Time Reversal FEM Modelling in Thin Aluminium Plates for Defects Detection

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Abstract. A novel Non Destructive Testing technique for the detection and characterization of defects in thin plate-like structures is presented. When having large structures to be scanned, the use of guided waves is a useful tool to avoid the monitoring of the sample with conventional and very time-consuming techniques. These waves, Lamb modes, interact with the existing defects when travelling along the structure. However, the dispersive nature of these waves makes difficult defect identification because of the complex signals to be analysed. These signals are composed of the multiple modes propagating through the structure. Even in the case of having the possibility of exciting only one mode over the structure, Lamb wave conversion can occur if the wave travelling finds a discontinuity in the material, ie flaws, boundaries, thickness changes. A Time Reversal -TRM- process can help in the signal analysis. In this work, the first steps of the study and development of ultrasonic techniques to detect the relative variation of the integrity of a structure are described. Finite Element models using PZFlex have been developed to study the distortion of the TRM signature when appearing cracks in thin aluminium plates. An experimental set-up was used to validate the models.

Introduction

The use of NDT methods in aeronautics for defects location in thin aluminium plates, or delaminations on aircraft carbon reinforced structures, is growing steadily. There are well-established procedures to inspect these structures using ultrasonic techniques. Normally, location and defect sizing is made by using pulse-echo ultrasonic measurements. Through-transmission methods are also used. These techniques are very time consuming because all the structure must be scanned with the pitch needed to obtain the lateral resolution written in the corresponding inspection standard procedure.

When only the growth of a delamination flaw in the structure must be detected or when the delamination statistically occurs in a specific zone, faster detection approaches can be developed.

The acoustic signature of a cavity can be measured after defining the frequency range, the excitation and recording systems and the frequency domain resolution. After knowing the acoustic signature, some parameters can be defined to correlate their variation with the structural changes. The Time Reversal Method -TRM- can be used to this end. Kim et al. [1] studied a TRM approach for damage detection in thin plate-like structures based also in Lamb wave propagation. However, they do not consider the contribution to the TR of reflections originated at the boundaries of the structure, which contradicts the TR theory applied to finite and reverberant structures. As is described by Fink in [2], in a Time Reversal process the reflections from the structure must be taken into account, as if they were virtual emitters, in order to obtain an optimal focusing of the energy at the desired point. That is normal if a focused high elastic energy level is wanted.

In this paper, a damage detection method applying the TRM to Lamb wave propagation in thin aluminium plates is presented. A plate sample has been implemented with two piezoceramics, both actuating as emitters and receivers. The Lamb wave response measured in the receiver sensor is then reversed and reemitted focusing the energy in one point. This signal is composed of the multiple reflections from the boundaries of the structure and the possible existing defects. It is demonstrated that there exists a correlation between the maximum of amplitude of the TR focused signal and the crack growth.

Time Reversal Method using Lamb Waves

Fink demonstrated that in Chaotic Cavities, where the generated elastic waves propagate suffering multiple reflections, it is possible to reconstruct the initial excitation signal at one point [3]; that is, to focus the energy in only one point. One condition that must be satisfied to obtain a good focusing is that the attenuation must be low. In this case, Draeger demonstrated that the TRM can be developed using only one couple of emission and transmission channels [3]. This property will be used in this work in order to follow the variations in some of the signatures of the TRM process when the cavity varies as, for example, is the case of cracks in thin plates.

Waves that propagate in thin plates -small thickness compared with the wavelength- are called Lamb waves [4]. They are commonly used in the field of Non Destructive Testing (NDT) for defect location. These guided waves have the advantage of its capability of travelling over large distances with little attenuation. This makes possible fast long-range testing and eliminates scanning the whole sample. However, they have the drawback of its dispersive nature and multimodal propagation. At a given excitation frequency, multiple modes travelling at different velocities can exist. Therefore, before defining the experiment, it is necessary to choose the frequency and the optimal excitation mode. The dispersion curves of the Lamb wave phase velocity in aluminium are depicted in Figure 1. As it can be observed, several modes are present. At lower frequency-thickness products, below 5 mm·μs^{-1}, only two modes remain present.

