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Non-Destructive Testing of Nuclear Structures behind Screen using Leaky Lamb Waves

Pierre Kauffmann^{1,2, a)}, Marie-Aude Ploix², Jean-François Chaix², Cécile Gueudré²,
Gilles Corneloup² and François Baqué^{1, b)}

¹ CEA Cadarache DEN/DTN/STCP/LISM (Laboratoire d'Instrumentation, Systèmes et Méthodes), 13108 Saint Paul
Lez Durance, France.

² Aix Marseille Univ, CNRS, Centrale Marseille, LMA, Laboratory of Mechanics and Acoustics, Waves and Imaging
group, IUT GMP, 413 Avenue Gaston Berger, 13 625 Aix en Provence Cedex1, France.

^{a)}Corresponding author: pierrekauffmann@hotmail.fr

^{b)}francois.baque@cea.fr

Abstract. The challenge is here to inspect a set of two or three parallel and immersed plates using leaky Lamb waves. The first plate(s) acts like a screen to be going through. The Energy Based Model (EBM) that has been validated in previous work is used here to study the forward propagation and the backward propagation after reflection on a defect. We found that it is possible to inspect a set of three parallel plates 7.8 mm thick and a set of two parallel plates 20 mm thick with pulse/echo configuration. Moreover, EBM predictions are in good agreement with in water experimentation results.

INTRODUCTION

France is developing the sodium-cooled fast reactor concept (SFR) for 4th generation of nuclear power plants [1]. The improvement of in-service inspection and repair (ISI&R) is a major issue for the sodium cooled ASTRID prototype (Advanced Sodium Technological Reactor for Industrial Demonstration) [2]. Ultrasonic solutions are well adapted to this harsh environment, and therefore are being studied for the inspection of the main vessel and different parts of ASTRID (structures and components). The first way is to immerse specific ultrasonic transducers in liquid sodium (at about 200°C): this is currently under investigation [3]. The second way aims to perform inspection with a transducer located outside the main vessel (in gas). This is the way of interest here and it has already shown promising potential [4,5]. The objective is to perform non-destructive testing (NDT) of the main vessel itself, and also of structures located inside the main vessel. These internal structures are immersed in liquid sodium. Diameter of the main vessel and internal baffles is quite large (about 16 m), which enable us to locally approximate its shape by parallel plates (see FIGURE 1). The challenge is then to propagate ultrasonic waves from one plate to another through the liquid (sodium) in order to inspect the different plates. Leaky Lamb waves appear as a good candidate for this kind of propagation.

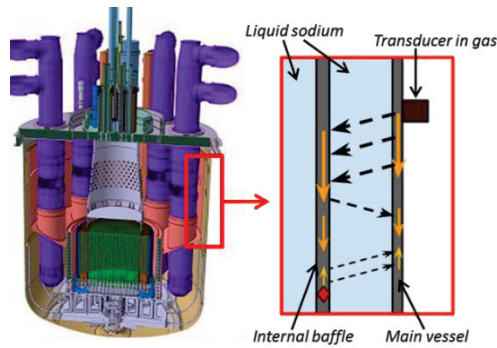


FIGURE 1. Cross section of the ASTRID reactor block with the area to be inspected (box with arrow) and a schematic view of this area showing the expected ultrasonic path

Velocities of Lamb waves are well understood in the literature [6,7]. Lamb modes propagate in a dispersive manner, which means that both phase and group velocities are usually different [8,9] and their respective values are frequency dependent. Being frequency-dependent may result in the large spreading of wave packets. For NDT and local defect location, this spreading can be reduced by choosing a specific Lamb mode and a frequency where the rate of spreading is low, i.e. where the group velocity is locally stable with frequency [10] (see FIGURE 2.b). If a dispersive propagation cannot be avoided, the original shape of the signal can be reconstituted by a post-process technique [11]. But dispersive propagation complicates velocity and attenuation measurements anyway [8], leading to frequency methods that have been successfully used for the cases of a plate in air [12,13] and in water [14,15].

