DETECTION AND CLASSIFICATION OF DEFECTS IN THIN STRUCTURES USING LAMB WAVES

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ABSTRACT

The possibility of using Lamb waves in contact mode to detect and classify defects in thin structures is analyse in this work. By the fact that is usually desirable to transmit a single mode, excitation method and limitations are discussed, as well as the necessity of signal processing to correct identify the propagation modes. For this propose two different techniques are used: amplitude and phase spectrum methods. Experimental results obtained on aluminium samples agree very well with theory. The detection of notches of different depths, widths and orientations using pulse-echo and transmission techniques are investigate. Phase velocity and spectrum behaviour are correlated with defect dimensions/orientations with satisfactory results.

INTRODUCTION

The use of Lamb waves is potentially a very attractive solution when large structures inspections are needed since they can be excited at one point and can be propagated over considerable distances. If a receiver is positioned at a remote point of the structure it can collect information about the line between transmitter and receiver that could be related with defects in surface or internal cracks. The advantages are obvious comparing with conventional ultrasonic non-destructive testing using bulk waves, that usually inspects the region of the structure immediately below or adjacent to the transducers, and could be very time-consuming when large inspection areas are needed.

One of the main problems in Lamb wave testing is the dispersive nature of Lamb waves. When the excitation of a particular mode is made by a broadband pulse the different components of the wave will travel with different speeds and the shape of the propagating wave will change along the propagation path. This could make long-range inspection difficult due to interpretation of received signal and signal-to-noise problems since the peak amplitude in the signal envelope decreases rapidly with distance if dispersion is strong. Limitation of the bandwidth of the excitation to a low dispersion range (where group velocity does not change very much with frequency) should be done.

Other problem is the difficult of generate a single pure mode. At least two modes are present even at low frequency range. As frequency increase more modes are possible and the interpretation of the signals tends to be more complicated. Usually is desirable to excite one single mode. However, even if this is achieved, mode conversion will occur in presence of boundaries, defects and other impedance changes and the received signal could include several propagation modes.

Despite this problems, a large number of workers have recognised the advantages of using Lamb waves for fast and long-range inspection. Viktorov[1] was probably the first that study intensively Lamb waves in the past sixties. Since then there has been great development in several fields such as: quick inspection of plates and stripes[2,3], adhesive bond inspection[4,5] and damages and delaminations detection in composites[6,7]. Lately Alleyne and Cawlley[8] have developed a lot of work in the detection and classification of defects using Lamb waves. With the help of some tools like 2-D Fourier transform[9] and finite elements simulation good results have been obtained.

The selection of propagation mode is an important step when we work with Lamb waves. In this work s_0 mode was selected using the coincidence principle due to the low dispersion on the frequency range used. Practical considerations are analyse, like finite beam width, that take us, not only to a pure excitation mode but to an excitation zone. Even with only one mode selected was verified that different modes were collected in the receiver. This different modes may be used as an indication of presence of defects.

Theoretical phase velocity behaviour obtained from the Lamb wave equations were confirmed with two experimental techniques: phase[10] and amplitude[11] spectrum methods. Study of influence of dimensions of simulated notches in the phase velocity in aluminium sheets were experimental carried out with satisfactory results.

MODE SELECTION

The key to obtain the number of propagation modes available at any frequency is given by solving the well know Rayleigh-Lamb frequency equations

$$\frac{\tan(K_{ts}b/2)}{\tan(K_{ls}b/2)} = \frac{4\beta^2 K_{tl} K_{ts}}{(K_{ts}^2-\beta^2)^2} \qquad \text{Symmetric Modes} \qquad (1a)$$

$$\frac{\tan(K_{ts}b/2)}{\tan(K_{ls}b/2)} = -\frac{(K_{ts}^2-\beta^2)^2}{4\beta^2 K_{tl} K_{ts}} \qquad \text{Anti-Symmetric Modes} \qquad (1b)$$

were K_{tl} and K_{ts} are given by

$$K_{tl}^2 = \left(\frac{\omega}{V_l}\right)^2 - \beta^2 \qquad \text{and} \qquad K_{ts}^2 = \left(\frac{\omega}{V_s}\right)^2 - \beta^2 \qquad (2)$$

β is the wavenumber, numerically equal to ω/V_{ph} where V_{ph} is the phase velocity and ω the angular frequency. The quantities V_l and V_t represents the longitudinal and shear wave velocities in the bulk material.

