Focused borehole radiator

Dmitry Kas'Yanov

Radiophysical Research Inst., 25 Bolshaya Pecherskaya, 603950 Nizhny Novgorod, Russian Federation
vo-kak@yandex.ru

A promising type of borehole acoustic radiators intended for both affecting geotechnological processes and investigating the borehole environment is considered. The basic difference of the radiators under consideration from the existing ones is the possibility of focusing the acoustic field into a preset region of the borehole environment. Elastic fields produced by focusing borehole radiators in rock are studied. Limiting abilities of focusing borehole systems are investigated. It is demonstrated that borehole radiators with a variable focal distance can be designed, which provides a real opportunity to control the distribution of elastic fields in the borehole environment. This property may be very important in developing the acoustic technologies for affecting productive reservoirs of geotechnological boreholes.

1 Introduction

Acoustic fields are used more and more often for stimulation in modern borehole geotechnologies, such as gas and oil extraction, underground leaching, underground dissolution of salts, etc. The mechanisms of the action of elastic oscillation fields on the transfer processes in multiphase media are still not clearly understood. Only several general features had been established [1]. Nevertheless, the requirements imposed on the acoustic borehole radiators designed for the use in a specific geotechnological cycle can be rather clearly defined. The main requirement is the generation of the highest possible amplitudes of elastic fields at preset frequencies at the preset points of the medium under processing, since the efficiency of intensification mainly depends on the amplitude and frequency of the acting field. The main factors limiting the field intensity in the near-borehole zone are the attenuation of elastic fields in rock and the nonoptimal character of acoustic field radiation from the borehole. Almost nothing can be done with attenuation in rock, apart from using very limited opportunities for reducing the radiation frequency. As to different processes connected with the radiation from the borehole, it is possible to improve them rather effectively and in several ways. First, one can increase the specific power of the radiator. However, there are some limitations connected, on the one hand, with the mechanical strength of active materials, their nonlinearity, and intrinsic loss, and, on the other hand, with the cavitation strength of the liquid within the borehole and the conditions of matching the radiator with the medium. Another way to increase the intensity of elastic fields in the region near a borehole is connected with the formation of a specific distribution of acoustic field in it. The borehole geometry allows one to position a point or linear acoustic source in it. The acoustic fields generated by a point source are spherically divergent, and their intensity decays proportionally to the square of the distance, which restricts the region of the action of acoustic field. Linear sources distributed along the borehole axis generate fields with a cylindrical divergence, and the intensity in this case decays in inverse proportion to the distance, which expands to some extent the region of acoustic action. Moreover, it turns out that it is possible to compensate for the cylindrical spread characteristic of a quasi-linear antenna [2-4]. This may be accomplished with the help of focusing phase distributions formed along the generatrix of the antenna. The competition between the cylindrical divergence along one coordinate and convergence along the other results in the formation of a focal region shaped as a torus. Its position may be controlled under certain conditions [5]. The theory of similar antennas radiating into an infinite medium and their laboratory simulation are presented in [4]. Their first application to a geotechnological process is described in [5].

Focusing phase distributions along the generatrix of a linear antenna may be both quasi-continuous (spherical, parabolic, etc.) and discrete (zone lenses and plates). It is known that, from the point of view of focusing properties, zone systems cannot compete with systems with quasi-continuous phase distributions. However, a significant advantage of zone systems is the simplicity of their manufacture, which is especially important in the case of radiating acoustic systems, for example, in borehole acoustics. Indeed, the formation of quasi-continuous phase distributions is expedient only in receiving antennas, whereas in the case of radiating power antennas, this method encounters great difficulties associated with the manufacture of high-power delay lines with stable parameters, especially if the antennas are intended for operation in severe conditions (high pressure and temperature). However, if a focusing antenna is manufactured in the form of a zone lens, there is no need in additional phase-shifting elements. The antenna is divided according to a certain law [4] into zones, and active elements belonging to neighboring zones are excited in antiphase. Additionally, for zone lenses, the focus position can be controlled by changing the radiation frequency. Retuning is restricted only by the quality factors of the transducers constituting the antenna and by the matching conditions for the antenna-borehole-rock system [7].