When the plate is immersed, attenuation increases because of the re-emission of bulk waves in the fluid [16–19]: in this case, Lamb waves are referred to as leaky Lamb waves. The specific attenuation process due to leakage into the fluid is called leaky attenuation: it has been theorized in the sixties [17] (see FIGURE 2.a) and more recently experimentally measured [14,15]. The leaky attenuation coefficient quantifies the ability of the leaky Lamb mode to re-emit energy on each side of the plate. By reciprocity, it also describes the ability of the leaky Lamb mode to be generated by an incident acoustic beam: the higher the leaky attenuation is, the easier the Lamb mode is excited [20].

The idea is to use the re-emission capability of leaky Lamb waves to create and sustain a second leaky Lamb wave in a second parallel and immersed plate, as in [21,22]. Re-emission pattern created by the first plate have been studied in [23], and the creation and propagation of leaky Lamb mode in the second plate are investigated in [15]. We will now apply this to the detection of plate's edges in a set of two and three parallel plates. We will optimize the transmission of Lamb waves in the second plate by choosing proper couples {mode, frequency}, and use these specific modes to experimentally detect edges of plates (equivalent to through-thickness defect).

MODELIZATION AND OPTIMIZATION

We have shown in [15] that amplitudes in a set of several parallel plates can be easily computed using a simple modelization based on energy exchanges between plates. This Energy Based Model (EBM) is easy to compute and has been validated using finite element simulations and experimental measurements.

As it could be foreseen from the literature, the EBM confirmed that the second plate is more insonified for a maximum value of the leaky attenuation coefficient. As seen in FIGURE 2.a, this indicates three couples {mode, frequency} below 5 MHz.mm: the S0 mode at 2.5 MHz.mm, the A1 mode at 4.7 MHz.mm and the S2 mode at 4.9 MHz.mm. As a bonus, it appears that the group velocity at these points reaches a local minimum (for S0 and A1) or a zone where variations with frequency are locally small (for S2). This means that the wave packet will keep its original shape as it propagates if its bandwidth mainly laid where variations of group velocity are weak [10] (see FIGURE 2.b).

Finally, the A0 mode has been chosen at 1.4 MHz.mm because it is below the cut-off frequency of A1 (1.6 MHz.mm), so it will prevent the creation of A1 by mode conversion at the edge [24]. Moreover, this frequency corresponds to the maximum of the A0 group velocity, which is the best place for a non-dispersive propagation.