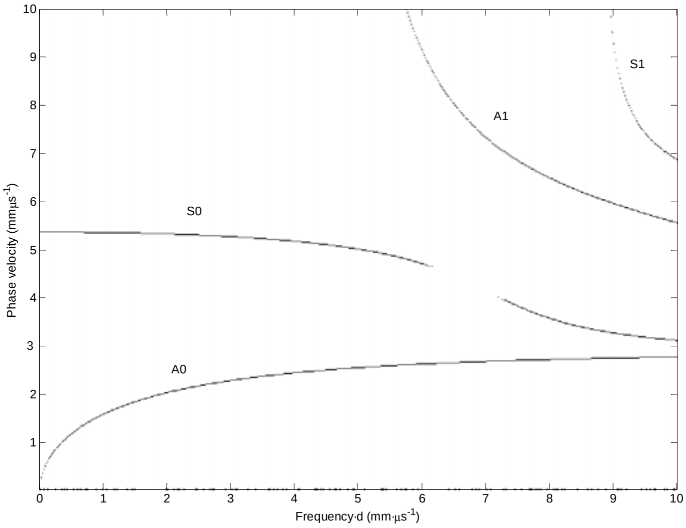


Figure 1. Phase velocity dispersion curves for an aluminium plate.

The Time Reversal process can be explained as follows. A piezoceramic actuator bonded to a plate, P1, is used as emitter. When exciting it with a predefined electric waveform it generates Lamb waves that propagate along the structure. Then, other piezoceramic bonded in a different place, P2, used as receiver measures the response signal of the arriving Lamb waves. This response signal is time reversed and re-emitted from P2. The signal reemitted from P2 is supposed to be time-and-space focused in transducer P1.

Time Reversal FEM Simulations

A three-dimensional model using the commercial simulation program PZFlex (Weidlinger Associates Inc, Los Altos, CA. USA) was developed. A pristine aluminium plate of dimensions 200x50x1.1 mm was used in the model. Two piezoceramics elements 7x7x0.5 mm, PZ-27 (Ferroperm), were modelled fixed to the plate and located on the main axis at 40mm and 30 mm from the opposite sides -see Figure 2-. One symmetry plane, perpendicular to the plate along the main axis was set to reduce the simulation time. Meshing chosen was accurate enough to model several elements per wavelength.

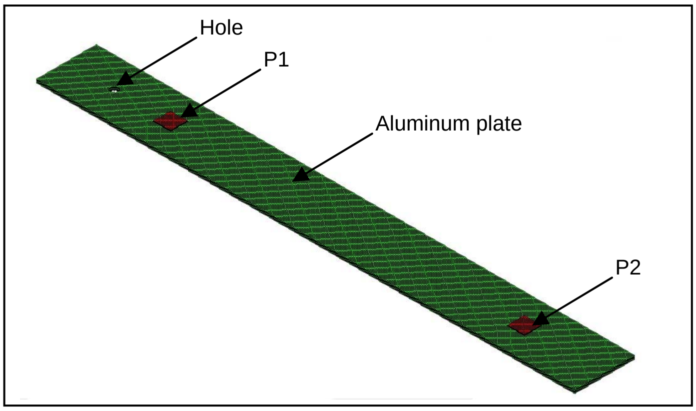


Figure 2. Modelled plate with the piezoceramic elements and a hole.

The modelling steps are as follows:

1. A three cycles sinusoidal tone burst of 365 kHz was used as exciting signal. The elastic propagation from P1 is calculated along the time during 250 μs and the electric signal at the terminals of the piezoelectric receiver P2 is calculated.
2. The signal is reversed and used as exciting signal to model the back propagation from P2 during 500 μs. The electric signal at P1 is then calculated -focused TR signal-.
3. The maximum of the module of the FFT of the main lobe of the TR signal is then calculated.
4. A 2 mm diameter hole in the aluminium plate placed at 20 mm on the main axis at 20 mm from the border of P1 -see figure 2- is then introduced in the model.
5. The steps 2, using the measured signal in P1 of the non-holed plate, and 3 are then repeated, comparing the maximums of the module of the main lobe of the FFT of the corresponding TR signal with that of the non-holed plate.
6. The same steps were repeated modelling a 3 mm hole.

