**V.A.Alexandrov, Yu.A.Korjakin, V.A.Majorov,
O.B.Ostrovsky, V.B.Zhelezny, V.B.Zhukov**

NEW CAPABILITIES OF APPLICATION OF ACOUSTIC METHODS AT MIDDILE AND LOW FREQUENCIES TO GEOPHYSICAL PROBLEMS

Research Institute Morphyspribor
Russia, 197376, Saint-Petersburg, Chkalovsky prospect, 46
Tel.: (812) 320-8040 Fax: (812) 320-8052
E-mail: mfp@mail.wplus.net

The paper considers opportunities of borehole piezoceramic cylindrical sound sources designed to solve various geophysical tasks at middle and low frequencies. Basis equations in approximation of longitudinal waves are presented for characteristics of the sources operating in linear acoustic and parametric modes. The prospects of application of borehole piezoceramic sources for acoustic action, interwell profiling and measuring of acoustic parameters of rocks are demonstrated.

Seismic acoustic methods developed in the twentieth century have been resulting to considerable advance in the area of knowledge about the Earth. Conventionally seismic acoustic methods prevails in prospecting of mineral sources and studies of the Earth's surface. These methods are based on radiation of seismic waves with frequency below 100 Hz by vibration-testing machines, pneumatic guns or explosive sources and reception of direct and refracted waves by seismic receivers with following processing and interpretation [1].

Basic seismic acoustic methods have been practically preserved during last decades, their advance has been stimulated by implementation of computer facilities, enlarging the areas of seismic exploration and development of methods of interpretation of results. For enhancing the capabilities of seismic acoustic methods the sources and seismic receivers have been placed not only on the ground but also in the wells [2, 3]. Thus, at the same time with vertical seismic profiling the new geophysical methods have been developed, for instance, interwell seismic translucence (IST), including interwell tomography, acoustic action (AA) in the near-face area as well as passive acoustic logging (PAL) [2, 4, 5].

Methods IST, AA and PAL in their turn affected development of acoustic methods in well geophysics and extending of the frequency range from 0.1 to 40 kHz. However, design of the acoustic sources and receivers for well works was conducted similar to seismic instruments and they could hardly provide required results during their service.

In this paper the alternative approach is proposed to the problem of acoustic technology in geophysics, or formulating more exactly, the potential of conversion of underwater acoustic technology into well acoustics taking into consideration geophysical tasks. According to this approach the borehole sound source is to be defined by the following characteristics: the acoustic projector (AP) type; power source or generator unit (GU); power transmission from GU to AP over large distances; prediction of the character of acoustic fields from borehole AP, signal power and type.

Borehole AP may be represented by a cylinder with radius R_O and height h_O, in this case AP radius and height will be limited by well's radius and shaft respectively. For cylindrical AP it is possible to obtain expressions which describe its field in approximation of longitudinal waves (L-waves). The experience accumulated during the work with such sources confirms that the AP acoustic field in continuous medium can be generated by linear acoustic or parametric methods [6-8].

In case the AP field is formed at frequency f by linear acoustic method in quasi-homogenous area where the sound velocity is c_O, density r_O, parameter of non-linearity is e_O, the area size is not less than h_O^2/l, ($l=c_O/f$), then the expression for initial pressure field is defined according to [6] as

$$P_f(W, j) = \sqrt{\frac{W r_0 \tilde{n}_0 h_0}{2pl}} \cdot \left| \sin\left(\frac{p h_0}{l} \sin j\right) \Big/ \left(\frac{p h_0}{l} \sin j\right) \right|, \qquad (1)$$

where W is radiated power, j - vertical angle from the AP surface. (In (1) and hereinafter expressions the effective values of pressure and power are used.)

