Influence of Borehole-Eccentered Tools in Wireline and LWD Sonic Logging Measurements

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ABSTRACT

We describe a numerical study to quantify the influence of tool-eccentricity on wireline and logging-while-drilling (LWD) sonic logging measurements. Simulations are performed with a *hp*-adaptive Fourier Finite-Element method that delivers highly-accurate solutions of linear elasto-acoustic problems in the frequency domain. Analysis of the main propagation modes obtained from dispersion curves indicates that, for both types of logging instruments, additional high-order modes appear with increasing distance between the center of the tool and the borehole center. These new propagating modes may slightly interfere with the main modes, such as the Stoneley mode, which otherwise remain nearly insensitive to tool eccentricity.

INTRODUCTION

Sonic measurements are essential for the characterization of hydrocarbon reservoirs —Tang and Cheng (2004)—. They provide an important elastic and petrophysical nexus and they are widely used in combination with surface seismic amplitude measurements. In addition, acoustic logging measurements are routinely acquired during drilling and production phases to quantify mechanical properties of rock formations.

Acoustic logging measurements provide quantitative estimates of shear and compressional velocities of the subsurface in the proximity of the borehole —Bassiouni (1994)—. They also contain information about in-situ rock stress, presence of fractures, and elastic anisotropy.

There exist two types of sonic logging instruments: wireline and logging-while-drilling (LWD). LWD tools have a larger diameter than wireline tools, thereby comprising a significant part of the borehole and leaving only a small fluid-filled annulus between the tool itself and the borehole wall. Likewise, they contain an inner fluid filled channel which poses significant challenges to the computer-aided simulation of full-waveform sonic measurements.

For both LWD and wireline tools, the main physical principles behind sonic measurements are fairly well-understood in the case of a logging instrument located at the center of a vertical borehole (axis of symmetry) penetrating a horizontal layered formation. However, in the presence of deviated wells and/or borehole-eccentered logging instruments, proper interpretation of sonic measurements is substantially more challenging. The aim of this paper is to study numerically the influence of borehole eccentricity on sonic measurements.

Although most sonic logging instruments utilize stabilizers to place the logging instrument at the center of the borehole, the location of the tool is often borehole-eccentered in

real logging conditions. We show that sonic measurements can be highly affected by the distance from the center of the tool to the borehole center (eccentricity distance), as well as by the design of the logging instrument (*e.g.*, type of tool and its thickness). Thus, it is imperative to simulate borehole-eccentered tools to quantify and interpret acoustic measurements acquired under those conditions.

Previous numerical studies in this area include the pioneering results obtained by Roever et al. (1974); Willis et al. (1982); Leslie and Randall (1990); Schmitt (1993); Zhang et al. (1996), and some numerical results for LWD tools (Huang et al. (2004); Zheng et al. (2004)), dipolar, and quadrupolar (Byun and Toksoz (2006)) sources. In this paper, we make use of a *hp*-Fourier-Finite-Element (*hp*-FFE) method to perform a detailed numerical study of the influence of borehole-eccentered tools in full-wave sonic measurements for both wireline and LWD instruments. The method is flexible in the sense that enables simulations of different scenarios and sonic logging instruments, including wireline and LWD tools. This paper is a continuation of Pardo et al. (2010), where we described and verified the *hp*-FFE solution method, and confirmed the high numerical accuracy of the method by showing a perfect matching between numerical results and existing analytical solutions. Developments included in this paper utilize the *hp*-FFE method for analyzing and understanding the sensitivity of sonic logging measurements to distance of tool eccentricity.

The remaining components of the paper introduce the method and provide additional verification results to subsequently study in detail the sensitivity of sonic measurements to the eccentricity distance in different borehole scenarios involving both wireline and LWD tools.

METHOD

The hp -FFE method is intended to solve the following linear time-harmonic coupled elasto-acoustic problem expressed in its variational (weak) form in terms of the fluid pressure p and the solid displacement $\mathbf{u}$ as:

$$\left\{ \begin{array}{l} \text{Find } (p, \mathbf{u}) \in H^1(\Omega_A) \times (H^1(\Omega_E))^3 \text{ such that:} \\ \langle \nabla q, \nabla p \rangle_{L^2(\Omega_A)} - k^2 \langle q, p \rangle_{L^2(\Omega_A)} - \rho_f \omega^2 \langle q, \mathbf{n}_f \cdot \mathbf{u} \rangle_{L^2(\Gamma_I)} = \langle q, f_A \rangle_{L^2(\Omega_A)} \\ \langle \epsilon(\mathbf{v}), C \epsilon(\mathbf{u}) \rangle_{L^2(\Omega_E)} - \omega^2 \langle \mathbf{v}, \rho_s \mathbf{u} \rangle_{L^2(\Omega_E)} + \langle \mathbf{n}_s \cdot \mathbf{v}, p \rangle_{L^2(\Gamma_I)} = \langle \mathbf{v}, \mathbf{f}_E \rangle_{L^2(\Omega_E)}, \\ \forall q \in H_0^1(\Omega_A), \mathbf{v} \in (H_0^1(\Omega_E))^3, \end{array} \right. \quad (1)$$