2 Objectives and Model

Here we study some of the problems connected with the radiation of quasi-linear focusing antennas in the form of cylindrical zone lenses positioned in a borehole.

In the general case, the problem on the acoustic radiation from a borehole into rock is rather complicated. This is connected with the multiplicity of situations determined by the type of radiator, the phase front generated by it, the structure of the borehole, and the rock characteristics. This is especially true for a productive reservoir. The necessity to consider the radiator in a diffraction problem is dictated by the fact that it is difficult to simulate a radiator within a borehole with the help of ideal boundary conditions. For every type of a borehole transducer, the pressure and velocity at its surface are related in a specific way. If one does not take into account this relationship, it is difficult to solve correctly the problem of matching a borehole radiator to rock. This problem is studied in detail in [6]. The same publication presents the boundary conditions for an extended uncompensated piezoelectric antenna within a borehole.

Let us consider the following model. Let an infinite circular cylindrical cavity with the radius r_2 be located in a homogeneous elastic infinite isotropic medium. Let the cavity be filled with an ideal compressible fluid. The solid medium is characterized by the density ρ_s, the longitudinal sound velocity c_l, the transverse sound velocity c_t, and the elastic modules λ and μ. The fluid is characterized by its density ρ_f and the sound velocity c_f. An extended piezoelectric antenna with the external radius r_1 is positioned axisymmetrically within the cavity. The geometry of the antenna-liquid layer-rock coaxial system is presented in Fig. 1.

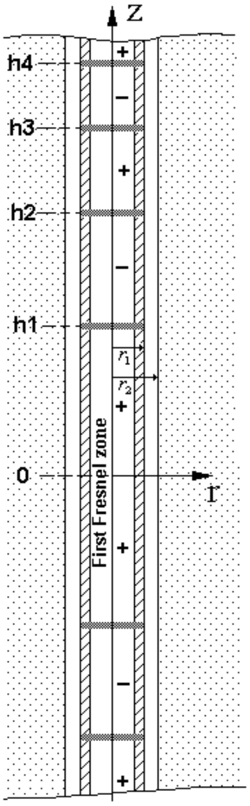

Fig. 1. Geometry of the antenna–liquid layer–rock coaxial system.

We assume that the piezoelectric antenna performs axisymmetric vibrations and that the polarization of antenna's elements (hollow piezoelectric cylinders) is radial. The antenna is excited by a variable voltage $U = U_0 f(z)\exp(i\omega t)$, where $f(z)$ is the normalized voltage distribution along the generatrix of the extended cylindrical antenna. In the case of the zone lens under investigation, the following expressions are valid [4]:

$$f(z) = \begin{cases} 0, |z| > h_{n+1} \\ 1, z \in [-h_1; h_1], [h_2; h_3], [-h_3; -h_2], \ldots \\ -1, z \in]h_1; h_2[,]-h_1; -h_2[, \ldots \end{cases} \qquad (1)$$

$$h_n = \sqrt{(n - 1/4)\lambda_l F}$$

where λ_l is the longitudinal wavelength in rock and F is the focal length.

Equations of motion in terms of the displacement potential in the fluid φ, the longitudinal φ_l and transverse ψ displacement potentials in rock, relations between potentials, stresses σ_{rr}, σ_{rz} and displacements u_r, u_z are written down by ordinary way (see, e.g. [7]).

The following boundary condition is true at the boundary r_1 [6]:

$$\nabla\varphi + \frac{\rho_f \omega\varphi}{iZ_m} = \frac{U_0 f(z) n}{i\omega Z_m} \qquad (2)$$

where Z_m is the mechanical impedance of the antenna, n is the coefficient of electromechanical conversion, and ω is the angular frequency. The conditions of continuity for the normal components of displacements and stress and the equality to zero for tangential stress are satisfied at the boundary r_2:

$$u_r\Big|_{r_2} = \frac{\partial\varphi}{\partial r}\Big|_{r_2}; \quad \sigma_{rr}\Big|_{r_2} = -P_f\Big|_{r_2}; \quad \sigma_{rz}\Big|_{r_2} = 0 \qquad (3)$$

