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Acoustic reflection log in transversely isotropic formations

G. Ronquillo Jarillo, I. Markova, M. Markov *

Instituto Mexicano del Petróleo, Eje Central Lázaro Cárdenas Norte 152, C.P. 07730 México, DF, Mexico

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ABSTRACT

We have calculated the waveforms of sonic reflection logging for a fluid-filled borehole located in a transversely isotropic rock. Calculations have been performed for an acoustic impulse source with the characteristic frequency of tens of kilohertz that is considerably less than the frequencies of acoustic borehole imaging tools.

It is assumed that the borehole axis coincides with the axis of symmetry of the transversely isotropic rock. It was shown that the reflected wave was excited most efficiently at resonant frequencies. These frequencies are close to the frequencies of oscillations of a fluid column located in an absolutely rigid hollow cylinder. We have shown that the acoustic reverberation is controlled by the acoustic impedance of the rock $Z = Vp_h \rho_s$ for fixed parameters of the borehole fluid, where Vp_h is the velocity of horizontally propagating P-wave; ρ_s is the rock density. The methods of waveform processing to determine the parameters characterizing the reflected wave have been discussed.

1. Introduction

The acoustic field generated by a source of elastic waves contains a huge amount of information about the physical properties of rocks (Mavko et al., 2009; Vernik, 2016). Conventional logging tools are destined mainly for the measurement of velocities and attenuations of elastic waves in boreholes (Ivakin et al., 1978; Paillet and Cheng, 1991; Brie et al., 1998; Tang and Cheng, 2004; Arroyo Franco et al., 2006; Haldorsen et al., 2006; Baron and Holliger, 2010). In the 80s of the last century, a development of a new type of acoustic logging tools destined to measure parameters of the waves reflected from the borehole wall was started. For measurements, fixed-frequency sources of monochromatic oscillations were being used. After turning off the source, the time, within which the signal amplitude decreases a given amount of times, is measured. The source frequency bands used lie within the first dozens of kilohertz (10–30 kHz). The main purpose of these tools is the measurement of the acoustic impedance of the borehole wall and acoustic reverberation time of the borehole (Krutin et al., 1978; Goutsaliuk, 1979). It should be noted that the tools of this type are considerably different from the well-known acoustic borehole scanner (acoustic televiewer), because the acoustic TV is destined to obtain a borehole wall image. In the case of acoustic televiewer, high-frequency (above 500 kHz) sonic impulses are emitted, and an image of the borehole wall is generated. Using lower frequencies (10 and more times lower compared to the acoustic TV frequencies) allows us to decrease the influence of the absorption in the borehole fluid and the borehole walls irregularities on the acoustic signal parameters, as well as to increase the penetration depth of the waves.

In the tools considered for modeling in the works by Krutin et al. (1978); Goutsaliuk (1979), the emitters are much longer than those used in acoustic borehole scanners. These long emitters generate oscillations of considerably lower frequencies (tens of kHz). Because of the focusing system, such emitters generate a quasi-cylindrical wave (discussion of this lies outside the scope of the present work). As a rule, in such a measurement system, the acoustic source is used as a receptor of acoustic oscillations.

In the work of Krutin et al. (1986), the acoustic reverberation time of a borehole in a saturated porous medium was estimated. A simplified model was proposed: an acoustic source of infinite length in time-harmonic regime. The authors have shown that the acoustic reverberation time of a borehole depends on the rock permeability.

In the paper by Markov et al. (2014), the problem of acoustic reverberation time determination was considered for an impulse axisymmetric source of a finite length in a porous fluid-saturated formation. In the paper (Markov et al., 2015), the reflected acoustic field was calculated for a multipole acoustic source located in open or cased borehole. All the above mentioned results were obtained for isotropic rocks, meanwhile, many rocks are anisotropic (White, 1983; Mavko et al., 2009; Vernik, 2016). Nowadays it is possible to detect intervals containing systems of subvertically oriented cracks by using cross-dipole acoustic log data (Sinha and Kostek, 1996; Tichelaar and Hatchell, 1997; Tang and Chunduru, 1999). Unfortunately, this method is not applicable in certain cases, as in the case where the anisotropy is caused by the presence of layered clay, interlayered fine-grained rocks or sub horizontal cracks (Market et al., 2015).

