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A NEW METHODOLOGY OF NDT IN TWO PARALLEL PLATES USING TIME REVERSAL PROCESS OF LEAKY LAMB WAVES

Jean-Christophe Vallée[1*] **Marie-Aude Ploix**[1] **Matthieu Cavaro**[2] **Jean-François Chaix**[1]

[1] Aix Marseille Univ, CNRS, Centrale Marseille, LMA UMR 7031, 13625 Aix-en-Provence, France
[2] CEA, DES, IRESNE, DTN, STCP, LISM, Cadarache F-13108 Saint-Paul-Lez-Durance, France

ABSTRACT

Ultrasound has been identified as a suitable method for inspecting complex structures (such as nuclear reactors), as it can propagate through both liquids and steel elements to be inspected. Leaky Lamb waves have been extensively researched to detect damages in plate-shaped structures, which are guided waves that reemit bulk waves towards the surrounding fluid. An imaging method based on the time reversal of Lamb waves has been applied in preliminary work to detect the edge of a single immersed plate and a machined notch. In this study, the frequency-domain topological energy method is applied to a set of two parallel immersed plates to accurately localize defects represented by the edges of the plates. Firstly, the behavior of leaky Lamb waves is briefly addressed. A 2D-STFT (two-dimensional Short Time Fourier Transform) is then used to separate the different Lamb modes, which is a powerful tool for tracking the modes involved in the propagation over time. The Fast Topological Imaging Method (FTIM) is introduced, which allows for faster computations with less data storage. Then an original methodology is proposed based on spots (maxima) analysis for interpreting the results of this topological energy and identifying the edges of the two plates.

Keywords: *non-destructive testing, ultrasound, immersed parallel plates, topological energy method, leaky Lamb waves*

1. INTRODUCTION

The structural integrity of primary vessels in Nuclear Sodium Fast Reactors (SFRs) must be periodically inspected using non-destructive testing. However, unlike in Pressurized Water Reactors (PWRs), optical inspections are not possible due to the opacity of liquid sodium. Ultrasound, which can propagate through both liquid sodium and steel elements, has been identified as a suitable method for inspecting internal structures. Leaky Lamb waves, which exist in some immersed structures, are utilized to detect damages in plate-shaped structures. These waves reemit bulk waves back into the surrounding fluid, and their velocity is dependent on frequency, exhibiting a dispersive behavior. To overcome the challenges posed by the dispersion phenomenon and mode selection, several approaches, such as the Short Time Fourier Transform (STFT), have been studied. Combining these tools with imaging methods allows for the reconstruction of the image of a medium to detect and localize potential defects in it. The present work focuses on the Fast Topological Imaging Method (FTIM) that allows for faster computations with less data storage. The aim is to apply this method to a set of two parallel immersed plates and to accurately localize potential defects, such as a through-crack, represented by the edges of the plates. The behavior of Leaky Lamb Waves is briefly addressed, and the 2D-STFT is used to separate the different Lamb modes and retropropagate some of them. The FTIM is then introduced and applied. Finally, the so-called “topological spots” are introduced, and an original methodology is proposed for interpreting the results in this geometry and identifying a defect in the second plate represented by its edge. This work represents a significant step in non-destructive testing for

*Corresponding author: vallee@lma.cnrs-mrs.fr.

SFRs, with potential implications for nuclear safety and maintenance.

2. THEORETICAL AND METHODOLOGICAL BACKGROUND

2.1 Leaky Lamb waves propagation

The Lamb waves can travel over long distances, making them useful for long-range inspection of free plates. When a fluid envelops the plate, a leaky attenuation arises, as Merkulov explained [1]. Figure 1 illustrates the conversion of a part of the energy of Lamb waves into compressional waves in the surrounding liquid.

