Selective Excitation of Lamb Wave Modes in Thin Aluminium Plates using Bonded Piezoceramics: Fem Modelling and Measurements

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Abstract. This work deals with the mode selection of Lamb waves generated in thin aluminium plates by using bonded piezoceramics. The experimental dispersion curves were obtained applying a 2D FFT algorithm to the data collected from an optical vibrometer. A Finite Element Model, using a commercial simulation program, PZFlex, was also developed to calculate the dispersion curves and to compare them with the analytical and experimental ones. Next, the Lamb wave modes were selectively reinforced or cancelled by bonding another piezoceramic to the plate at an appropriate location. Different models using PZFlex were developed to calculate the dispersion curves verifying the mode cancellations. The experimental measurements show good agreement with the models.

Introduction

Lamb wave techniques are emerging as one of the most effective methods for damage detection in aeronautic structures. Lamb waves are guided waves that exist in thin wall structures with free boundaries. For a plate having a thickness of the order of a wavelength or so, surface Rayleigh waves can degenerate into Lamb waves [1]. These waves can travel over large distances with little attenuation thus allowing the inspection of large plate-like structures with little loos of energy. The problem arrives with their dispersive nature. That is, for a given frequency multiple modes can exist, making defect identification difficult. The analytical dispersion curves give us an idea of the various existing modes and its velocities for each frequency of excitation. Therefore, it becomes necessary to choose the optimal frequency excitation, and the appropriate actuator location, to obtain the modes more adequate to defects detection. A finite element program can help in this task.

1. Lamb Waves generation – Experimental, analytical and FEM dispersion curves

Different type of transducers, materials, structures, can be use to excite Lamb Waves in plates: Interdigital transducers, PZT actuators, PVDF patches, piezocomposites, etc... PZT actuators, 7x7 mm square 0.5 mm thick, were used in this work because of their high force output at relatively low voltages, and their good response qualities at both low and high frequencies.

1.1 Experimental dispersion curves

One piezoceramic 7x7x0.5 mm, glued to the plate using an instant bonding cyanoacrylate adhesive, was placed at the centre of an aluminium plate 1200x1200x1.1 mm. The piezoceramic when excited resonated in its thickness mode to generate an omnidirectional Lamb wave. A 5052 Panametrics Pulser-Receiver was used to excite the actuator with a broadband signal to be able to generate all the Lamb Wave modes. A needle hydrophone - Medisonics, UK - coupled to the plate with a thin layer of baby oil, was then used to measure the acoustic pressure immediately above the plate. The hydrophone displacement was controlled by a 3D computerized displacement system. The signal received at the hydrophone was captured each millimetre over a total distance of 50 mm. A LabVIEW program, controlling a Tektronix TDS 220 Oscilloscope, was developed to digitize the measured signals, 50 in total, and record them in a computer for its post-processing. The collected signals were 2500 points length and 64 signals averaged. The experimental dispersion curves, figure 1, were then obtained applying to the data collected a 2D FFT algorithm [2] implemented in a MATLAB program.

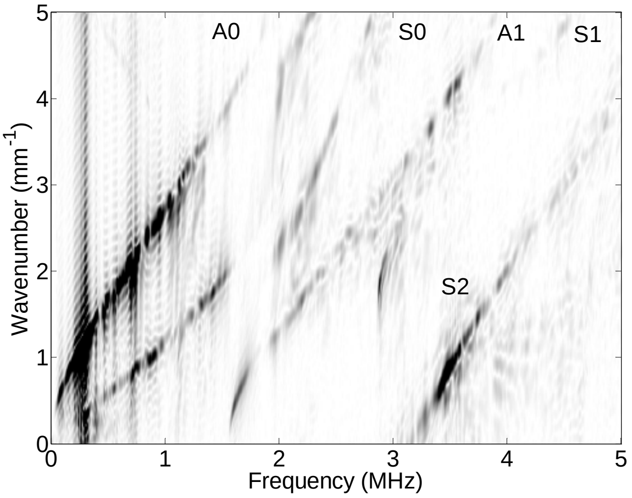

Figure 1. Experimental dispersion curves for an aluminum plate of thickness *2h*.

