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# STEERING AND FOCUSING ACOUSTIC MODAL ENERGY IN CASED-WELLBORES

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## ABSTRACT

*As unconventional reservoirs seize a more and more pronounced market share today, to understand the mechanical behavior of such systems throughout the production lifetime is becoming increasingly intriguing. The current acoustic logging tools emit energy to the full azimuth without control, thus limited spatial resolution and depth of investigation can be achieved due to the lack of penetration power. A next generation transduction technology that is able to steer the sound beam azimuthally, axially and radially are therefore in urgent need. In this talk, we present an acoustic beam steering and focusing method in cased-wellbore geometry. The method is valuable for cement evaluation in multi-string cased-wells and a high resolution scanning of mechanical properties in surrounding rock formations.*

Keywords: well integrity evaluation, acoustic energy control, borehole guided waves

## NOMENCLATURE

| | |
|---|---|
| $A_n^M$ | Amplitude factor of borehole mode |
| $\beta_n^{M*}$ | Complex wave number |
| $\mathbf{v}_n^{M*}$ | Particle displacement distribution function |
| $\mathbf{T}$ | Loading function on the inner borehole wall |
| $\mathbf{n}_1$ | Unit normal in radial direction |

## 1. INTRODUCTION

Historically, major advancements of acoustic well logging technologies, both Wireline and Logging While Drilling (LWD), occur with the emergence and commercialization of innovative transduction and receiving modalities [1-3]. Monopole acoustic logging enables reliable compressional/shear wave velocity measurement in fast formation and estimation of formation permeability with low frequency Stoneley waves [2]. However, monopole tools are not able to determine shear speed in slow formations as no shear head wave is generated. Consequently, the dipole acoustic logging tools are developed with which the shear wave speed in slow formation are estimated with the low frequency limit of flexural waves. The further advancement of cross dipole logging provides capabilities of anisotropic elastic moduli inversion and horizontal stress estimations. The strong interferences between formation and tool flexural waves renders the LWD (Logging-While-Drilling) shear wave speed measurement with dipole sources impractical, thus quadrupole techniques are developed to offer answers that were not available from monopole and dipole tools [2,3]. As unconventional reservoirs seize a more and more pronounced market share today, to understand the mechanical behavior of such systems throughout the production lifetime is becoming increasingly intriguing [3-6]. The current acoustic logging tools emit energy to the full azimuth without control, thus limited spatial resolution and depth of investigation can be achieved due to the lack of penetration power[3]. A next generation transduction technology that is able to steer the sound beam azimuthally, axially and radially are therefore in urgent need[7].

In this talk, we present a phased array acoustic logging system in the lab, for which time delays and amplitude controls are applied to the 8 or 16 channels of transduction elements to scan the acoustic beam through the area of interest. By properly adjusting the time delays and amplitude control among the elements, the acoustic waves can be steered and focused dynamically without requiring mechanical scanning in the lab[7,8]. Moreover, a self-adjustable beam steering algorithm could be achieved by a combination of phased array and time reversal firings. The benefits of the proposed system include enhanced borehole imaging with higher resolution and penetration power, which are advantageous for the characterization of vertical fractures or faults near a vertical borehole, sedimentary interfaces near a horizontal well, and cement imperfections evaluation in multistring cased wellbores, etc. In conjunction with the understanding of the migration and maturation of the hydrocarbons they contain, this research leads to improved strategy of how to place and design wells for maximum efficiency and stability. Ultimately, we are aiming at providing the unparalleled advantage of 3-D scanning of the mechanical

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properties of the reservoir and enhanced well integrity evaluation.

## 2. MATERIALS AND METHODS

Experiments have been conducted in immersed single and double strings to demonstrate the capability of steering the acoustic wave energy in cylindrical waveguides. The steel pipe used in the experiments is of OD 4.75'' and thickness 0.262''. The phase velocity dispersion curves for the immersed pipe are shown in Fig. 1. It is noted that the monopole and high order multiple waves with circumferential order up to 5 are plotted in Fig. 1. An angle beam with incident angle 25.5 degrees has been used to excite L(M,2) mode family at 230 kHz, for which the excitation spectra has been shown as red and orange shade areas in Fig. 1. The A-scan signals received by a 50-element axial array for L(M,2) excitation at 230 kHz are shown in Fig. 2. The experimental group velocity for the first receiving wave packet can be extracted from axial array signals, which is about 4650 m/s. This is exactly the group velocity of L(M,2) mode family at 230 kHz. The good agreement between experimental and theoretical group velocities demonstrate that we are exciting the correct mode family for the acoustic beam steering experiments.

