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The effects of air gap reflections during air-coupled leaky Lamb wave inspection of thin plates

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ABSTRACT

Air-coupled ultrasonic inspection using leaky Lamb waves offers attractive possibilities for non-contact testing of plate materials and structures. A common method uses an air-coupled pitch–catch configuration, which comprises a transmitter and a receiver positioned at oblique angles to a thin plate. It is well known that the angle of incidence of the ultrasonic bulk wave in the air can be used to preferentially generate specific Lamb wave modes in the plate in a non-contact manner, depending on the plate dimensions and material properties. Multiple reflections of the ultrasonic waves in the air gap between the transmitter and the plate can produce additional delayed waves entering the plate at angles of incidence that are different to those of the original bulk wave source. Similarly, multiple reflections of the leaky Lamb waves in the air gap between the plate and an inclined receiver may then have different angles of incidence and propagation delays when arriving at the receiver and hence the signal analysis may become complex, potentially leading to confusion in the identification of the wave modes. To obtain a better understanding of the generation, propagation and detection of leaky Lamb waves and the effects of reflected waves within the air gaps, a multiphysics model using finite element methods was established. This model facilitated the visualisation of the propagation of the reflected waves between the transducers and the plate, the subsequent generation of additional Lamb wave signals within the plate itself, their leakage into the adjacent air, and the reflections of the leaky waves in the air gap between the plate and receiver. Multiple simulations were performed to evaluate the propagation and reflection of signals produced at different transducer incidence angles. Experimental measurements in air were in good agreement with simulation, which verified that the multiphysics model can provide a convenient and accurate way to interpret the signals in air-coupled ultrasonic inspection using leaky Lamb waves.

1. Introduction

Air-coupled ultrasonic testing provides an attractive couplant-free and non-contact alternative to immersion or contact methods of ultrasonic non-destructive testing. Because of the non-contact nature of transduction and improvements in transducer efficiency, it offers possibilities in many applications such as in-line inspection of materials, management of manufacturing processes, and quality assurance of the products [1–6].

In the cases concerning plate materials and structures, air-coupled ultrasonic testing can be implemented by utilising leaky Lamb waves and a pitch–catch configuration. Relevant investigations have been done in recent years for applications such as materials characterisation, defect detection and tomographic imaging [7–15]. Although most of these previous works were focused on the experimental systems, the availability of simulation models is important for a good understanding of the observed ultrasonic effects [15–17]. Air-coupled inspection is still restricted in use by the energy loss due to the large impedance mismatch at the interface of the solid and the air. Accurate numerical simulation models are required to facilitate the design and improvement of the experimental systems [18].

Castaings and Hosten [13] applied a transfer matrix method to simulate the propagation of leaky, guided modes in stratified plates made of anisotropic, viscoelastic materials. Kazys et al. [14] implemented the 2D numerical simulations of wave interaction with the defect using Wave2000 software. Ramadas et al. [15] used the finite element package ANSYS to model the interaction of air-coupled Lamb waves with delaminations in composite plates. Other work by Hosten and Biateau [16] has looked at finite element modelling for computing the wave propagation in air and

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the dynamic equations of equilibrium inside the plate. Later, Delrue et al. [17] investigated two distinctive methods for ultrasonic imaging of the defect. The first one was based on a ray tracing (shadow) approach, and the second one used a spectral solution implemented with COMSOL. Dobie et al. [18] applied a linear systems approximation to simulate transducer behaviour, and the local interaction simulation approach for wave propagation in the structure. Recently, Vilpisauskas and Kazys [19] introduced an analytical model for an isotropic single layer plate combined with the Impulse Response Method for calculating acoustic pressure.

Although many simulation methods have been investigated, these previous studies have concentrated on modelling the propagation of Lamb waves within the plates of various materials or the behaviour of specific transducer types. However, little attention has been paid to the effects of the reflections in the air gap between the transducers and the plate, which is the focus of the current study.

It is well known that the excitation of specific Lamb wave modes may be achieved by careful selection of the ultrasonic frequency and angle of incidence to match the plate thickness and material. As many air-coupled transducers are quite large and need to be close to the test surface to minimise attenuation in air, the significant amounts of ultrasonic energy reflected from the surface of the plate may also reflect again from the surface of the transducer back towards the plate at a different angle of incidence, producing a delayed secondary Lamb wave source. Similarly, reflections of the leaky Lamb waves in the air gap between the plate and the receiver may produce other instances of the received signal. These additional air–gap reflections may thus produce more complex signals and affect air-coupled inspection signal analysis. Few studies of air-coupled inspection using leaky Lamb waves have used multiphysics modelling, which is a convenient and accurate method to allow detailed study of the wave behaviour, and can include the configuration of the transducers, the propagation of waves in the plate, and any influences due to multiple reflections between the plate and the transducers. A relevant experimental study supported by the multiphysics modelling will thus be useful to reveal the reflection effects and improve air-coupled inspection systems.