1.2 Analytical dispersion curves

The analytical dispersion curves of an aluminium plate of thickness 2h can be obtained by solving the Rayleigh-Lamb frequency equations.

$$\frac{\tan(qh)}{\tan(ph)} = -\left[\frac{4k^2pq}{\left(q^2-k^2\right)^2}\right]^{\pm 1} \tag{1}$$

where +1 applies for symmetric modes, while -1 applies for antisymmetric modes. The variables p and q are defined as:

$$p^2 = \left(\frac{\omega}{c_L}\right)^2 - k^2 \text{ and } q^2 = \left(\frac{\omega}{c_T}\right)^2 - k^2 \tag{2}$$

The wavenumber *k* is numerically equal to ω/c_p, where c_p is the phase velocity of the Lamb wave mode and ω is the circular frequency. The phase velocity is related to the wavelength by the simple relation

$$c_p = (\omega/2\pi)\ \lambda \tag{3}$$

An analytical model of the Lamb dispersion curves was developed using the variation of the Rayleigh-Lamb frequency equations made by Rose [3]. When plotting the dispersion curves, we are only interesting in the real solutions of the equations, which present the (undamped) propagating modes of the structure. By collecting the terms α and β, the equations take on only real values for real or pure imaginary wavenumbers *k*. The equations become:

$$\frac{\tan(qh)}{q} + \frac{4k^2 p \tan(ph)}{\left(q^2 - k^2\right)^2} = 0 \tag{4}$$

for symmetric modes

$$q \tan(qh) + \frac{\left(q^2 - k^2\right)^2 \tan(ph)}{4k^2 p} = 0 \tag{5}$$

for antisymmetric modes

These reduced equations (4), (5) were solved using MATLAB, thus obtaining the analytical dispersion curves for a plate of thickness 2h, which are plotted on the next figure, figure 2.

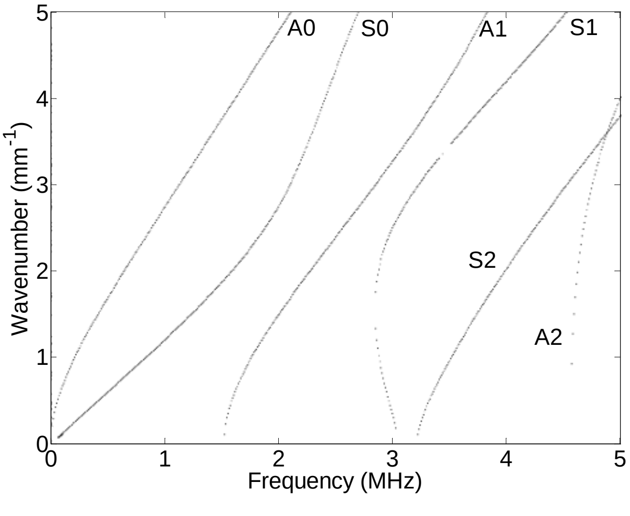

Figure 2. Analytical dispersion curves for an aluminum plate of thickness *2h*.

Figure 2, shows a plot of the wavenumber versus the frequency for the symmetric and antisymmetric Lamb wave modes. It can be observed that the first six Lamb propagating modes are present. Note that, at a given frequency value, several Lamb modes may be present. The branches corresponding to each Lamb mode are clearly identifiable. At low frequencies, below 1 MHz, only two Lamb modes are present: the A0 mode and the S0 mode. Frequency excitation ranges above 1,5 MHz would produce other modes making difficult lamb mode selection. Consequently, a frequency range up to 500 kHz have been chosen for this study.

1.3 FEM dispersion curves

The PZFlex finite element analysis program was used to simulate the wave propagation through the aluminium plate [4,5]. PZFlex has multiple element and material types available, including fully coupled piezoelectric materials, and isotropic and anisotropic elastic solids, in both 2D and 3D. The aluminium was modelled as an isotropic solid, while the piezoelectric plates considered the full anisotropic material properties. The element order and time integrator are both 2nd order, and linear interpolation is used between elements for field calculations. Single point integration is used, and mesh density was at least twenty elements per wavelength of interest. While PZFlex is capable of variable mesh spacing, a regular element spacing was chosen throughout the model.

Since PZFlex is a time domain code, the full dispersion analysis could be carried out with a single simulation. Simulations ranged in duration from a few minutes for the 2D cases, up to a few hours for the large 3D cases. All simulations were run on desktop PCs under the Windows XP operating system.

A simulated piezoelectric element was placed above the aluminium plate, and excited by a single cycle sinusoid to excite a broadband pulse in the plate. Electrode thickness was assumed to be negligible. Displacements at a number of positions were recorded for later post-processing to create the FEM dispersion curves, figure 3.

