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# Reducing liquid layer ambiguity of well integrity measurements through extensional mode analysis

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***Abstract*—Acoustic non-destructive evaluation is widely used in the oilfield industry to evaluate the state of the material behind the steel pipes, called casings, which are used in the construction of subterranean oil and gas wells to retrieve hydrocarbons. The annular region between a casing and the surrounding geological formation is usually cemented to provide mechanical support for the casing as well as to ensure zonal isolation between different geological layers. The proper placement of the cement is typically evaluated using sonic and ultrasonic techniques. However, these measurements are often perturbed in the presence of a liquid-filled microannuli, a thin layer of liquid between the pipe and the cement, which renders the interpretation prone to ambiguity and error. To reduce uncertainties in the presents of microannuli, we investigate the benefits of supplementing the industry-standard thickness mode resonance technique with a measurement using the zero-order extensional mode. We built a full analytical model of a cemented borehole which included all the layers present and allowed to finely tune the boundary conditions between them. To validate this model, we developed an experimental apparatus and a set of procedures to produce highly controlled cases of liquid-filled microannuli in the lab. Finally, we benchmarked the results of the model against these experimental scenarios. The validity of the analytical model was evaluated through the comparison with several experiments. We showed that the model's predictions were consistent with the experimental results and allowed a comprehensive assessment of the presence of liquid-filled microannuli. Using our modeling approach, we further demonstrated that the presence of a liquid-filled microannulus lead to a much stronger response of the zero-order extensional mode (compared to the other techniques) due to its high sensitivity to shear coupling between the steel and the annular material. As a result, we propose to complement the current pulse-echo measurement with a pitch-catch measurement based on the zero-order extensional mode of the pipe which allows a much easier and less ambiguous detection of liquid-filled microannuli.**

***Index Terms*—ultrasonic, pulse-echo, flexural wave imaging, lamb modes, borehole, imaging, geological formation, non-destructive evaluation, well cementing, cement evaluation, zonal isolation, microannulus, layered structures**

## I. INTRODUCTION

Acoustic nondestructive evaluation is widely used in the oilfield industry to evaluate the state of the material behind the steel pipes, called casings, which are used in the construction of subterranean oil and gas wells to retrieve hydrocarbons. The annular region between a casing and the surrounding geological formation is usually cemented [1] to provide mechanical support for the casing as well as to ensure zonal isolation between different geological layers [2]. However, placement of the cement in the annulus is a difficult operation which can fail in several ways [3]. One frequent issue is the presence of another fluid between the pipe and the cement which is called a microannulus [4], [5]. Currently, the dominant measurement technique in the industry is based on pulse-echo ultrasonics [6] which evaluates the resonance characteristics of the thickness mode inside the pipe steel to discriminate between solid and liquid [7]. These measurements are sometimes complemented with pitch-catch measurements based on analyzing the propagation of the zero-order flexural mode in the steel to generate azimuthally resolved images of the annular region [8], [9] and the state of the material therein [10], [11]. However, these two measurements are often perturbed in the presence of a liquid-filled microannulus which renders the interpretation prone to ambiguity and error—their main drawback being their sensitivity to the state of the interface between the pipe and the cement [12]. In presence of liquid-filled microannulus, the response of the tool can be ambiguous and lead to erroneous evaluation of the annulus material [13]. This is often circumvented by pressurizing the well to close this small gap between casing and cement sheath [14] which increases the cost and complexity of the operation, or by additional postprocessing of the measurement data [15]. Here we evaluate the reduction of uncertainties in the presents of liquid-filled microannuli by investigating the benefits of supplementing the industry-standard thickness mode resonance technique with a measurement using the zero-order extensional mode of the steel pipe.

## II. THEORETICAL BACKGROUND AND MODELLING

Several modes of guided waves can propagate in a steel plate. At low frequency, there are only two modes that exist, zero order symmetric and anti-symmetric, which are referred here as extensional and the flexural mode. The wave motion of these two modes is displayed in Fig.1 in a side view of a steel plate.

These modes are dispersive which means that to excite optimally one particular mode at a given frequency the wavefront must hit the steel plate at a specific angle of incidence. Using Snell's Law, this angle can be determined. For a guided wave with a velocity $V = 5500\, m.s^{-1}$ (low frequency velocity of the extensional mode) with water on one side of the steel plate, this angle is close to $16^o$ [1].