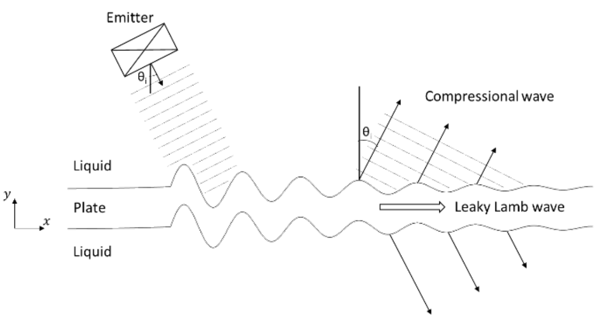

Figure 1. Generation of a compressional wave in the liquid by a leaky Lamb wave in the plate

Each Lamb mode corresponds to an angle of reemission, which is related to its angle of incidence by reciprocity. As depicted in Figure 1, an incident beam can generate Lamb waves in an immersed plate. The acoustical wave gives rise to a reflected and a transmitted wave. By determining the angles θ that optimize the transmitted wave in the plate for a given mode, one can also obtain the angles predicted by Snell's law and the phase velocity of each mode.

2.2 2D Short Time Fourier Transform

The 2D-STFT, or 3D-Fourier Transform, consists in applying a 2D Fourier transform on successive portions of a set of signals recorded at different points x in space. Similarly to the classic STFT, a temporal weighting window is applied to a portion of the signals to extract the frequency content and wave numbers at selected moments. The weighting apodization window is then shifted to analyze the entire signal:

$$\mathrm{STFT_{2D}}\big(u(x,t)\big) = \iint u(x,t)\, h^{*}(t-\tau) e^{-i(kx+2\pi ft)} dx\, dt \qquad (1)$$

where h* is the complex conjugate of the apodization window h and τ is the translation parameter. As for the classic STFT, the window is defined by its size and the overlap between two consecutive windows. This allows tracking of wave packet propagation over time.

By using the 2D-STFT on the B-Scan image of Figure 2 (a), the different modes that compose it () can be tracked over time. Knowing the propagation frequency, the wave numbers of the different existing modes are theoretically known. Figure 2 (b) illustrates this 2D-STFT. Each column is the average over the frequency of the 2D-FFT evaluated for each apodization window along the B-Scan. The 2D-STFT has been normalized and is represented in logarithmic scale.

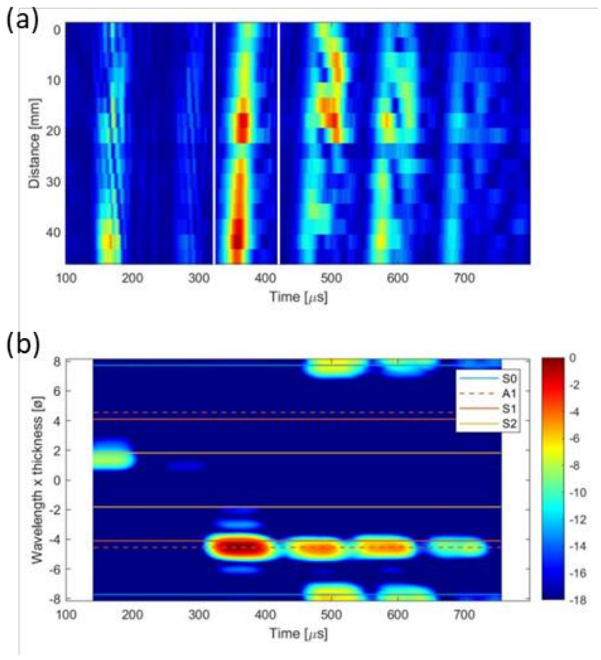

Figure 2. (a) Experimental B-Scan – (b) 2D-STFT of the experimental B-Scan

2.3 Topological energy method in the frequency domain

The topological energy [2] can be seen as a measure of the temporal correlation between two simulated wave fields: the direct field U_0, which represents the propagation of waves through the undamaged (reference) medium, and the adjoint field V_0, which represents the field induced by the backward propagation of the residue, *i.e.* the acoustic signature of the difference between the reference medium and the experimental medium with defects. At the location of defects, where the two fields overlap, the topological energy reaches its maximum value.

