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POSSIBILITY OF DETERMINING THE QUALITY OF WELL PERFORATION BY LOCAL ACOUSTIC PROBING

V. Sh. Shagapov,[1] I. G. Khusainov,[2] and A. A. Ishmukhametova[2]

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A theoretical problem of local acoustic probing of a perforated segment of the well is considered. The effect of porosity and permeability of the porous medium surrounding the well and the quality of perforation (porosity, length, and radius of perforation channels) on the velocity and the coefficient of decay of harmonic waves and on the evolution of finite-duration waves propagating in the perforated segment is studied.

Key words: *acoustic probing, perforated well, perforation channels.*

Introduction. Geophysical investigations of wells in operation or under commissioning are the main source of information for studying, controlling, and optimizing the processes of development of oil and gas deposits. Wells and rocks around them are often studied by methods based on the fact that the acoustic characteristics of rocks are functionally dependent on their physicomechanical properties, porosity, structural features, and character of saturation.

For real-time monitoring of the state of the borehole zone of the well before and after its treatment, it was proposed [1–3] to use acoustic methods that take into account the specific features of the evolution of wave pulses propagating over the fluid inside the well.

The objective of the present activities is to study the influence of the quality of well penetration by means of radial perforation on the evolution of acoustic signals in the fluid that fills the gap between the surfaces of the probe body and the well wall.

1. Propagation of Linear Waves in the Perforated Segment of the Well. Let the payout bed be connected with the well hole in a cased well through orifices made in the casing string. The process of creating such orifices is called perforation. One of the perforation methods implies that the orifices in the casing string are made by bullets shot from the perforator shafts; as a result, radial tubular channels are obtained. The bullet penetration depth inward the payout bed depends on the strength properties of the porous medium surrounding the well.

Let a cylindrical probe of radius a_s and length L be placed into a cased well (Fig. 1) of radius a. The axes of the probe and the well coincide with each other. A source D1 and detectors D2 and D3 of acoustic signals are mounted into the probe surface. The channels formed after perforation on the well surface are assumed to be uniformly distributed with a density n per unit area and have identical length l and radius b. Let us make the following assumptions: the gap between the probe and the well wall, the tubular channels, and the ambient permeable space are filled by the same acoustically compressible fluid; the skeleton of the porous medium is incompressible; the probe length L is much greater than the wave length λ ($L \gg \lambda$), which, in turn, is greater than the thickness of the gap between the probe body and the well wall ($\lambda > a - a_s$) and also greater than the distance between two neighboring channels. In addition, we neglect the effect of fluid viscosity on the decay of the pulse in the gap between the probe body and the well wall (the signal evolution is mainly determined by effects of filtration from perforation channels into the ambient porous space).

[1]Institute of Mechanics, Ufa Scientific Center, Russian Academy of Sciences, Ufa 450054. [2]Sterlitamak State Pedagogical Academy, Sterlitamak 453103; mslika@yandex.ru. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 50, No. 1, pp. 52–57, January–February, 2009. Original article submitted November 6, 2007; revision submitted December 27, 2007.