The problem on the radiation of a focusing extended uncompensated piezoelectric antenna within an uncased borehole filled with a fluid is determined using conditions Eqs. (1)-(3). The problem for the case of the radiation of a focused acoustic field from the borehole into rock through a casing pipe and a reinforcing cement ring can be formulated analogously. The boundary conditions that appear in addition to Eqs. (3) for this multilayer coaxial system are written down, e.g., in [7]. Moreover, Eq. (2) is obtained under the assumption that the antenna is uncompensated. Using the technique presented in [6], it is possible to obtain the boundary conditions for the cases of both a compensated piezoelectric antenna and antenna consisting of magnetostrictive units. A model problem (Eqs. (1)-(3)) is selected from the whole multiplicity of situations, because it demonstrates most simply and illustratively the special features of propagation of a focused front generated by an extended borehole antenna in rock.

3 Results and Discussion

The procedure of solving the diffraction problem formulated by Eqs. (1)-(3) is standard. The integral Fourier transformation with respect to the coordinate z is used for all system (Eqs (1)-(3), Equations of motion, relations between potentials, stresses and displacements). Than it is possible to obtain expressions for the displacements and stresses in rock that are produced by a focusing borehole antenna made in the form of a cylindrical zone lens.

The problem of matching the antenna described by Eq. (2) to rock through a liquid layer is investigated in [6], and the optimal relations between the parameters are obtained. In what follows, we assume that the antenna is optimally matched with rock. Analyzing the elastic fields, for the parameters characterizing the antenna and the rock, we use the numerical values that are given in [5, 6].

To simulate a zone lens, one has to use discontinuous conditions of the type of Eq. (1), but, since these conditions are set in an ideal fluid with zero shear stress, it is possible to avoid the difficulties associated with setting such conditions in an elastic medium.

Figure 2 presents the process of formation of the focal region for the displacement field that is produced by a cylindrical zone lens in rock. At the bottom of Fig. 2, the field distribution in the focal plane (in this case, the focal plane is considered to be perpendicular to the symmetry axis of the system and to contain the points *0* and *F* in the *r* coordinate) is given. The upper part demonstrates the field distribution along the generatrix of the cylindrical surfaces intersecting the focal plane. Thus, the focal region is a toroid.