We used a commercial software called Disperse [16] to compute and generate dispersion curves in flat structures. With Disperse we computed the phase and group velocity of those

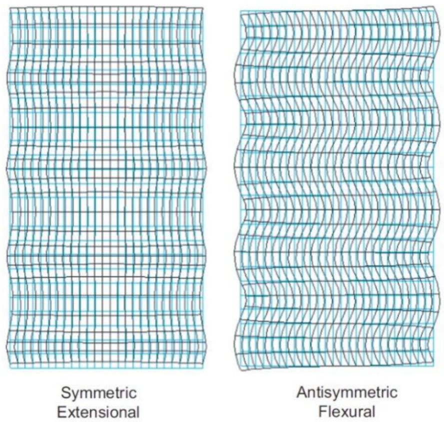


Fig. 1. Representation of the motion of the both zero-order symmetrical and anti-symmetrical mode of a guided wave in a steel plate. (from Disperse [16])

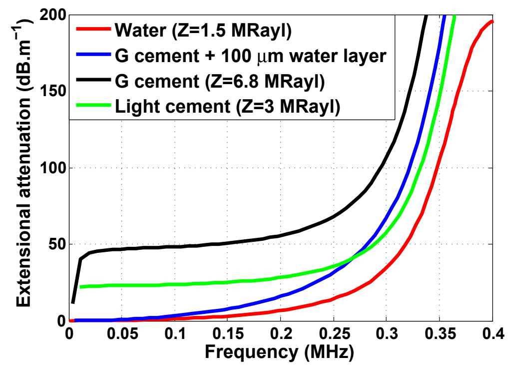


Fig. 3. Modal attenuation of the zero order symmetrical mode of a 6.5 mm thick steel plate using Disperse [16] for various materials adjacent to it.

modes for a plate thickness of 6.5 mm (see Fig.2). We can see that around 100 kHz the group velocity of the extensional mode is flat which means that the wave packet remains compact during its propagation. Additionally, we also notice that around 100 kHz the velocities of both modes are very different which means that the extensional mode is not polluted by the flexural mode. Hence, the amplitude of the wave packet should be efficient to measure the attenuation due to the leakage into the annulus.

The modal attenuation of the extensional mode resulting from different materials on one side of a steel plate and vacuum on the other side was computed (see Fig.3). The properties of the different cements used for the simulations are shown on Table I. The expected attenuation at 100 kHz is around 1.2 dB/m and 0.6 dB/m for water and air while for a class G cement the attenuation reaches 54.5 dB/m. This significant difference in attenuation allows discriminating without ambiguity between fluid and solid in the annulus.

For the liquid-filled microannulus, a computation was made with a water layer of $100\mu m$ between the steel plate and the class G cement. Because of this liquid layer, there is no more shear coupling at the interface between the steel and the cement which should lead to a significant drop of the attenuation.

As stated before, the extensional mode is particularly sensitive to the shear coupling at the casing-to-cement interface due to its strong in-plane motion. When this coupling with the annulus material is lost, the wave is no longer attenuated and the situation becomes analogous to the case with only liquid in the annulus. Unsurprisingly, this is exactly what is observed in the simulations at low frequency (see Fig.3). In fact, below 100 $kHz$ the attenuation in presence of the small liquid layer converges to the case with only water behind the steel which provides a strong difference compared to the case in the absence of the water-filled microannulus. By coupling this extensional measurement with a pulse-echo measurement, which is not highly affected in presence of a small liquid-filled microannulus, it becomes possible to differentiate between contaminated cement, which shows lower impedances on the pulse-echo, from a small liquid-filled microannulus, which would have the similar impact on the reading of the impedance. Finally, Fig.3 shows also that starting from 200 $kHz$ the attenuation of the liquid-filled microannulus starts to diverge from the response of a homogeneous liquid. Hence, to select the frequency of the mesurement, care should be taken to ensure that the liquid-microannulus can be detected while still having an azimuthally resolved measurement.

Two different measurements are made from the inside of the sample. The first one is a pulse-echo measurement in which an ultrasonic transducer with a central frequency of 500 $kHz$ sends a short pulse toward the inner part of the tubes and receive the specular as well as the resonance of the casing thickness mode (see Fig.4). This resonance is processed to invert the acoustic impedance of the annulus [7], [17]. The second measurement involves two transducers with central frequency of 250 $kHz$ in a pitch catch configuration (one emitter and one receiver). Both transducers are inclined at $16^o$ with respect to