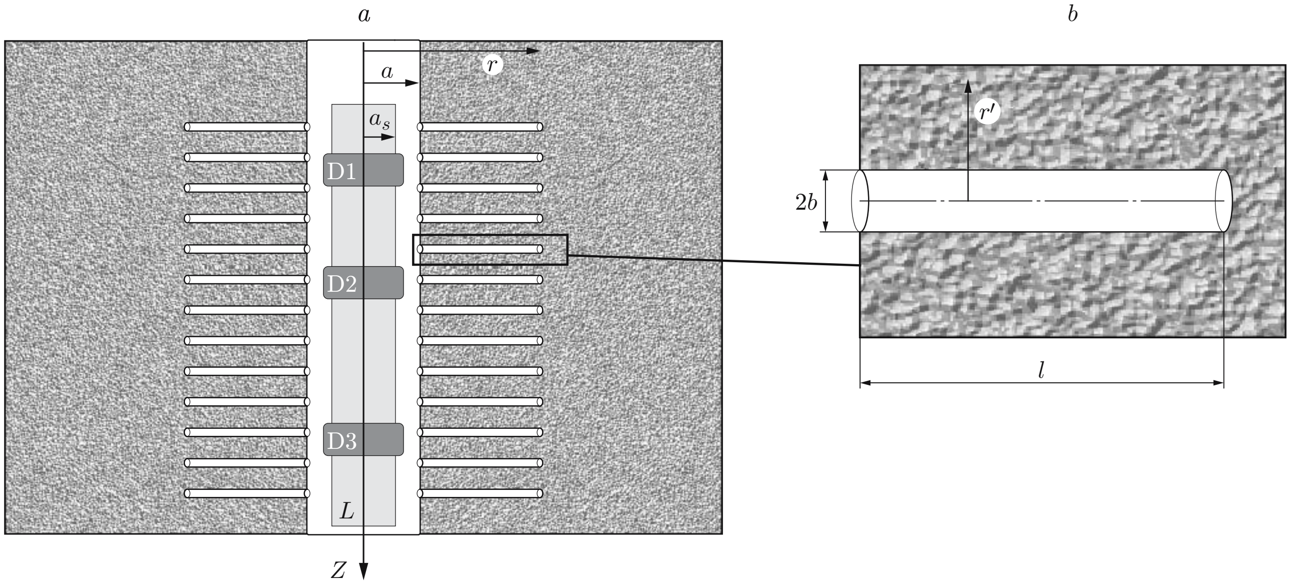

Fig. 1. Sketch of the perforated segment of the well with a cylindrical probe (a) and tubular channel (b).

To describe wave propagation in the fluid in the gap between the well wall and the probe, we write the equations of continuity, momentum, and state in the form

$$\frac{\partial \rho}{\partial t} + \rho_0 \frac{\partial v}{\partial z} = -\frac{2\pi a n b^2 \rho_0}{a^2 - a_s^2}\, u, \qquad \rho_0 \frac{\partial v}{\partial t} = -\frac{\partial p}{\partial z}, \qquad p = C^2 \rho, \tag{1}$$

where ρ and p are the perturbations of density and pressure of the fluid, respectively, ρ_0 is the density of the fluid in an undisturbed state, v is the velocity of the fluid in the gap between the probe body and the well wall, u is the velocity of fluid overflow from the well to the radial tubular channels, and C is the velocity of sound in the fluid. The right side of the continuity equation describes the process of sink (inflow) of the fluid from (to) the well through the radial perforation channels during wave propagation.

To determine the velocity of fluid overflow from the well u, we write the equation of conservation of fluid mass inside the perforation channel in the form

$$\pi b^2 l \frac{\partial \rho}{\partial t} = \rho_0 \pi b^2 u - 2\pi b l \rho_0 \tilde{u}. \tag{2}$$

Based on the solution of the equation of piezoconductivity and Darcy law for fluid filtration from these channels to the ambient porous medium, we determine the rate of fluid filtration through the channel walls $\tilde{u}$:

$$\frac{\partial p'}{\partial t} = \chi \frac{1}{r'} \frac{\partial}{\partial r'}\Big(r' \frac{\partial p'}{\partial r'}\Big), \qquad \tilde{u}' = -\frac{k}{\mu} \frac{\partial p'}{\partial r'} \qquad \Big(\chi = \frac{k C^2 \rho_0}{\mu m}\Big). \tag{3}$$

Here μ is the fluid viscosity, m and k are the coefficients of porosity and permeability of the porous medium surrounding the well, χ is the coefficient of piezoconductivity, p' and $\tilde{u}'$ are the distributions of pressure and filtration rate around the channel, and r' is the radial coordinate.

Using the condition of continuity of velocity and pressure on the boundary $r' = b$, we write the following boundary conditions for Eqs. (3):

$$\tilde{u}' = \tilde{u}, \qquad p' = p \qquad (r' = b).$$

For the second boundary condition for the piezoconductivity equation (3), we consider two limiting cases: 1) the depth of penetration of the pressure waves r'_ω is smaller than the mean distance between the neighboring channels r_*; hence, the filtration flows of the fluid from two neighboring perforation channels weakly interact with each other; 2) the value of r'_ω is comparable with the value of r_* or exceeds the latter. We assume that there are identical pressure fields around the neighboring channels and there is no overflow of the fluid through the boundary between the neighboring channels. For these cases, the boundary conditions can be written as

$$p' = 0 \qquad (r' = \infty) \tag{4}$$

or

$$\frac{\partial p'}{\partial r'} = 0 \qquad (r' = r_*). \tag{5}$$

Let us take a half of the mean distance between the bases of the perforation channels on the well surface as the quantity r_*. Then, under the assumption that the perforation channels are uniformly distributed with a density n per unit area, we obtain $r_* = 0.5\sqrt{1/n}$.

