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MODELING CASEDHOLE LAMB-WAVE CHARACTERISTICS FOR AN ORIENTED TRANSMITTER AND RECEIVER SYSTEM

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ABSTRACT

Due to the finite beam radiation and reception of the cased well Lamb-wave measurement and the plane-wave propagation approximation, the influence of wave spreading on wave amplitude attenuation is often ignored. To investigate the problem, the logging response characteristics of the ultrasonic pitch-catch measurement system in cased wells are analyzed using numerical modeling and experimental measurement. The snapshots of displacement wave field in the casing for different offsets are compared, from which the apparent radiation spreading of the wave field is observed. In the measurement, the receivers have reception directivity and the flexural Lamb wave propagation is in the arcuate casing. As a result, the attenuation measured from the waveform amplitude of the near and far receivers is affected by these effects; the closer the ultrasonic pitch-catch system gets to the inner wall of the casing, the greater the measured attenuation value is, as is caused by the Lamb wave spreading from the arcuate casing. The results of this study demonstrate that a correction for this wave radiation or spreading effect is needed for using the attenuation measurement for cementing quality evaluation.

Keywords: attenuation, Lamb wave, radiation spreading, reception directivity

NOMENCLATURE

1. INTRODUCTION

In the completion of a well for production, it is very important to provide isolation between neighboring zones over the production interval. Failure in isolation can cause problems like water production, depletion of hydrocarbon production and loss of production to neighboring zones, etc. The conventional acoustic cement evaluation techniques such as CBL (Cement Bonding Log) and VDL (Variable Density Log), have no azimuthal sensitivity because the received acoustic signal is the average from all directions around the casing. To determine the poorly cemented azimuthal sector(s) and increase the axial resolution, the segmented bond tool (SBT) was developed, which measures the quality of the cement bond in six angular segments around the casing (Bigelow, et al., 1990). To differentiate the lightweight cement from liquids, the pitch-catch ultrasonic logging tool has been developed. An example is the Isolation Scanner Tool (Kuijk, et al., 2005). This tool induces and measures the flexural wave (called anti-symmetric Lamb mode A0) in the casing. Some recent reviews of the exciting techniques are presented by Zeroug et al (2002, 2003, 2004, 2008), Viggen et al. (2016), Xu et al. (2013, 2017), and He et al. (2014). A source transducer emits an ultrasonic pulse toward the casing at an oblique angle and excites the casing flexural wave modes. The flexural wave propagates along the casing while radiating acoustic energy into materials on both sides of the casing. The wave is then recorded by two obliquely oriented receivers at some distance from the source. The measured wave attenuation between the two separate receivers mainly reflects the acoustic property of the material behind the casing. In a highly deviated well or horizontal well the measured attenuation values along the circumference of the casing vary with azimuthal angle if tool eccentralization occurs. In this case, the distance from the transducer to the inner casing surface varies at different azimuth angles and the wave travel distance also varies. The azimuthal sensitivity of receiving transduces of the pitch-catch ultrasonic system should also be considered. The reception directivity depends on the distance from the transducer to the inner casing surface. When the flexural Lamb wave travels in the casing while leaking or radiating energy into surrounding medium, the received wave energy at the far and near receivers is affected by the radiation effected. The following study shows that the measured attenuation needs to be corrected or calibrated for the measured values to be closely related to cement bonding quality.

2. Numerical Modeling

To Visualize the flexural Lamb wave propagation in the casing, the 3D staggered grid finite difference models were developed to model the Lamb wave propagation in casing in connection with the finite beam excitation and reception of the source and receivers of the measurement system. The casing model dimension is 0.29×0.29×0.5m. Casing ID and OD are 9.625in and 11.99mm respectively. The diameter of orientated source and receiver is 0.03m. Figure 1 illustrates the configuration of the source and receiver transducer in the casing model. Receivers are azimuthally distributed inside casing at a 15° increment. A 250kHz center frequency source is used to actuate wave propagation in finite difference model. Steel casing density and compressional velocity and shear velocity are 7800kg/cm^3, 5903m/s and 3200m/s, respectively. The fluid density and velocity are 1000kg/cm^3 and 1500m/s, respectively.

