Abstract

This paper introduces an ultrabroadband array sonic logging tool and related processing for wireline logging in both open and cased holes. The tool consists of six broadband monopole and dipole transmitters and 104 highly sensitive wideband receivers, enabling deep-reading formation evaluation in axial, radial, and azimuthal directions around the tool.

The transmitter drive pulses from the six broadband monopole and dipole transmitters are dynamically optimized and controlled to cover a large dynamic range in formation slowness. The low-frequency monopole source is designed for measuring Stoneley dispersion curves. A high-frequency monopole source array helps enable extraction of compressional slowness and arrivals that can generate enhanced radial compressional slowness profiles. These deep readings are then used to evaluate the formation in three directions around the sonic logging tool.

The orthogonal dipole sources help enable direct measurement of the shear slowness from the low-frequency flexural asymptotes without the need for dispersion correction. Real-time processing, including quality control of transmitter and receiver sensitivities, delivers high-quality compressional, shear, and Stoneley wave slowness. Subsequent post-acquisition answer products include formation compressional and shear slowness, shear anisotropy, and Stoneley reflections and permeability. Further interpretation of low-frequency compression waves helps enable measurement through high attenuation gas zones and also measure the true formation compressional slowness in very slow formations where leaky compressional modes are prominent. Also, shear slowness measurements through very slow formations allow improved seismic ties from mudline to depth.

This next-generation ultrabroadband array sonic logging tool allows for deeper reading and more comprehensive formation evaluation in cased and open holes. In addition to discussing the process for using the tool in wireline logging, this paper provides examples for logs of both slow and fast formations.

Introduction

Sonic logging as a specialized wireline logging method produces an important oilfield measurement—an acoustic log—which can be used extensively for formation evaluation in geophysical and geomechanical applications, such as seismic-well ties, velocity model building, or pore-pressure prediction, etc. The
formation properties measured using acoustic waves in a borehole, particularly in an open hole, are subject to the conditions of a borehole. The dynamic and complicated borehole environments are challenging for acoustic logging, such as in some situations of anisotropy, mud invasion, stress concentration near the borehole side-wall, wash-out, formation permeability, etc. The propagation of acoustic waves is altered by these conditions, which might result in difficulties of obtaining accurate formation properties (Passey et al. 2005; Ellis 2007).

The application for sonic measurements has been improved significantly in past decades. It has evolved from a basic transmit-time measurement of compressional wave (Vogel 1952) to full-wave measurements for more sophisticated formation evaluations. Correspondingly, the wireline logging tool has been evolved from two-receivers to array-based measurements (Morris et al. 1984; Kimball and Marzetta 1984).

A well-designed array-based sonic logging tool has advantages of improving measurement accuracy, achieving deep and three-dimensional (3D) readings of the formation elastic properties. Accurate formation compressional and shear velocity are important information for geophysical and geomechanical applications (Cheng 2015). With an acoustic logging tool, there are typically two types of sources: monopole and dipole. Monopole excites a spherical uniform wavefield in an ideal homogeneous medium, and dipole excites waves at specified directions. Compressional waves are excited by monopole sources and are one of the major measurements of an acoustic log. While the formation compressional velocity is faster than the borehole fluid, the refracted-compressional waves are measured by the receiver array at a distance. The velocity of shear waves is another important measurement for formation characterization. The detection of refracted shear wave is only possible in a fast formation; this is because there are no refracted shear waves when the shear velocity of the formation is slower than the borehole fluid. Instead of measuring shear wave velocity directly, the low-frequency asymptote of flexural waves is used for shear wave measurements. The flexural waves are guided waves and exist in both fast and slow formations. To excite flexural waves with an acoustic logging tool, a dipole source was introduced (Zemanek et al. 1984). It usually uses a unidirectional displacement or pressure source. In addition, the measurements of Stoneley and pseudo-Rayleigh waves can be used to study formation permeability in a porous medium (Auriault et al. 1985).

