3-D Imaging of Cracks in Metal Plate with Guided Waves Generated by Angle Adjustable Ultrasonic Probe

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Abstract

The use of guided Lamb waves in nondestructive testing allows a faster and more sensitive inspection when compared with other ultrasound techniques. The process is not easy to carry on because of the multimodal and dispersive nature of guided Lamb waves.

This paper explains all the procedures to image linear defects machined in an aluminum plate in detail. An angle adjustable ultrasonic transducer was used to generate the Lamb guided wave for inspection. The technique is effectively able to determine the positioning of surface and subsurface linear defects, their length and depth.

Keywords: guided wave, Lamb wave, ultrasonics, nondestructive testing, angle adjustable transducer, defect imaging

1. Introduction

The use of Lamb waves in nondestructive testing allows a faster and more sensitive inspection when compared with other ultrasound techniques [1]. Lamb waves are ultrasonic waves guided between the two parallel free surfaces, such as the upper and lower surfaces of a plate. Hence, they produce both longitudinal and shear energy in the structure to be inspected. Therefore, this technique is capable to detect defects in the whole thickness of thin walled structures over a large area from a single location [2]. In addition, when compare with ultrasonic technique, other benefits can be listed like low attenuation, low energy consumption and superior sensitivity. The main drawback of Lamb wave inspection method is due to the multimodal nature of the Lamb waves [3]. As the modes are generally dispersive, the received signal at a given frequency can have multiple wave packets and, in consequence, is very complicated to analyze.

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In recent years, plate like structures are being widely used in engineering and its inspection is increasingly required. In this paper we will explain in detail all steps required to characterize linear defects machined in an aluminum plate using Lamb waves.

Guided waves can be excited and acquired by a variety of means. A conventional ultrasonic transducer placed on an angle adjustable perspex wedge has been proved to be very effective to generate and to collect Lamb waves [4]. Appropriate adjustment of the wedge angle is the key to the success of crack imaging [5]. In this work, in order to set the appropriate angle, the dispersion curve of Lamb waves for the plate was calculated first. Then, the angle was obtained according to Snell's law as in [6]. The probe was scanned around the edge of an aluminum plate. Once there is a crack in the path of wave propagation, a reflected wave is received by the probe. Based on the arrival time of the reflected wave, the distance between the crack and the probe (i.e. the location of the crack) can be calculated. The crack depth is estimated by the amplitude of the reflected wave and the length of the crack is estimated by the scanning distance in which the probe receives reflected waves. Finally, an image that shows all the cracks in the plate along with their locations and dimensions, is presented.

2. Lamb guided waves to identify defects

2.1 Lamb's Theory

According to Lamb's theory there is an infinite number of modes of which a plate can vibrate. When a transducer emits a beam of ultrasonic waves which impinges on a plate it generates waves. Several propagating and non-propagating modes may be simultaneously excited by the excitation signal and the total response, at a given frequency, is the summation over all modes. Therefore, the entire analysis of signals is complex and a strategy to choose a suitable mode has to be selected for the inspection. It will depend not only on the structure to be tested, but also on the defects to be detected.

Lamb waves can propagate in two orthogonal modes: symmetric (S) and antisymmetric (A). This means that the displacement of the vibrations propagating in the plate with free boundary conditions are symmetric or antisymmetric respectively, with respect to the middle of the plate. A schematic illustration is depicted in Fig. 1.

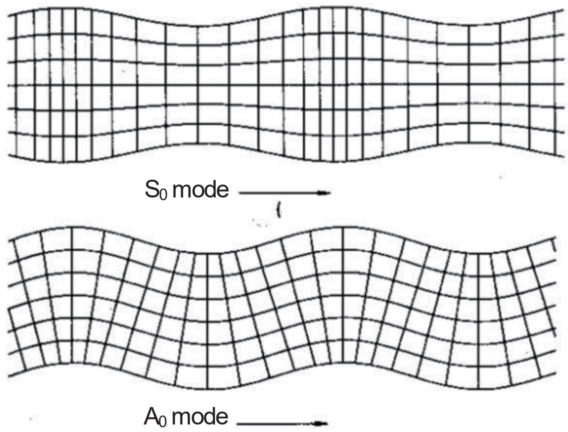


Fig.1 Symmetric and antisymmetric modes

S and A modes are also called "extensional" and "flexural", respectively, due to the nature of the motion of the particles. At low frequencies, the S0 wave is "stretching and compressing" the plate in the wave motion direction and with the A0 mode wave is the body of the plate that "bends" as the two surfaces move in the same direction.

