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Airborne ultrasonic technique to measure leaky Lamb waves with narrowband and low-frequency excitation

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Abstract
Air-coupled non-destructive testing has become very valuable because eliminates the use of liquid couplants and enables a contactless fast inspection of structures. Multimodal leaky Lamb waves can be excited and sensed with this technology in plate-like specimens varying the excitation frequency and the inclination of the transducers. To reduce undesired effects, as the existence of unwanted modes, narrowband and low-frequency excitation signals can be used. In this paper, the generation and detection of ultrasonic leaky Lamb waves in a metallic plate with capacitive air-coupled transducers have been performed. Theoretical and experimental data have been matched, showing good correlation.

Keywords
Leaky Lamb waves, air-coupled ultrasound, dispersion curves, Snell's law, phase velocity

I. Introduction

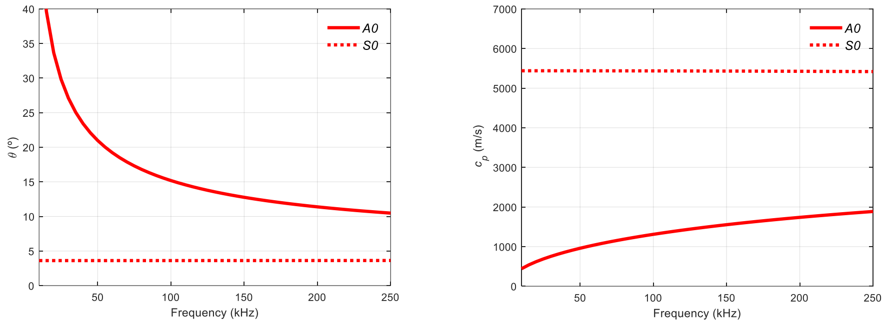
Air-coupled ultrasonic inspection has gained great relevance last years in the non-destructive testing field, since avoid the use of couplants and direct contact with specimens, enabling a fast scanning of them. Two transducer technologies exist in air-coupled testing: piezoelectric and capacitive, the latter usually having a large bandwidth [1][2]. However, this technique present disadvantages, as the need of high amplification due to the acoustic impedance mismatch between air and the inspected material and high averaging to enhance the signal-to-noise ratio (SNR) of the received waveforms[1][3][4].

A type of waves that can be generated and received with air-coupled transducers are Lamb waves. They are found in plate-like structures and can propagate over long distances with low attenuation. Besides, they can provide global information of a structure from a single probe position, which also allows a rapid inspection. Metals as aluminum or stainless steel are common in Lamb wave testing. If the tested plate is surrounded by a coupling media, as air, leaky Lamb waves (LLW) appear, since the energy of the Lamb waves generated in the plate leaks to that media. A problem that these guided waves present is dispersion (the propagation velocity depends on the frequency) which modifies the amplitude and the shape of the propagating signals. Furthermore, as excitation frequency increases, more Lamb wave modes appear in the received signals, which difficult signal analysis. Depending on the particle displacements in plate thickness, these modes can be classified as antisymmetric and symmetric. The two fundamental Lamb modes exist at low frequencies: the antisymmetric A0 and the symmetric S0 mode. The problem at low frequencies is the spread of the ultrasonic beam. In air-coupled ultrasonic testing, the fundamental A0 Lamb mode is prone to be excited and detected in comparison to the fundamental S0 Lamb mode due to its large (out-of-plane) particle displacement[3][4][6]. There is interest in the A0 mode, since has been proved to be sensitive to surface defects[3][7]. In Lamb wave testing, narrowband excitation (tone burst signals) is preferred instead of broadband excitation (chirp signals), since it reduces the dispersive effects by controlling excited modes by means excited frequency. Additionally, it injects more energy than broadband signal at the fundamental frequency, but it requires a frequency swept to evaluate different frequencies. Nonetheless, the main advantage of broadband excitation is that enables a faster measurement than narrowband excitation[2][8]. In order to selectively excite Lamb modes, oblique incidence can be used, i.e., varying the angle (with respect to the normal) of the transmitter. For an efficient reception of a specific mode, the receiver has to be oriented at the same angle that the transmitter[3][5].

Therefore, the aim of this paper is the proper excitation and detection of the A0 Lamb wave mode in an aluminum plate with both frequency and angle sweep using an airborne ultrasonic contactless technique.

II. Methodology

Lamb wave antisymmetric and symmetric modes present in a plate are governed by the dispersion equations (also called Rayleigh-Lamb frequency equations)[7]. The graphical representations of these frequency-dependent equations are known as the dispersion curves. Parameters as the incidence angle θ or the phase velocity c_p (the speed at which the phase of every frequency component propagates) can be represented with respect to the frequency, as it is shown in Figure 1.



a) b)

Figure 1. Theoretical incidence angle dispersion curves (a) and phase velocity (b) of an aluminium plate with a longitudinal wave velocity of 6320m/s, transverse wave velocity of 3130 m/s and thickness of 2 mm.