For a given frequency these equations can de considered implicit transcendental functions of phase velocity alone, and they will be satisfied by an infinite number of real, imaginary or complex values of phase velocity. The real solutions for a given frequency represent undamped propagating modes of the structure whereas the imaginary and complex roots represent exponentially decaying modes which do not propagate.

The symmetric Lamb wave modes, governed by equation (1a), have deformation fields which are symmetric about the midplane of the layer, while the anti-symmetric modes, governed by equation (1b) have deformation fields which are anti-symmetric with respect to the midplane of the layer.

A plot of the real solutions of equations (1a) and (1b) are show in figure 1 for a aluminium plate with V_l=6540 m/s and V_t=3250 m/s.

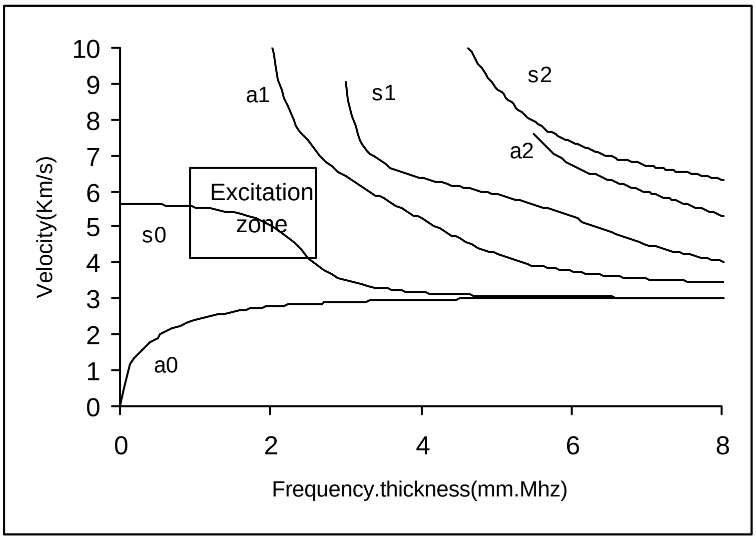


Figure 1 – Phase velocity dispersion curves for aluminium plate (V_l=6540 m/s and V_t=3250 m/s)

If a pure Lamb mode is to be generated, we have to ensure that the frequency content of the excitation signal is appropriate and also that the spatial variation of the force applied to the plate surface matches the wavelength of the desired Lamb mode. This is obtained by the coincidence principle, that is schematically represented in figure 2, and is given by

$$\lambda_p = \frac{\lambda_c}{\mathrm{sen}\,\theta} \tag{3}$$

where λ_c is the wavelength in the coupling medium, λ_p the wavelength of desired mode and θ the angle of incidence. With some manipulation we can obtain

$$\theta = \mathrm{sen}^{-1}(c / c_p) \tag{4}$$

where c is the longitudinal velocity in coupling medium and c_p is the phase velocity in the plate. So, varying the angle of incidence, different wavelengths may be preferentially generated. A similar transducer oriented at the same angle to the plate but in opposite sense may be used as a receiver. It is also possible to use a single transducer in pulse-echo mode for both transmission and reception.