Based on the latest development and the study of industry needs for wireline acoustic logging, the operating company developed a new state-of-the-art sonic logging tool. Its success represents an effort from four years of engineering and modeling and collaboration from the most prominent scientists in the industry and academia. The new tool is equipped with wideband transducers and highly-sensitive wideband receivers. It is designed for continuous depth investigations and improved capabilities in the most challenging borehole conditions. Also, it has capabilities to acquire full acoustic waves around the borehole and allows the sophisticated algorithms to perform deep and high-fidelity 3D investigations to the formation. These can include accurate formation velocity measurements, tomographic/reflection imaging, horizontally transverse isotropy (HTI)/vertically transverse isotropy (VTI) analysis, rock physics analysis, and so on.

This paper presents the new state-of-the-art tool and highlights its capability in acquiring high-quality acoustic data in an open hole for both fast and slow formations. Also, field data examples acquired using this tool are shown. Examples of these data for advanced computation are also presented.

**The New Ultrabroadband Array Sonic Logging Tool**

The logging tool is a 3.69-in. diameter tool and spans a total of approximately 52 ft (Fig. 1). The tool includes a receiver-array section (hydrophone section in Fig. 1) and multiple transmitter sections (monopole/dipole sections in Fig. 1). The receiver array spans 6-ft long with 13 rings of receivers. Each ring contains eight receivers (marked from letter A to H in Fig. 1) spaced azimuthally for every 45° along the circumference of the tool. In total, there are 104 highly sensitive wideband receivers. In the transmitter sections, there are four monopole sources referred to as the upper monopole (UMP), lower monopole
(LMP), far monopole (FMP), and ultrafar monopole (UFMP). There are also two dipole sources (DX and DY) that are orthogonal and offset from one another by 1 ft.

Figure 1—Logging tool diagram. The length of the tool is 52 ft. In the upper section, a 6-ft receiver array comprises 13 levels of eight azimuthally separated piezo-electric microphone receivers; two near monopoles are positioned at the top and bottom of the array. There is another FMP transmitter and two cross-dipole transmitters in the middle section. The lower section contains an UFMP.

High-quality waveforms are acquired by the logging tool using wideband transmitters and receivers. The tool has four piezo-electric transmitters and two orthogonal shaker transmitters. These transducers are tested and can inject modally pure acoustic energy into specific source modes as much as possible with adequate energy of low-frequency band. Even in soft or unconsolidated formations, this tool is still capable of obtaining high-quality waveforms, and in a challenging borehole environment, continuous formation characterizations can be performed with such hardware systems while logging with the logging tool. In addition, Fig. 1 shows there are 104 receivers positioned in axial and azimuthal directions along the circumference of the tool. This allows the tool to perform a 3D investigation around the borehole.

Fig. 1 shows there are four monopole sources equipped in the tool when the full length of the tool is used. Fig. 2 shows the positions of them are chosen optimally for continuous depth measurements. From Figs. 2a to 2c, the illustration shows continuous depth readings when LMP, FMP, and UFMP are located at a common depth and the receiver arrays are combined to form a long 39-receiver array. Ray tracing is
shown in Fig. 2 for continuous depth reading. The ray traces travel into deeper formation when using a large offset between receiver array and the transmitter, such as UFMP, whereas the ray path is shallower with LMP sources. By combining LMP, FMP, and UFMP, such a long receiver array is formed, which allows continuous depth investigation. Therefore, the improved depth resolution in tomography or reflection imaging becomes possible. Fig. 3 shows a field data example, where Stoneley firings are used for simplicity. All four firings of Stoneley waves are used to form this long array of waves, including UMP, LMP, FMP, and UFMP. Note that UMP and LMP are placed on both sides of the array with equal distance, so the graph shows that waves from these two firing are stacked. After combining all four firings, the array spans 18 ft instead of approximately 6 ft when a single source is used.