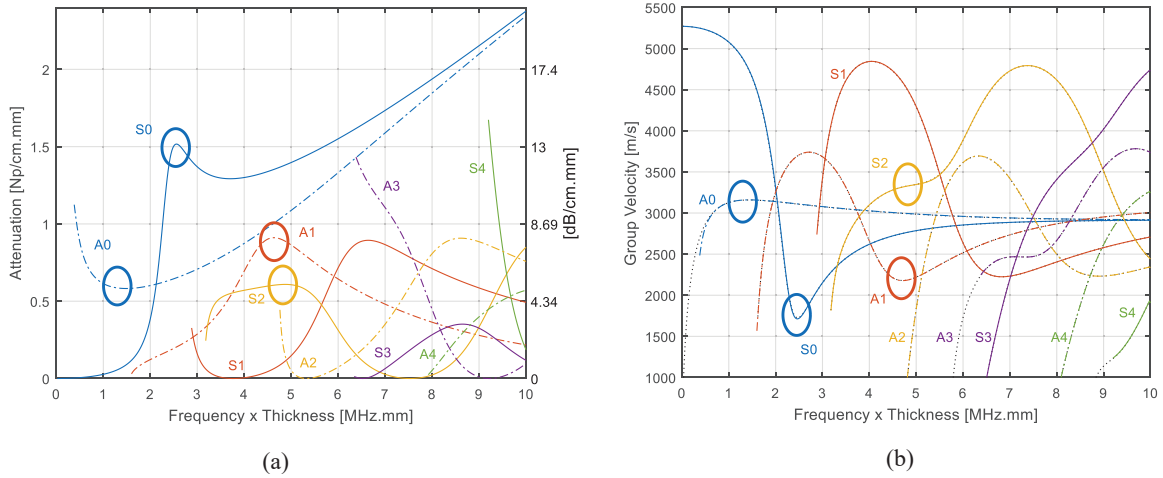


FIGURE 2. Selection of four couples {mode, frequency} that optimize the NDT of several parallel and immersed plates based on the leaky attenuation coefficient that maximizes re-emission (a) and group velocity (b) that testify a non-dispersive propagation

Dispersion curves in FIGURE 2 have been computed using the equations of dispersion for an homogeneous isotropic linear plate immersed in water [17] with bulk and shear wave velocity in the plate respectively at 5 750 m/s and 3 150 m/s, density of the plate at 7 950 kg.m⁻³, density of water at 1 000 kg.m⁻³ and speed of sounds in water at 1 490 m/s.

EXPERIMENTS

Experiments have been performed for a set of two and three parallel plates 7.8 mm thick and a set of two parallel plates thicker (20 mm). Plates are made of stainless steel for every case. Leaky Lamb modes were excited using the incident beam technique [20]. The wave packet sent was a 10 cycle sinusoid at the selected frequency: in this way the bandwidth was restrained and this helped to achieve a non-dispersive propagation.

Two parallel plates 8 mm thick

To generate the incident beam, we used an immersed transducer centred at 250 kHz (Ø 46 mm) for A0 and S0 modes. For the A1 and S2 modes at higher frequencies, we used a transducer centred at 500 kHz (Ø 38.1 mm). The FIGURE 3 shows the experimental bench: two plates (7.8 mm thick) are parallel and immersed separated by 132.4 mm of water. A scan parallel to the plates has been made: it starts from the edge of the first plate and stops where echoes are no more recorded (around 500 mm).

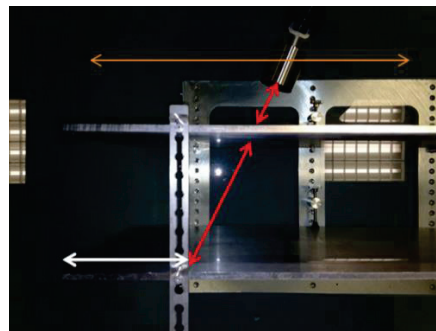


FIGURE 3. Top view of the experimental bench in pulse/receiver configuration with two plates and schematic acoustic path for the echo of the end of the second plate (bold arrows). The transducer moves from the left to the right along the thin arrow.

Signal is recorded for every millimeter, and the envelope of these signals is plotted to obtain a B-scan type image in the FIGURE 4.a (for the S0 experimentation). The propagation is almost non-dispersive as expected. We superposed in white dotted lines the theoretical time of flight and location of echoes: the agreement with experimentation is excellent.

We can notice the arrival of more than two echoes: as schematized in the FIGURE 4.b, we are observing successive reflection in the inter-plates space. However because edges of plates are located at the same abscissa, there are places where echoes from the edge of both plates are superposed (because they are in phase) by taking different acoustic paths. This is the case for echoes labeled 2b and 3b in the FIGURE 4.a.