2.2 Dispersion curves

In a free flat plate with thickness of $2h$, the Rayleigh-Lamb frequency relations are [4]:

For symmetric modes:

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

For antisymmetric modes:

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

where $p^2 = \left(\frac{\omega}{c_L}\right)^2 - k^2$ and $q^2 = \left(\frac{\omega}{c_T}\right)^2 - k^2$; c_L the longitudinal wave velocity and c_T the shear wave velocity. The wavenumber k is equal to ω / c_p , where c_p is the phase velocity of the Lamb wave mode and ω the angular frequency. The phase velocity is related to the wavelength by the relation:

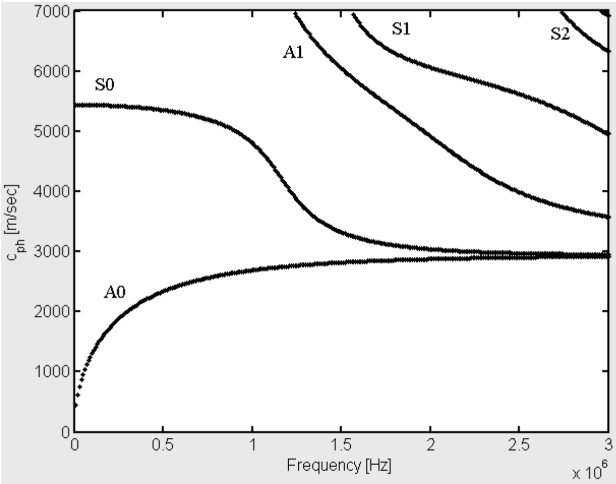
$$c_p = \left(\frac{\omega}{2\pi}\right)\lambda \tag{3}$$

Equations (1) and (2) can be considered as relating the phase velocity to the frequency ω, resulting in dispersion curves.

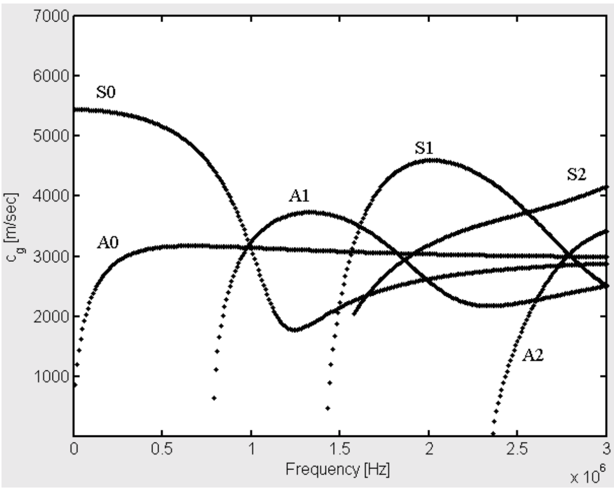
The group velocity is calculated from the phase velocity:

$$c_g = c_p - \lambda \frac{dc_p}{d\lambda} \tag{4}$$

Dispersion curves characterize the behavior of traveling guided waves. They describe how the velocity of each mode changes with frequency. The dispersion curves for an aluminum plate of 2 mm thickness were computed using GUIGUW and are depicted in Fig. 2. GUIGUW is a graphical user interface program based on the semi-analytical finite-element (SAFE) core code [7].



(a) Dispersion curves for the phase velocity c_p of Lamb wave



(b) Dispersion curves for the phase velocity c_p of Lamb wave

Fig. 2 Dispersion curves

2.3 Snell's Law for Angle Beam Analysis

One way to generate Lamb waves is using a longitudinal wave piezoelectric transducer on a plexiglass wedge. In this method, according to Snell's law, transducer incident angle depends on wedge velocity and Lamb wave phase velocity. Snell's law, in which θ_i is the plexiglass wedge angle, c_ω is the longitudinal wave velocity in the wedge and c_p the Lamb wave phase velocity:

$$\theta_i = \sin^{-1}\frac{c_\omega}{c_p} \tag{5}$$

3. Experimental Setup

The experimental setup is shown in Fig. 3, where the angle adjustable probe used to generate the desired guided wave at specific frequency is depicted. The piezoelectric element in the probe has a resonant frequency of 2 MHz. The adjustable range for the angle is from 0º to 90º. The probe was connected to an ultrasonic pulse/receiver (Ultratek USB-UT350) through a BNC cable. The pulse/receiver is able to send a user-defined wave to the probe and at the same time act as a receiver by amplifying the received analog signal and converting it to a digital signal. This digital signal is sent to a computer through an USB cable.

