MODELS IN LWD APPLICATIONS

V. N. Rama Rao, Daniel R. Burns, and M. Nafi Toksoz

Earth Resources Laboratory
Department of Earth, Atmospheric, and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139

ABSTRACT

A model for a fluid-filled borehole with an LWD tool is used to identify and analyze the monopole, dipole, and quadrupole modes that are present. The modes can be classified into three groups and have dispersion behavior that is influenced predominantly by the geometry and material properties of the three borehole layers (inner fluid column, tool, and annulus fluid column). However, this simple dependence gets complicated in regions of the frequency-wavenumber plane, where modes related to different layers interact and exchange their dispersion characteristics. The dipole modes exhibit the effects of interaction below 2 kHz and above 20 kHz.

INTRODUCTION

Logging While Drilling (LWD) tools are gaining prominence with increased pressures on improving drilling efficiency. Some of the challenges in developing LWD capabilities are in designing a robust tool capable of operating in the harsh drilling environment, designing for downhole power, data storage and processing requirements and developing an understanding of the excitation and response of a fluid-filled borehole with pipe. However, once these challenges are met, formation logging can be done simultaneously while drilling thus reducing rig time. In addition, with sophisticated logging capabilities downhole, and improved downhole-to-surface telemetry systems, there is significant potential for almost real-time formation evaluation, ‘look-ahead of the bit’ and better control of well trajectories.

LWD tools are typically installed in the Bottom Hole Assembly (BHA), near the bit, with OD around 7.5” – 9” and an ID of around 3”. The tool is almost as rigid as a drill collar, and much stiffer than a wireline tool (about 2.5” ID and 3.5” OD). The most significant difference between wireline and LWD operations is the presence of a continuous pipe in the borehole in the latter. This separates the borehole fluid
Rao et al.

into two fluid columns and introduces additional modes that can be excited by logging sources. Wireline tools rely on formation refracted arrivals and appropriate modal arrivals (pseudo-Rayleigh, borehole flexure and Stoneley) to estimate formation properties. LWD tool operation is complicated by the presence of numerous additional modes (e.g., tool flexure, inner fluid Stoneley) due to the presence of the tool; picking the appropriate modal arrivals sensitive to formation properties is more difficult. Thus it is important to identify the various modes and their characteristics in LWD operation.

Early studies examined the effects of formation logging tools and casings that introduce radial layering within the borehole. Cheng and Toksöz (1981) modeled the presence of a wireline logging tool in the borehole. The modeled tool was solid and did not include fluid inside it. Their results showed that the lowest-order propagating mode was the Stoneley mode. The presence of a tool reduced the cross-sectional area of the borehole and hence increased the cutoff frequencies of the pseudo-Rayleigh modes. Tubman et al. (1986) investigated another form of radial layering, a poorly bonded casing, to examine its effect on formation logging. They used a layer matrix technique to model an elastic cylinder in the borehole with fluid trapped between the cylinder and borehole wall, and showed that the Stoneley mode and an additional fluid mode were present. A similar result was reported by Lee (1991), who developed a comprehensive model of a drillpipe in a fluid-filled borehole under a low-frequency approximation. He predicted a total of three modes, with two Stoneley-like modes and a mode localized in the pipe. Later, a model based on 3D elastodynamic equations was developed (Rao and Vandiver, 1999), which overcame the low-frequency limitation, to study the effect of drilling tubulars on borehole wave propagation. The present study generalizes that model further by including nonaxisymmetric modes.

FORMULATION

The model consists of alternating fluid and elastic layers with the innermost layer being fluid and the outermost being elastic. The fluids are assumed to be inviscid and the solids are assumed to be elastic and isotropic. The fluids and solids are assumed to be lossless. The model used here closely follows that in Rao and Vandiver (1999). Assuming an axial wave propagation of the form \( e^{-ikz + iwt} \), a frequency and axial wavenumber transform of the wave equation yields,

\[
\frac{\partial^2 \phi_j}{\partial r^2} + \frac{1}{r} \frac{\partial \phi_j}{\partial r} + \left( \frac{p_{rj}^2 - \frac{\nu_j^2}{r^2}}{r^2} \right) \phi_j = 0, \quad (1)
\]