The phase velocity c_p and the incidence angle θ derive from the Snell's law [3][4][5][6] :

$$c_p = {}^{c_{air}}\!/_{\sin\theta} = \lambda \cdot f \tag{1}$$

$$\theta = \sin^{-1}\left({}^{c_{air}}\!/_{c_p}\right) \tag{2}$$

where c_{air} is the longitudinal wave velocity in air (343 m/s), f is the excitation frequency and λ is the wavelength of the desired mode. By controlling the excitation frequency and the angle of inclination of both transmitter and receiver, a mode of a determined phase velocity can be excited and received. In order to control the frequencies and angles, a contactless automatic testing system was built (see Figure 2). Capacitive air-coupled transducers with oblique incidence and pitch-catch configuration were used to generate and receive LLW in a 2 mm-thickness-aluminium plate. The transducers were Series 600 Environmental Grade Transducers from SensComp[2], with a circular aperture size of 38.4 mm, a bandwidth centered at a low frequency (50 kHz) and a theoretical operating range from 20 kHz up to 100 kHz. The angle of inclination of both transmitter and receiver was controlled by rotation stages. They were swept from 0º to 40º in 0.25º increments (159 angles). At each angle, two kind of signals were generated: narrowband and broadband. The narrowband excitation was a five-cycle tone burst signal ranging from 10 kHz to 250 kHz in 5 kHz increments (49 frequencies). The broadband excitation was a unique chirp signal with a bandwidth from 10 kHz to 250 kHz. Then, 50 different signals were generated: 49 narrowband signals (1 signal per frequency) and 1 broadband signal (1 signal for all frequencies). An arbitrary signal generator (HandyScope HS5) sent these signals to a linear amplifier with a gain factor of 50 (Falcosystem WMA-300) and 200 V bias voltage before feeding the transmitter transducer. Every signal detected by the receiving transducer was amplified by a gain factor of 100 (EG&G Princeton 5113) and then were captured by a digital oscilloscope (HandyScope HS5) with a sampling frequency of 10 MHz and 20,000 samples, which correspond to a temporal interval of 2 ms. To improve the

SNR, each measurement was averaged 16 times. A computer was used to automatically control the whole system. In order to absorb the direct wave through the air, a polystyrene board was placed between the transducers.

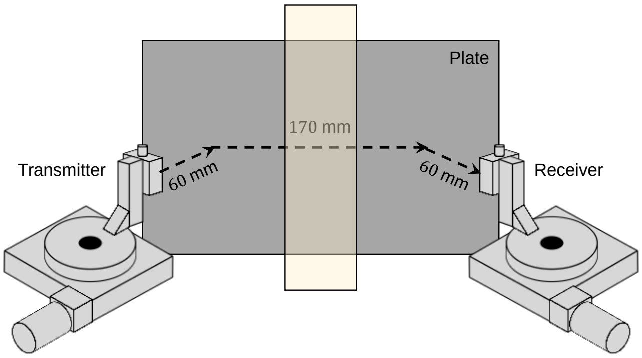
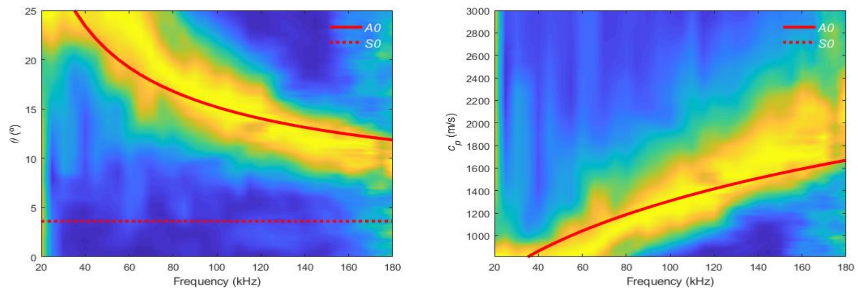


Figure 2. Layout of the airborne non-contact system.

The fast Fourier transform (FFT)[5] was applied to the narrowband detected signals (49 signals per angle so 159*49=7791 signals). For every angle (159), the 49 detected FFTs were combined in a resulting one. The (159) combined FFTs were assembled to build the experimental angle dispersion curves. Respect to the broadband signal, the FFT was also applied to the 159 detected signals (1 signal per angle) and a similar experimental angle dispersion curve was generated. Then, from Eq. (1), experimental phase velocity dispersion curves were obtained. To verify if the A0 Lamb mode has been excited, the theoretical dispersion curves were superimposed on the experimental curves[4][5].