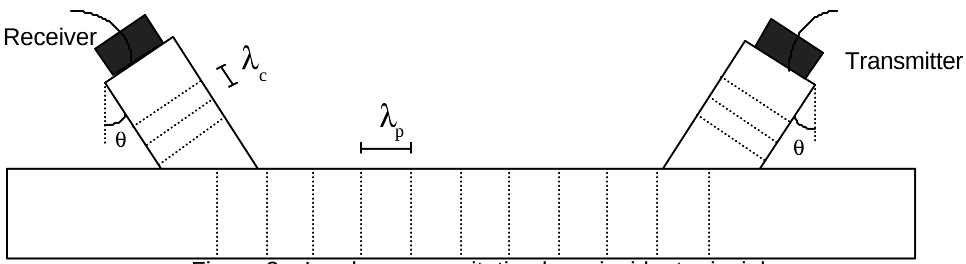


Figure 2 – Lamb wave excitation by coincident principle

The control of frequency range of excitation is very important when we work with Lamb waves. If the excitation signal as a large bandwidth is easy to see from figure 1 that we could obtain more then a single mode, what is not generally desirable. Then, typically, toneburst excitation[12] is used due to is reduced bandwidth. However pulse excitation also can be used if the bandwidth do not conducts to an excitation zone that includes more them one mode. Figure 3 shows the amplitude spectrum of s_0 mode obtained by pulse excitation in a 2 mm tick aluminium plate. If the bandwidth were considered at –40dB, the frequency range of excitation is like that given in figure 1.

When Lamb waves are excited using a conventional ultrasonic transducer via the coincidence principle (figure 2) the purity of the mode generated will depend of the beam spreading, that is given by

$$\phi = \mathrm{sen}^{-1}\left(\frac{1{,}22\ \lambda}{D}\right) \qquad (5)$$

where *D* is the diameter of the transducer. In practice we have two incident angles given by (θ+φ) and (θ-φ) that gives two different phase velocities

$$c_{p1} = \frac{c}{\mathrm{sen}\,(\theta-\phi)} \quad \text{and} \quad c_{p2} = \frac{c}{\mathrm{sen}\,(\theta+\phi)} \qquad (6)$$

Combining frequency range and phase velocity range we obtain an *"excitation box"* that is represented in figure 1 and includes all the possible modes. *The "excitation box*" that is shown in this case was obtained in contact mode, using perspex blocks as coupling with the plate. The incident angle was selected using equation (3) to excite s_0 mode considering the central frequency of the transducer.

PHASE VELOCITY

Time domain analysis of Lamb waves usually is done when separation of modes is needed. For example when a single mode wave propagates in a plate with a defect, the receiving signal normally includes another mode due to mode conversion. The amplitude of this mode can be correlated to the defect properties.

When accurate velocity measurements are needed, time difference between *n*th peak of the signal can be done for two different locations only if the shape of the wave remains the same. When we wave dispersive waves like Lamb waves, frequency domain techniques are demanded. The techniques used for phase velocity evaluation are the phase and amplitude spectrum methods.

In phase spectrum method the phase velocity is given by

$$C_p = \frac{2\pi f L}{\Delta\varphi} \qquad (7)$$

where $\Delta\varphi$ is the difference in the phase spectrum of two signals that were collected with a different distance between them of *L* and *f* is the frequency.

In the amplitude spectrum methods the two signals are also collected at different measurement points after are summed and Fourier transform of the result is performed. Phase velocity is given by