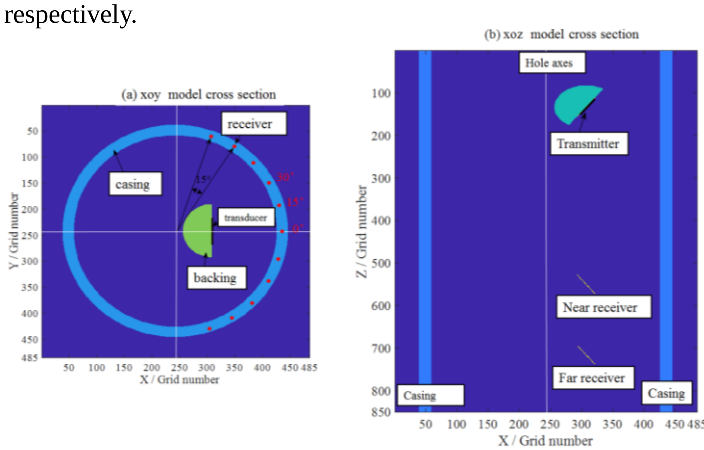
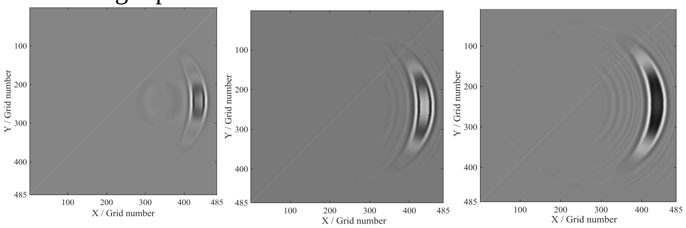


FIGURE 1: SCHEMATIC OF SIMULATION MODEL

3. RESULTS AND DISCUSSION

3.1 Radiation spreading of the Lamb wave in the casing

In the modeling, the transmitter is at 0.04m from the inner wall of the casing. The flexural Lamb wave displacement wave field snapshots with 0.125m, 0.25m and 0.35m offsets along the casing are illustrated in Figure 2, where the casing displacement distribution is visualized. The amplitude of the displacement at the inner and outer surface of casing is larger than that at the mid-plane. By comparing snapshots at the 3 offsets, it can be seen that the covered segment area by the Lamb wave becomes progressively larger and larger as it travels father and farther along the casing. At the 0.125m offset, the energy of the Lamb wave concentrates on a small part of the casing. At 0.25m and 0.35m offsets, the wave energy spreads to cover a larger part of the azimuthal sector.



(a) 0.125m (b) 0.25m (c) 0.35m

FIGURE 2: LAMB WAVE PROPAGATION SNAPSHOTS WITH 3 DIFFERENT OFFSETS

For depicting the radiation spreading of the Lamb wave away from the casing the waveforms from the azimuthally distributed 11 receivers (see Figure 1a) are analyzed. Because of the symmetry with respect to the 0 ° azimuth, Figure 3 only shows the waveforms at 6 receivers from 0° to 75° for 3 different offsets along casing. At the 0.125m offset, the amplitudes of the Lamb waves decrease sharply away from the central sector(0°) at 0.125m offset. At the 0.35m offset the decrease is more gradual. The Lamb wave amplitudes measured from the wave packet envelope versus azimuth are shown in Figure 4. With the Lamb wave travels farther away along the casing, the Lamb wave spreads and covers on a larger azimuthal parts of the casing. With the distance between the transducer and the inner casing surface increasing from 0.04 to 0.07, the spreading effect becomes smaller, as shown in Figure 4.

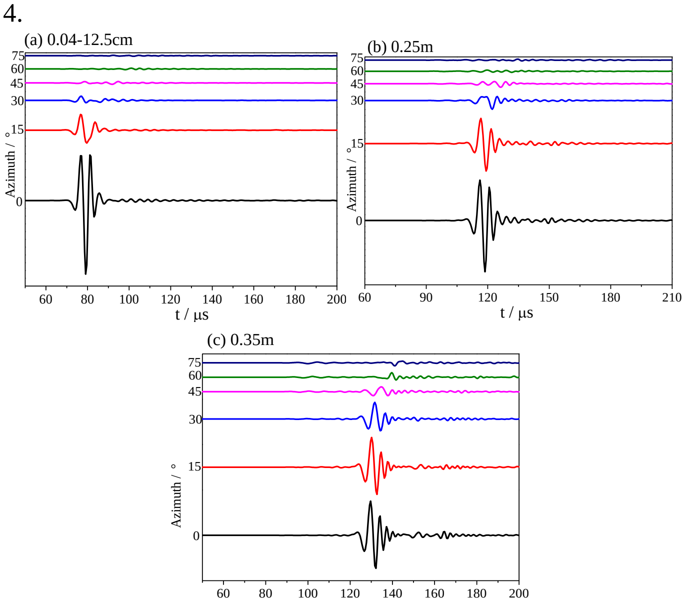


FIGURE 3: DISPLACEMENT WAVEFORMS WITH DIFFERENT AZIMUTHAL ANGLES

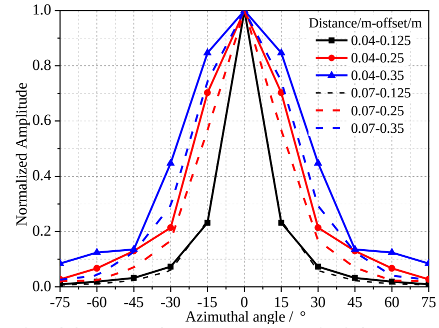


FIGURE 4: DISPLACEMENT AMPLITUDE VERSUS AZIMUTHAL ANGLE

3.2 Reception directivity

Because the transmitter emits an oriented finite beam toward the casing, the flexural Lamb wave is generated only in a finite part of the casing in front of the transmitter. As the wave travels in the casing, it spreads in the casing and covers a larger part of the casing. The wave signals are recorded by the receivers inside the casing. Figure 5 shows the wave reception configuration. When the transducer gets closer to the casing inner surface, the sector area from which the wave energy leaking from the casing can be received becomes smaller because of the reception directivity. As a result, the receivers may not effectively record the casing wave energy in some situations.

