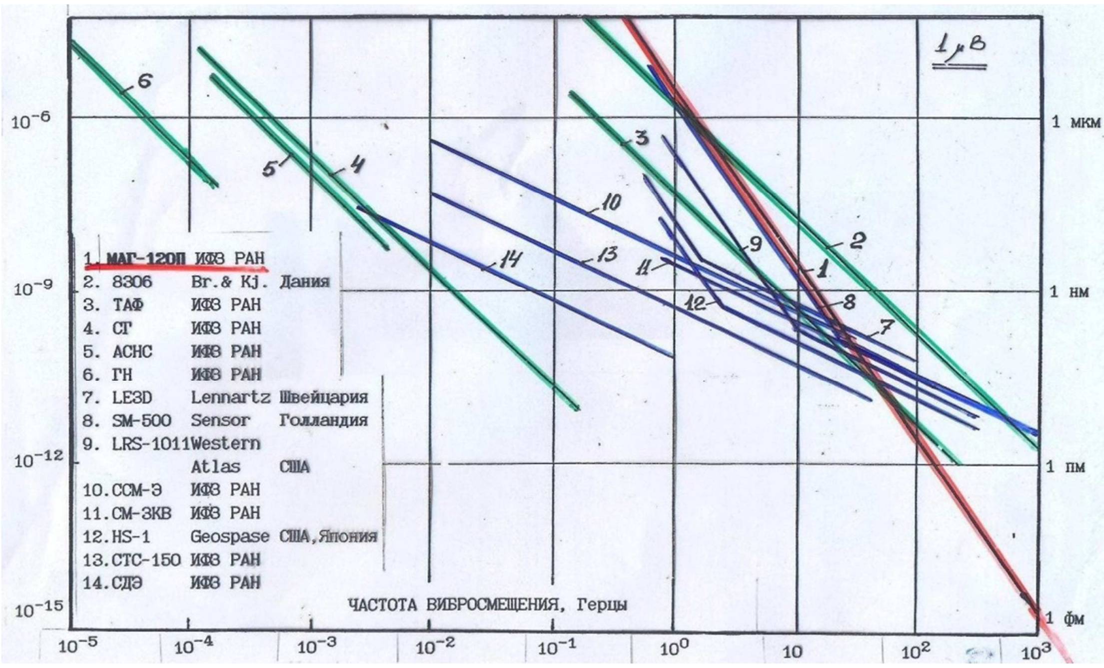

***Figure 2.** Comparative characteristics of some seismic devices.*

2. The Fifth-Generation Geophone and the New-Type Hydrophone

The new generation MIG-3B geophone of the fifth generation [4] is designed for vector control of acoustic activity in a solid geological environment in the frequency range from 1 to 5000 Hz by the registered method: RF patent application No. 4790033 [5] and RF patent No. 322720 [6]. Its design uses proven solutions for RF patents No. 1721564 [7] and No. 1833501 [8], and the know-how for the construction of the sixth-generation sensor, where all three components are symmetrical and protected against electromagnetic interference, can be used.

A hydrophone with a new type of sensor can provide vector control of high-frequency wave processes in a liquid medium. It uses a fifth generation geophone sensor, and it was developed using constructive solutions for the author's certificate of the Russian Federation No. 1672391 [9] and RF patent No. 1833501 [8]. Both new instruments, a geophone and a hydrophone use a sensor with similar characteristics: the orthogonal components of the vector are measured; frequency measuring range 1-5000 Hz; the dynamic range of the output voltage of the magnetoelastic sensor is not less than 160 dB; the range of measured displacements is not less than 240 dB. The geophone and hydrophone sensors consist of a magnetoelastic transducer, a high-energy permanent magnet, three electrical windings, a single inert mass and a magnetic casing. The seismic receiver in a robust, non-magnetic sealed enclosure can be installed on the bottom of the reservoir and converts three components of the acoustic surface vibration vector into three orthogonal directions. The sonar receiver, whose design and sensor characteristics are similar to the seismoacoustic receiver, is installed in a robust, non-magnetic sealed housing equipped with angled reflectors, which is provided with positive buoyancy.

Magnetoelastic sensors are nonvolatile inertial devices. They have a simple and sturdy construction, do not have moving parts and do not require power. Surface and borehole analogues of receivers with magnetoelastic sensors have successfully passed many years of testing in deep and super deep wells in various regions of the Earth. The trouble-free operation of the receivers in the continuous monitoring mode for many years has confirmed their high reliability and long-term stability of the conversion characteristics.