* Corresponding author.
E-mail addresses: gronqui@imp.mx (G. Ronquillo Jarillo), imarkova@imp.mx (I. Markova), mmarkov@imp.mx (M. Markov).

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The objective of the present work is to investigate the field of the elastic wave reflected from the wall surface of a borehole located in a transversely isotropic medium. We present the synthetic microseismograms for a borehole containing an acoustic impulse source with the characteristic frequency of tens of kilohertz that is considerably less than the frequencies of acoustic borehole imaging tools. In the second section of this article we give a short description of the model used to calculate synthetic microseismograms. Numerical results are presented in the third section. In the fourth section of the paper we discuss a method of sonic reflection log data processing based on the determination of acoustic signal decay in the borehole. In this section the dependences between the reflected wave characteristics and rock elastic properties are considered.

2. Acoustic field generated by an axisymmetric source in a borehole located in a transversely isotropic medium

Let us consider a system: linear acoustic source – infinite borehole filled with a compressible fluid – transversely isotropic elastic medium. The linear axisymmetric acoustic source is located on the axis of symmetry of the borehole (Z-axis).

The propagation of elastic waves in the fluid-filled borehole is described by the equation:

$$\Delta\varphi_f = \frac{1}{c^2}\ddot{\varphi}_f, \tag{1}$$

where φ_f is the displacement potential of the compressional wave in the borehole fluid; c is the compressional wave velocity in the fluid, $c = 1/\sqrt{\beta_f\,\rho_f}$; β_f and ρ_f are the compressibility and the density of the borehole fluid, respectively. The fluid displacement $\mathbf{W}$ satisfies Eq. (2):

$$\mathbf{W} = \nabla\varphi_f. \tag{2}$$

In the frequency domain, this potential satisfies the Helmholtz equations, and in the time domain, it is described by the following expression (Tang and Cheng, 2004; Markova et al., 2011):

$$\varphi_f(r,z,t) = \int_{-\infty}^{\infty} d\omega \int_{-\infty}^{\infty}\left[P_0 f(k_z)K_0\left(k_r^f r\right) + X_1 I_0\left(k_r^f r\right)\right]S(\omega)\,\exp[i(k_z z - \omega t)]dk_z, \tag{3}$$

where P_0 is the emitted impulse amplitude; $\omega = 2\pi f$ is the angular frequency; $f(k_z)$ is the space spectrum of the source (Kurkjian and Chang, 1983), for a point source $f(k_z) = 1$; $S(\omega)$ is the frequency spectrum of the source; $I_0(z), K_0(z)$ are the modified Bessel functions of the first and second kinds; $k_r^f = \sqrt{k_z^2 - \omega^2/c^2}$ is the radial wave number; X_1 is the amplitude of the reflected wave; X_1 is a function of the radial wave number and the angular frequency.

Usually, the parameter measured is the acoustic pressure P in the borehole fluid. Its Fourier transform $p(\omega)$ is related to the Fourier transform of the potential $\tilde{\varphi}_f$ by the equation:

$$p(\omega) = -\omega^2\rho_f\tilde{\varphi}_f(\omega). \tag{4}$$

The wave equations for transversely isotropic media in cylindrical coordinates are (White and Tongtaow, 1981):

$$\begin{aligned}\rho_s\frac{\partial^2 U_r}{\partial t^2} &= \frac{\partial\sigma_{rr}}{\partial r} + \frac{\sigma_{rr} - \sigma_{\theta\theta}}{r} + \frac{\partial\sigma_{rz}}{\partial r},\\ \rho_s\frac{\partial^2 U_z}{\partial t^2} &= \frac{\partial\sigma_{zr}}{\partial r} + \frac{\sigma_{rr}}{r} + \frac{\partial\sigma_{zz}}{\partial r},\end{aligned} \tag{5}$$

where ρ_s is the density of the solid phase; U_r, U_z are the radial and tangential components of the displacement vector. Hooke's law has the form:

$$\begin{aligned}\sigma_{\theta\theta} &= (C_{11} - 2C_{66})e_{rr} + C_{11}e_{\theta\theta} + C_{33}e_{zz},\\ \sigma_{rr} &= C_{11}e_{rr} + (C_{11} - 2C_{66})e_{\theta\theta} + C_{13}e_{zz},\\ \sigma_{rz} &= C_{44}e_{rz},\\ \sigma_{zz} &= C_{13}e_{rr} + C_{13}e_{\theta\theta} + C_{33}e_{zz},\end{aligned} \tag{6}$$

where C_{ij} are the components of the Voigt stiffness matrix; e_{ij} are the components of the tensor of deformations (Mavko et al., 2009).

We calculate the displacement vector $\mathbf{U}$ using the decomposition in the frequency domain (White, 1983):

$$\mathbf{U}(\omega) = \nabla\varphi_s + \nabla\times\mathbf{\Psi}_s, \tag{7}$$

where $\varphi_s(\omega)$ and $\mathbf{\Psi}_s(\omega)$ are the scalar and vector potentials of the displacement:

$$\varphi_s(\omega) = \int_{-\infty}^{+\infty}[X_2K_0(mr) + bX_3K_0(lr)]\,\exp(ik_z z)dk_z, \tag{8}$$

$$\mathbf{\Psi}_s(\omega) = \mathbf{n_z}\int_{-\infty}^{+\infty}[aX_2K_1(mr) + X_3K_1(lr)]\,\exp(ik_z z)dk_z, \tag{9}$$

and

$$m = \omega\sqrt{\frac{-B + \sqrt{B^2 - 4DE}}{2D}},\ l = \omega\sqrt{\frac{-B - \sqrt{B^2 - 4DE}}{2D}},\ D = C_{11}C_{44},$$

$$B = \left(C_{11}C_{33} - C_{13}^2 - 2C_{13}C_{44}\right)\left[\frac{\rho_s(C_{11} + C_{44})}{C_{11}C_{33} - C_{13}^2 - 2C_{13}C_{44}} - \left(\frac{k_z}{\omega}\right)^2\right],$$

$$E = C_{44}C_{33}\left[\frac{\rho_s}{C_{44}} - \left(\frac{k_z}{\omega}\right)^2\right]\left[\frac{\rho_s}{C_{33}C} - \left(\frac{k_z}{\omega}\right)^2\right],$$

$$a = \frac{-m}{ik_z}\frac{(C_{13} + 2C_{44})k_z^2 - C_{11}m^2 - \rho_s\omega^2)}{C_{44}k_z^2 - (C_{11} - C_{13} - C_{44})m^2 - \rho_s\omega^2},$$

$$b = \frac{-ik_z}{l}\frac{C_{44}k_z^2 - (C_{11} - C_{13} - C_{44})l^2 - \rho_s\omega^2}{(C_{13} + 2C_{44})k_z^2 - C_{11}l^2 - \rho_s\omega^2}.$$

The coefficients X_i are found from the boundary conditions at the borehole wall ($r = R$). The boundary conditions at the borehole wall for a fluid-filled borehole are based on the continuity of radial displacement, continuity of radial stress and vanishing of tangential stress:

$$U_r = W_r;\sigma_{rr} = -p;\sigma_{r\theta} = 0. \tag{10}$$

By substituting the expressions (3), (8) and (9) in the boundary conditions (10), we have obtained the system of equations that allows to calculate the unknown coefficients X_1, X_2, X_3 which determine the amplitudes of reflected and outgoing waves. The explicit form of the system of equations to determine the coefficients X_i is given in Appendix A.

For the emitted pulse we have used the expression:

$$P(t) = P_0\,\sin(\omega_0 t)t^2 e^{-\delta t}, \tag{11}$$

where ω_0 is the central frequency of the acoustic source; $\delta = \omega_0/\sqrt{3}$ is the attenuation coefficient; P_0 is the normalization constant.

The integrand in Eq. (3) has singularities: the poles and the branch points. The branch points correspond to the compressional (P) and shear (S) waves propagating along the borehole wall. The poles