where $q, \mathbf{v}$ are test functions, Ω_A and Ω_E are the acoustic and elastic parts of the domain, respectively, Γ_I is the interface between the acoustic and elastic parts, k is the wave-number in a fluid, ω is the angular frequency, $\mathbf{n}_f$ and $\mathbf{n}_s$ are the unit normal (outward) vectors with respect to the fluid and solid, respectively, ϵ denotes the strain (symmetric part of the displacement gradient), C is the fourth-order elastic stiffness tensor, ρ_s and ρ_f are the solid and fluid mass densities, respectively, f_A and $\mathbf{f}_E$ are the acoustic and elastic forces, respectively, and $H^1(\Omega)$ denotes the proper Sobolev space setting for Finite Element computations (in this case, the set of L^2 functions whose gradients are also L^2 functions).

The simulation method is a combination of the following schemes:

1. **A Change of Coordinates for Simulation of Borehole-Eccentered Logging**

Instruments. This change of coordinates is designed to parameterize the geometry of a borehole-eccentered logging instrument in such a way that all materials are constant along the new quasi-azimuthal direction. For details, we refer to Pardo et al. (2010).

2. **A Fourier Series Expansion Along the Quasi-Azimuthal Direction.** Since

materials are constant along the newly created quasi-azimuthal direction, the solution is expected to be smooth, and a high-order method should provide highly accurate solutions. Thus, we perform a Fourier series expansion along the quasi-azimuthal direction.

3. **A 2D hp -Adaptive Finite Element Method (FEM).** The remaining spatial components are solved with a 2D self-adaptive hp -FEM. This method automatically performs an optimal distribution of element sizes h and polynomials orders of approximation p throughout the computational grid (c.f. Demkowicz (2006); Pardo et al. (2007)).
4. **A Perfectly Matched Layer (PML) for truncation of the computational domain.** The method also incorporates a PML for truncation of the computational domain, as first proposed by Berenger. Our understanding and implementation of the PML is consistent with the one provided by Chew and Weedon (1994), which is based on a change of coordinates of the governing equations into the complex plane within the PML layer Michler et al. (2007).

The numerical method also incorporates an implementation of a Prony's based inversion procedure to obtain dispersion curves directly from frequency-domain data. This inversion algorithm fails to provide a unique solution when the Nyquist frequency sampling theorem is not satisfied, which occurs at high frequencies. This is not an algorithmic problem but rather a fundamental physical problem, since at high frequencies different formations may provide the exact same acoustic pressures at the receivers. In order to overcome this problem and determine the correct dispersion curves, it is necessary to include two receivers very close to each other. More precisely, the proximity between the receivers should be inversely

proportional to the frequency to be resolved. This physical observation seems to suggest that sonic logging instrument should contain non-equally spaced receivers, which is confirmed with our numerical experiments. We have included additional receivers in our numerical simulations in order to obtain a unique set of dispersion curves for each case.

For illustration purposes, time-domain results (waveforms) obtained from frequency-domain simulations via inverse Fourier Transform are also displayed.

VERIFICATION

We describe verification results that are complementary to those performed in Pardo et al. (2010). We consider two different changes of coordinates for our method, as illustrated in Figure 1. The inner-dotted line denotes the outer-boundary of the cylindrical system of coordinates within the tool, and the outer-dotted line represents the inner-boundary of the cylindrical system of coordinates within the formation. Both parameterizations correspond to the same physical problem and, therefore, solutions associated to both changes of coordinates should coincide for an infinite number of Fourier modes. Figure 2 describes the convergence history of both parameterizations with respect to a reference solution (obtained with a third parametrization) for a model wireline logging instrument, and it exhibits a fast convergence as we increase the number of Fourier modes. Similar results are obtained for a model LWD tool, as shown in Figure 3. These results constitute a strong verification of our implementation.

[Figure 1 about here.]

[Figure 2 about here.]

[Figure 3 about here.]

NUMERICAL RESULTS

In this Section we present numerical simulations of sonic measurements acquired with borehole-eccentered logging instruments. In order to study the effects of borehole-eccentricity, we shall consider two different homogeneous formations: slow and fast. Table 1 describes the elastic properties of our material data.

[Table 1 about here.]

Wireline logging

First, we consider the wireline logging instrument described in Figure 4, which is composed of a hard tube, a transmitter, and 13 receivers.

[Figure 4 about here.]