We seek for the problem solution in the form of a traveling harmonic wave:

$$\begin{gathered} p = A_p \exp{(iKz - i\omega t)}, \qquad v = A_v \exp{(iKz - i\omega t)}, \qquad u = A_u \exp{(iKz - i\omega t)}, \\ p' = A_{p'}(r') \exp{(iKz - i\omega t)}, \qquad \tilde{u}' = A_{\tilde{u}'}(r') \exp{(iKz - i\omega t)} \qquad (b < r'). \end{gathered} \tag{6}$$

Here K and ω are the complex wavenumber and the circular frequency of perturbations, respectively.

Substituting Eq. (6) into Eqs. (1)–(3) and performing appropriate transformations, we obtain a system of equations relating the amplitudes p, p', and $\tilde{u}$:

$$A_u = -i\,\frac{a^2 - a_s^2}{2\pi anb^2\omega}\Big(K^2 - \frac{\omega^2}{C^2}\Big)A_p, \qquad A_p = i\,\frac{C^2}{\omega}\,\rho_0\Big(\frac{A_u}{l} + 2\,\frac{k}{b\mu}\Big(\frac{dA_{p'}}{dr'}\Big)\Big|_{r'=b}\Big). \tag{7}$$

For the amplitude of the pressure distribution in the fluid around the perforation channel, we obtain the Bessel equation

$$\frac{d^2A_{p'}}{dr'^2} + \frac{1}{r'}\,\frac{dA_{p'}}{dr'} - q^2A_{p'} = 0 \qquad \Big(q^2 = -\frac{i\omega}{\chi}\Big).$$

For the pressure amplitudes, the boundary conditions (4) and (5) yield

$$A_{p'} = A_p \qquad (r' = b); \tag{8}$$

$$A_{p'} = 0 \quad (r' = \infty_*) \quad \text{or} \quad \frac{dA_{p'}}{dr'} = 0 \quad (r' = r_*). \tag{9}$$

With allowance for Eqs. (8) and (9), we obtain the following dispersion expression from system (7):

$$K = \frac{\omega}{C}\sqrt{1 + \frac{2\pi anb^2l}{a^2 - a_s^2} - i\,\frac{4\pi anlC^2ky}{\omega\nu(a^2 - a_s^2)}\,\Psi(y)} \qquad \Big(y = \sqrt{-\frac{i\omega b^2}{\chi}}\Big) \tag{10}$$

($\nu = \mu/\rho_0$ is the kinematic viscosity of the fluid). Depending on the boundary conditions (8) and (9), the function $\Psi(y)$ is determined, respectively, by the formulas

$$\Psi(y) = -\frac{K_1(y)}{K_0(y)} \quad \text{or} \quad \Psi(y) = \frac{K_1(y_*)I_1(y) - I_1(y_*)K_1(y)}{K_1(y_*)I_0(y) + I_1(y_*)K_0(y)} \quad \Big(y_* = \sqrt{-\frac{i\omega r_*^2}{\chi}}\Big).$$

Here $K_\gamma(y)$ is the MacDonald function and $I_\gamma(y)$ is the Bessel function of the first kind of the order γ. The phase velocity C_p and the decay coefficient δ of the pressure waves are determined by the formulas $C_p = \omega/\operatorname{Re}(K)$ and $\delta = \operatorname{Im}(K)$.

It follows from the dispersion relation that the dependence of the wavenumber on the geometric parameters of the well and the probe and also on the quantities b, l, and n responsible for the quality of well penetration is expressed by the complex of parameters $anlb/(a^2 - a_s^2)$. The channel radius is determined by the bullet size, and the density of the channels is determined by the type of the perforator [4]. Hence, the unknown quantity responsible for the quality of well penetration is the perforation depth l.