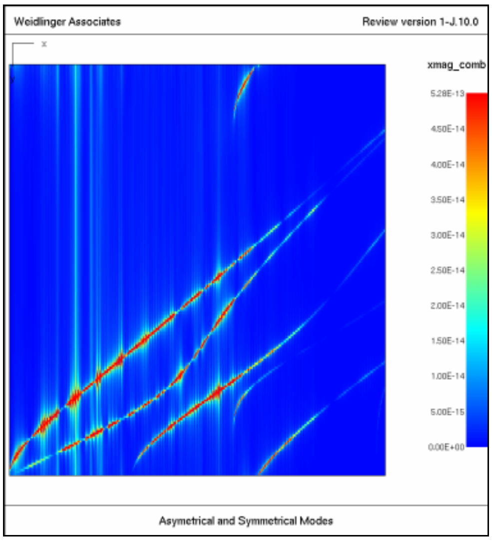

Figure 3. FEM dispersion curves for an aluminum plate of thickness *2h*.

2. Selective excitation of Lamb modes

2.1 Experimental results

A detailed part of the experimental dispersion curves is plotted in figure 4. In order to display the changes in the frequency region of interest, the X-axis has been set to be 0 to 500 kHz. As depicted in figure 4, only two modes are present, the antisymmetric fundamental Lamb mode, corresponding to the superior branch and the symmetrical fundamental Lamb mode, inferior branch.

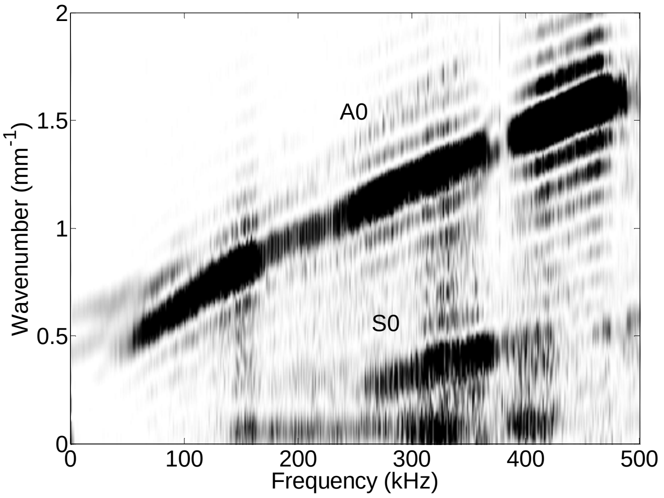

Figure 4. Detailed part of the symmetric and antisymmetric modes showing the frequency region of interest of the experimental dispersion curves.

Selective mode excitation was then achieved by bonding another piezoceramic on the other side of the plate in front of the first. If we excite the second actuator in phase with the first one, the symmetric mode, S0, is reinforced whereas the antisymmetric mode, A0, is partially cancelled. In figure 5, it can be seen that the superior branch (A0) practically extinguish, while the inferior one (S0) remains present.

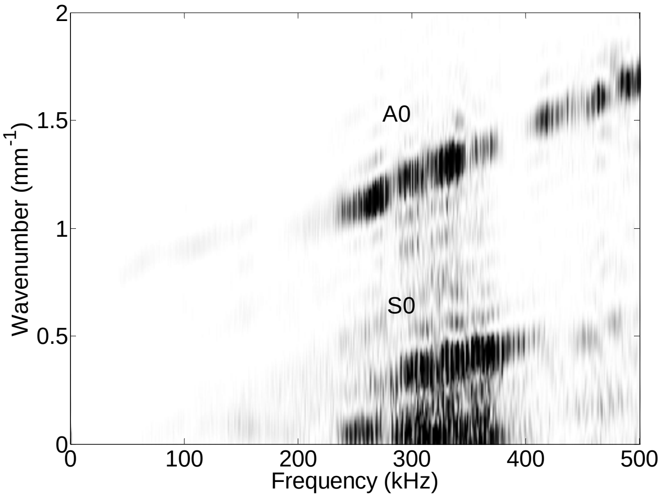

Figure 5. Reinforcement of the symmetric Lamb mode. Experimental results.

In the case of figure 6, when the two actuators are excited out of phase, is the antisymmetric mode that remains unaltered whereas the symmetric mode is cancelled. This can be seen in the figure by observing the antisymmetric branch is still present and the other branch corresponding to the symmetric mode disappears.