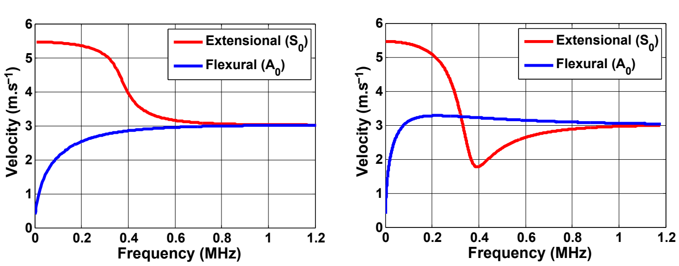


Fig. 2. Phase velocity (left) and group velocity (right) in vacuum in a 6.5 mm steel plate. (from Disperse [16])

| | Water | G cement | Light cement |
|---|---|---|---|
| $\rho\ (kg.m^{-3})$ | 1000 | 1900 | 1120 |
| $V_p\ (m.s^{-1})$ | 1480 | 3600 | 2700 |
| $V_s\ (m.s^{-1})$ | 0 | 2000 | 1500 |

TABLE I
ACOUSTIC PROPERTIES OF MATERIALS USED IN DISPERSE'S SIMULATIONS

the inner tube vertical surface to optimize the coupling into the extensional mode of the tube (see Fig.4). The emitter sends an acoustic pulse toward the tube's inner surface which is coupled into the extensional mode of the tube. This extensional wave proceed to radiate into both the inside fluid and the annulus and the inner radiation is picked up by the receiver. The picked up signal is filtered using a low pass filter with a 150 $kHz$ cut-off. One particular feature of this setup is that the transmitter-receiver spacing can be increased-decreased by 20 $mm$ to compute an attenuation. Both measurement are run successively with 20 $mm$ vertical sampling and $10^o$ azimuthal sampling and the two maps, impedance and attenuation, can be compared.

## III. Results

For each pulse-echo waveform a proprietary inversion algorithm is used to compute the annulus impedance $Z_{annulus}$ [18]. For the pitch-catch measurement, each couple of waveforms corresponding to small and large transmitter-receiver spacing are low pass filtered at $150\,kHz$ and the amplitude of the first negative peak is measured ($E_{near}$ and $E_{far}$). Finally,the attenuation is computed as follow with $L = 20\,mm$ corresponding far and near receiver length

$$A_{tt} = \frac{20}{L}\log(\frac{E_{near}}{E_{far}}) \quad (1)$$

For comparison, we report in Table II typical impedance and extensional attenuation measured in this setup for different reference materials in the annulus such as air, water, a lightweight cement and a dense cement.

The two maps generated are displayed in Fig.5 and Fig.6. The deposition pattern of the thin layer of drilling fluid is evident on both measurements. In the area where the casing was initially clean the impedance and the attenuation are large which is coherent with the fact that the cement is well coupled to the steel pipe. In the area initially polluted by the mud layer we observe that the attenuation and the impedance are lower. In the case of the impedance map, the impedance is still mostly above the liquid threshold which is set at 2.5 MRayl whereas the attenuation shows a very low and very narrow attenuation range. This first observation seems to confirm that the extensional mode measutrement is in fact more sensitive to the presence of the liquid-filled microannulus. The interpretation can be greatly improved by displaying the attenuation versus the impedance as it is done already for other measurement [19], [20]. Fig.7 displays such cross-plot for the impedance and attenuation map displayed before. Two clouds of points can be identified on this plot. They correspond to the well-bonded cement (upper right cloud) and the cement separated from the steel tube by a thin liquid layer (bottom left cloud). The well bonded cement has a high impedance (7 MRayl) and high attenuation (82 dB/m) as expected due to the good coupling between the cement and the steel. On the contrary, the cement separated from the steel by a thin liquid layer has a moderate impedance (3 MRayl) and a very low extensional attenuation ($39 db.m^{-1}$). This result is very interesting because this attenuation level corresponds to the attenuation expected for a fluid-filled annulus which is in complete agreement with the simulations presented before. In addition, note that the impedance measured can be mistaken for a lightweight cement as presented in Table II. Hence, this experiment demonstrates how the coupled measurement proposed is in fact significantly better at identifying the presence of liquid-filled microannulus than the pulse-echo measurement on its own which reduce the

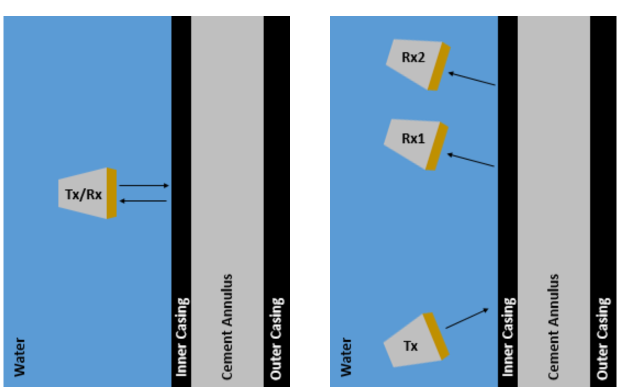


Fig. 4. (Left) Pulse-echo thickness mode and right Pitch-catch extensional mode measurement setup.