The magnetoelastic receiver is a velaccmeter, in comparison with traditional instruments that measure vibro-displacement, has a high frequency-selective sensitivity to displacements. If the frequency is increased by a factor of 10, the sensitivity is increased by 1000 times. For comparison, it should be pointed out that with the same frequency increase, the sensitivity of electrodynamics seismometers in the operating range increases by a factor of 10, and the piezocrystalline accelerometers by a factor of 100. The intrinsic noise of a magnetoelastic sensor is comparable to the intrinsic noise of an electrodynamics seismometer and is much smaller than that of a piezocrystalline accelerometer. A magnetoelastic sensor with a steep amplitude-frequency characteristic can simultaneously record displacements in a huge range - more than 260 dB. This makes it possible to simultaneously measure displacement amplitudes of less than 10^{-15} m at frequencies above 1000 Hz and more than 10^{-2} m at frequencies below 0.1 Hz. Experimental broadband recording with a sampling frequency of 10 kHz is illustrated by figure 3, which shows three acoustic tracks of 14 seconds duration in the directions: North-South - upper track, West-East - middle track and vertical - lower track [3].

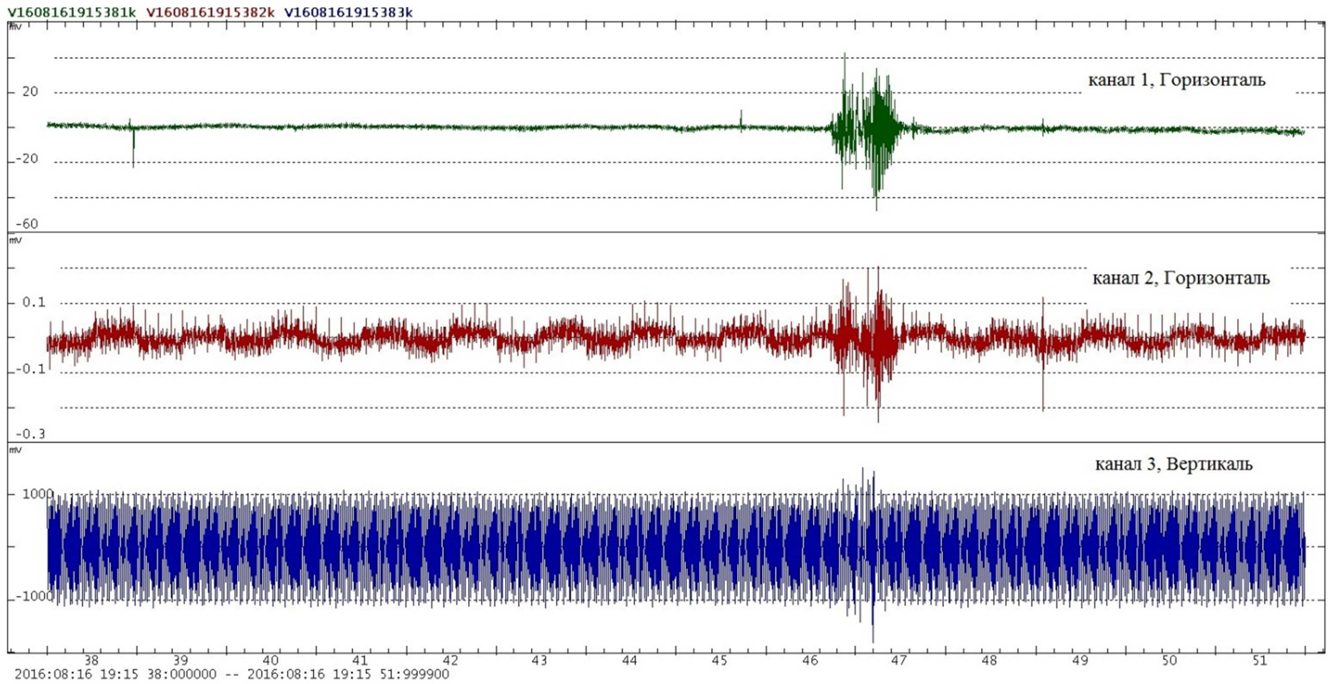

Figure 3. Tracks, 14 s at a depth of 1400 m in the well.

On the middle track, the frequency of 1 Hz is clearly recorded. This is the frequency of the turbines of a hydroelectric power station located 30 km to the East. But, if we consider in detail, in figure 4, three components of the acoustic event with large amplitudes and apparent frequency of about 5 kHz are seen, which occurred at the beginning of 49 seconds of the track shown in the previous figure 3.