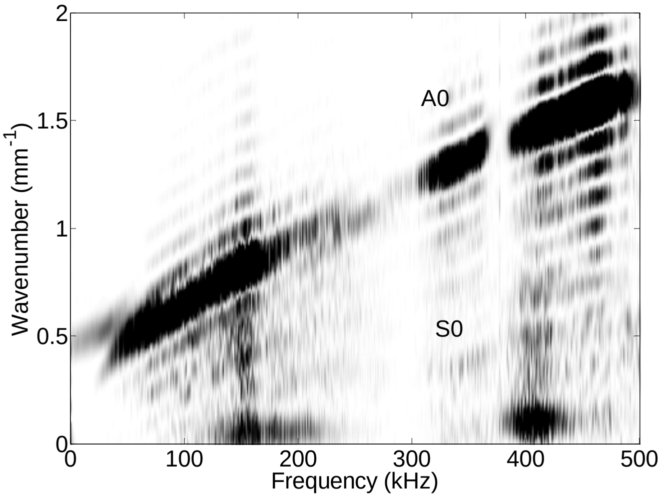

Figure 6. Reinforcement of the antisymmetric Lamb mode. Experimental results.

2.2 FEM results

In this case, the simulated piezoelectric elements were placed faced above and below the aluminium plate. The excitation signal was a single cycle sinusoid to excite a broadband pulse in the plate. Once again, FEM results, figures 7 (a) and (b) show very good correlation with experimental results. The differences between the total cancellation of the branch modes in the FEM results and the partial cancellation in the experimental results might be due to the bonding position of the piezoceramics. In the experiments they are not perfectly glued opposite each other.

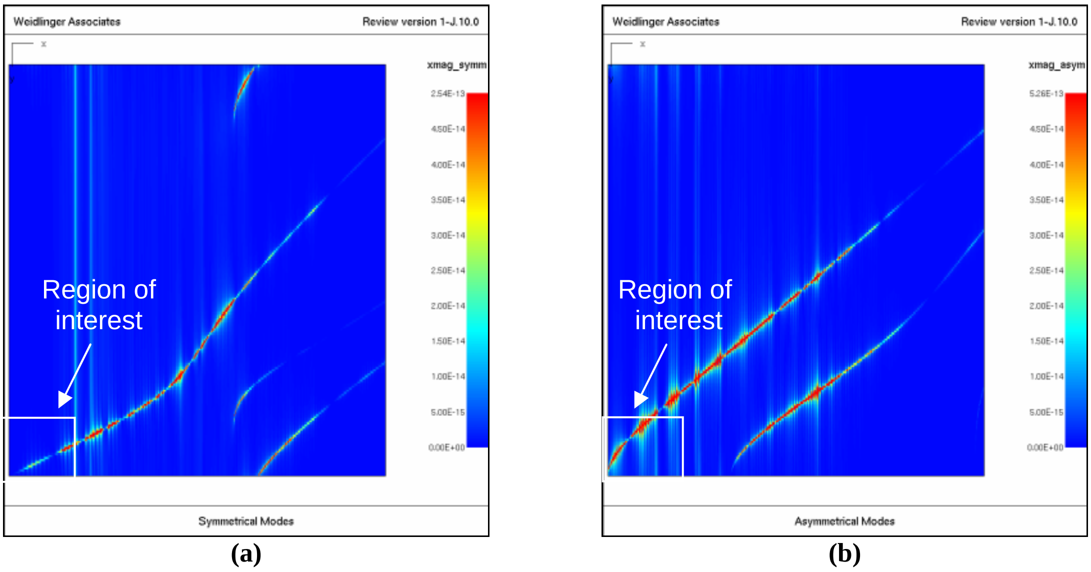

Figure 7. (a) Reinforcement of the symmetric Lamb mode. FEM results. **(b)** Reinforcement of the antisymmetric Lamb mode. FEM results.

Conclusions

In this work, the study and generation of the Lamb wave dispersion curves in thin aluminium plates has been presented. Lamb waves were generated and received by using PZT actuators bonded onto the plate. The use if these piezoceramics has demonstrated to be an effective technique to generate Lamb waves.

The experimental dispersion curves of an aluminum plate obtained with the 2D FFT algorithm show a very good agreement with the analytical and FEM dispersion curves calculated.

Bonding another piezoceramic in the appropriate location of the plate has demonstrated to be an easy and effective method to selectively filter individual Lamb modes. In this way, by filtering the appropriated Lamb modes, defects identification can be achieved easily.

Acknowledgements

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