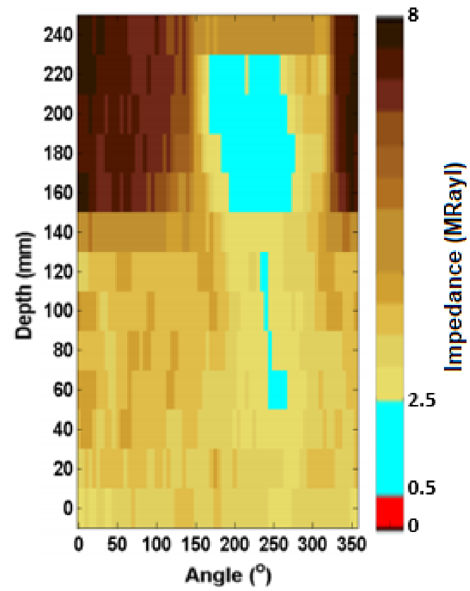


Fig. 5. Pulse-echo impedance map of cemented sample.

| Material | Density ($kg.m^{-3}$) | Impedance ($MRayl$) | Attenuation ($dB.m^{-1}$) |
|---|---|---|---|
| Air | 0 | 0.00 | 40.5 |
| Water | 1000 | 1.47 | 43.4 |
| Light Cement | 1438 | 2.95 | 64.4 |
| Heavy Cement | 2037 | 8.37 | 101.5 |

TABLE II
Acoustic properties measured for different reference materials.

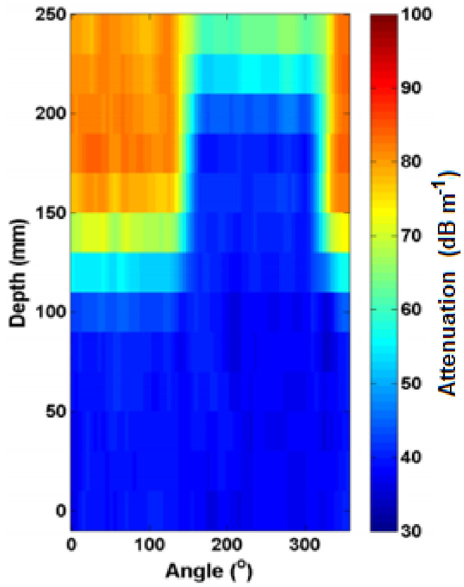


Fig. 6. Extensional attenuation map of cemented sample.

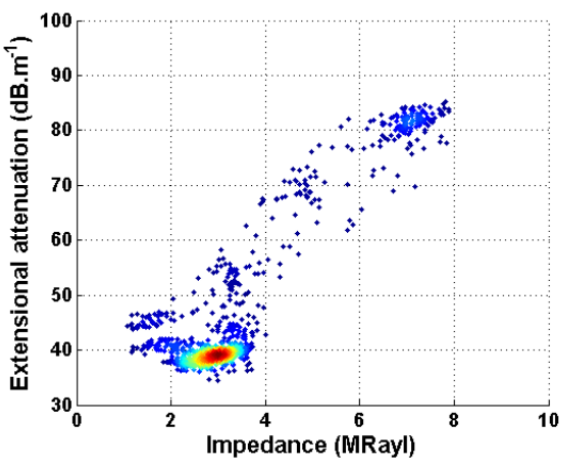


Fig. 7. Cross-plot of extensional attenuation versus pulse-echo impedance.

possible ambiguities doing the interpretation.

## IV. Conclusion

We experimentally studied the response of a new measurement combining both an existing pulse-echo measurement based on the excitation of the thickness mode of a steel pipe with a newly designed azimuthally resolved pitch-catch measurement based on the first order extensional Lamb mode of the steel pipe. We built an experimental setup to create artificially a thin layer of fluid between the pipe and the cement and measure its response versus the two coupled measurements. As predicted by the simulations in Disperse, the extensional mode was in fact very sensitive to the presence of this thin layer of liquid between the steel and the cement. This observation confirms that the ambiguity brought by the liquid microannulus can in fact be solved using both modes. Finally, we noted that the azimuthal resolution obtained on both measurements contribute to the success of the identification of the liquid-filled microannulus which was made possible by exciting the first order extensional mode around 100-150 kHz instead of the regular 12-20 kHz [1].

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