In the tests that followed, the excitation function was selected as a 3-cycle sinusoidal wave centered at 2 MHz to match the resonant frequency of the probe. According to the dispersion curve shown in Fig. 2 and the Snell's law, the suitable angles to generate A0 and S0 mode Lamb waves are respectively 71º and 63º. The A0mode has generally a higher group velocity. Therefore, after being reflected at the defect, it always arrives earlier than S0 mode and is easier to identify. Mode S0, with lower group velocity, arrives later and may superimpose with other waves that are due to reflection from boundaries or mode conversion at defects. Therefore, the adjustable angle of the transducer was set to 71º to maximize the generation of A0 mode waves.

Fig. 3 Experimental Setup

3.1 Experiments for measuring group velocity

In the proposed method, the location of defect is calculated based on the arrival time of the reflected Lamb wave and on the group velocity of the corresponding mode. Therefore, the accuracy of localization depends on the accuracy of the group velocity. In Section 2, the group velocities of various Lamb wave modes were calculated and were represented in the dispersion curves. However, the group velocities may vary due to the slightly change of material composition. Therefore, the group velocity should be experimentally measured for the plate to be tested.

A schematic representation of the experiment is shown in Fig. 4, in which the group velocity is measured using the wave reflected from the plate edge. The distance between the probe edge and the plate edge is represented by d. The real distance for the wave to travel from the piezoelectric element to the plate edge is $d + d_0$, where d_0 is due to the size of probe wedge. Then, the following equation can be obtained:

$$2 \times (d + d_0) = c_g \times (t - t_0) \tag{6}$$

where c_g is the group velocity, t is the arrival time of the reflected wave and t_0 is the time when the excitation is applied. Both d_0 and t_0 are constants but they are unknown, so it is not possible to obtain the group velocity with only one test.

Eq. (6) can be re-arranged as:

$$d = \frac{c_g}{2} t - (d_0 + \frac{c_g}{2} t_0) \tag{7}$$

It can be noticed from Eq. (7) that d changes linearly with t, and the group velocity corresponds to the slope of the d-t function. Therefore, experiments were performed with various distances as: d = 100, 150, 200, 250 mm. The arrival times of the reflected wave for the four cases were obtained. First degree polynomial fitting is applied to get the d-t function. Then, the obtained slope is used to estimate the group velocity.

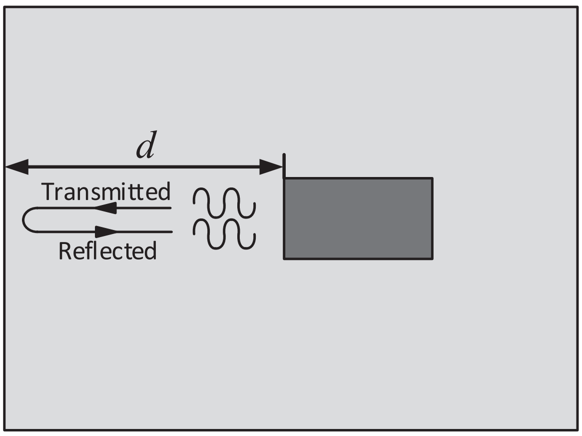


Fig. 4 Scheme of the experiment to determine the group velocity

3.2 Experiments to image the defects

One advantage of guided wave testing is that there is no need to implement scanning through the whole surface of the plate due to its low attenuation in most materials. However, the guided wave generated by the ultrasonic probe only travels in one direction and only detects the defects along that path. In order to test the whole area, a linear scanning is still needed. The testing scheme is shown in Fig. 5. The probe is placed at the bottom-right corner and sends guided waves in the negative x-axis direction. When there is no defect, the probe only receives a reflected wave from the edge. Due to the long travelling distance, the reflected wave is quite small. After the test at a first location, the probe is moved, with 5 mm steps, along the positive y-axis direction until the end of the plate. In the presence of a defect, a reflected wave will be received by the probe. The distance between the defect and the probe (i.e. the location of the defect) is estimated by the arrival time of the reflected wave together with the group velocity. The depth of the defect is estimated by the amplitude of the reflected wave. After finishing scanning along one of the edges, the probe is scanned along the other three edges.