S. Rodriguez [3] carries out the reformulation of the problem of topological energy in the frequency domain : the Fast Topological Imaging Method (FTIM). A simplified formulation of the frequency-domain topological energy is employed, by summing over the discretized frequencies f_k, k ∈ ⟦1;N⟧:

$$ET_f(\vec{r}) = \left|\sum_{k=1}^{N} U_0(\vec{r}, f_k)\, V_0(\vec{r}, f_k)\right| \quad (2)$$

The frequency domain version offers two main advantages over its temporal counterpart which are the reduction in data size and computation speed.

3. APPLICATION OF THE FTIM ON A SET OF TWO PARALLEL IMMERSED PLATES AND NEW METHODOLOGY OF ANALYSIS

3.1 Experimental protocol

The experimental setup is shown in the Figure 3. The two plates are identical, made of stainless steel, with density ρ = 7950 kg.m^{-3}, length L = 70 cm and thickness e = 7,8 mm. The measured longitudinal and transverse wave velocities are c_L = 5738 m.s^{-1} et c_T = 3143 m.s^{-1}. The distance between the plates is fixed at d_{IP} = 9 cm.

The two plates can slide one with respect to the other along the x axis. A single shift (noted X_{shift} on Figure 3 (a)) is studied here: 10 cm.

The Sonaxis® transducer is composed of 16 elements, with a pitch of 3 mm and a center frequency of 400 kHz.

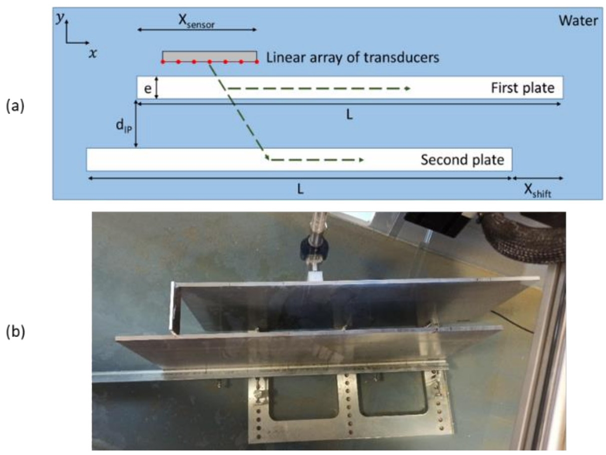

Figure 3. (a) Geometry of the experimental setup – (b) Experimental setup picture

3.2 Simulated direct problem

Two infinite parallel plates are modelled in a surrounding water medium. A single element is used in emission when calculating the radiation pattern. The radiation pattern is calculated over the frequency range [1 kHz; 700 kHz] with a step of 1 kHz. The calculation of the radiation patterns allows to simulate any signal and any incidence for any delay law. The direct problem in the "healthy" medium (without plate edge) is computed in COMSOL Multiphysics®. The horizontal displacements (according to x) are recorded in both plates every 0.2 mm along the length of the plate (x-axis) and every 0.1 mm in the thickness (y-axis).

3.3 Topological spots

The topological energy is calculated in the frequency domain by the formula (2) at all points of both plates. At each abscissa, the topological energy is then summed across the thickness of each plate and normalized by the global maximum over the two plates in Figure 4. The edge of the second plate, which we seek to detect, is positioned at x = 60 cm.