In this paper, we investigate multiphysics modelling using a finite element method of a two-sided pitch–catch transducer configuration, where the transmitter and receiver are positioned at oblique angles on opposite sides of a simple test plate. An ultrasonic wave, generated in air by the transmitter, enters the plate, converts to a Lamb wave and leaks energy into the coupling air as it propagates. Depending on the air gap between the transducers and the plate, and the angle of incidence, reflections of the transmitted wave and the leaky Lamb waves may exist in the air gap between the transducers and the plate and produce secondary signals. All the wave behaviour was modelled in COMSOL Multiphysics.

In Section 2 of this paper, details of multiphysics modelling are given. Section 3 covers the results and analysis of the numerical simulations. The relative intensity of the air-coupled Lamb waves excited by different incidence angles is also evaluated. Experimental measurements are observed and discussed in Section 4, and compared with the results from simulation. Conclusions about this method are drawn in Section 5.

2. Multiphysics modelling

The purpose of this study was to concentrate on the reflected signals in the air gaps between the transducers and the plate rather than the behaviour of the transducer or the properties of the plate used, so the choice of transducer type and plate material was rather arbitrary. To reduce unnecessary model complexity, the mechanism of operation of the transducer itself was not included in the simulation, and the plate material was chosen to be a homogenous polymer (polycarbonate) to (i) simplify the signals produced during leaky Lamb wave propagation and (ii) to ensure a relatively low impedance mismatch to aid experimental production and detection of the signals. However, it should be pointed out that the modelling approach used here can be extended to include specific transducer types (piezoelectric, capacitive, etc.) and more complicated plate structures and materials, such as metals and fibre-reinforced composites.

To determine the Lamb wave modes present in the plate, the velocity dispersion curves may be readily derived from the Rayleigh–Lamb frequency equations [20]. It is well known that careful selection of the correct ultrasonic frequency to match the thickness and material of the plate can restrict the modes that will propagate. Fig. 1 shows the theoretical dispersion curves for the first six antisymmetric and symmetric modes in polycarbonate, where it is clear that, for frequency-thickness products of less than 0.5 MHz mm, only the zero-order modes A_0 and S_0 can exist, and that at frequency-thickness products of less than 0.2 MHz mm there is high A_0 dispersion but low S_0 dispersion. Hence, a frequency of 100 kHz in a polycarbonate plate of thickness 1 mm to give a frequency-thickness product of 0.1 MHz mm was chosen to further simplify this preliminary study.

Multiphysics modelling aims to be a closer representation of the reality of the physical test. The implementation here is based on a finite element method using COMSOL Multiphysics, and contains the following steps. First, the geometry of the problem was established. In this study, a two-dimensional representation of the experiment was set up, and subdivided into different subdomains (the air, the plate and the transducers). Then the governing equations were defined for each subdomain. Boundary conditions between different subdomains were specified. In order to get an accurate solution, triangular mesh elements were chosen and then the optimum mesh size of the model was determined (the total number of domain elements was 411,986). Finally, before running the time dependent simulations by using a direct (segregated) solver, an appropriate time step was chosen.

2.1. Geometry

The basic geometry of the model is shown in Fig. 2. The plate used was polycarbonate with the following properties: length

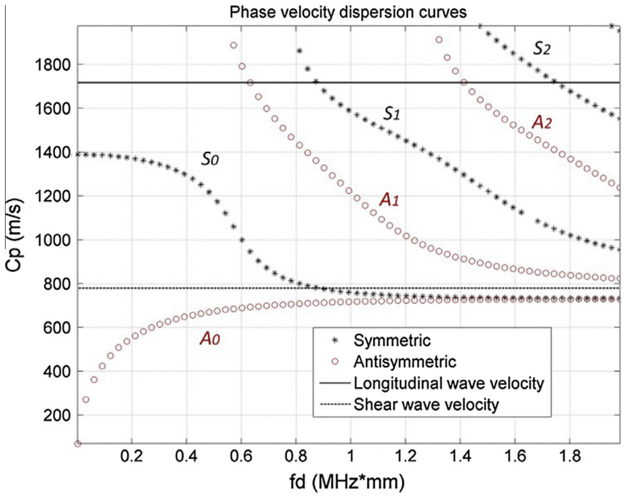

Fig. 1. Phase velocity dispersion curves of the first six symmetric and antisymmetric modes in polycarbonate.

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