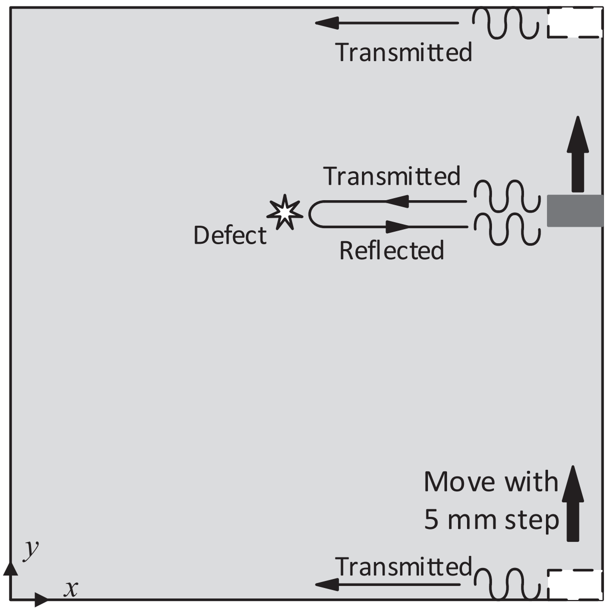


Fig. 5 Testing scheme to image the plate

4. Results and Discussion

4.1 Measurement of group velocity

In Fig. 6 the reflected signals received by the transducer for the four experiments described in 3.1 are shown in Fig. 6.

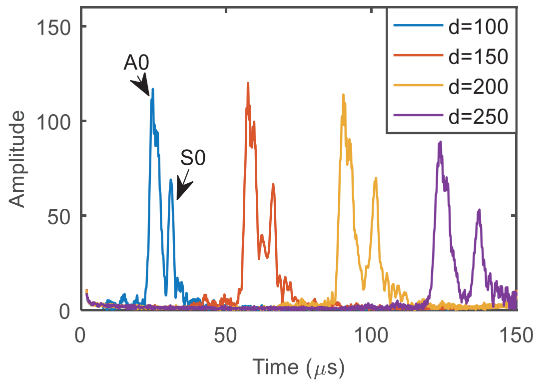


Fig. 6 Signals received by the transducer for different probe locations

The wedge angle was selected as 71° to generate A0 mode.

However, from the results show in Fig. 6, the S0 mode is also presented. The reason is that the angle calculated according to Snell's law is the angle that maximize the energy of a specific mode. Using nearby angles, the guided wave is still excitable, but with less energy [8]. The angle that maximize the S0 mode is 63º, however, with the angle of 71º, the S0 mode is also generated with relatively weak energy. According to the dispersion curve shown in Fig. 3, the A0 mode travels faster than the S0 mode. Therefore, as indicated in Fig. 6, the first wave packet for each test is the A0 mode and the second one is the S0 mode.

The arrival times of the A0 mode waves for the four cases were extracted and are plotted in Fig. 7. The first degree polynomial fitting was applied to the data and the fitted curve is also plotted in Fig. 7. The fitted function with distance in millimeters and arrival time in microseconds is given as:

$$d = 1.514t + 62.69 \tag{8}$$

The root-mean-square error for this fitting is 0.3997. The group velocity is estimated to be 3028 m/s.