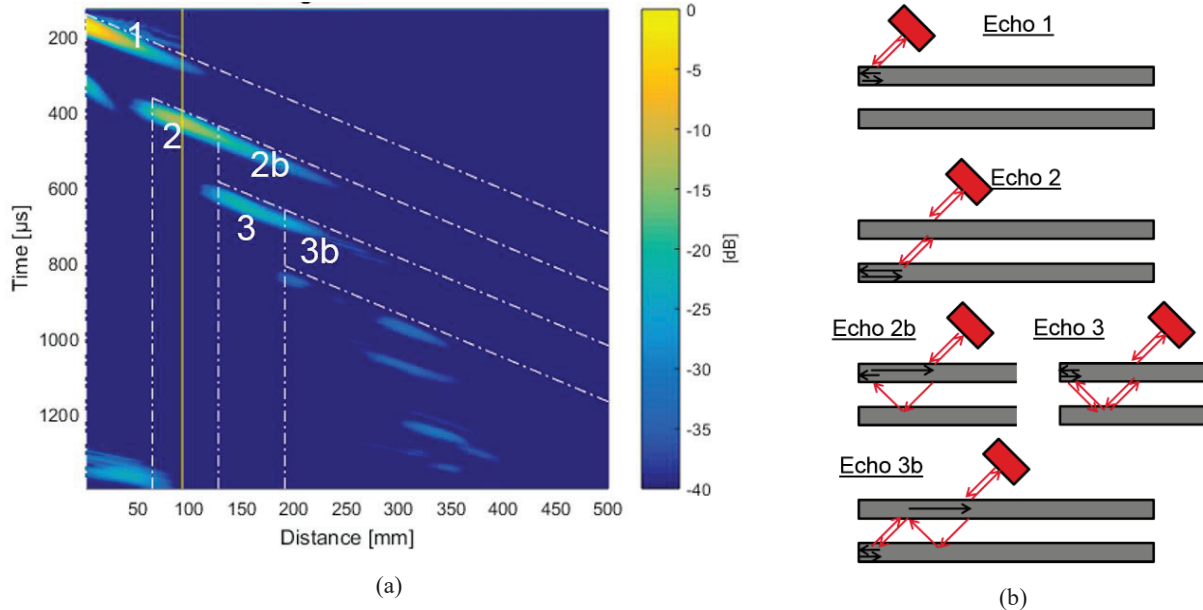


FIGURE 4. B-scan representation of envelopes with the S0 mode at 1.5 MHz.mm in a set of two parallel plates (a). Theoretical arrivals of echoes are underlined in white dotted lines and each corresponding acoustic path are schematized (b).

We do not report the observation of mode conversions that should occur with the reflection as in [12,25]. This has two reasons: first, we are below the S1 cut-off frequency, which means that only S0 and A0 modes can propagate. Secondly, the defect observed (an immersed end of plate) is symmetrical with respect to the middle plane of the plate, which means no conversion from a symmetric mode to an antisymmetric mode (or conversely) [26]. So in this case, the S0 incident mode is reflected, but no mode conversion is possible. Mode conversion is possible for the A1 and S2 experiments, but they are not observed because the transducer can mostly detect re-emitted modes at its corresponding incident angle. Another leaky Lamb mode that re-emits at a different angle would impact the front face of the transducer sideways, and therefore be more difficult to be detected.

To compare experiments with EBM prediction, we have selected one signal sample around $x = 90$ mm corresponding to the vertical yellow line in the FIGURE 4.a. This signal sample contains the direct echo from the end of the first plate (labeled 1) and the echo coming from the end of the second plate (labeled 2) without the pollution of the first reflection in the inter-plate (labeled 2b). Moreover, this signal also corresponds to the maximum reflection of the second plate. The envelope of the signal is plotted in FIGURE 5.a: we can clearly observe the two echoes coming from each plate edges.

The simulation of this configuration with the EBM model is presented in FIGURE 5.b and shows the re-emitted pressure (because this is the experimentally measured parameter). A full reflection is assumed at $x = 90$ mm to simulate the plate edge effect, and the EBM is used a second time to calculate the backward propagation (along the second plate and through the first plate). A level in dB between the reflection in the second plate and in the first plate (not represented) is then calculated using the equation 1. In this case, the intensity of the reflection has no effect on the final result, because the same reflection is happening at the end of the first plate.