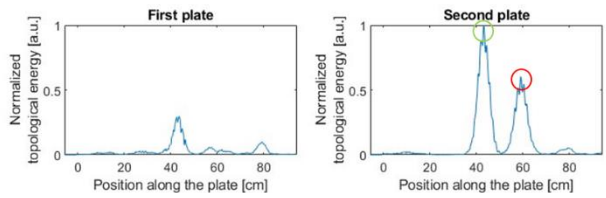

Figure 4. Topological energy in the region of interest from horizontal displacements in both plates

The maximum of topological energy in the second plate is observed at x = 43.2 cm (green circle on the Figure 4), for a plate edge actually located at x = 60 cm. A second maximum is observed at x = 59.1 cm (red circle).

In order to understand the origin of these maxima interfering with the detection of the edge of the second plate, we transpose the direct and adjoint fields into the time domain and study them together. The topological energy in the time domain is interpreted as the correlation between the ultrasonic fields from the direct and adjoint problem, respectively. The time reversed residue refocuses towards the defect that generated it. The topological energy then takes significant values where the fields of the direct and adjoint problems cross each other and interfere constructively both in time and space. We can represent this interaction as in Figure 5 by superimposing the direct field and the adjoint field, which have been faded for a better reading. The dashed lines represent the wave propagation after a single propagation in each plate (numbered 1), the wave propagation after one round trip between the plates (2), two round trips between the plates (3) of the fields from the direct problem (D) and the adjoint problem (A) respectively. From this superposition, topological spots are defined and highlighted, as in Figure 5 that represents the topological energy in the time domain. These are the areas where the different paths intersect.

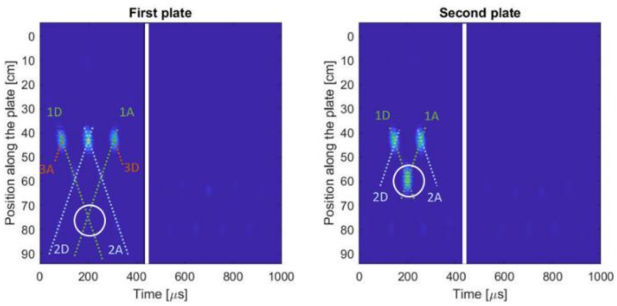

Figure 5. Topological energy in the region of interest from horizontal displacements in both plates

The topological spot corresponding to the defect is therefore the spot created by the interaction between the 1D and the 1A pathes. The two fields interfere only once in each plate: a solution exists in each plate. They are circled in white in Figure 5. The real defect is located at one of these positions. In our case, the edges of the two plates are located at x = 70 cm for the first plate and x = 60 cm for the second plate.
The edge of the second plate corresponds to the second local maximum in the topological energy, circled in red on the Figure 4 (x = 59.1 cm). The difference with the real position of the edge is less than a wavelength and is totally acceptable.
The global maximum (x = 43.2 cm) circled in green on the Figure 4 corresponds to the combination of secondary spots, at the intersections of 1D/2A and 2D/1A paths.

4. CONCLUSION

This study has presented the 2D-STFT transform for tracking Lamb modes' propagation and identification. The benefits of the 2D-STFT include the ability to retropropagate a specific mode in the frequential topological imaging method (FTIM). Experimental measurements are conducted on a set of two parallel steel plates immersed in water, and the FTIM is applied to detect and localize the edge of the second plate. The topological energy is evaluated in both plates by selecting the wave packet with the most energy using the 2D-STFT and retropropagating it. The global maximum of the topological energy is not found at the position of the edge of the second plate. However, local maxima are also detected, which are explained by overlaying the direct and adjoint fields, leading to the new concept of topological spots. The interpretation of these spots is combined with the intersection of the different paths in order to accurately identify the maxima representing the sought defect. The proposed methodology successfully detects and precisely localizes the edge of the second plate.
This study highlights the potential of the combination of the 2D-STFT and the FTIM in Non-Destructive Testing and Evaluation of structures. The proposed methodology could be applied in further studies and applications to detect other types of defect, in various materials and geometries, and it could have significant implications for a range of applications, particularly in industries where the early detection and accurate localization of defects is crucial.

5. ACKNOWLEDGMENTS

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