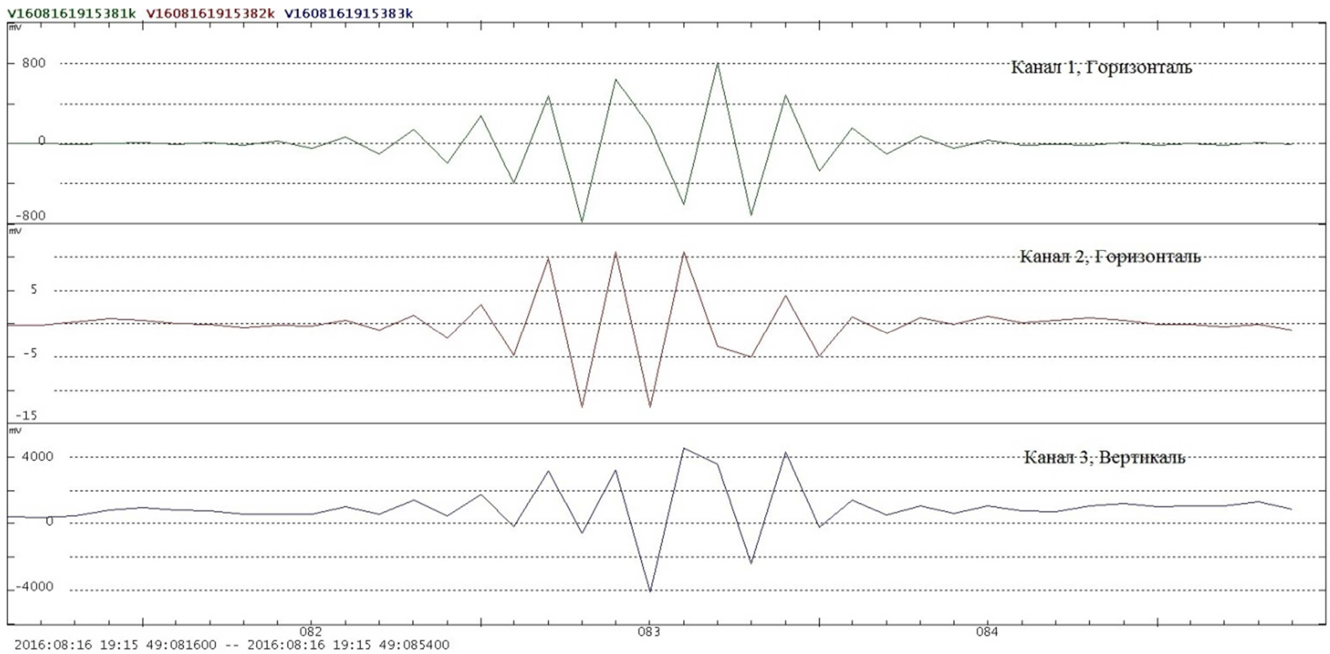

Figure 4. Tracks, 0.0038 s.

Depending on the task, the sensing devices can be one, two or three-component with directional patterns in the form of a volumetric cosine-shaped dipole. Optimum for scientific research design of the magnetoelastic sensor is a completely symmetrical sensor. Its basis is a symmetric inertial mass whose center of gravity coincides with the center of symmetry. The inertial mass is strengthened in a rigid symmetrical casing by means of six identical rods from a magnetoelastic crystalline ferromagnetic, which are magnetized by samarium cobalt magnets of high energy. Each rod is supplied with the same measuring windings. Each of the three pairs of measuring windings, which are located on coaxial rods, are connected in series. The total voltage arising in each pair of measuring windings is proportional to the magnitude of the projection of the motion vector of the common center on the orthogonal axes that coincide with the axes of the corresponding pairs of rods, and the sign of the voltage depends on the direction of motion of the common center. The design of the instrument with such a sensor makes it possible to most accurately convert the complete vector of the acoustic signal and calculate its azimuth at one point. Two devices will allow you to locate the signal source.