\[
\frac{\partial^2 \psi_j}{\partial r^2} + \frac{1}{r} \frac{\partial \psi_j}{\partial r} + \left( \frac{s_{rj}^2 - \frac{\nu_j^2}{r^2}}{r^2} \right) \psi_j = 0, \quad (2)
\]

\[
\frac{\partial^2 \chi_j}{\partial r^2} + \frac{1}{r} \frac{\partial \chi_j}{\partial r} + \left( \frac{s_{rj}^2 - \frac{\nu_j^2}{r^2}}{r^2} \right) \chi_j = 0, \quad (3)
\]

where \( \phi_j \) is the compressional and \( \psi_j \) and \( \chi_j \) are the two shear displacement potentials in the layer \( j \). \( p_{rj} \) and \( s_{rj} \) are the compressional and shear radial wavenumbers in that
into two fluid columns and introduces additional modes that can be excited by logging sources. Wireline tools rely on formation refracted arrivals and appropriate modal arrivals (pseudo-Rayleigh, borehole flexure and Stoneley) to estimate formation properties. LWD tool operation is complicated by the presence of numerous additional modes (e.g., tool flexure, inner fluid Stoneley) due to the presence of the tool; picking the appropriate modal arrivals sensitive to formation properties is more difficult. Thus it is important to identify the various modes and their characteristics in LWD operation.

Early studies examined the effects of formation logging tools and casings that introduce radial layering within the borehole. Cheng and Toksoz (1981) modeled the presence of a wireline logging tool in the borehole. The modeled tool was solid and did not include fluid inside it. Their results showed that the lowest-order propagating mode was the Stoneley mode. The presence of a tool reduced the cross-sectional area of the borehole and hence increased the cutoff frequencies of the pseudo-Rayleigh modes. Tubman et al. (1986) investigated another form of radial layering, a poorly bonded casing, to examine its effect on formation logging. They used a layer matrix technique to model an elastic cylinder in the borehole with fluid trapped between the cylinder and borehole wall, and showed that the Stoneley mode and an additional fluid mode were present. A similar result was reported by Lee (1991), who developed a comprehensive model of a drillpipe in a fluid-filled borehole under a low-frequency approximation. He predicted a total of three modes, with two Stoneley-like modes and a mode localized in the pipe. Later, a model based on 3D elastodynamic equations was developed (Rao and Vandiver, 1999), which overcame the low-frequency limitation, to study the effect of drilling tubulars on borehole wave propagation. The present study generalizes that model further by including nonaxisymmetric modes.

**FORMULATION**

The model consists of alternating fluid and elastic layers with the innermost layer being fluid and the outermost being elastic. The fluids are assumed to be inviscid and the solids are assumed to be elastic and isotropic. The fluids and solids are assumed to be lossless. The model used here closely follows that in Rao and Vandiver (1999). Assuming an axial wave propagation of the form \( \sim e^{-i(kz + \omega t)} \), a frequency and axial wavenumber transform of the wave equation yields,

\[
\frac{\partial^2 \phi_j}{\partial r^2} + \frac{1}{r} \frac{\partial \phi_j}{\partial r} + \left( \frac{p_j^2 - \nu_j^2}{r^2} \right) \phi_j = 0 ,
\]

\[
\frac{\partial^2 \psi_j}{\partial r^2} + \frac{1}{r} \frac{\partial \psi_j}{\partial r} + \left( \frac{s_j^2 - \nu_j^2}{r^2} \right) \psi_j = 0 ,
\]

\[
\frac{\partial^2 \chi_j}{\partial r^2} + \frac{1}{r} \frac{\partial \chi_j}{\partial r} + \left( \frac{s_j^2 - \nu_j^2}{r^2} \right) \chi_j = 0
\]