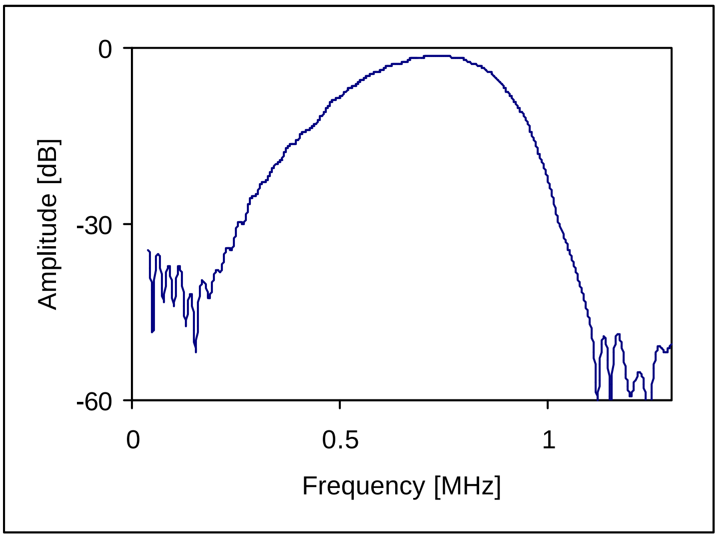
$$C_p = \frac{L f_n}{n} \qquad (8)$$

where f_n is the frequency of the *n*th resonance peak in amplitude spectrum. If one of the signals is subtracted instead of summed the result leads to dips rather than peaks in the amplitude spectrum.

The difference between this two method is the fact that while amplitude give us discrete points, phase spectrum give a continuos function.

In figure 4 is represented s_0 mode signal after travel 100 mm in a 2 mm thick plate. Figure 5 shows the sum of collected signals at 100 mm and 150 mm from transmitter (the second signal is inverted) and figure 6 shows the amplitude spectrum of this two signals. Considering the dips and using equation (8) it is easy to obtain phase velocity.

Finally in figure 7 we can see theoretical and experimental values of the phase velocity using both techniques for a 2 mm tick aluminium plate. Is obvious from figure that both methods agree very well with theory and can be used to estimate phase velocity.



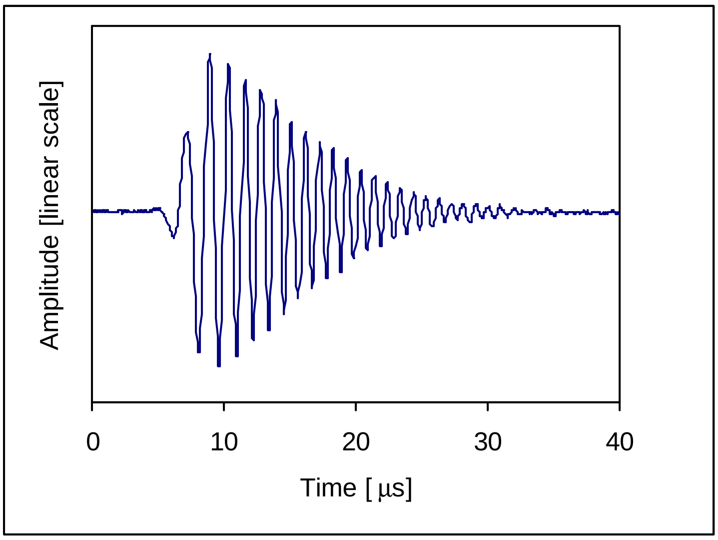
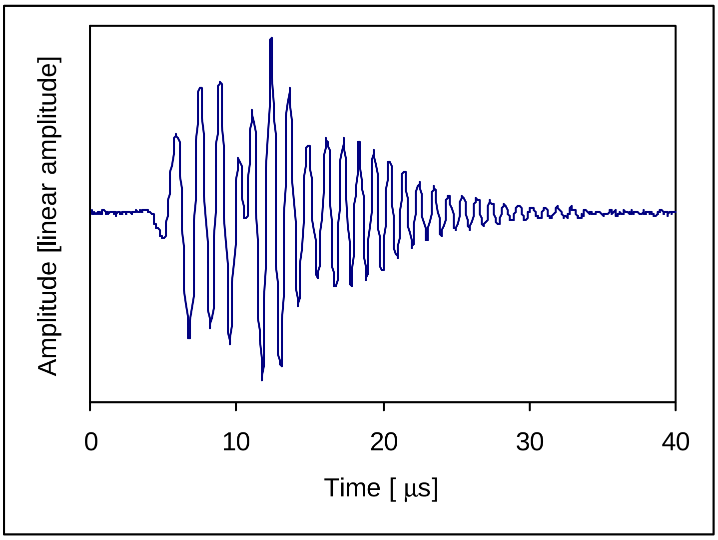