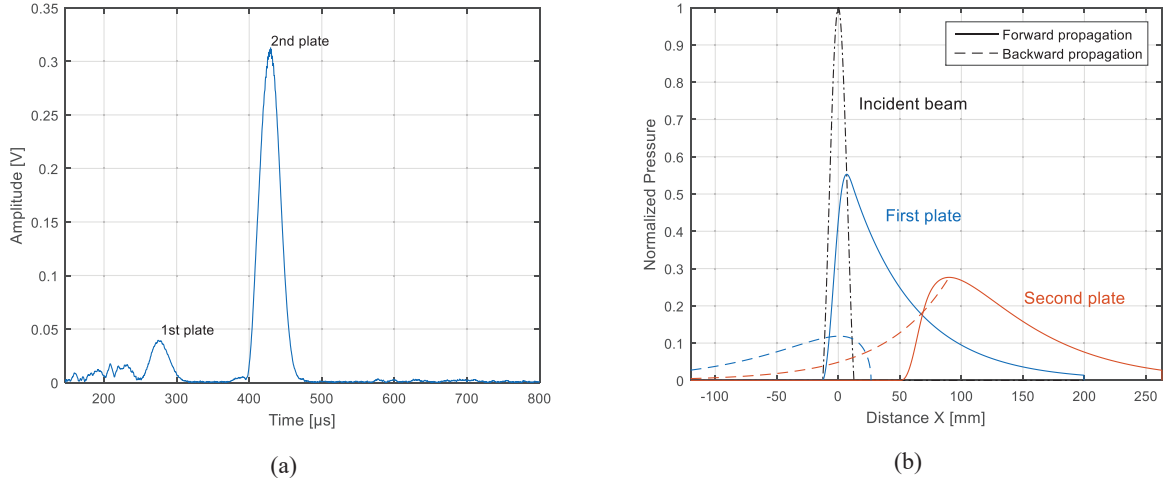


FIGURE 5. Envelope of the experimental signal chosen at the maximum reflection of the second plate (a) showed by a yellow line in FIGURE 4.a, and its corresponding simulation with the EBM of the re-emitted pressure (b) assuming a full reflection

The same level in dB is also calculated from the experimentation using the maximum amplitude of each echoes in the FIGURE 5.a and the equation 1.

$$\text{Level}_{\text{dB}} = 20 \log \left(\frac{A_{p2}}{A_{p1}} \right) \quad 1$$

With A_{p1} and A_{p2} the maximum amplitude coming respectively from the first and the second plate.

Comparison between experimentation and theory is presented in the TABLE 1 for the four investigated modes: a very good agreement is reached, showing that the EBM is correctly used for modeling the propagation of leaky Lamb waves in two parallel and immersed plates.

TABLE 1. Comparison of dB level calculated with the EBM and measured with experimentation for a set of two parallel plates 7.8 mm thick

| dB Level | A0 | S0 | A1 | S2 |
|--------------------|-----|------|-----|------|
| Energy Based Model | 8.6 | 15.4 | 5.6 | -1.8 |
| Experimentation | 7.5 | 17.8 | 3.5 | -2.0 |

We will now investigate the capability of the EBM to model leaky Lamb wave propagation in a set of three parallel and immersed plates.

Three parallel plates 8 mm thick

In the set of three parallel plates, the space between the first two plates is the same than in the former two plates case (132.4 mm). The space between the second and the third plate is chosen smaller (90.2 mm) to avoid having the echoes of the third plate polluted by the first reflection occurring between plates.

Experiments were performed using the same protocol and the same transducer than for the former two plates case. The B-scan images of signal envelopes are presented in the FIGURE 6 for two different modes: S0 and A1. White lines indicate theoretical arrivals of echoes coming from the first two plates, where echoes coming from the third plate are indicated by red lines. The agreement is still very good for the third plate.

A vertical yellow line locates the signal sample ($x = 108$ mm) selected for the calculus of the dB level by equation 1. We have selected it before the first reflection between the second and the third plate, even if the corresponding signal is not taken at the maximum echo coming from the third plate.