Acoustic field outside the quasi-homogeneous area at fixed azimuth angle may be written as:

$$P_f\,(r,\varphi) = P_f(W,j)\cdot \xi(r,j)\cdot\exp(-r\alpha_f(r,j)), \qquad (2)$$

where ξ is a function affected by the beam pattern of propagation in the ground and defined by spatial distribution of density and sound velocity fields; $a_f(r,j)$ is an averaged absorption factor at frequency *f*. Possible focusing along azimuth angle is not taken into consideration in (2).

In case of quasi-homogeneous medium (2) becomes:

$$P(r,\varphi) = P_f(W,j)\cdot\exp(-r\cdot\alpha_f)/r\,. \qquad (3)$$

While forming the field by the parametric radiation method AP radiates simultaneously two signals at frequencies f_1 and f_2 in the same area, thus providing generation of difference signal at frequency $F = |\,f_1 - f_2\,|$ due to the medium nonlinearity. In underwater acoustics cylindrical AP in parametric radiation mode are not commonly used because of low efficiency of difference signals in case of omnidirectional waves and water nonlinearity factor e=3.5-5. On the contrary, parametric radiation is rather effective in the rocks due to more high nonlinearity factor $e = 10^2 - 10^4$ [8]. It is possible to use the expressions obtained in [8,9] for description AP field in mode of parametric radiation. Besides, different variants of the field may be realised depending on parameters of the area of difference frequency signals. Thus, the effective pressure value reduced to 1 m $P_F(j)$ at $R > 2R_h$ and $2R_h \leq 1/a_f$, $R_h = h_o^2 f/c_0$, $f = (f_1 + f_2)/2$ may be represented using the method of wave elements [9] in a form:

$$P_F(j) = \frac{\sqrt{2}pe_0F}{r_0c_0^3}\,P_f^2(j)\int\limits_{R_h}^{R}\frac{\exp\left(-2a_f\left(r-R_0\right)\right)}{r}dr\,, \qquad (4)$$

where $P_f(j) = P_{f1}(j) = P_{f2}(j) = P_f(W,j)$ are described by (1).

In case of highly absorbing medium at frequency *f* in condition of $1/a_f < h_0f/c_0$ it is possible to use similar estimates from the papers [8, 9]:

$$P_F(j) \cong \frac{pe_0F^2W_f}{2\sqrt{2}c_0^3a_f}\cdot\frac{\sin\left(B\sin j\right)}{B\sin j}\cdot\frac{\sin\left(A(1-\cos j)\right)}{A(1-\cos j)} \qquad (5)$$

or

$$P_F(j) \cong \frac{e_0F^{1,5}W_f}{\sqrt{2}c_0^{2,5}}\cdot\frac{\sin(B\sin j)}{B\sin j}\cdot\frac{\sin(A(1-\cos j))}{A(1-\cos j)}\cdot\int\limits_{R_0}^{1/\acute{a}_f}\frac{\exp(-2a_f(R-R_0))}{\sqrt{R}}dR, \qquad (6)$$

where $A = pf/(2a_f\cdot c_{\hat{\imath}})$, $B = phf/c_0$, supposing that $W_f = W_{f1} = W_{f2}$.

Expressions (5, 6) are differed by that (5) is obtained using the method described in [8], while (6) is obtained using in partly the model of wave fronts [9].

Expressions (5, 6) are valid when linear absorption prevails over non-linear absorption, while the latter is called as saturation regime [7]. In saturation regime the sine wave of frequency *f* transfers to saw-type wave with the breaks in leading compression front (edge) and is absorbed to a high degree. Parameters of this process are described in [10]. Thus at the strong saturation the condition of Manly-Raw may be applied [7]: $W_F \quad FW_f/f$, where W_f and W_F corresponds to acoustic power at initial and difference frequency, respectively. In case saturation appears at the distance $R < h_0$, the field will be formed due to the AP aperture height and will be described by:

$$P_F(\varphi) = \sqrt{\frac{F^2 W_f \rho_0 h_0}{2\pi f}} \cdot \left| \sin\left(\frac{\pi h_0 F}{c_0}\sin\varphi\right) \Big/ \left(\frac{\pi h_0 F}{c_0}\sin\varphi\right) \right|. \qquad (7)$$