Figure 3 – Amplitude spectrum of s0 mode Figure 4 – Time domain s0 mode



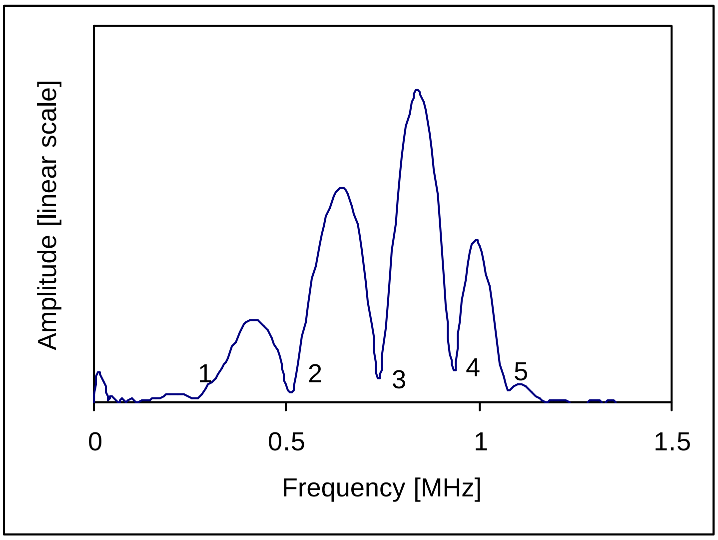


Figure 5 - Sum of collected signals at 100 mm and 150 mm from transmitter.

Figure 6 - Amplitude spectrum of the signals represented in figure 5.

EXPERIMENTAL WORK

Experimental setup

In figure 8 we can see schematically the setup used to generate and detect Lamb waves in an aluminium plate. Two Panametrics transducers with central frequency of 700 kHz are used in through transmission mode coupled with plate by perspex blocks with correct inclination to generate s_0 mode. The transducers are glued to the blocks and coupling between blocks and plate is done by coupling gel. A Panamatrics pulser/receiver is used as a main power system. After propagation on the plate, the signals are collected by a digital oscilloscope and transferred to a computer via RS-232 to further processing.

Pulse-echo method was also tried to use but some problems appears. Due to low amplitude of the generated Lamb waves they are masked by the tail of the excitation signal that makes the detection very difficult.

The simulated notches used in this work are located under the test plate and have three different deeps (0.5; 1 and 1,5 mmm) and five different widths (3; 4; 5; 7 and 10 mm).

Time domain analysis

Time domain analysis of Lamb waves is possible only if we can separate and measure individual modes present in a multimode dispersive signal. In figure 9 is presented the s_0 mode signal after passing through a notch with 1mm deep and 3mm width. Is obvious (comparing with figure 4) that exists an additional signal produced by mode conversion in the notch. Due to the working frequency-thickness range used (figure 1) the new signal must be a_0, because no other mode is possible to generate is this range. The group velocity was measured using time of flight method and the result agree with theoretical velocity obtained from dispersion curves of a_0.

One of the benefits of using s_0 mode is because his group velocity is quite different from a_0 velocity that makes amplitude measurements easier. Nevertheless phase opposition between s_0 an a_0 could give rise to confusion on the measurements and adjustments in distance between transducers may be needed. In other situations were group velocities are similar the amplitude measure of different modes is not possible and other techniques like 2D-FFT[9] should be used.

