LWD Sonic Tool Design for High-Quality Logs
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Summary
The design of a logging-while-drilling (LWD) sonic tool is always a challenge; the acoustic propagation along the tool cannot be ignored, nor can effects on measurements due to tool presence. It is well known that collar arrivals can interfere with compressional waves in fast formations. The interaction of the collar with other modes such as Stoneley and quadrupole must also be considered while designing an LWD acoustic tool. Because the LWD tool occupies a significant area of the borehole cross section, it is known that the presence of a sonic tool in a borehole shifts a dispersion curve in the slowness frequency domain. In this paper, we present an approach to optimize tool design for minimizing tool effects on measurements or making tool presence effects predictable for enabling a broadband use of the acquired data. Experimental results validate the design of the tool, and real log examples illustrate the quality of the acquired waveforms.

Introduction
Sonic measurements provide useful information for understanding the rocks and fluids of a reservoir and surrounding formations. Therefore, sonic logging is one of the principal measurements used to evaluate the presence of hydrocarbons in the reservoir and to enable efficient and safe oil production. For example, in geomechanical analysis, sonic data can provide information for pore pressure, rock strength, formation alteration, stress direction, and magnitudes (Sinha, 2006). In petrophysical analysis, sonic data can be used to evaluate formation lithology and/or identify the fluid in the pore. LWD technology has progressed rapidly in recent years to address the needs of rig time savings and real-time decisions for drilling efficiency and risk management. Real-time LWD sonic measurements provide timely data for borehole stability analysis, drilling optimization, and assisting with pore-pressure prediction and seismic well ties.

As sound waves propagate very efficiently along steel tool housing, tool arrivals are a significant issue when designing sonic logging tools, especially for LWD acoustic tools. Looking back through the history of wireline sonic logging, tool designers have made continual efforts to minimize tool arrivals by isolating the transmitters from receivers by means of a tortuous path of machined slots or grooves in the steel sonde. In the case of LWD, because the tools operate under very severe environments (torque, shock, vibration, etc.), the major structural part of the tool is a rigid drill collar (thick steel pipe), which is favorable for tool wave propagation. Minimizing tool arrivals is, therefore, one of the keys to obtaining a high-quality acoustic measurement while drilling.

Field test data in different formation and borehole conditions show that LWD tools can acquire high-quality waveforms in a wide frequency band, providing reliable compressional and shear slownesses. Additionally, the tool has the capability to acquire low-frequency Stoneley data, thus enabling applications such as formation damage indicators and fracture evaluation.

Methodology
To achieve high-quality measurement, modeling and experiments are essential, instead of solely relying on iterative experiences and intuition in the design process. Finite-difference method (FDM) modeling for elastic wave propagation plays an important role predicting the tool response in a borehole. By employing fine grid spacing, details of the tool design such as structure of receiver module as well as grooves on the collar are incorporated into the model.

The governing equations considered in this study are the three-dimensional elasticity equations. In a linear isotropic elastic medium, the particle velocity \( \mathbf{v} \) and the stress tensor \( \mathbf{T} \) satisfy the first-order hyperbolic system of equations.

\[
\frac{\partial \mathbf{v}}{\partial t} = \nabla \cdot \mathbf{T} \quad (1)
\]
\[
\frac{\partial \mathbf{T}}{\partial t} = \lambda (\nabla \cdot \mathbf{v}) \mathbf{I} + \mu (\nabla \mathbf{v} + \mathbf{v} \nabla) \quad (2)
\]

where \( \mathbf{I} \) is the identity tensor, \( \rho \) is the density, and \( \lambda, \mu \) are the Lamé constants of the medium, respectively. To obtain second-order accuracy, the unknowns in the velocity-stress formulation are staggered in both space and time. Because the tool and borehole shapes are basically axis-symmetric, three-dimensional cylindrical coordinates are employed. Figure 1 shows a schematic view of an LWD sonic tool and computational grids for the attenuator section and a borehole. To incorporate tool details, grid-spacing for radial and axial directions for the real simulation can be adjusted accordingly.

This type of acoustic modeling gives us valuable insights to decide key parameters of the tool and refine the detailed design. Nonetheless, the modeling results do not always reflect the reality. For instance, a slight difference in compressibility of the receiver module results in non-
negligible shift of a dispersion curve. Therefore, the FDM model itself needs to be validated based on real data for accurate prediction of the tool response. For validation and calibration of the model, we used a water tank and test wells which have been fully characterized (density, velocity, etc.). To measure response in free field, the LWD tool is surveyed in the water tank with an array of hydrophones. Through a series of iterations in conjunction with the hardware developments, the FDM model is tuned so that the tool-borehole-formation response can be reproduced in reference environments (test wells, and acoustic tank). As a result, tool effects can be predicted accurately in all isotropic homogeneous formations.

Modeling and experimental results

To attenuate the propagation along the collar, multiple grooves of different sizes are machined inside the LWD tool collar. We have conducted intensive acoustic modeling to optimize the pattern of the grooves. Figure 2 shows an example of the energy of collar propagation recorded at the first receiver with and without the attenuator grooves. With the aid of iterative computer simulations, we have decided the frequency band in which formation P- and S-waves are measured, the transmitter-receiver (T-R) geometry, and the optimal groove pattern for the T-R spacing. Because a single set of transmitter and receivers is used for multipole measurements, the T-R spacing and groove pattern need to be optimal for both monopole and quadrupole modes.