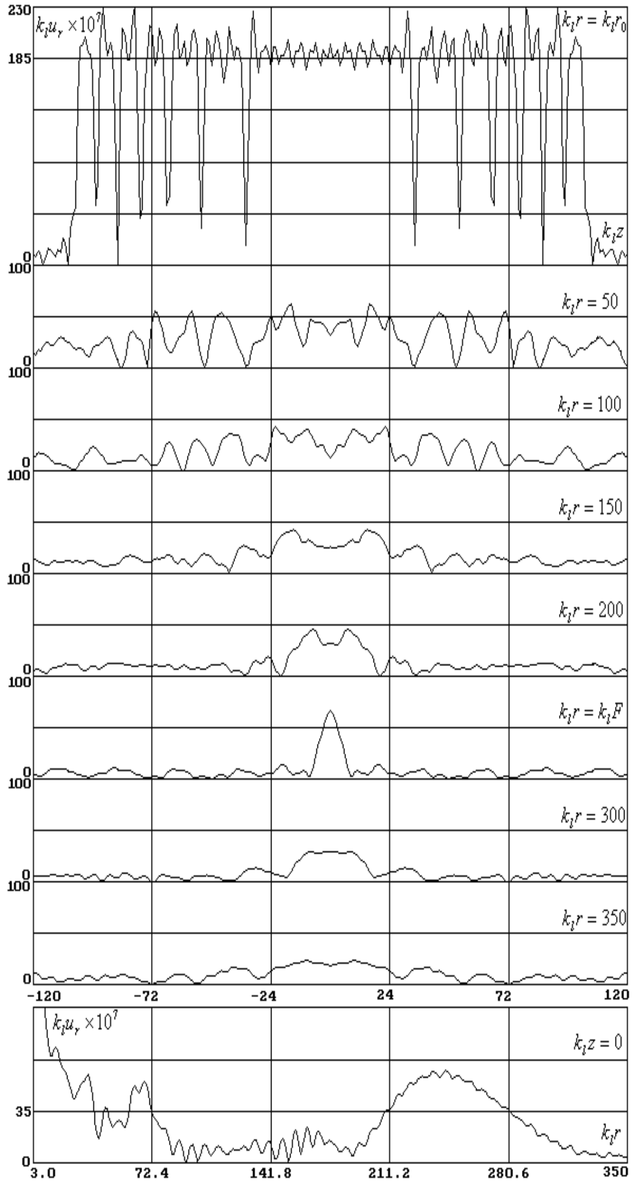

Fig. 2. Process of the formation of the focal region for the displacement field produced by a cylindrical zone lens in rock. A zone lens with seven Fresnel zones; $k_lF = 245$, $k_lh_7 = 100$, $k_lr_2 = 2.5$, and $U_0 = 300$ V.

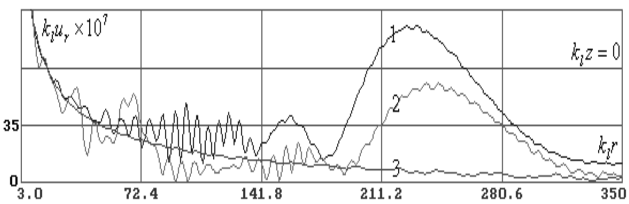

Fig. 3. Distribution of the field of radial displacements. (*1*) a spherical focusing distribution over the initial cylindrical aperture with the dimensions $2k_la = 200$ and $k_lF \sim 245$; (*2*) a cylindrical zone lens with $n = 7$, $k_lF = 245$, and $2k_lh = 200$; and (*3*) common cylindrical divergence, the initial aperture is $2k_la = 200$.

In the case considered above, the ratio of the radial displacement amplitudes at the focus and at the borehole wall is about 0.4, but here we can see a considerable compensation of cylindrical divergence. This fact is demonstrated in Fig. 3, where the fields of the radial displacements produced by a spherical focusing distribution over the initial cylindrical aperture, by a cylindrical zone lens, and by a common cylindrical divergence are given. The amplitude of the field produced by a cylindrical zone lens is an order of magnitude higher than the field amplitude characteristic of a common cylindrical divergence. The maximal focusing is produced by a spherical phase front (curve 1 in Fig. 3), but manufacture of borehole sources generating this kind of a front is very difficult. Apart from its simplicity, a cylindrical zone lens has one more advantage: in the case of a preset partition of the initial aperture into zones, it is possible to control the focus position in the focal plane (see Eq. (1)) by varying the radiation frequency. It is sufficiently difficult to make an effective antenna with a low quality factor. Moreover, in the process of frequency variation, the condition of antenna matching to rock may be violated. However, in some cases one can select such a relationship between the characteristic dimensions of the borehole and the acoustic source that the multifocus mode of radiation will be possible [5, 6]. Thus borehole zone lenses provide an opportunity to develop new technologies for acting with an acoustic field from the borehole on the geotechnological processes. On the one hand, these antennas provide an opportunity to treat selected regions of the near-borehole zone with the field that is highest possible from the point of view of effective radiation from the borehole; on the other hand, they allow one to scan with the focus over the near-borehole space (e.g., along the borehole axis by a simple motion of the antenna).

A narrowband borehole antenna consisting of a set of resonance transducers is a widely used instrument. If we fix the frequency, the focal length will change with the variation of the dimensions of the Fresnel zones at the initial cylindrical aperture. Figure 4 demonstrates the variation of the field of radial displacements in the focal region of a zone lens at a fixed frequency in the case of the focal length variation. As the focal length grows, the amplitude of radial displacements at the focus decreases as the amplitude of a cylindrically divergent wave.

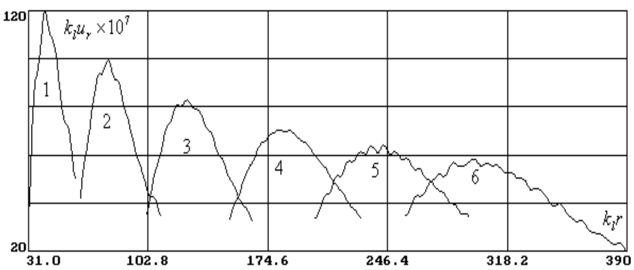

Fig. 4. Field of radial displacements in the focal region of a zone lens at a fixed frequency in the case of the variation of the focal length. A zone lens with seven Fresnel zones; (*1*) $k_lF =$ 41, (*2*) 79, (*3*) 125, (*4*) 181, (*5*) 245, and (*6*) 289. Dimensions of the Fresnel zones are determined by Eq.(1)

If one sets the frequency and the focal length, the field amplitude at the focus can be increased by increasing the number of the Fresnel zones. Figure 5 presents the amplitude variation for the field of radial displacements in the focal plane of a cylindrical zone lens in the case of variation of the number of the Fresnel zones.