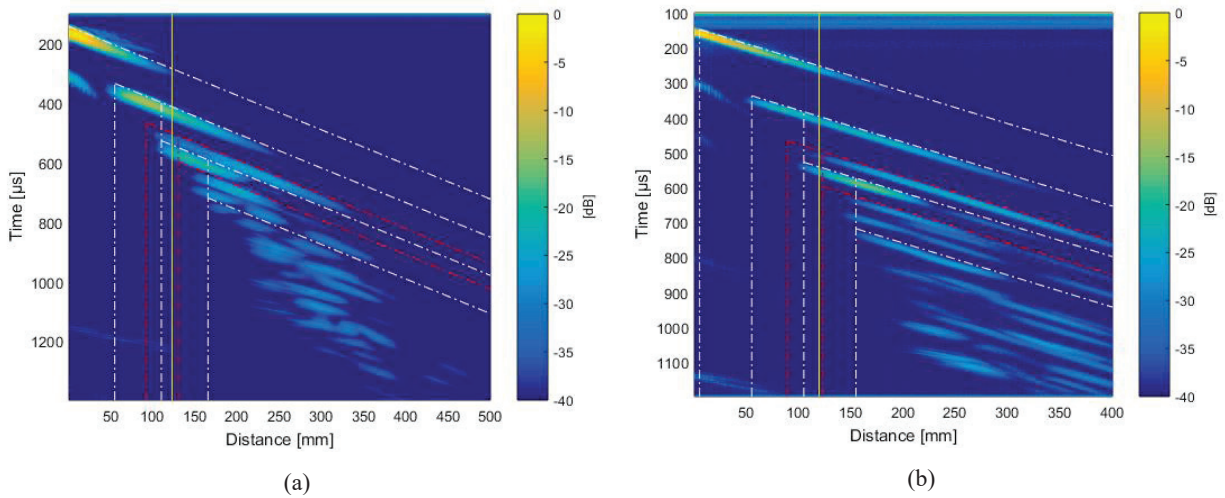


FIGURE 6. B-scan representation of envelopes for incident modes S0 (a) and A1 (b) in a set of three parallel plates. Theoretical arrival of echoes from the first two plates are underlined in white dotted lines, and in red dotted line for echoes arriving from the third plates

The envelope of the selected signal sample ($x = 108 \text{ mm}$) for the S0 mode is shown in FIGURE 7.a. Again, we can distinguish echoes coming from the first plate and the second plate, but we now see the first reflection between plate one and two, because the signal is chosen further than in the two plates case ($x = 90 \text{ mm}$). We can also distinguish the echo coming from the third plate: its maximum amplitude is used to calculate its relative dB level with the echo coming from the first plate.

The corresponding modelization using the EBM is shown in FIGURE 7.b. As expected, the reflection at the end of the third plate occurs before its maximum amplitude.