Figure 2—Continuous depth reading with the logging tool. When LMP, FMP, and UFMP are at common-depth, a continuous gradient in seismic velocity, as expected from near-borehole formation alteration, causes diving P-waves to be refracted back to the tool’s 13 rings of receivers.
Field Data Examples

Figs. 4 and 5 show waveforms acquired using the logging tool from soft and hard formations, respectively. The compressional and Stoneley waves are acquired from monopole firings. The flexural waves are from dipole firings. Each compressional wave shown in both figures is averaged from eight azimuthal receivers of the ring, and all waves are bandpass filtered. The flexural waves are obtained by subtraction from the inline pair of receivers for DX or DY, which are called as XX or YY for corresponding dipole firings. The Stoneley waves are fired by monopole but with a much lower frequency compared to compressional firings.

Figure 3—An example of combined receiver array. Stoneley firings from UMP (pink), LMP (green), FMP (blue), and UFMP (yellow) are formed to construct the long array of waveforms.
Figure 4—Onshore hard-rock formation logging tool data: (a) XX waveforms; (b) YY waveforms; (c) monopole waveforms—P and S waves are indicated as dashed lines; (d) Stoneley waveforms.
Fig. 4 shows the flexural waveforms for hard-formation data, XX and YY in Figs. 4a and 4b. The waveforms are bandpass filtered between 500 and 8000 Hz with a clean and high signal-to-noise ratio (SNR) presence. Fig. 6 shows the dispersion curves for XX and YY, respectively. It is shown that the flexural waves are highly dispersive in hard-rock formations, and the dispersion curves also have high SNR. In Figs. 4c and 4d, the refracted compressional and the Stoneley waves are shown, respectively. The compressional waves are bandpass filtered between 5000 and 25,000 Hz. It is shown that the amplitudes of refracted compressional are small compared to shear waves, but they are still visible with good SNR. Also, the Stoneley waves are filtered between 700 and 3000 Hz. Only the Stoneley wave mode is shown in the wave trains.
Fig. 5 shows the waveforms acquired using the logging tool from a slow formation. It also includes XX, YY, compressional, and Stoneley waves from Figs. 5a to 5d, respectively. Also, the same filters as Fig. 4 for corresponding waves are applied to these waveforms. Similar quality data are shown here compared to the hard formation, high SNR waveforms, and wide band. This is also proven from the coherence map of XX and YY in Fig. 7. In the compressional waves, the P waves are followed with leaky P-mode, but there are no refracted shear waves.

![Figure 6](image1.png)  
**Figure 6**—Coherence map for XX (left) and YY (right) of Fig. 4 for onshore hard-rock formation data.

![Figure 7](image2.png)  
**Figure 7**—Slow formation frequency coherency map for XX and YY from Fig. 5.

The quality of waveforms is dependent on the performance of receivers and transmitters. It sometimes can occur that one waveform can mismatch from others caused by degradation of the receiver performance. It is therefore important to have a receiver quality-control (QC) method to monitor their status. A receiver performance-monitoring mechanism has been developed by using low-frequency Stoneley waves as the measuring tool. Stoneley waves usually suffer minimum attenuation and less alteration by borehole condition in comparison to other wave modes. All 104 receivers’ Stoneley wave signal levels are measured for each acquisition when logging is conducted in a cased-hole section. The signal levels are grouped by rings, and variations for each receiver are derived from the average of the ring signal level.
By acquiring adequate data for a depth range, the final statistical results representing the receiver status are derived (Fig. 8), where the status for all 104 receivers is shown. Note that 5% is used as a threshold to identify any receiver outliers. The amplitude shows variations from most receivers are less than 2%, but the receiver 4F is approximately 6%, indicated as a red flag, and this receiver might need a correction. The gains for each receiver and ring can be calculated with this QC method to improve the waveform quality for more advanced calculations.

In addition to receiver amplitude QC, receiver travel-time QC is also performed in a similar way. The travel-time variation is calculated and compared to the averaged result of the ring. Fig. 9 shows that the receiver 4F has a time shift from others, and then an automated calibration report will be provided after these QC steps, low-performance receivers will be identified, and associated gain and phase information will be provided.
High-quality waveforms consequently result in improved post-acquisition answer products, including formation compressional and shear slowness, shear anisotropy, Stoneley reflections, and permeability. Herein, two products are shown from the logging tool as examples—VTI anisotropy and a sonic log.