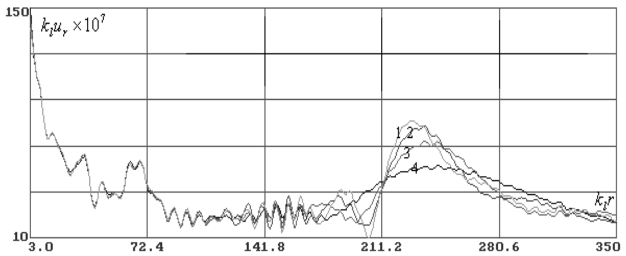

Fig. 5. Amplitude variation of the field of radial displacements in the focal plane of a cylindrical zone lens in the case of variation in the number of the Fresnel zones: n = (*1*) 17, (*2*) 13, (*3*) 9, and (*4*) 5; $k_l F$ = 245.

Variation of the field amplitude at the focus is proportional to the following expression:

$$k_l u_r \sim \sqrt{\pi/2k_l F}\left[1+\frac{2}{\pi}\sum_{m=1}^{n}(m-1/4)^{-1/2}+\frac{1}{\pi}(n+3/4)^{-1/2}\right] \quad (4)$$

The right-hand side of formula (4) was obtained theoretically and tested experimentally in [4] for the case of a medium without shear stress. In essence, this expression represents the factor of field amplification and holds for any n.

One can see in Fig. 5 a feature that is characteristic of the majority of focusing systems: as the amplification factor grows, the focus shifts towards the radiating aperture. However, it is necessary to note that it is difficult to introduce the factors of field amplification in the case of radiation into rock from a borehole through a liquid layer in the way similar to that used in [4]. This is connected with the fact that radiation and focusing occur in different media, and the displacement distribution at the borehole wall is sufficiently non-uniform along the antenna aperture (see Fig. 1). The most acceptable approach seems to be the comparison of the energy characteristics of the acoustic field radiated into the borehole and the elastic fields propagating in rock. The electric power consumed by the antenna is $W_e = U^2/R_{f\text{-}i}$, where U is the effective voltage and $R_{f\text{-}i}$ is the input resistance of the antenna; the radiated acoustic power is $W_a = W_e \eta_{ea}$, where η_{ea} is the efficiency of electro-acoustic conversion. The methods of measuring $R_{f\text{-}i}$ and estimating η_{ea} can be found in, e.g., [8]. If the antenna is filled uniformly with transducers and it is possible to ignore the fact that interaction between the transducers in structure and field leads to variation of the functions of amplitude and phase distributions over the initial aperture, it is possible to use the concept of the specific power of an antenna or the intensity $J_0 = W_e \eta_{ea}/S_a$, where S_a is the area of the antenna's active aperture. For example, in the process of preparing the experiment described in [5], the non-uniformity of amplitude and phase distribution over the aperture of borehole antennas was measured thoroughly. It turned out that this non-uniformity lies within the limits of 5%. This provided an opportunity to ignore the interaction of transducers while estimating the fields.

It is possible to demonstrate [9] that, in the case of an extended quasi-linear antenna, the total active power emitted into rock and the acoustic power at the vibrating surface of the antenna are equal. Taking this as the basis, it is possible to introduce the energy amplification factor K_F^J relating, for example, the initial intensity J_0 and the intensity transferred by the elastic field through the focus. The major part of energy is transferred through the focal region by the field of radial displacements. Estimates of the ratio between the total power of the radial displacement field and the total power of the tangential displacement field at the focal cylinder in the case of an antenna from [5] yields a value of ~ 12. The maximum intensity of both fields lies, naturally, in the focal region. Figure 6 presents the characteristic distributions of the intensities produced by a focusing zone lens in the focal plane (the intensity of the field of tangential displacements in the focal plane is zero) and at the focal cylinder. The distribution of the field of radial displacements for the same zone lens is given in Fig.2.