Figure 3 shows an image of the waves propagating through the plate at three different time snaps for the case of the pristine plate. In Figure 4, the evolution of the FFT module correlated with the increase of the hole diameter is shown.

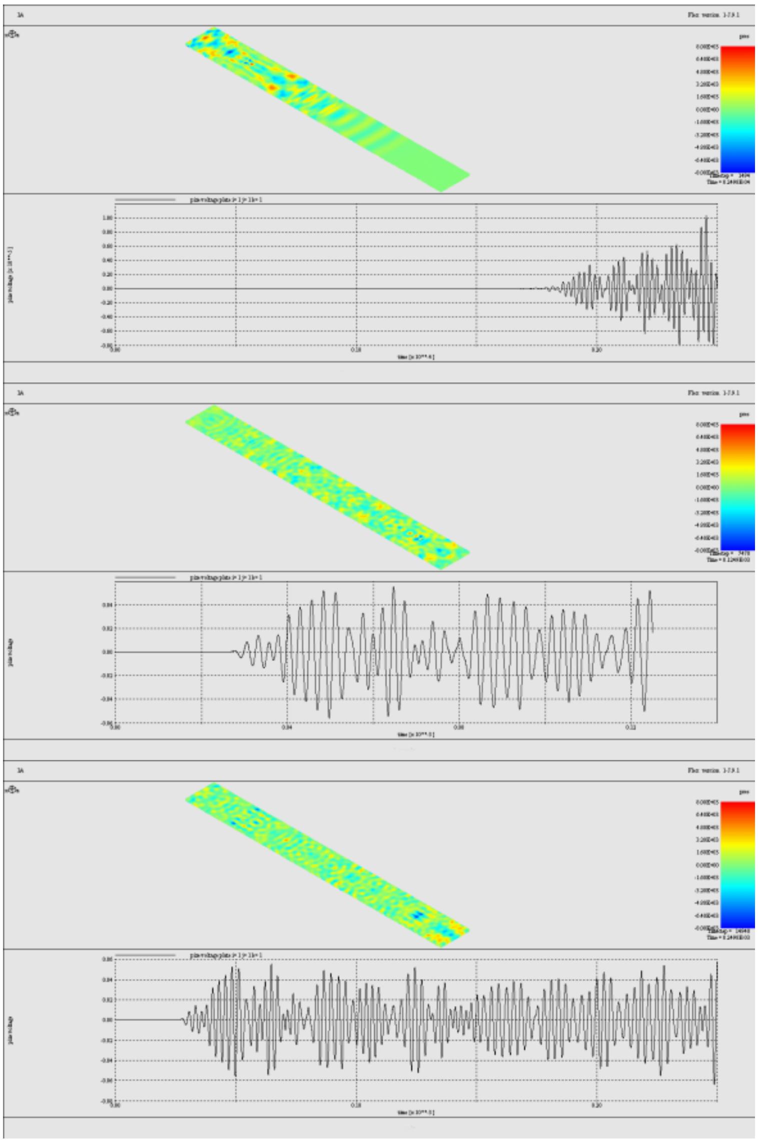


Figure 3. Lamb waves propagation snapshots calculated with PZFLEX.