![Figure 2: Example of power spectra of collar propagation measured at the bottom receiver with (blue) and without (red) attenuator grooves. The formation P- and S-waves to be measured are in the frequency band of the spectrum trough.](image)

Figure 3 shows an example of the effect of LWD tool presence on the quadrupole slowness dispersions in the cases of finite-difference modeling results and experiment in a test well. The size of the dots represents the spectral amplitude of each mode. Agreement between modeling and experiment is good, and both dispersion curves are almost on top of each other. The dashed curve indicates the theoretical dispersion curve without the tool in the hole. We can see significant shift of the dispersion curve due to the tool presence, which would impact the processing results if the tool effect were not properly accounted for. As this effect is a complex function of the tool and borehole parameters, such as formation properties, mud density, and borehole size, it must be well understood and accurately predicted.

![Figure 3](image)

As mentioned above, a slight difference in a tool design can have a huge impact on sonic measurements. Figure 4a shows borehole quadrupole mode in a 6.5-inch borehole for different collar thickness. The collar for the left figure is thicker than that for the right figure by 0.5-inch, while the outer diameter of the tool is the same. The formation shear is \(160 \text{ μs/ft}\). The dispersion curve of the collar quadrupole in free field is overlaid by a red curve in the plots. The 0.5-inch difference in thickness gives rise to a big difference in collar and borehole quadrupole mode. With a thinner collar,
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both modes are strongly coupled, and borehole mode becomes more dispersive. Figure 4b shows overlay of borehole quadrupole modes for 160 and 158 μs/ft shear. The thicker collar contributes to a much better separation of dispersion curves for slightly different shear slowness. The modeling results tell us that a thick collar is indispensable for extracting accurate shear from quadrupole in fast formations.

Figure 3: Slowness-frequency dispersions of borehole quadrupole mode measured in a test well (red dots) and computed with finite-difference modeling (blue dots). The dashed curve indicates the theoretical dispersion curve without the tool.

New tool and its field test examples

The geometry of the new tool was carefully designed to ensure that borehole modes are well established before reaching the bottom receivers. In addition, the array aperture is long enough to accurately extract the required information for the long wavelengths featured by these modes. The tool features 12 axial receiver stations separated by 4-inch inter-receiver spacing, for a total aperture of 3.67 ft for the receiver array. Four azimuthal receivers are located every 90 degrees around the tool and the 48 total sensors enable accurate modal decomposition of the quadrupole mode.

The receiver array is the key to the next generation of multipole LWD sonic tools. Large efforts have been made in the feasibility study, and the design and qualification of the digital receiver array. We decided to digitize the analog signals close to the sensors and digitally multiplex the signals to decrease the interconnection complexity between the inside and outside of the collar and to maximize reliability. The receiver module containing electronics must have durability for harsh downhole environments, and various restrictions are imposed in the design and choice of the materials. We have refined the design after various iterations, and the resulting high-fidelity receivers have been verified to provide a stable response.

Figure 5: Monopole compressional and shear logs acquired with the new LWD sonic tool (second track) and a wireline sonic tool (third track). The first track shows overlay of wireline and LWD logs.
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The log shown in the second track of Figure 5 is derived from monopole high-frequency waveforms acquired while drilling. The compressional slowness ranges from 55 μs/ft to 99 μs/ft in the zone. Most of the interval in the log is a fast or intermediate formation and is suitable for evaluating monopole response. A wireline sonic logging tool (Pistre et al., 2005) was run after the drilling job to provide a reference of the sonic log (third track). The first track shows good agreement between the wireline and LWD tool, as indicated by DTc and DTs overlay.

Figure 6 compares the real-time log and the recorded-mode log in the same interval of a horizontal well. Three or four most coherent peaks and associated attributes are computed downhole, and then they are sent to surface. These data can be reconstructed into a pseudo projection log on the surface as shown in Figure 6a. The comparison with the recorded mode log processed on surface (Figure 6b) demonstrates that the downhole processing is robust and the important features of the formation can be sent to the surface in real-time.

The major structural part of the LWD tool is a rigid drill collar and the LWD tool flexural mode is much faster than that for a wireline tool. The LWD tool flexural mode and the borehole flexural mode are strongly coupled and make it difficult to determine slow-shear with a dipole source.

It is known that a quadrupole source can be used to extract shear in a slow formation (Kurkjian and Chang, 1986). Chen (1989) verified that a quadrupole source is capable of direct S-wave logging in laboratory scale-model experiments. In terms of determining slow shear with an LWD sonic tool, a quadrupole source has clear advantage over a dipole source. The LWD tool quadrupole mode is generally faster than a borehole quadrupole mode and their frequency bands are shifted. In other words, the two modes are well separated in a frequency-slowness plane and the coupling is considered to be fairly weak.

Figure 7a shows an example of the quadrupole waveforms and the dispersions extracted with a modified matrix pencil algorithm (Ekstrom, 1995). They were acquired while drilling. We can see strong dispersions from 4 kHz to 8 kHz and they explain the changes in waveform shape across the array. Figure 7b shows an example from the monopole low-frequency firing at the same depth in the same well. The dispersion curve is continuous from 1 to 10 kHz and the quality of the dispersions is considered to be good.

Conclusions

The new LWD sonic tool and sensors were thoroughly designed so that they enable high-quality measurement for all the propagating modes as well as robust compressional and shear logs. The acoustic response of the new tool has been accurately characterized in several environments and the tool effect is predictable. The combination of high-quality data acquired with new tool and the predictability of the tool effect will expand the applications of LWD sonic measurements.