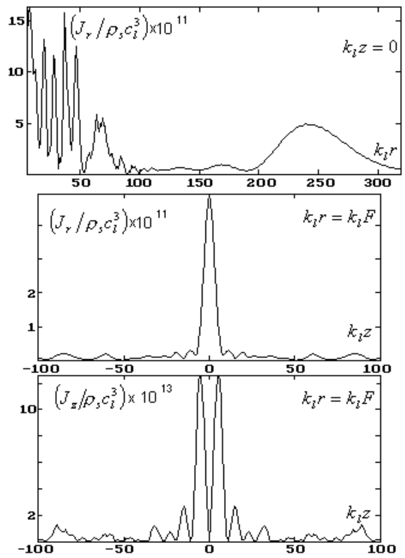

Fig. 6. Intensity distributions in the borehole region of a zone lens. A zone lens with seven Fresnel zones; $k_l F$ = 245, $k_l h7$ = 100, $k_l r_2$ = 2.5, and U_0 = 300V.

Thus, the value of K_F^J can with fair accuracy be represented in the form $K_F^J = J_F^r / J_0$, where J_F^r is the intensity of the field of radial displacements at the focus. For a harmonic case, J_F^r can be represented in the form: $J_F^r = -(i\omega/2)\sigma_{rr} u_r$.

Analysis shows the total power of the field of tangential displacements has an equally small value for all cross-sections. Thus, an extended borehole focusing antenna radiating into rock through a liquid layer can be considered to be a source of radial displacements. The main sound energy flux at the distance $k_l F$ from the borehole axis is concentrated in a narrow toroidal region extended along the r axis, and this flux is directed along the same axis. A numerical experiment shows that, if the condition $F > h_n$ and $F >> r_2$ is satisfied, the value of K_F^J can be estimated using the expression which is in its essence the square of Eq. (4). If the number of zones increases, the value of $K_F^J(n)$ grows slowly. For example, at $k_l F$ = 125, we have $K_F^J(7) = 0.176$, $K_F^J(8) = 0.194$, and $K_F^J(9) = 0.212$; at $k_l F$ = 245, we have $K_F^J(7) = 0.093$, $K_F^J(8) = 0.103$, and $K_F^J(9) = 0.114$. This slow growth is characteristic of diffraction focusing [4]. In addition, estimates does not take into account the factors connected with damping of elastic fields in rock. Therefore, the values of

$K_F^J(n)$ obtained from Eq. (4) can be considered as the limiting values of this coefficient. If one knows the damping decrement of longitudinal waves in rock *d*, the dissipation of elastic energy in rock can be taken into account by multiplying $K_F^J(n)$ by exp($-2dr/\lambda_l$).

It follows from the experience in designing borehole zone lenses that antennas consisting of 5-9 zones are most practicable. For example, seven-zone lenses with the limiting coefficient $K_F^J(7) \approx 0.1$, $k_l F \sim 250$ ($F \sim 5$ m) were used in experiments on intensification of geotechnological processes [5]. The intensities $J_0 \sim 1.1$ W/cm^2 were reached at the initial aperture in [5], and the measured damping decrement for longitudinal waves was d ~ $1.5 \cdot 10^{-3}$, which provides an opportunity to estimate J_F^r in the experiment [5]: $J_F^r \sim 0.1$ W/cm^2.

The radiation frequencies for effective focusing borehole antennas occupy the range from units to tens of kilohertz (at the average velocities of longitudinal waves in sedimentary rock from 2 to 4 km/s). At lower frequencies, the dimensions of antennas are very large, which hinders their use in boreholes. In the case of higher frequencies, damping in rock becomes significant, which limits the region of acoustic field action. It is desirable that the condition $L_d \geq F$ be satisfied, where L_d is the decay length of acoustic wave in rock. This condition also imposes limitations on the focal length. Damping decrements in productive rock are usually on the order of 10^{-2}-10^{-3}, and, therefore the focal lengths $F \sim$ 10-15m are attainable. However, as a rule, it is useless to treat a producing rock at these distances. Most frequently, treatment of a borehole zone (the critical area of the productive formation) is performed for improving the filtration characteristics. It is known that the law of pressure distribution between the external boundary and the borehole is of a logarithmic character, and, in this case, the major part of pressure difference is applied to a narrow zone near the borehole (see [15], for example). The permeability of precisely this zone determines the well yield. In most cases, the size of the critical area does not exceed several meters. This determines the required focal lengths for the focusing borehole antennas: $1 \leq F \leq 5$ m, which is quite possible from the practical point of view.