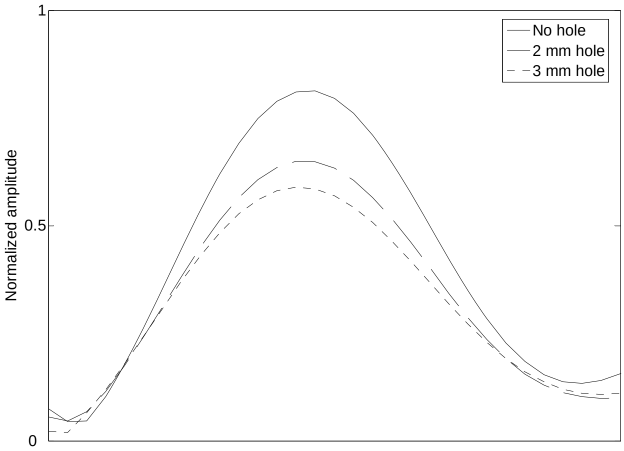


Figure 4. Evolution of the FFT module correlated with the increase of the hole diameter.

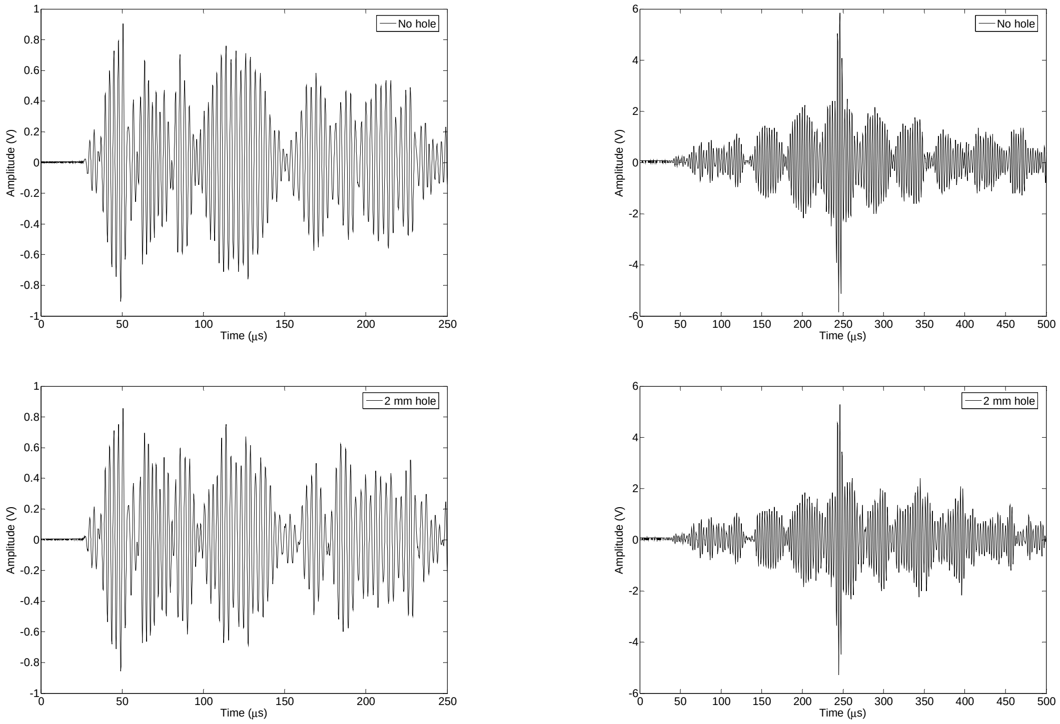
As it can be observed in figure 4, clear indication of the hole diameter increase can be evaluated from the decrease of the module maximum at the central frequency spectrum.

Time Reversal Experimental Measurements

An aluminium plate of dimensions 200x50x1.1 mm, was used in the experimental measurements. Two square piezoceramics elements 7x7x0.5 mm, PZ-27, were bonded on the plate surface at different position along the axis. A stiff polymer was used -cyanoacrylate-. Following the TRM method, both were used as emitter and receiver. One piezoceramic must be chosen to excite the selected Lamb wave mode and to receive the time-reversed signal. The other piezoceramic measures the initial input signal that will be time reversed and reemitted. One actuator was separated 30 mm form the border of the plate and the other was separated 40 mm from the opposite border.