Outside the zone of forming the signals of different frequency propagate similar to linear acoustic signals, then the expression of the field becomes similar to (1):

$$P_F(r,\varphi) = P_F(\varphi)\cdot\psi(r, \varphi)\cdot\exp(-r\cdot\alpha_F(r,\varphi)). \qquad (8)$$

In case of quasi-homogeneous medium

$$P_F(r,\varphi) = P_F(\varphi)\cdot\exp(-r\cdot\alpha_F)/r. \qquad (9)$$

The expressions (1-9) allow to evaluate the characteristics of the fields of cylindrical borehole AP. Thus, expressions (1, 4-7) describe the AP fields in linear and various parametric modes, while the expressions (3, 9) describe spatial distribution of acoustic field in quasi-homogeneous medium. Expressions (2, 8) are related to general case of the field in non-homogeneous medium, where it is necessary to know the form of the function î(r,j) and a(r, j).

For approximation estimate of the AP efficiency during AA and IST regarding operating range it is possible to apply modified expression for acoustic range in infinite homogeneous medium [6] to quasi-homogeneous medium in the following form:

$$P_{f,} \ge p_L\cdot r\cdot\exp(\alpha_f\cdot r) \text{ èëè } P_F \ge p_L\cdot r\cdot\exp(\alpha_F\cdot r), \qquad (10)$$

where p_L is the given level of threshold signal, at which AA regime is realised or useful signal is detected by receive antenna during IST at initial f or difference F frequency respectively. The analysis of relations (1-10) shows that operating range of borehole acoustic projectors in modes of AA and IST depends mainly on radiation power given to the medium and source dimensions. Radiation of large power, improving of directivity in radiation as well as opportunity of transfer from middle (5-30 kHz) to lower frequencies (0.3-5 kHz) in the medium by means of parametric radiation gives reliable chance of overcome limiting factors, for instance, divergence and strong absorption of acoustic signals in hard and sedimentary rocks.

The above approach has been used for development of the series of borehole piezoceramic acoustic sources featured by high power: AP-1, AP-2, AP-3, AP-3M and ground generator units: GU-03, GU-04, GU-05, GU-06. Tables 1 and 2 demonstrate their technical characteristics.

Table 1.

Technical characteristics of the borehole acoustic projectors

Type of the projector	ÀP-1	ÀP-2	ÀP-3	ÀP-3 Ì
Type of active element	Cylindrical	rod	rod	cylindrical
Overall length, mm	1600	1800	2010	1900
Length of active part, mm	560	800	920	920
Pump frequency range, kHz	13-18	11-14	10-13	23-27
Efficiency, %	70	35	40	70
Acoustic power, kW	5	1	3	5

Table 2.

Technical characteristics of the ground generator units

Type of the generator	GU -03	GU -04	GU -05	GU -06
Mass, kg	45	60	100	35
Output power, kVA	6	9	16	8
Frequency band, kHz	10-28	8-30	10-30	10-60
Pulse duration, ms	20-1000	10-2000	10-2000	1-1000
Relative pulse duration (Duty ratio)	1-50	1-100	1-100	1-50
Efficiency, %	85	90	88	95
Type of power transistor	2Ò841À	2Ò847À	2Ò847À	2SK956
Type of output signals*	T, FM	T, FM. DF	T, FM. DF	T, FM. DF

* Signals: T-tonal, FM- frequency modulated, DF - double frequency.

The above devices are designed to operate in the wells filled by liquid at maximum depths to 5 km.