III. Results and discussion

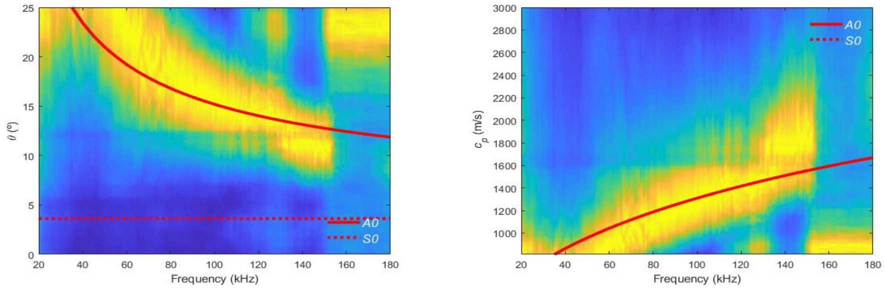
The angle and phase velocity experimental dispersion curves are overlapped with their corresponding theoretical dispersion curves, as shown in Figure 3 a) and b), respectively. The frequency working interval was selected from 20 to 180 kHz, since the SNR is low outside that range. To compensate the spread of the ultrasonic beam at low frequencies[5], the angles of incidence were corrected by a factor of β =13º.



a) b)

Figure 3. Angle (a) and phase velocity (b) experimental dispersion curves along with their respective theoretical curves using narrowband excitation.

The A0 mode has been excited and detected successfully, since there is good agreement between the yellow hot spot (experimental curve) and the flat red curve (theoretical curve). The phase velocity experimental curve starts at a value of approximately 800 m/s $\left({}^{343}/_{\sin(40º - \beta)}\right)$. The theoretical phase velocity curve of the S0 mode is not shown because it is out of the vertical range. Note that this mode has not been generated due to its low particle displacement[3][6]. It is expected that the generated A0 mode could not propagate a long distance due to dispersion (the phase velocity changes significantly with frequency)[3]. In order to check the difference between using narrowband and broadband excitation to generate LLW, broadband measurements (chirp signal excitation from 10 kHz to 250 kHz) were performed and their results are shown in Figure 4.



a) b)

Figure 4. Angle (a) and phase velocity (b) experimental dispersion curves along with their respective theoretical curves using broadband excitation.

As can be seen, the results are similar, but the narrowband excitation injects more energy for each fundamental frequency, therefore the useful bandwidth of the “narrowband” experimental curves is greater (up to 180 kHz, see Figure 3) than in the “broadband” experimental curves (up to 150 kHz, see Figure 4). Nevertheless, the measurement time is reduced in the broadband case, as it requires 159 signals respect to 7791 signals of the narrowband case.

IV. Conclusion

In this study, ultrasonic leaky Lamb waves have been generated and sensed in an aluminium plate by means of an airborne non-contact automatic testing system which enables frequency and angle sweep. Narrowband excitation at low frequencies was used to minimise dispersion and multimodal effects. The experimental angle and phase velocity dispersion curves have been compared to the computed theoretical dispersion curves in order to identify the excited A0 Lamb mode, showing close correspondence between them. A brief comparison between broadband and narrowband excitation was performed and similar results were achieved, although narrowband case presents greater bandwidth but much more acquisition time. With this methodology, the next step is to measure air-coupled leaky Lamb waves in non-homogeneous materials, as mortar.

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References

[1] T.E. Gómez Álvarez-Arenas, *Acoustic Impedance Matching of Piezoelectric Transducers to the Air*, *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control* 51 5 **2004,** 624–633.

[2] J. Gosálbez, W.M.D. Wright, W. Jiang, A. Carrión, V. Genovés, I. Bosch, *Airborne non-contact and contact broadband ultrasounds for frequency attenuation profile estimation of cementitious materials*, *Ultrasonics* 88 **2018,** 148–156.

[3] M. Castaings, P. Cawley, *The generation, propagation, and detection of Lamb waves in plates using air-coupled ultrasonic transducers*, *The Journal of the Acoustical Society of America* 100 5 **1996,** 3070–3077.

[4] M.S. Harb, F.G. Yuan, *A rapid, fully non-contact, hybrid system for generating Lamb wave dispersion curves*, *Ultrasonics* 61 **2015,** 62–70.

[5] T. Ghosh, T. Kundu, P. Karpur, *Efficient use of Lamb modes for detecting defects in large plates*, *Ultrasonics* 36 7 **1998,** 791–801.

[6] L. Mažeika, R. Raišutis, A. Maciulevičius, E. Žukauskas, R. Kazys, G. Seniūnas, A. Vladišauskas, *Comparison of several techniques of ultrasonic Lamb waves velocities measurements*, *Ultragarsas* 64 1 **2009,** 11–17.

[7] Z. Su, L. Ye, *Identification of Damage Using Lamb Waves - From Fundamentals to Applications*, *Springer* **2009**.

[8] J.E. Michaels, S.J. Lee, A.J. Croxford, P.D. Wilcox, *Chirp excitation of ultrasonic guided waves*, *Ultrasonics* 53 1 **2013,** 265–270.