An analysis of the dependence of the phase velocity C_p and the coefficient of decay of acoustic disturbances δ in the gap between the probe and the well on frequency on the basis of Eq. (10) was performed with the following values of parameters of the well, probe, fluid, and porous medium: $a = 6 \cdot 10^{-2}$ m, $a_s = 4 \cdot 10^{-2}$ m, $n = 100$ m^{-2}, $b = 4 \cdot 10^{-3}$ m, $L = 2$ m, $C = 1500$ m/sec, $\nu = 1.06 \cdot 10^{-6}$ m^2/sec, $k = 10^{-12}$ m^2, and $m = 0.1$. For these values of parameters, we determined the range of frequencies where Eq. (10) is applicable. Under the assumptions made, we obtained $\lambda > a - a_s$ and $\lambda > r_*$. As we had $a - a_s = 0.02$ m and $r_* \simeq 0.1$ m for the parameters used in the

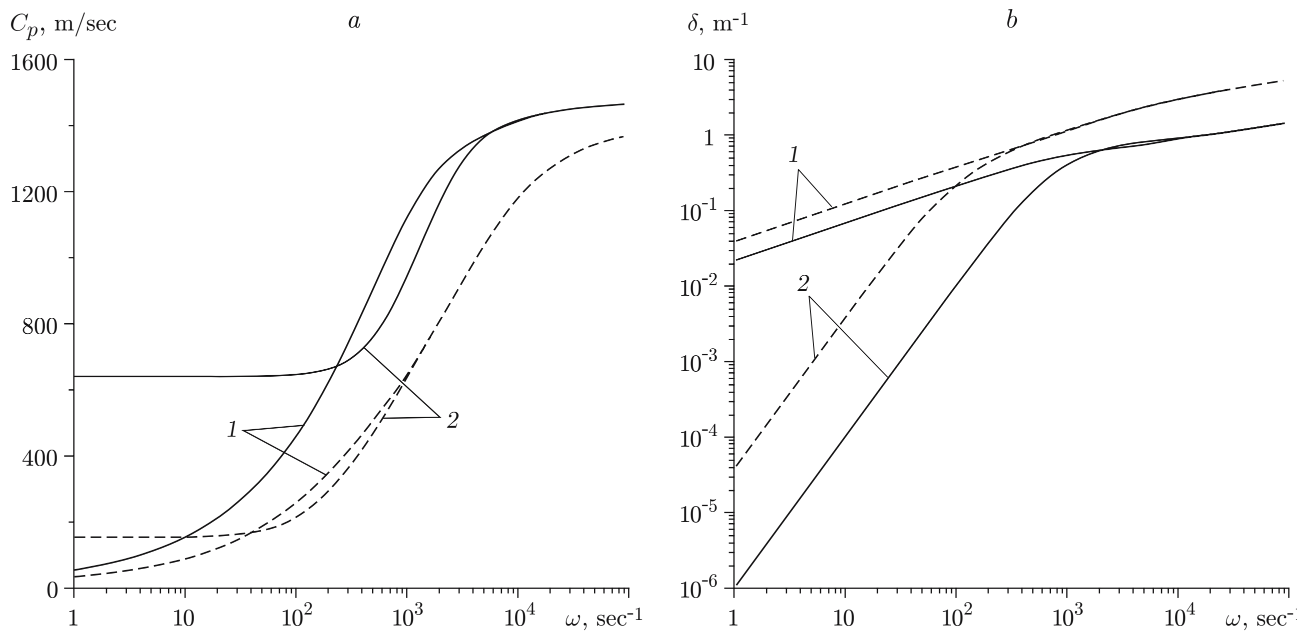

Fig. 2. Phase velocity (a) and decay coefficient (b) of harmonic pressure waves versus frequency: the solid and dashed curves refer to $l = 0.1$ and 0.4 m, respectively; curves 1 and 2 show the solutions obtained with the boundary conditions (4) and (5), respectively.

study, the wave length was $\lambda > 0.1$ m. Taking into account that $\lambda \simeq 2\pi C/\omega$, we obtained the condition for the perturbation frequency: $\omega < \omega_d$ ($\omega_d \approx 2\pi C/r'_* \approx 10^5$ sec^{-1}).

Figure 2 shows the phase velocity and the decay coefficient of acoustic perturbations in the gap between two coaxial channels as functions of frequency. It follows from Fig. 2 that the perforation depth l exerts a significant effect on the presented dependences, especially on the decay coefficient δ. In particular, at high frequencies ($\omega \geqslant 10^3$ sec^{-1}), the decay coefficient increases approximately by a factor of 4 with a four-fold increase in the perforation depth.

A decrease in the phase velocity and decay coefficient of the waves propagating in the fluid in the perforated segment of the well occurs owing to fluid overflow from the well to the perforation channels and fluid filtration through the side surface of the channels into the ambient porous space.