Two LabVIEW programs were developed to perform the experimental TRM process. An arbitrary waveform generator, Agilent 33220A, and a Tektronix TDS 220 oscilloscope, controlled by the LabVIEW programs were used to emit and receive the different signals from the actuators. The first program was used to record the initial (Reference) and time reversed (Time Reverse Reference) signals. Then the second program uses the Reference signal to perform the new time reversed signals following the same steps as indicated in the modelling section.

Figure 5 shows the received signal at P2 and the TR signals at P1 for the case of the non-holed plate and when 2 and 3 mm holes were modelled. No clear indications of the influence of holes can be directly identified.



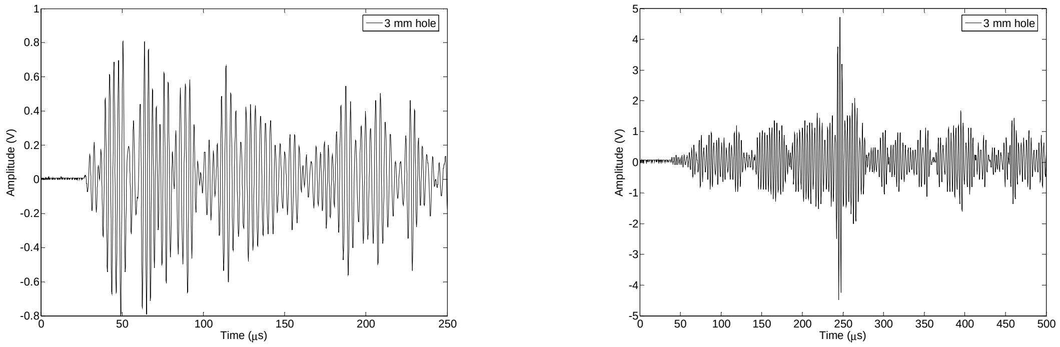


Figure 5. Received signals at P2 and its corresponding TR signals measured at P1 for the cases of non holed plate, 2 mm hole and 3 mm hole.

Figure 6 represents a comparison of the main lobe of the TR signals and the experimental FFT module for the non-holed and holed cases. The same behaviour of the FFT module as the hole diameter increases as modelled in Figure 4 is observed

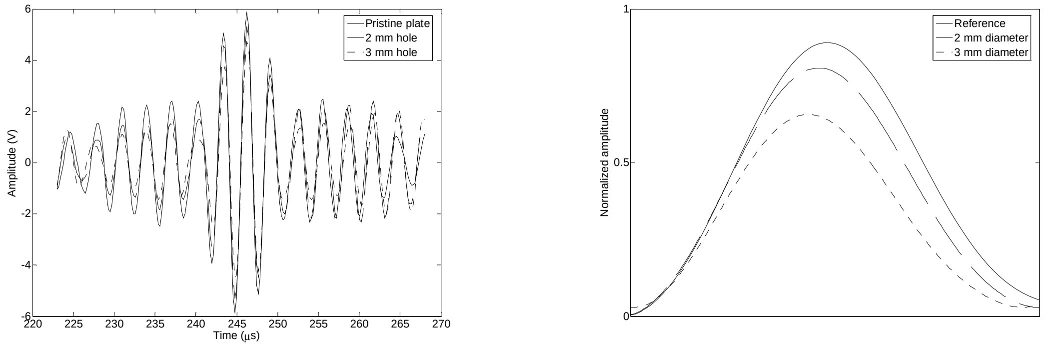


Figure 6. Comparison of the main lobes of the TR signal and experimental FFT modules for the non-holed and holed cases

Conclusions

A set of simulations substantiated with experimental measurements have been performed to ascertain the possibility of using a procedure based in the time reversal Method- TRM- to detect and size crack growth in thin aluminium plates.

The procedure developed shows that the growth can be correlated with the maximum amplitude of the Fourier transform of the Time reversal signal recorded by a transducer placed in some place of the plate.

Acknowledgements

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References

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