Three-component magnetoelastic receivers used in the wells are supplied with partially symmetrical sensors. This is due to the specificity of the downhole equipment, which forces the structure to extend in the direction of the vertical axis. The parameters of the vertical component signal conversion in the downhole sensor are different from the parameters of horizontal component signal conversion by the sensitivity and the frequency of the mechanical resonance. The sensitivity of the horizontal component of the sensor for the downhole receiver is higher than for the vertical component, but the frequency of the mechanical resonance and, accordingly, the band of the converted frequencies is smaller. If necessary, these differences can be reduced by reducing the vertical dimensions of the sensing element and the inertial mass. However, in this case, in order to maintain the required sensitivity level, it will be necessary to replace the material of inert mass and use not steel with a specific gravity of 7.87, but tungsten with a specific gravity of 19.3. The design of the sensor for downhole tools can be significantly upgraded by using know-how to provide 3D symmetry of conversion and protection of the vertical sensor channel from electromagnetic interference. The dimensions of a single-component seismic-acoustic sensor can be significantly reduced if the converter is made of a more sensitive alloy (with the addition of silicon), and the inert mass will be made of a metal with a high specific gravity.

3. Some Possibilities of Seismoacoustic and Hydroacoustics Receivers

Seismoacoustic and hydroacoustics receivers are designed for broadband vector registration of acoustic vibrations of the solid bottom and acoustic oscillations in the water of the bottom layer of the World Ocean. The obtained data can be used to solve fundamental scientific and applied problems in seismology, geoecology, seismic exploration of minerals, oceanology, as well as for acoustic monitoring of underwater boundaries of protected water areas and state borders.

In the interests of seismology, oceanology and geoecology, bottom seismoacoustic and hydroacoustics receivers installed at a sufficiently large depth will make it possible to obtain seismoacoustic and hydroacoustics data with minimal influence of anthropogenic noise. Such data can be very useful in studying the state of the geological environment in the coastal seismically active regions of the Pacific and Indian Oceans, and will allow the creation of reliable systems for monitoring the seismic hazard of the ocean coast. Seismoacoustic and hydroacoustics receivers with similar vector characteristics used together will allow investigating the correlation of bottom seismic and near-bottom hydroacoustics noises in order to identify their sources and causes of variability.

For Earth sciences it is important to be able to study the nature of the variability of acoustic noise in the bottom of the Mariana Trench in wide frequency bands and displacements. This is due to the fact that the deepest point of the World Ocean lies in the Mariana Trench. Its depth is 11,022 m. With the minimum thickness of the earth's crust under the oceans from 5,000 to 10,000 m, the bottom of the Mariana Trench is closest to the Mohorovicic boundary. Broadband acoustic measurements with high resolution in this unique place on Earth will provide new and very valuable data on the level of acoustic noise and their variability at the Mohorovicic boundary. Studies can be conducted both with the help of a separate seismoacoustic receiver, and with the help of a matched pair of seismoacoustic and hydroacoustics receivers. Using a simple and lightweight drop from a ship or a helicopter, a very pop-up design, you can get a unique, very interesting for fundamental science information about geoacoustic noise at the shortest distance from the border of Mohorovicic. At the same time, the costs will be minimal. For a preliminary study, you can confine yourself to one single-component receiver with a vertical radiation pattern and a pop-up recording device designed for autonomous work with the longest duration. In this version, the sensor in the concrete capsule serves as an anchor. It remains at the bottom, and the registrar in the body with positive buoyancy emerges at a specified time or at a signal from the surface. The low cost of one-component sensors will allow a series of such studies to be carried out, using a new sensor each time, or simultaneously measuring at several points of the cavity profile.

Seismoacoustic and hydroacoustics receivers that have high selective sensitivity, when installed on the bottom and in the bottom layer in the gulfs, straits, bays, canals and harbors can provide effective control of the passage and identification of passing objects according to their specific noise. To do this, you need to install a new three-component geophone on the bottom, and a three-component hydroacoustics receiver with a corner reflector is complimentary over it, providing it with positive buoyancy.

Seismic acoustic receivers when installed in deep wells on land and at the bottom of deep water bodies can be a very sensitive and effective monitoring tool in the international monitoring system under the comprehensive test-ban treaty. Experimental confirmation of the possibility of detection of chemical explosions at long distances was obtained during the continuous monitoring of acoustic noise in the well by a vertical instrument at a depth of 100 m in the region of Kislovodsk in the North Caucasus in 2003 [10].

Unfortunately, the record in figure 5 is made according to a technique developed for long-term monitoring in the interest of studying tidal gravitational processes in the earth's crust, and not for detecting impulse events. Therefore, the low recording frequency (1 record per minute) of the mean values from 2000 intermediate measurements per minute, at least 1000 times reduced the amplitudes of the impulse events. But, nevertheless, one can see the difference between the four days on the left (March 18-21) and the four days on the right (March 25-28), when bomb strikes were fired on Iraq. A modern recording system would make this more visible.