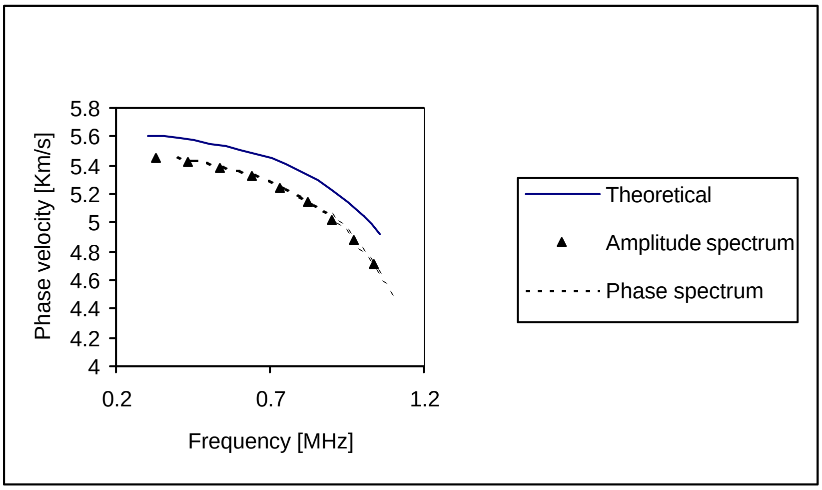
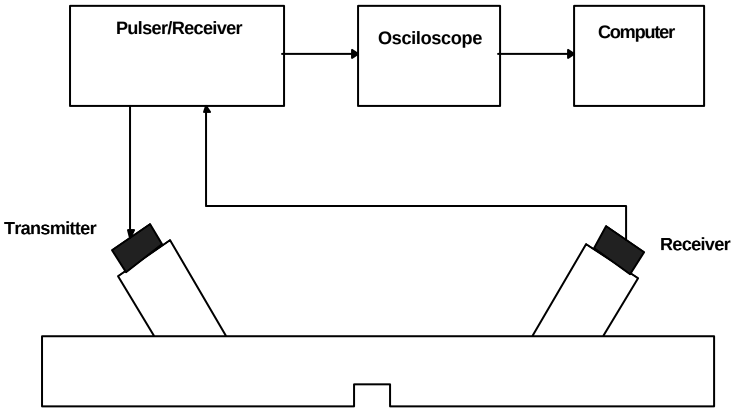


Figure 7 – Theoretically and experimental phase velocity measurements using amplitude and phase spectrum methods of s_0 mode.

Despite these problems, in our experimental work we verify that even for the smaller notch used (0.5 mm) mode conversion exists. So, measuring a_0 could be a way for detection and perhaps sizing of defects on plates. The relation of defect size with wavelength at central frequency is approximately 7%. It means that if we have an accurate detection of a_0 it is possible to detect defects with dimension at least 7% of the wavelength of excitation signal.

With this contact mode setup is difficult to relate amplitude measurements with defects because we can not guarantee the same coupling conditions. In future other kind of coupling should be used like that referred by Alleyne[8].



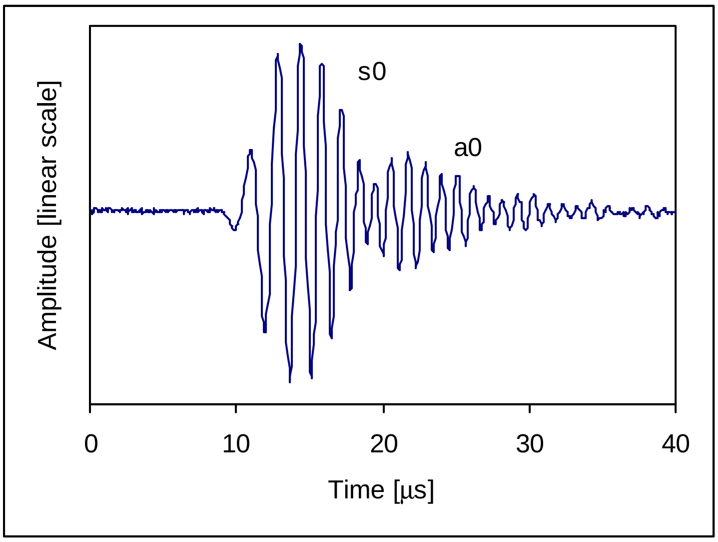


Figure 8 - Experimental setup.

Figure 9 – Mode conversion in 1mm notch.

Frequency analysis domain

Some authors have already prove that the amplitude of transmitted s_0 mode is not sensitive to the notches width[8]. As real defects could be assumed as large area defects like for instance corrosion, in the present study we had analyse the qualitative behaviour of phase velocity for several combinations of width and deep notches.