VTI anisotropy is one of the common situations in many sedimentary rocks (Tang and Cheng 2004). It has a vertical axis coinciding with the borehole axis, such as the commonly known VTI case of shale. Borehole acoustic Stoneley and flexural waves are sensitive to different shear velocities propagating in vertical and horizontal planes (Walker et al. 2015). High-quality data are important for a reliable VTI analysis, as the borehole conditions impose significant influence to those dispersive signals, such as borehole irregularities, tool effects, modally impure sources, and transmitter/receiver mismatching.

Fig. 10 shows an example of VTI analysis. This method uses the Stoneley and flexural dispersion curves to invert for both VTI anisotropy percent (Thomson gamma) and vertical shear slowness (Tang and Cheng 2004; Collins 2013). The log shows a significant Thomson gamma of approximately 0.3. For the selected depth of 2,085 ft, the predicted flexural and Stoneley curves overlay the observations well. The blue curves are adaptive weighting functions used in the inversion. The 95% confidence region permits the derivation of the optimum parameters and is shown throughout the logs as thin black lines. The elastic effects of the tool in this inversion are considered. The dispersion curve for the same VTI solution without the tool correction is shown as a dashed curve in the flexural and Stoneley upper right graphs. The existence of the tool structure has a significant influence on flexural dispersion in fast formations and on the very lowest frequencies of Stoneley dispersion in a slow formation.

Figure 9—Receiver QC using Stoneley wave travel-time variation. The graph shows similarly to the amplitude QC, but here they are representing travel-time QC results.
Fig. 11 shows an example of slowness selection from the logging tool data for a small section of a hard-formation well, including far-monopole compressional slowness (DTC), dipole flexural (DTXX and DTYY), and Stoneley (DTST) with the coherence variable density logs (VDLs) as their QC metrics. These VDLs show well-correlative peaks associated with borehole waves and low noise levels, and on the top of the VDLs, slowness curves are overlain. The high-frequency monopole processing provides logs of DTC, DTRS, and high-frequency DTST. The dipole processing shows dipole shear slowness at the XX component (DTXX) and YY component (DTYY). The specifically designed low-frequency monopole firing provides high-quality low-frequency Stoneley waves, which are ideal for advanced acoustic analysis, such as permeability extracting and anisotropy calculation. Note that the slowness logs are smooth, stable, and well correlated with one another. This suggests that the logging tool provides slowness logs of extremely high quality.
Conclusions

A new state-of-the-art logging tool is presented. The tool hardware design and application development represents an effort from four years of engineering and modeling. The new tool has some key fundamental features representing the advancement in the latest science research for borehole acoustic logging, such as source-receiver placement, modal purity of sources, transmitter and receiver matching, receiver isolation, the recording of acoustic waveforms in high fidelity, and the flexibility to configure the tool for new applications. Herein, the two main aspects of the tool features are emphasized—hardware design and quality of data. The two fundamental features are the basis and enable the most advanced algorithms to be performed with the tool and produce reliable borehole acoustic investigations.

The tool hardware configuration is flexible. Its full length is 52 ft when all transmitter sections are attached. There are four monopole piezo-electric sources and two orthogonal dipole shaker sources that are located at different offsets to, and different sides of, the receiver array for multiscale, 3D interrogation of the formation with a continuous depth of investigation. The status of receivers and transmitters are monitored, and their waveforms are balanced within 5% for additional SNR improvement. A unique dogbone isolator section is designed to attenuate tool modes while also minimizing hostile logging loads to the tool. All recordings are saved in 24 bits to tool memory, permitting a complete re-analysis in post-processing.

Figure 11—The logging tool logs for far-monopole compressional (DTC), flexural dipole (DTXX), flexural dipole (DTYY), and Stoneley (DTST). Gamma ray and borehole diameter (caliper) logs are also shown on the far left.
References