where \( \phi_j \) is the compressional and \( \psi_j \) and \( \chi_j \) are the two shear displacement potentials in the layer \( j \). \( p_j \) and \( s_j \) are the compressional and shear radial wavenumbers in that
The introduction of a pipe (tool in an LWD setting) in a fluid-filled borehole complicates the wave propagation characteristics by the introduction of additional modes. The modes that exist in a fluid-filled borehole without a tool are present. In addition, there exist modes that can be attributed to the tool itself and to the inner fluid column bounded by the tool. Therefore, the modes that are present in a fluid-filled borehole with a tool can be associated to the modes of three layers—an inner fluid column, tool, and annulus fluid column/formation. The dispersion characteristics of the modes are governed mainly by the properties of the associated layer. Specifically, the modes associated with the inner fluid column are very similar to the modes of a fluid column bound by an infinite solid. The modes associated with the tool are very similar to the modes of a tool suspended in air, and the modes associated with the annulus fluid column are similar to those of a fluid-filled borehole without a tool. However, there are regions where dispersion curves of modes associated with different layers intersect. The resulting dispersion plot has the modes exchanging their dispersion characteristics above or below the intersection point. Identifying the origin of the various mode sets is helpful in keeping track of formation-sensitive arrivals and in developing an intuitive understanding of the modal characteristics. For example, an increase in annulus thickness due
Models in LWD Applications

to the tool operating in a larger borehole affects the annulus fluid modes dominantly. Cutoff modes corresponding to this layer would shift to lower frequencies.

Thus, estimating formation speeds requires that annulus fluid column modes be used, since they are most affected by formation properties. Of the remaining modes, those which are in close proximity to the annulus modes (in phase/group speed-frequency domain) would produce arrivals that could mask or corrupt the formation sensitive arrivals. The excitation function of these modes would quantify the extent to which these modes would interfere with the signals of interest.

All modes that are present in hard and soft formations below 30 kHz are summarized in Table 1 in the third and fourth columns, respectively. The layer which predominantly influences the dispersion is identified in the second column.

Monopole Modes \((\nu = 0)\)

The dispersion curves for \((\nu = 0)\) in hard and soft formation are shown in Figures 1 and 2. Two Stoneley modes, one associated with the annular fluid column and one with the inner fluid column, are present in both formations. The phase speed of the inner fluid Stoneley mode is faster of the two and is close to the speed of sound in water since it is bounded by the stiff steel tool. The annular Stoneley mode is sensitive to the formation properties and is slower than the former.

In both formations the lowest-order mode associated with the tool (phase speed 5400 m/s at 0 Hz) has the 'bar velocity' at low frequencies and transitions to a Stoneley surface wave on the tool at high frequencies. The 1\(^{st}\) and higher-order cutoff modes also asymptote to the same phase speed as the fundamental mode, at high frequencies. Only the modes with phase speeds greater than the formation shear speed are attenuated.

The mode that is strongly differentiated in hard and soft formations is the 1\(^{st}\) order cutoff mode of the annulus fluid or the pseudo-Rayleigh mode. This mode propagates at the fluid velocity at high frequencies and is cutoff at the formation shear speed at low frequencies. In soft formations, when the formation shear speed is slower than the fluid speed, this mode ceases to exist. Thus, a monopole tool in soft formation has to rely on the annulus Stoneley mode and refracted compression arrivals to estimate formation properties, while refracted compression and shear arrivals, and both pseudo-Rayleigh and Stoneley modes (depending on the operating frequency) can be used in hard formations.

Dipole Modes \((\nu = 1)\)

The dispersion curves for \((\nu = 1)\) in hard and soft formation are shown in Figures 3 and 4. The 1\(^{st}\) order cutoff mode of the inner fluid is typically very fast and occurs at high frequencies; it is of little consequence in LWD operation. The same is true of the 1\(^{st}\) order cutoff mode of the tool. However, the tool flexural mode and the aforementioned cutoff modes all interact around 20 kHz. There is a similar interaction between the tool flexural mode and the borehole flexural mode at 2 kHz.
The flexural mode of the tool, labeled 'a', appears to terminate at the formation shear speed at low frequencies and asymptotes to the fluid velocity at high frequencies. The phase speed of the flexural mode of a tool in air, however, reduces to zero phase speed at zero frequency and asymptotes to the Stoneley surface wave speed on the tool (3000 m/s) at high frequencies. Similarly, the borehole flexural mode, labeled 'b', tends to zero phase speed at zero frequency. However, the phase speed of the flexural mode of a fluid-filled borehole (without a tool) terminates at the formation shear speed at low frequencies. This apparent discrepancy is due to the interaction of the two modes around 2 kHz. In this frequency range the flexural waves in the tool are affected by the presence of the formation. The flexural waves in the borehole are affected by the tool and results in an exchange of trends below 2 kHz. A more complex interaction between the the tool flexural mode and the 1st order cutoff modes of the pipe and inner fluid takes place at 20 kHz. Similar to the 2 kHz interaction, the dispersion characteristics of the three modes are exchanged for frequencies above 20 kHz. For example, the segments 'a1', 'a', and 'a2' describe dispersion of the tool in air, and 'b1' and 'b' that of the borehole without the tool.