The depth of penetration r'_ω of filtration waves with a frequency ω into the porous space is determined by the formula $r'_\omega = \sqrt{\chi/\omega}$. If the boundary condition (4) is used, we have $r'_\omega \gg r_*$ for low frequencies ($\omega < 10^3$ sec^{-1}); hence, the perturbation propagates mainly in the radial direction, and the phase velocity along the z coordinate is small. If the boundary condition (5) is imposed, the depth of wave penetration into the porous space is bounded by the distance r_*; therefore, the perturbation penetrates only to the depth r_*, despite that fact that $r'_\omega > r_*$ for $\omega < 10^3$ sec^{-1}. As the pressures inside the perforation channels and in the ambient porous medium become rapidly equalized, the phase velocity at low frequencies is independent of frequency, and the decay coefficient is directly proportional to the latter.

For high-frequency waves ($\omega \geqslant 10^3$ sec^{-1}), we have $r'_\omega < r_*$; hence, the results obtained under the boundary conditions (4), (5) almost coincide.

2. Evolution of Pulsed Perturbations. Let us consider the propagation of finite-length waves in the gap between the probe and the well. Let the detector D1 register the initial bell-shaped pressure pulse, which is described by the expression

$$p^{(0)}(t) = \Delta p_0 \exp\left(-(t - t_m)^2/(t_*/2)^2\right).$$

Here t_* and t_m are the characteristic length of the pulse and the time instant when the maximum amplitude of the initial pulse is reached.

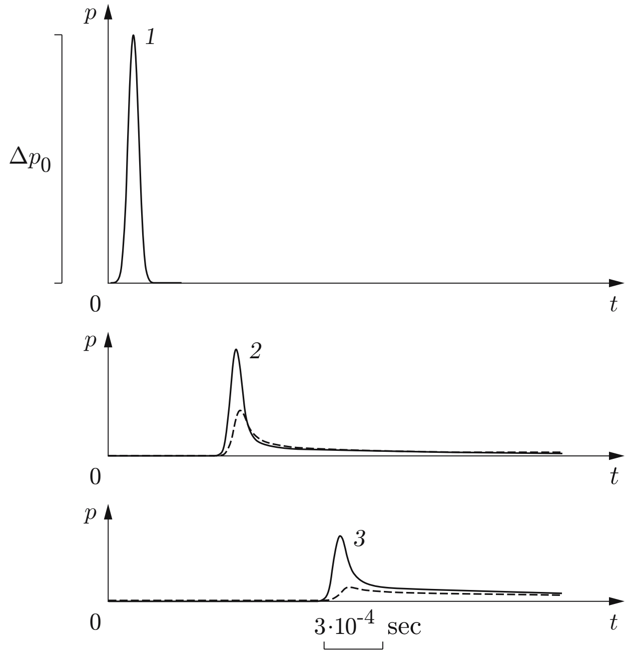

Fig. 3. Evolution of the pulse of the pressure waves versus the depth of the perforation channel for $k = 10^{-12}$ m^2, $m = 0.1$, and $b = 0.004$ m: the solid and dashed curves refer to $l = 0.1$ and 0.2 m, respectively; curve 1 shows the initial signal registered by the detector D1 ($z = 0$) and curves 2 and 3 show the signals registered by the detectors D2 ($z = 1$ m) and D3 ($z = 2$ m), respectively.

Let us consider the pressure pulses whose duration satisfies the condition $t_* < L/(2C_p)$. If this condition is fulfilled, it means that the spatial length of the pulse is smaller than $L/2$, which is the distance between two neighboring detectors.

The results calculated by the fast Fourier transform [5] for the pressure pulse evolution are plotted in Fig. 3. The pulse duration corresponds to the value $t_* = 3 \cdot 10^{-4}$ sec. The calculated oscillograms under the boundary conditions (4) and (5) are almost coincident, because such pulses are rather short, and the filtration perturbations between the neighboring perforation channels do not interact with each other.

Figure 3 shows the effect of the parameter l determining the perforation depth on the pulse evolution. It is seen that the pulse signal decay depends essentially on the depth of the perforation channel. A two-fold increase in the parameter l leads to additional decay of the pulse amplitude by more than a factor of 2 at a distance equal to 1 m and by a factor of 5 at a distance equal to 2 m. As the quality of well penetration due to perforation is determined by the value of the parameter l, the results obtained allow us to conclude that the method that takes into account the influence of the perforation depth on the decay of pulse perturbations can be used for express monitoring of the quality of well penetration.

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