The active development of offshore oil and gas fields is associated with the creation and operation of large offshore production complexes (platforms) that need timely warning of a possible seismic hazard. Reliable seismoacoustic control in the locations of such complexes can be performed by a unified set of borehole (bottom) geophones and sonar receivers.

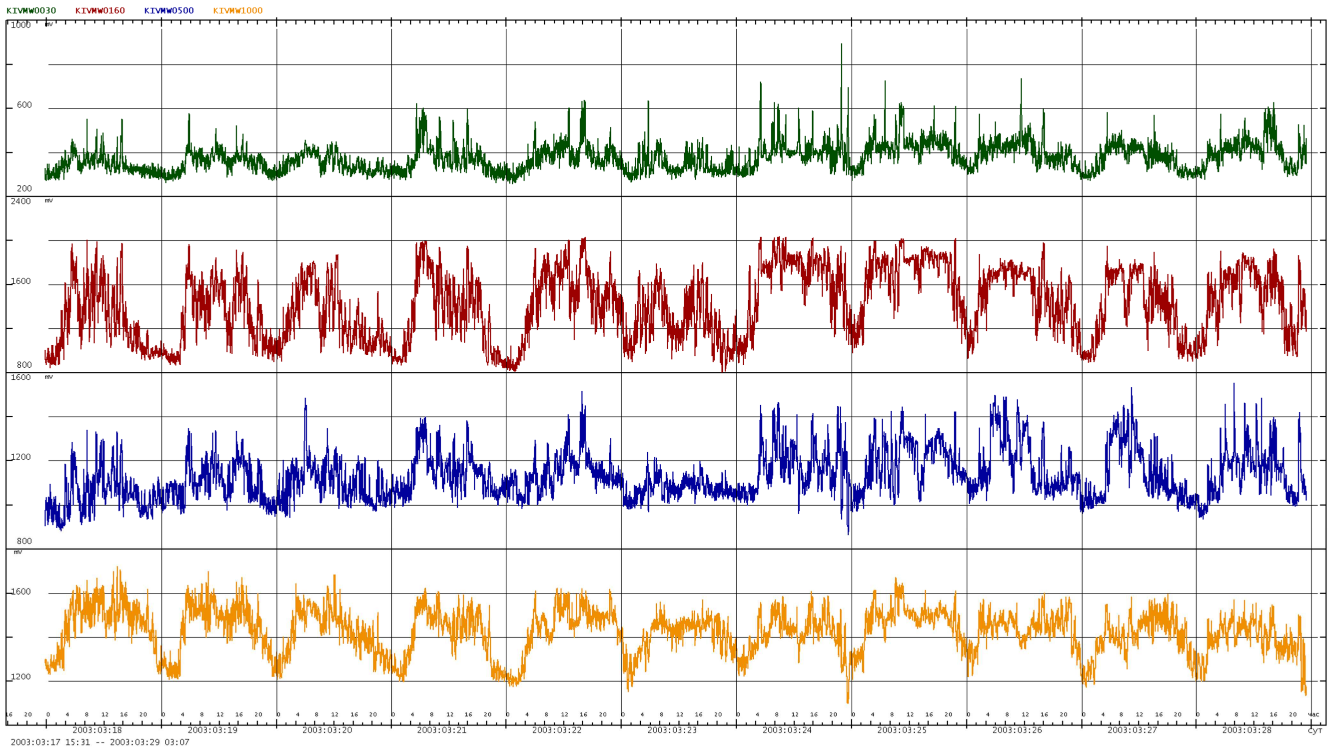

Figure 5. *Record acoustic noise in the frequency bands (from top to bottom): 30, 160 500 and 1000 Hz.*

4. Signal Recording Systems

The intrinsic noise of the magnetoelastic sensor in the working frequency band at the output of the measuring winding is much less than 0.1 µV and has the character of "white noise". The registration system should provide input noise of the preamplifier less than 0.1 µV. During the test registration we used: a preamplifier with a differential input, a bandwidth of 0-20 kHz, amplification up to 60 dB with variable gain factors of 1, 10, 100 and 1000 and a four-channel analog-digital 24-bit converter with a sampling frequency of up to 100 kHz for each channel, a control laptop and an external hard drive with a capacity of 2 TB.