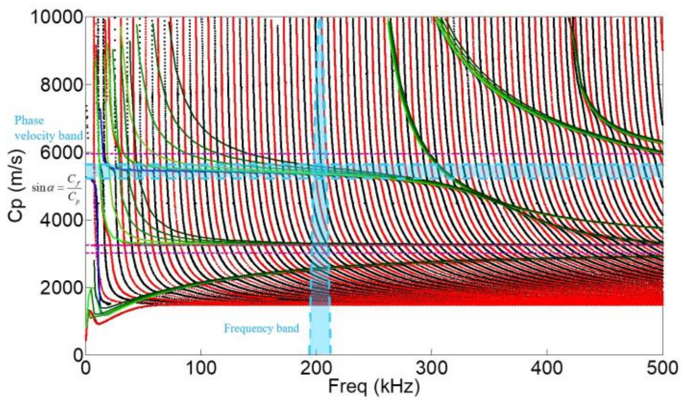


**FIGURE 1:** PHASE VELOCITY DISPERSION CURVE FOR THE IMMERSED STEEL PIPE USED FOR PHASED ARRAY BEAM STEERING EXPERIMENTS. THE RED AND BLACK DASHED LINES REPRESENT FOR THE MONOPOLE AND DIPOLE MODES, WHILE THE GREEN LINES INDICATE THE SKELETON MODES FOR THE GEOMETRY.

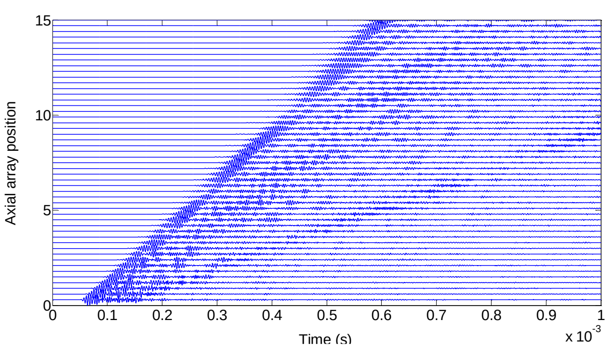


**FIGURE 2:** THE A-SCAN SIGNALS RECEIVED BY A 50-ELEMENT AXIAL ARRAY FOR L(M,2) MODES AT 230 KHZ

## 3. RESULTS AND DISCUSSION

A partial loading condition is defined when the transmitter covers only a limited azimuthal section of the cylindrical waveguides. The resulted acoustic wave field is a complicated function of the loading function, transducer size, launching angle, waveguide properties and geometries, etc. The azimuthal wave energy distribution at an arbitrary axial location is defined as angular profile, which can be analytical predicted by a Normal Mode Expansion method (NME)[7,8],

$$A_n^M(z) = \frac{e^{-i\beta_n^{M*}z}}{4P_{nn}^{MM}} \int_c^z e^{i\beta_n^{M*}z} \left( \int_{\partial_1 D} \mathbf{v}_n^{M*} \cdot (\mathbf{T} \cdot \mathbf{n}_1) ds \right) d\eta \quad (1)$$

where $A_n^M$ is the amplitude factor of the excited borehole mode of circumferential order M and family order n, $\beta_n^{M*}$ is the complex wave number, $\mathbf{v}_n^{M*}$ is the particle displacement distribution function, $\mathbf{n}_1$ is the unit normal in radial direction, and $\mathbf{T}$ is the source loading function on the inner borehole wall.

