Behavior Of $A_0$ Mode Transduced Using Synchronised Rotationally (Same Direction) Misaligned Air-coupled Transducers

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Abstract

Transmission and reception of single selective Lamb mode is feasible using air-coupled ultrasonic transducers. However, alignment of air-coupled probes influences amplitude of Lamb mode. Properly oriented and aligned air-coupled probes satisfy Snell’s law and coplanarity condition. This results in transduction of high amplitude Lamb waves. In this work, a misalignment termed ‘synchronized (same direction) rotational misalignment’ was introduced between the air-coupled transducers in isotropic plates. It was found from experiments that, due to the misalignment, variation in normalised amplitude of the fundamental anti-symmetric Lamb mode ($A_0$) with respect misalignment angle follows Gaussian fit.

Keywords: Lamb wave; Air-coupled transducers; Misalignment; Gaussian distribution; Isotropic plates

1. Introduction

Successful employment of ultrasonic Lamb waves for Structural Health Monitoring (SHM) and Non-destructive Evaluation (NDE) is due to sensitiveness of these waves to surface and sub-surface defects (Su and Lin, 2009). Lamb wave has multi-modal propagation characteristics, i.e., at a given frequency of excitation, more than two modes propagate. Because of complex interaction, and multi-modal and dispersion characteristics of Lamb waves, efforts were kept to excite a desired single Lamb mode for SHM and NDE applications.

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Excitation of a single Lamb mode is possible using either contact or non-contact transducers (probes). In contact probes, gel or oil or water (liquid or semi-solid) is used as coupling medium between the probe face and specimen. The thickness and distribution of the couplant, and pressure on the probe determine amplitude of Lamb wave.

Air-coupled transducers (Castaings and Hosten, 1998) fall under the category of non-contact transduction technique. In this, gap between the front surface of the transducer and specimen is filled with air column. Lamb mode with constant amplitude can be achieved as long as the air-column height doesn’t change. However, alignment between the transducers is very important in order to transmit and receive high amplitude Lamb mode in a given plate. To transmit and receive a particular Lamb wave, the transducer (axis) is to be oriented at a certain angle ($\theta$) with respect to a normal to the plate, as shown in Fig 1. Moreover, at each transducer, the axis of the transducer and normal to the plate should lie in a single plane, as shown in Fig 1. This is ‘coplanarity condition’. In practice, even though the orientation of the probes is appropriate, but, coplanarity condition may not be satisfied because of misalignments. If the coplanarity condition is violated, it results in reduction in amplitude Lamb modes. Moreover, alignment of probes is very important in NDE applications, where amplitude is the criterion (or one of the criteria) for damage evaluation.

One can envisage various types of misalignments such as linear offset, circumferential and own rotation of probe (Ramadas et al., 2013) etc between air-coupled probes. In the present work, one of the misalignments termed ‘Synchronized (same direction) Rotational Misalignment’ (SsRM) was introduced between the probes and the effect of this misalignment on change in amplitude of the fundamental anti-symmetric Lamb mode ($A_o$) in isotropic plates was studied experimentally.

2. Experimental work

2.1 Introducing SsRM

To transmit and receive a particular Lamb mode in a plate, orientation of air-coupled transducer ($\theta$), with respect to a normal to the plate is calculated using Snell’s law, expressed as follows.

$$\sin \theta = \frac{V_{air}}{V_p}$$

($V_{air}$ and $V_p$ are acoustic wave velocity in air (= 330 m/s) and phase velocity of the Lamb mode, which is to be excited in the plate, respectively. Once the orientation of transducers is fixed, they have to be aligned in order to satisfy the coplanarity condition, as shown in Fig 2(a), to ensure reception of high amplitude Lamb mode. Now, transmitter and receiver were synchronized and rotated by an angle $\phi$ in the same direction (either anti-clockwise or clockwise), as shown in Fig 2(b). When the transducers were rotated, the orientation of the transducers was unaltered. However, the rotation ($\phi$) of the probes had introduced SsRM between the transducers. The severity of misalignment between the probes was expressed in terms of angle of rotation of the probes.
2.2 Experimental setup

Experimental setup shown in Fig. 3 was used to record $A_0$ Lamb modes for various configurations of the transducers. High voltage pulse was sent to transmitter and received from receiver using a pulse-receiver. Experiments were carried out using planar air-coupled probes of 200 kHz central frequency to transmit and receive the $A_0$ mode. Display and digitization of captured signals was carried out using Digital Storage Oscilloscope (DSO), and the digitized data was stored in a computer.