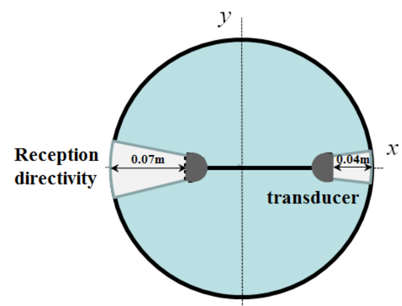


FIGURE 5: DIAGRAMMATIC SKETCH OF RECEPTION DIRECTIVITY

3.3 Influence of Radiation spreading and reception directivity on attenuation

In case of a deviated well, the tool may be systematically off-centered toward to the low side of the casing. Figure 6 shows the measured attenuation values at different distances from tool to casing. It can be seen that the measured attenuation increases gradually as the tool gets closer to the casing. The attenuation from the numerical simulation agrees with the experiment measured attenuation, showing increasing attenuation with decreasing source to casing distance. This effect is jointly caused by the Lamb-wave radiation spreading and reception directivity.

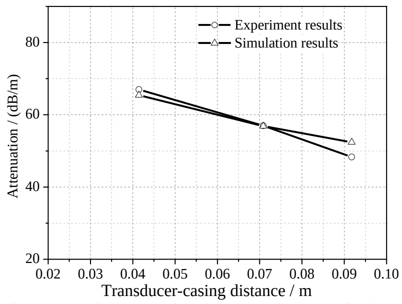


FIGURE 6: MEASURED ATTENUATION VERSUS TRANSDUCER-CASING DISTANCE

Tool eccentralization may cause both the distance variation between transducer and casing and the incident angle variation from the source. In the systematically tool eccentering case, the recorded leaky Lamb-wave amplitudes vary with azimuthal angles (see Figure 7). When the radiation or reception plane is facing the inner casing surface for the 0 °(the smallest distance) and 180 °(the smallest distance), the Lamb-wave amplitudes are the strongest. But the attenuation values with 0 ° and 180 ° azimuths are different. The 0 ° attenuation is greater than 180 ° because the transducer is closer to casing for 0 ° than for 180 °. The Lamb-wave amplitudes are the weakest at the 90 ° and 270 ° azimuths. Figure 8 shows attenuation variation versus azimuthal angles for the 0.01m and 0.02m off-centering cases. The attenuation variation can be quite significant for an off-centered measurement tool.

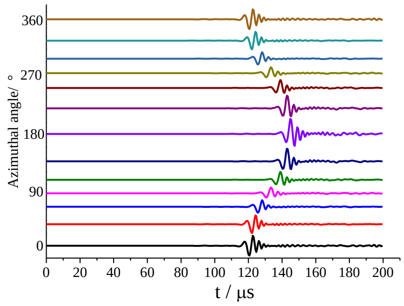


FIGURE 7: RECEIVED WAVEFORMS VERSUS AZIMUTHAL ANGLES WITH A 0.01M OFF-CENTERED TOOL

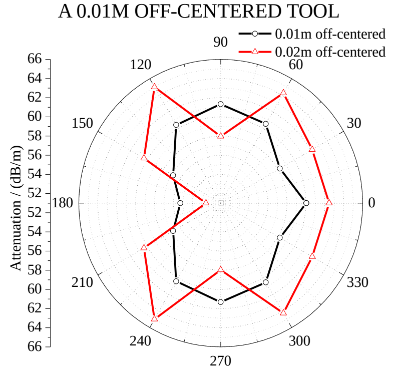


FIGURE 8: ATTENUATION VERSUS AZIMUTHAL ANGLES WITH DIFFERENT OFF-CENTERED PERCENT

4. CONCLUSION

In this paper, we have analyzed the Lamb wave attenuation measurement using oriented finite beam transducers in a cased borehole. The radiation spreading and reception directivity can significantly influence the measured attenuation values. The attenuation increases as the pitch-catch ultrasonic logging tool gets closer to the inner wall. The results of our work show that when using the Lamb-wave attenuation to evaluate the cement bonding quality, the effect of transmitter radiation or spreading and the receiver reception directivity need to be corrected or calibrated in order to obtain the attenuation related to the cement bond quality.

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