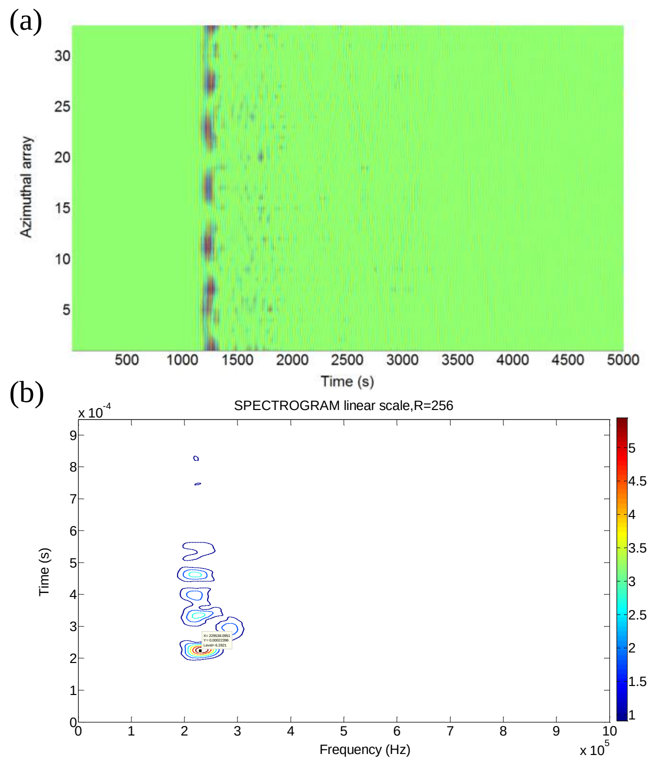


**FIGURE 3:** PHASE VELOCITY DISPERSION CURVE FOR THE IMMERSED STEEL PIPE USED FOR PHASED ARRAY BEAM STEERING EXPERIMENTS. THE RED AND BLACK DASHED LINES REPRESENT FOR THE MONOPOLE AND DIPOLE MODES, WHILE THE GREEN LINES INDICATE THE SKELETON MODES FOR THE GEOMETRY.

We have experimentally measured the angular profile for an angle beam excitation (with azimuthal coverage 22.5 degrees) at multiple axial distances from the transmitter. The axial locations and the azimuthal arrays for angular profile measurement in the experiments are evenly distributed. In Fig. 3 (a), we present the azimuthal array signals received at propagation distance 39.370l inches. It is noted that the L(M,2) is the fastest mode group at 230 kHz, therefore the wave packets are clearly separated as the first receiving signals. In Fig. 3 (b), we show the short time Fourier Transform of the azimuthal array signals. The time-frequency representation of the array signals are particularly important for beam steering processing in recognizing the modal contents due to the multi-modes and dispersive nature of the guided waves. In Fig. 4 (a), we present the experimental and theoretical angular profile for L(M,2) mode family at propagation distance 39.3701 inches. The experimental angular profile are created by normalizing the integration of the STFT of the azimuthal array signal in a proper time and frequency range. By applying proper amplitude factors and phased delays to each individual channels, we were able to steer and focus acoustic energy in the immersed steel casings, as indicated by Fig. 4 (b). The current work provide solid foundations for the acoustic beam steering in the next phase of the work.

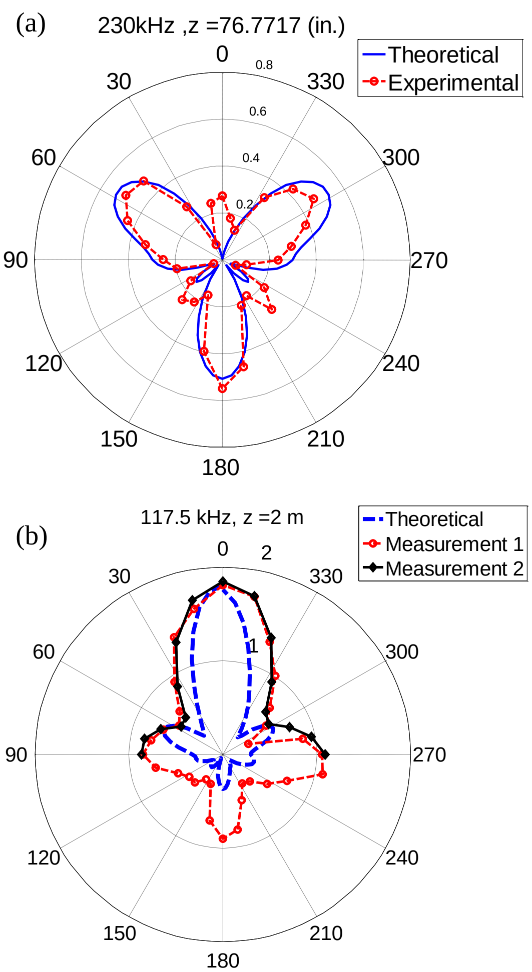


**FIGURE 4:** THEORETICAL AND EXPERIMENTAL PARTIAL LOADING ANGULAR PROFILE AND THE FOCUSED ACOUSTIC BEAM

## 4. CONCLUSION

In this short paper, we present the theoretical and experimental results on acoustic beam steering and focusing in cased-wellbores. The immersed single and double casings are established as mock-ups for the cased-wellbores. The results indicates that the acoustic modal energy can be successfully steered and focused with a 8 or 16 channel circular transducer array. The study provide the basis for the further investigation on well-integrity evaluation in multi-string cased-wellbores and 3D geomechanics through casing.

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