Experiments were performed out on assortment of aluminium plates of thickness 1 mm, 3 mm and 6 mm. Mechanical properties of the aluminium material are given in Table 1. At 200 kHz, phase velocity of $A_0$ mode in aluminium plates depends on thickness. From DISPERSE (Lowe, 2009) the phase velocity of the $A_0$ mode in the 1 mm, 3 mm and 6 mm thick plates is 1292.4 m/s, 1984.2 m/s, and 2418 m/s, respectively. The orientation of air-coupled transducers estimated using equation (1) in the 1 mm, 3 mm and 6 mm thick plates is 14.79°, 9.6° and 7.8° respectively.
Table 1 Material properties of aluminium material

| Material | E in GPa | ν | ρ in kg/m³ |
|----------|----------|---|-----------|
| Aluminium | 70       | 0.30 | 2750      |

2.3 Experimental A-scans

The following exemplifies the procedure followed to capture A-scans in the three mm thick aluminium plate. Initially, air-coupled probes were oriented at ten degrees. Then the probes were positioned over the three mm thick plate in such a manner that the coplanarity condition was satisfied, as shown in Figs 1 and 2(a). This was the configuration represents the reference configuration. An A-scan captured in this configuration represents the reference A-scan, which is shown in Fig 4(a) and the Lamb mode indentified in this A-scan was A₀ mode. Afterwards, both the transmitter and receiver were rotated in anti-clockwise direction by 5⁰ (= ϕ), as shown in Fig 2(b). Because of this rotation SsRM was introduced between the probes. The orientation of the probes with the normals was unchanged during this rotation. One more A-scan, shown in Fig 4(a), was captured in this configuration as well. Rotation of the probes in anti-clockwise direction was continued till the receiver stops receiving the A₀ mode. One more set of A-scans were captured by rotating the probes in clockwise direction also. Similar set of experiments were carried out on the other two aluminium plates of thicknesses 1 mm and 6 mm.

3. Analysis of experimental data

Hilbert Transform (HT) was carried out on each A-scan. Envelope obtained after carrying out HT on the voltage-time history data represents energy magnitude in temporal domain (Mustapha et al., 2011). Fig 4(b) shows HT envelopes on the reference A-scan and the one captured at 5⁰ SsRM in the three mm thick aluminium plate. Peak value of the reference envelope was considered as the reference amplitude. Peak values of all other envelopes in each sample (plate) were calculated and normalized with respect to that of the reference amplitude. This procedure was adopted in the other two plates also.

![Fig. 4 (a) A-scans captured in three mm thick plate, (b) Hilbert Transform of the A-scans](image)

Variation in normalised amplitude with respect to angle of rotation of the probes (misalignment angle) is shown in Fig 5. Here, anti-clockwise and clockwise rotation of the transducers was taken as positive and negative misalignment angles, respectively.

Curve fitting was carried out over experimental data captured in all three aluminium plates. It was observed that the curve represents Gaussian fit, given by the following expression.
Here, \(a\), \(b\) and \(c\) represent coefficients, which are to be determined from the curve fitting over the experimental data. In equation (2), \(\phi\) is an independent variable, which is nothing but the misalignment angle (rotation of probe, \(\phi\)), expressed in degree. Goodness-of-fit, denoted by \(R^2\) was defined to estimate the accuracy of the fit. Table 2 lists the values of \(R^2\) and, \(a\), \(b\) and \(c\) of each curve fitted over the measurements carried out in all the three plates.

\[
f(x) = ae^{-((\phi-b)/c)^2}
\]

(2)

![Graph showing the variation in normalised amplitude of A0 mode with respect to misalignment angle in 1 mm, 3 mm and 6 mm thick plates](image)

**Table 2. Values of coefficients in the Gaussian curve**

| Thickness in mm | \(a\)   | \(b\)   | \(c\)   | \(R^2\)   |
|-----------------|---------|---------|---------|-----------|
| 1               | 0.969   | -0.0034 | 11.95   | 0.9958    |
| 3               | 0.9808  | 0.4615  | 16.08   | 0.9962    |
| 6               | 0.9823  | 0.3919  | 18.25   | 0.9945    |

**4. Results and discussion**

Synchronized rotational misalignment in same direction was introduced between air-coupled transmitter and receiver. Experiments were performed on three aluminium plates of thicknesses one mm, three mm and six mm. In all the three plates propagation of high amplitude A0 mode was noticed when Snell’s law and coplanarity condition were satisfied. Without disturbing the orientation of the probes, when the synchronized rotational misalignment was introduced between them, amplitude of the A0 mode started decreasing with increase in angle of misalignment. It was computed from curve fitting that variation in normalised amplitude follows Gaussian fit. The goodness-of-fit of each curve is more than 0.99 as shown in Table 2.

From Fig 5 it was observed that, for a given misalignment angle, reduction in amplitude is high in thinner plate (one mm) than in thicker one (six mm). This can also be found from the values of \(c\) given in Table 2. The thicker plate has higher value of \(c\) than the thinner one. Furthermore, it can also be inferred that the A0 mode ceases to flow at lower misalignment angle in the thinner plate than the thicker one. For instance, at 30° misalignment angle amplitude of the A0 mode was 5%, 20% and 30% of the reference amplitudes in one mm, three mm and six mm thick plates, respectively. In other words, effect of SsRM is more in air-coupled probes, which are set at higher orientation angle. Therefore, when air-coupled probes are used for transmission and reception of the A0 mode in NDE applications, proper care should be exercised to satisfy the coplanarity condition.
5. Conclusions

From the experimental work it is concluded that alignment of air-coupled probes is vital in order to receive high amplitude $A_o$ mode in NDE applications. Gaussian fit represents, with good accuracy, the variation in normalised of the $A_o$ mode with misalignment angle. Moreover, thinner plate shows more sensitiveness to the misalignment angle than thicker plate.

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