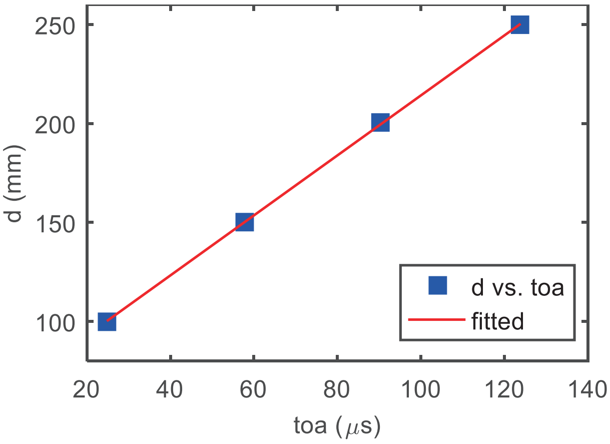


Fig. 7 Probe locations versus time of arrival

The experiments were performed as described in Section 3.2. In order to get the image, a matrix **M** with size of 601 × 601 was constructed. Each element in the matrix M(x, y) corresponds to one point in the plate with the coordinate (x, y) with a resolution of 1 mm. All the elements in the matrix were preset to 0 before the scanning. As the probe scans, reflected waves were obtained when there were defects in the paths of the guided waves. One example of the reflected wave is shown in Fig. 8. Similar to the signals of reflected waves from plate edge, the reflected wave from a defect also has two wave packets. In this paper, only the A0 mode is used to image defects because it arrivals first and will not superimpose with other waves. The arrival time of the reflected A0 wave is brought into the fitted function in Eq. (8) to estimate the distance between the probe and the defect. Once the location the defect is calculated, e.g. the defect coordinate is (x_0, y_0), then the corresponding element in the matrix $M(x_0, y_0)$ is set to the amplitude of the reflected A0 wave.

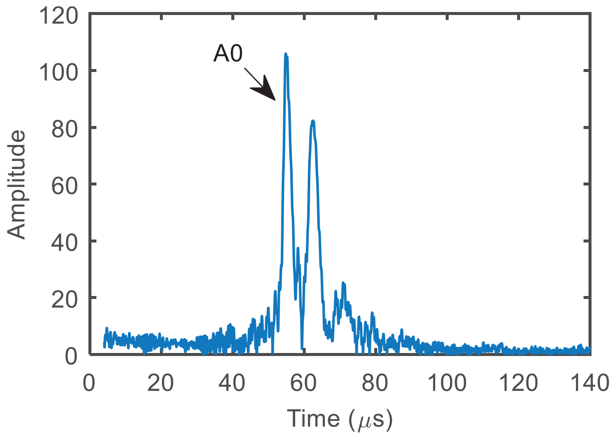


Fig. 8 Signal after defect reflection

After combining the results of the scanning along four edges, the final imaging result is shown in Fig. 9.

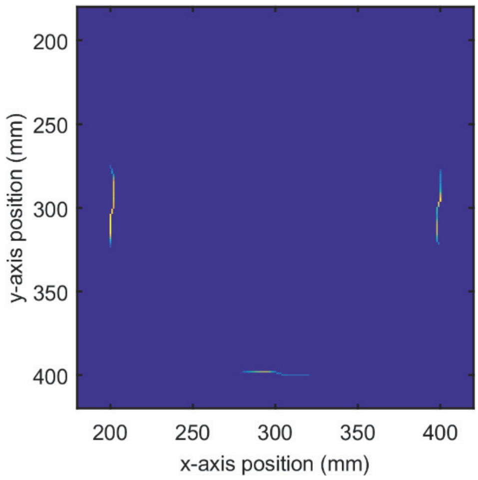


Fig. 9 3D image of the plate with linear machined defects

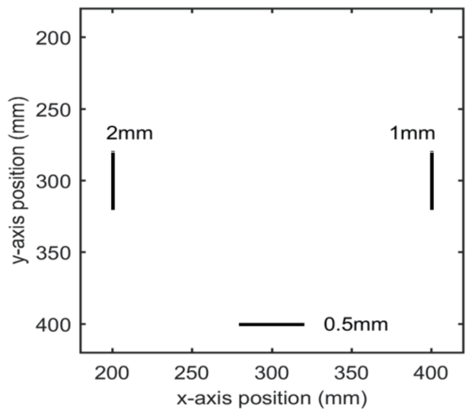


Fig. 10 Representation of the linear machined defects in plate

The real crack locations and their corresponding depths are plotted in Fig. 10 to compare. The three linear cracks can be clearly seen from the imaging result and the locations match the real crack locations. Besides, the relative depths of the cracks are also inferred from the color intensity (amplitude) in Fig. 9. The crack with 2 mm depth has the brightest intensity and the one with 0.5 mm depth has the lowest.

5. Conclusions

Lamb wave propagation was used to obtain a 3D image of a plate with three linearly machined defects. The angle of the transducer was adjusted to generate A0-mode Lamb wave. The arrival time and the amplitude of the reflected A0-mode Lamb wave from the defects are used as the parameters to image the defects. The results show that this method was able to successfully show the locations and lengths of the three cracks. The depths of the defects are also indicated by the color intensity of the image.

Acknowledgments

This work was developed at Instituto de Telecomunicações and it was supported by the Portuguese Science and Technology Foundation (FCT) projects UID/EEA/50008/2019 and PTDC/EEI/EEE/30723/2017. This support is gratefully acknowledged.

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