In figure 10 is presented the phase velocity for a plate without defects (reference) and several plots for different notch dimensions. Apparently phase velocity seems to increase with increasing of notch width. Similar results were obtained for the different width/deep notch relations.

The explication for this fact could be done by looking at the dispersion curves. When the notch width grows is like we have a plate with a new thickness. As this new thickness is smaller, there is a dislocation in frequency-thickness axis to the left which conducts to higher phase velocity. However, some discrepancies were found for smaller width values, phase velocity seems to be less sensitive for this dimensions and approach the reference one. In this situation the mode conversion must be assumed as the main phenomena involved and a time analysis could be used for defect evaluation. For larger widths (greater then half wavelength) mode conversion and plate thickness reduction are involved and significant variation in the phase velocity were found.

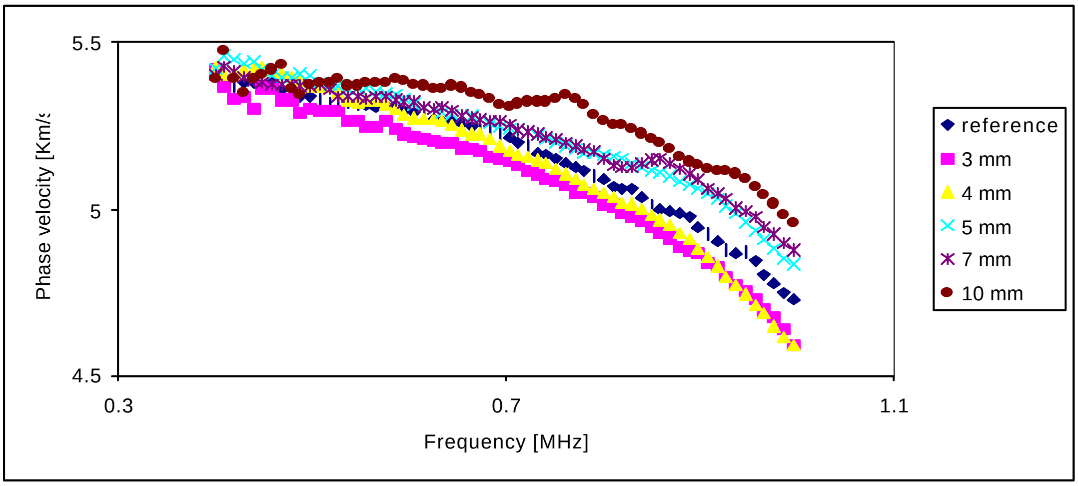


Figure 10 – Phase velocity behaviour for different notch widths.

The phase velocity method seems to be more sensitive to the notch width rather then the deep. So, for a correct defect evaluation/sizing a correlation between time domain and phase velocity should be done.

CONCLUSIONS

In this work Lamb wave propagation theory was review. Practical considerations like beam spreading and bandwidth of transducers were analyse, because they are the factors that rules the excitation zone where propagation modes are allowed. The importance of single mode propagation in a low dispersion region were also examined, due to is importance when a correct interpretation of signal is needed or to keep the capability of long-range inspection of thin structures.

In our work s_0 mode were chosen by the fact that is easy to guarantee single mode propagation.

Experimental phase velocity evaluation were made using amplitude and phase spectrum methods and the results agree very well with theory. Both methods can be used to estimate phase velocity when in the presence of a single mode. While amplitude spectrum give us discrete points phase spectrum give us a continuos function.

It was showed that Lamb waves could be used to detect notches in aluminium plates. If an accurate measurement of the a_0 mode that appears by mode conversion is possible, then a correlation of the amplitude with notch deep could be done. In our tests we verify the existence of mode conversion at least at a deep notch of 7% of the wavelength. In future different materials should be investigated to confirm this results using other frequency-thickness ranges.

Phase velocity measurements show us some notch width dependence, that give rise to high variations for widths larger then half wavelength. Further theoretical and experimental works are need in order to quantify variations on phase velocity.

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