For a fast formation, Figure 5 displays the Weighted Spectral Semblance (WSS) plots for the centered and the 2 cm borehole-eccentered cases. In the case of the centered tool, one can observe strong Stoneley mode (in low frequencies) and strong 1st pseudo-Rayleigh mode (in high frequencies). Additionally, there are two very weak modes: P-wave mode (mid frequencies) and 2nd pseudo-Rayleigh mode (very high frequencies). In the high-frequency spectrum we observe that new flexural modes appear and interfere with weaker monopole pseudo-Rayleigh modes for the borehole-eccentered case. This conclusion can also be inferred from the dispersion curves of Figure 6, where we note that the amplitudes of the formation and new flexural modes significantly decrease as we increase the eccentricity

distance. In the dispersion plot for the eccentered case we can observe additional flexural modes as well as a dipole tool mode which strongly interfere with the pseudo-Rayleigh and flexural modes. Waveforms (see Figure 7) corresponding to both cases also exhibit an influence of the presence of additional modes for the eccentered case (*e.g.*, weaker amplitudes of the wave-packages corresponding to pseudo-Rayleigh modes). Finally, Figure 8 displays various sets of dispersion curves corresponding to different eccentricity distances for the case of a fast formation. Again, we observe that the Stoneley mode is insensitive to the eccentricity distance. However, new flexural modes of amplitude proportional to the eccentricity distance appear as a result of tool-eccentricity. This interpretation of the results can also be clearly observed in Figure 9.

[Figure 5 about here.]

[Figure 6 about here.]

[Figure 7 about here.]

[Figure 8 about here.]

[Figure 9 about here.]

For the case of a soft formation, a similar situation occurs. Figure 10 displays dispersion curves corresponding to different eccentricity distances for the case of a monopole source in a soft formation. When the eccentricity distance attains 2 cm, we observe a new “dipole tool” mode, which also creates interferences in the main Stoneley mode at 2.5 kHz. Notice that these interferences are a numerical artifact of the inversion algorithm, and they do not affect the low- and high-frequency asymptotes of the Stoneley mode, as shown in Figure 11.

[Figure 10 about here.]

[Figure 11 about here.]

Now, we analyze the case of a wireline logging instrument equipped with a dipole source in a slow formation. Figure 12 displays dispersion curves corresponding to different eccentricity distances. Again, we observe the appearance of higher order modes as we increase the eccentricity distance. However, the original dipole tool mode is insensitive to the logging tool position, as illustrated in Figure 13.

[Figure 12 about here.]

[Figure 13 about here.]

Logging-While-Drilling (LWD)

Now, we consider the LWD instrument described in Figure 14, which is composed by a hard tube with an inner section filled with drilling fluid, a transmitter, and several receivers.

[Figure 14 about here.]

We first consider the case of a fast formation. Figure 15 displays the dispersion curves obtained for the monopole excitation and for the borehole-centered and 1 cm borehole-eccentered cases. The borehole-eccentered case contains all modes corresponding to the borehole-centered case (Stoneley mode, 1st pseudo-Rayleigh mode, two fast dispersive LWD tool modes, and compressional mode in the fluid) plus additional dipole modes: tool mode and flexural modes. We note that the main monopole modes are common to both cases (up to some small interferences due to the inversion process), as shown in Figure 16.

[Figure 15 about here.]

[Figure 16 about here.]

A similar situation occurs in the case of a LWD tool in a slow formation. In Figure 17 we see that, when we consider a borehole-eccentered tool, a new LWD tool mode is creating interferences in the low part of the spectrum. We also observe new higher-order tool modes with high speeds in the upper part of the spectrum. Again, the main modes are insensitive to tool-eccentricity, as shown in Figure 18.

[Figure 17 about here.]

[Figure 18 about here.]

CONCLUSIONS

The presented results show that the logging tool eccentricity always influences the excited borehole modes.

First, in all the cases, tool eccentricity causes excitation of high-order modes. In the case of the monopole source, the excited modes are those known from dipole logging, and in the case of large eccentricity distance even quadrupole modes can be observed. For a dipole source, flexural quadrupole modes are observed. The larger the borehole-eccentered distance, the stronger the effect and the larger the number and amplitudes of new high-order modes.

In wireline logging instruments, the tool-eccentricity effect is more prominent than in LWD instruments, since a wireline tool diameter is usually a fraction of the borehole diam-

eter, which enables large eccentricity distances. In addition, during real logging operations it is more difficult to assure a centered position of the wireline tool than of a LWD tool. Nevertheless, a LWD tool is stiffer and some degree of eccentricity can be observed when logging in curved boreholes.

In wireline logging, original borehole modes are insensitive to borehole-eccentered tools. Thus, Stoneley and pseudo-Rayleigh (for monopole source) and flexural (for dipole source) modes are unaffected by the eccentricity distance. However, eccentered tools typically excite the dipole tool mode, which can strongly interfere with the original modes (Stoneley and 1st flexural) and make difficult to properly interpret the recorded measurements. A similar situation occurs for high-order excited modes: they also interfere with high-order original modes. This phenomenon can significantly hamper the extraction of the formation parameters.

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	V_p [m/s]	$1/V_p$ [$\mu s/ft$]	V_s [m/s]	$1/V_s$ [$\mu s/ft$]	ρ [kg/m^3]
fluid	1524	200.0	—	—	1100
fast formation	4354	70.0	2620	116.3	2300
slow formation	2540	120.0	1269	240.2	2100
tool	5860	52.0	3130	97.4	7800

Table 1: Material data

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(a) Fast formation

(b) Slow formation

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Eccentricity effect on St, p-R and LWD tool modes in fast formation

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