The interaction of the modes of the underlying simple waveguides can therefore obscure the various dispersion curves of the composite waveguide. Unraveling the true origins of the various dispersion segments is important when identifying and tracking formation sensitive arrivals.

A dipole tool in soft formation has to rely on the borehole flexural mode for formation properties, whereas in hard formations refracted arrivals, borehole flexure, and the 1st cutoff mode can be used.

Quadrupole Modes ($\nu = 2$)

The dispersion curves for ($\nu = 2$) in hard and soft formation are shown in Figures 5 and 6. There are no modes associated with the inner fluid column in this frequency range. Like the monopole case, there is no modal interaction in this range. While quadrupole sources are not common in LWD, real monopole or dipole sources would likely excite these higher order modes. Depending on the frequency, either annulus mode could be used.

SUMMARY

A model for nonaxisymmetric wave propagation in fluid-filled boreholes with an LWD tool was developed. This was used to compute monopole, dipole, and quadrupole modes. All the modes that are present can be related to three layers—inner fluid, tool, and annulus fluid. The conventional dispersion characteristics of the modes are preserved, except in regions where the dispersion curves of different layers intersect.

Apart from refracted arrivals, the arrivals of most interest are those that are due to modes that are influenced by formation properties. The remaining arrivals are 'noise' that would mask the arrivals of interest. Computing the excitation functions of the
Models in LWD Applications

various modes to common LWD sources and estimating the relative strength of the various arrivals would be the next step. This would guide tool design and source frequency selection to strengthen formation-sensitive arrivals and aid in the development of processing algorithms that would discriminate signal from noise.

ACKNOWLEDGMENTS

This work was supported by the Borehole Acoustics and Logging/Reservoir Delineation Consortia at the Massachusetts Institute of Technology. We also wish to acknowledge the support of Sperry-Sun Drilling Services for this study.
Rao et al.

REFERENCES


Models in LWD Applications

Borehole in a HARD formation with tool: $n = 0$ (monopole)

Tool: 1.9" ID, 7.25" OD  Borehole: 8.75" ID

Figure 1: **Hard formation**—Dispersion and attenuation of **Monopole** modes. Only the tool modes are attenuated.
Borehole in a SOFT formation with tool: \( n = 0 \) (monopole)

Tool: 1.9" ID, 7.25" OD  Borehole: 8.75" ID

**Figure 2**: Soft formation—Dispersion and attenuation of Monopole modes. Only the tool modes are attenuated.
Models in LWD Applications

Borehole in a HARD formation with tool: n = 1 (dipole)
Tool: 1.9" ID, 7.25" OD  Borehole: 8.75" ID

Figure 3: Hard formation—Dispersion and attenuation of dipole modes. The flexure mode of a tool in air is given by connecting the segments 'a1', 'a', and 'a2'. Similarly, the borehole flexure without tools is given by 'b1' and 'b'. The tool flexure mode (b), first-order tool cutoff mode (c) and first-order inner fluid cutoff mode (d) are attenuated.
Rao et al.

Borehole in a SOFT formation with tool: n = 1 (dipole)
Tool: 1.9" ID, 7.25" OD  Borehole: 8.75" ID

Figure 4: **Soft formation**—Dispersion and attenuation of dipole modes. Similar to the hard formation but without the first-order borehole flexural mode.
Borehole in a HARD formation with tool: $n = 2$ (screw)
Tool: 1.9" ID, 7.25" OD  Borehole: 8.75" ID

Figure 5: Hard formation—Dispersion and attenuation of quadrupole modes.
Figure 6: Soft formation—Dispersion and attenuation of quadrupole modes. Similar to the hard formation without the first-order borehole quadrupole mode.