The following directions of using the equipment are to be mentioned:

- AA designed for operation in near productive zones of oil and water wells in frequency range 10-25 kHz with coverage 3-30 m;
- AA designed for operation in parametric modes in near and far zones of oil and water wells in frequency range 0.5-25 kHz with coverage 10-300 m;
- IST-tomography conducted at middle frequencies 10-25 kHz at the distances 10-100 m;
- IST-tomography conducted at low frequencies in parametric mode in frequency range 0.3-3 kHz at the distances 100-1000 m;
- IST-examination of the rocks in natural conditions using the results of propagation of acoustic signals in frequency range 0.1-25 kHz at the distances 3-1000 m.

Tonal, pulse, frequency-modulated or other wide-band signals may be applied for above applications. Estimates of coverage zones during AA and the distance during IST are obtained according to expressions (1-10) for sedimentary rocks of the type described in the paper [2] at e =1000-5000.

It should be noted that acoustic action in near-face zones of oil and gas wells is broadly used in the industry thus stimulating oil and gas production [8,11].

The opportunity of application of new type AP for geophysical studies in IST modes is confirmed by demonstration experiments [8,11] and computational estimations. Time delays over propagation paths in IST methods may be properly defined by using composite wide-band signals [6] with subsequent convolution during their processing in reception mode. Organization of acoustic receiving systems of the large aperture (borehole receiving antennas) for reception and preliminary processing of middle and low frequency signals should be additionally considered in IST modes. It is also necessary to take into consideration influence of pipe waves [3], excited by the projector placed in the well. Usually decrease of influence of pipe waves is provided by increase of power of single-period pulse of radiation from explosive or spark sources. For cylindrical ÀP the main directions of decrease of influence of pipe waves, are apparently, the methods of application of parametric radiation and increasing spatial energy concentration.

During parametric radiation at difference frequencies the signal is formed in a medium [7 - 9] outside the well, the reciprocal environmental effect on the well is rather insignificant. The spatial concentration is reached by increase of borehole AP height h, that according to expression (1) improves the beam pattern directivity and boosts the pressure $Đ_f$ in a field of main maximum. Besides, at constant specific power the increase of height h_0 allows to enlarge linearly power W_f.

Acoustic instruments (Tab. 1, 2) developed in 1994-99 were used for intensification and rehabilitation of more than hundred oil wells (AA-method), and also for realisation of two demonstration experiments related to observation of passage of sound waves between wells (IST-method). As a whole the efforts yielded to positive results and have confirmed prospects of using borehole piezoceramic sound sources. According to results of these experiments with AP of new type and taking into consideration earlier efforts [2 - 5], it is necessary to note that modern geophysics collected a very restricted library of the specific data relating to acoustic properties of the rocks at middle and low frequencies. In particular, these problems may be noted in respect of the absorption coefficients, parameters of non-linearity and response of multicomponent rocks to acoustic influence. So, the studies in this direction are of considerable concern.

Finally, generalising the problem it should be noted that the application of acoustic instrumentation using cylindrical projectors of large aperture and power allows to realise new capabilities for solution of geophysical problems in borehole geophysics:

- to apply wide-band signals with controlled spectrum and duration in AA modes;
- to extend AA-coverage using piezoceramic ÀP in parametric radiation mode;

– to use a directional sound radiation with a given spectrum at low and medium frequencies for implementation of IST and AA methods;

– to provide stability of an initial wide-band signal during reiterated experiments on passage of sound pulses or tomography;

– to support by proper instruments works on definition of non-linear properties of hard and sedimentary rocks at middle and low frequencies;

– to support by proper instruments woks on estimation of attenuation factors of hard and sedimentary rocks at middle and low frequencies.

The equipment to be developed is of universal nature and can be used both in technological activity and geophysical studies. Piezoceramic borehole ÀP can transmit directionally to 5 kJ at pulse duration to 1 sec. Perspective ÀP, according to above expressions (1-10) should have enhanced both aperture and total acoustic power thus providing the increased efficiency. The advanced technologies allow to develop borehole ÀP jointly with borehole GU, with borehole tool height 2-5 m and radiated power in a pulse up to 10-25 kW.

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