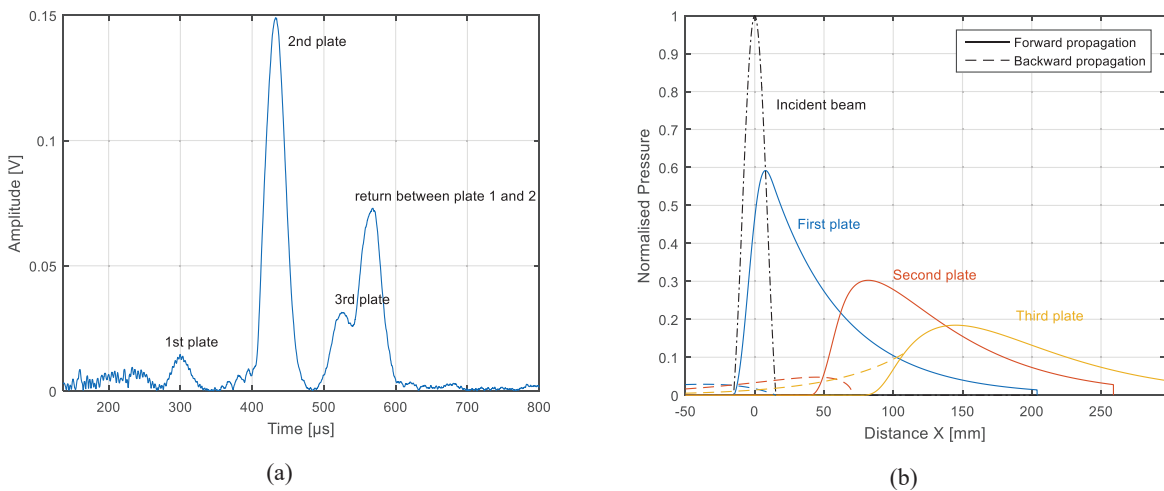


FIGURE 7. Envelope of the experimental signal chosen sample at $x = 108 \text{ mm}$ (a) showed by a yellow line in FIGURE 6.a, and its corresponding modelization with the EBM of the re-emitted pressure (b) assuming a full reflection

The dB levels are calculated in the same way for the four experimentations, and results are summed up in the TABLE 2. Predictions are in very good agreement with theory, demonstrating the ability of the EBM to model the propagation of leaky Lamb waves in three parallel and immersed plates.

TABLE 2. Comparison of dB level calculated with the EBM and measured with experimentation for a set of three parallel plates 7.8 mm thick

| dB Level | A0 | S0 | A1 | S2 |
|--------------------|------|-----|------|---------|
| Energy Based Model | -4.1 | 8.7 | -7.3 | -37.0 |
| Experimentation | -3.5 | 7.1 | -7.8 | < -23.0 |

Two parallel plates 20 mm thick

The same experimentation has been conducted for two plates 20 mm thick, which is a more realistic thickness for plates (we are expecting thickness from 20 to 40 mm in ASTRID). To reach the targeted frequency-thickness product, we had to lower the frequency and to use other transducers. For A0 and S0 modes, we used two different transducers centred at 100 kHz (\varnothing 50 mm and \varnothing 100 mm). For the A1 and S2 modes, we used a transducer centred at 250 kHz (\varnothing 46 mm). The plates are separated by 150 mm of water.

Experiments were performed following the same methodology than for thinner plates. The A0 mode at 1.4 MHz.mm was not workable in this configuration, because the wave train of 10 cycles at 71 kHz was too long: echoes from the end of both plates were overlapping.

The leaky attenuation is smaller because plates are thicker [17]: the top attenuation reached for S0 at 2.5 MHz.mm drops from 23 Np/m to 8 Np/m for the 20 mm thickness. As a result, there is less energy that goes through plates for the same propagation distance, but the detection of the end of the second plate is still possible. Experimental results are summed up in the TABLE 3 and show good agreement with EBM predictions.

TABLE 3. Comparison of dB level calculated with the EBM and measured with experimentation for a set of three parallel plates 20 mm thick

| dB Level | S0 (\varnothing 50) | S0 (\varnothing 100) | A1 | S2 |
|--------------------|------------------------|-------------------------|-------|-------|
| Energy Based Model | 1,0 | 1,0 | -8,5 | -21 |
| Experimentation | -3,2 | -0,2 | -10,5 | -24,2 |

CONCLUSION

We have shown that detection and localization of a defect in a set of several parallel plates is possible using leaky Lamb waves, even for large thickness (20 mm) coherent with real systems. Theoretical results were obtained using the Energy Based Model (EBM) developed in a previous work [15], and confirmed that we need to use leaky Lamb modes with high leaky attenuation to optimize the propagation in the last plate. Four interested couples {modes, frequency} have been identified that fulfill this condition, with in bonus non-dispersive propagation behavior. EBM predictions have been faced with experimental detection results and we found a very good agreement between them. We can therefore conclude that the EBM is well adapted to model the propagation of leaky Lamb waves in a set of several parallel plates.

Further study will focus on the reflection on a notch, which is a more realistic defect than the edge of a plate. The case of plates with different thickness needs to be treated. We may also study the use of time reversal technique.

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