4 Conclusion

In conclusion, it is necessary to note that it is possible to develop efficient techniques for diagnostics of near-borehole space with the help of focusing borehole antennas. A method for measuring the elastic nonlinear parameters of a geological medium beyond the anomalous zone of a borehole with the use of a focused front was discussed in detail in [5]. Here, we would like to draw attention to the possibility of diagnostics and investigation of certain geotechnological processes with the help of focused fronts. In the experiments on underground leaching that were described in [5], it was noticed that the concentration of the useful component in the pumped solution under the action of a focused acoustic field depends on time in such a way that it is possible to evaluate the filtration rate by the time dependence of concentration. The contrast character of the elastic field in the borehole zone leads to the fact that the regions with a relatively high field intensity can lie at a distance of several meters from each other; for example, such may be the region located immediately near the borehole and the focal region. If it were possible to relate this fact to the varying parameters of the pumped fluid, it would be possible to develop a technique for a continuous or express diagnostics of an acoustically intensified geotechnological process.

Acknowledgments

This work was supported by the ISTC (project No 2590) Russian Foundation for Basic Research (project No. 08-02-99046) and the Presidential Program in Support of the Leading Scientific Schools (grant No. NSh-1055.2008.2).

References

[1] *Proceedings of the First Conference on Elastic-Wave Stimulation of Fluid Flow in Porous Media, Gubkin Oil and Gas University, Moscow, 2002*.

[2] D. A. Kas'yanov, "Divergent Cylindrical Wave Focusing", *Akust. Zh.* 39, 1076-1087 (1993) [*Acoust. Phys.* 39, 566-571 (1993)].

[3] D. A. Kas'yanov, "Divergent Cylindrical Wave Focusing II" *Akust. Zh.* 40, 76-83 (1994) [*Acoust. Phys*. 40, 56-70 (1994)].

[4] D. A. Kas'yanov, "Cylindrical Zone Lens" *Izv. Vyssh. Uchebn. Zaved., Radiofiz.* 43, 782-792 (2000) [*Radiophysics and Quantum Electronics* 43, 701-710 (2000)]

[5] D. A. Kas'yanov and G. M. Shalashov, "Focusing of Divergent Cylindrical Waves and the Prospects for Borehole Acoustics" *Izv. Vyssh. Uchebn. Zaved., Radiofiz*. 45, 170-186 (2002) [*Radiophysics and Quantum Electronics*, 45, 153-167 (2002)].

[6] D. A. Kas'yanov, "Extended piezoceramic antenna radiating in a borehole" *Izv. Vyssh. Uchebn. Zaved., Radiofiz.* 46, 111-122 (2003) [*Radiophysics and Quantum Electronics*, 46, 98-108 (2003)]

[7] P. V. Krauklis and L. A. Krauklis, "About spectrum of longitudinal wave in a borehole with cemented casing pipe" *Problems of the Dynamic Theory of Seismic Wave Propagation,* 17, 156–164 (Nauka, Leningrad, 1976), [in Russian].

[8] L. V. Orlov and A. A. Shabrov, *Underwater Acoustic Instrumentation of the Fishing Fleet* (Sudostroenie, Leningrad, 1987) [in Russian].

[9] V. N. Krutin, "Power ratios for elastic waves radiating from borehole" in *New Geoacoustic Methods of Prospecting and Exploration of Mineral Deposits* (VNIIYaGG, Moscow, 1982), pp. 76–88 [in Russian].

[10] T. I. Barenblatt, V. M. Ezhov, and V. M. Ryzhik, *Motion of Liquids and Gases in Natural Strata* (Nauka, Moscow, 1984) [in Russian].