The recording systems of seismoacoustic and hydroacoustics signals are designed taking into account the specific purpose and conditions of application of magnetoelastic acoustic receivers. In an autonomous variant aimed at solving seismological problems, a system of multichannel low-frequency recording with the accumulation of digital information on solid-state carriers is the most acceptable system for recording broadband seismoacoustic and hydroacoustics signals. For its implementation, narrow (1/3 octave) frequency bands with central frequencies of 20, 40, 160, 500 and 1000 Hz are extracted from each broadband signal of the seismoacoustic receiver using analog means. Of course, these frequencies are not mandatory. For each specific task, a number of frequencies can be selected. Signals allocated in narrow bands are detected, and the carrier frequency is filtered. To digitize the detected signals, a frequency of not more than 500 Hz is sufficient. In total it is necessary to register 15 signals. For their digitization, an analog-to-digital converter with a 16-channel multiplexer can be used. The advantage of such a system is that, in parallel with the registration, it is possible to observe the seismoacoustic situation on the large screen in the ADC samples in the current time mode and to make an expert evaluation on them.

Signal amplitudes in a narrow-band measurement system are formed by: the electromechanical coupling coefficient of the sensor is K1 [$mV \times s^3 \times m^{-1}$], the preamplifier factor is K2 (1, 10, 100 and 1000), the band-amplifier factor is K3 (50) and the Analog-Digital Converter - K4 (1). The total coefficient of each measuring channel of the receiver: К=К1×К2×К3×К4 [$mV \times c^3 \times м^{-1}$]. The measured parameter (speed of acceleration in a longitudinal acoustic wave) - R [$m \times s^{-3}$] is determined by the formula R=N/K, where N is the number "mV" at the output of the ADC. For example, for N=1 mV, R1=1/K [$m \times s^{-3}$]. To determine the physical quantities corresponding to the selected parameters of the motion of the material points of the host environment: acceleration a, velocity v or displacement L at N=1 mV, the calculated parameter R1 must be divided into $2\pi f$ in the first, second or third degree respectively, where f is the central frequency of the selected band, and then multiply the result by the number of mV in this band. This can be done programmatically at the time of registration. In this case, the results in real time can be presented on the monitor screen in physical units, and not in the ADC samples.

5. Discussion

It should immediately be clarified that the author of the article has no practical experience in hydroacoustics and his judgments may not be professional. However, a great deal of experience with new sensors on the surface and in wells makes it possible to predict their successful use in the aquatic environment. It is known that in the transition from a gaseous medium to a solid medium, the acoustic wave loses more than 98% of its amplitude, and when passing from a liquid medium to a solid medium, about 30% is lost. This is encouraging.

At the very beginning of the development of magnetoelastic sensors, a one-component sensor of the first generation weighing about 20 kg was presented at a presentation that took place in an old church building with a large area and good acoustics. The sensor was installed on the concrete floor diametrically from the entrance (about 15 m) and measured the vertical component. As an indicator, an electronic oscilloscope was used. It was interesting that the noise generated at the entrance made the oscilloscope beam go off the screen. I'm not talking about clapping the palms (the traditional way of seismologists). Perhaps the role here was played by the high acoustic quality of the building and the large surfaces of the floor and walls. This was in the beginning of 1980, when the first sensors were made of siliceous transformer steel sheet, the magnetic flux was created by a winding and a galvanic cell, and modern digital recording systems were not known at that time.

Another field experiment was conducted after 1990 in the Caucasus, when a downhole tool with a fourth-generation sensor was suspended from a tree branch to check the directional pattern before going downhill. The emitter was a portable cassette tape recorder with a recording frequency of 1000 Hz, which was worn in a circle, in the center of which was the device. This experiment was successful, which cannot be said about the main task of downhole measurements at a depth of about 300 m in the interests of seismology. To check the quality of signals from the well by ear, the device was switched on to the tape recorders input. From the speakers of the tape recorder, household noise, barking of dogs and cock-singing were heard. As it turned out later, the downhole of the well drilled at the top of a steep hill was near the village where life was boiling.

The described observations cannot be considered a rigorous scientific justification, but they give hope for the correctness of the conclusions about the possibility of an effective use of a new geophone sensor in the aquatic environment.

6. Conclusion

The original design and unique amplitude-frequency characteristic of the new sensor suggest that measurements in the water environment will be an effective alternative to the traditional geophone. It is not yet clear what will measure a new device in water: displacement in a sound wave, sound pressure level, pressure gradient or vibration speed. To understand this, it is necessary to carry out experimental studies of the instrument in an aqueous medium. For this, there is a fourth-generation device and approved registration systems.

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