



A rapid, fully non-contact, hybrid system for generating Lamb wave dispersion curves



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ARTICLE INFO

Article history:

Received 13 August 2014

Received in revised form 11 March 2015

Accepted 12 March 2015

Available online 30 March 2015

Keywords:

Air-coupled ultrasound

Snell's law

Lamb waves

Dispersion curves

Non-contact nondestructive inspection (NDI)

ABSTRACT

A rapid, fully non-contact, hybrid system which encompasses an air-coupled transducer (ACT) and a laser Doppler vibrometer (LDV) is presented for profiling A_0 Lamb wave dispersion of an isotropic aluminum plate. The ACT generates ultrasonic pressure incident upon the surface of the plate. The pressure waves are partially refracted into the plate. The LDV is employed to measure the out-of-plane velocity of the excited Lamb wave mode at some distances where the Lamb waves are formed in the plate. The influence of the ACT angle of incidence on Lamb wave excitation is investigated and Snell's law is used to directly compute Lamb wave dispersion curves including phase and group velocity dispersion curves in aluminum plates from incident angles found to generate optimal A_0 Lamb wave mode. The measured curves are compared to results obtained from a two-dimensional (2-D) Fast Fourier transform (FFT), Morlet wavelet transform (MWT) and theoretical predictions. It was concluded that the experimental results obtained using Snell's law concept are well in accordance with the theoretical solutions. The high degree of accuracy in the measured data with the theoretical results proved a high sensitivity of the air-coupled and laser ultrasound in characterizing Lamb wave dispersion in plate-like structures. The proposed non-contact hybrid system can effectively characterize the dispersive relation without knowledge of neither the materials characteristics nor the mathematical model.

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1. Introduction

Ultrasonic inspection is becoming a standard non-destructive testing method for providing an in-service evaluation as well as a noninvasive means of probing the interior of a structure. In particular, measurement of the propagation characteristics of Lamb waves allows inspection of plates that are typical components in civil, mechanical, and aerospace industries. In most cases, a coupling medium is required between the transducer and any inspected structure to minimize the acoustic impedance mismatch at the boundary.

Ultrasonic inspection of materials has received considerable attention over the past few decades due to the need for more accurate material inspection techniques. Lamb wave-based technique is one of those testing methods that researchers have been investigating because of obvious advantages that are attractive in the field of non-destructive evaluation. Lamb waves remain confined inside a structure, can propagate over a long distance within,

and are generated in plate-like structures by the repeated reflections at the top and bottom surfaces resulting in a traveling wave guided by the plate surfaces. Thus, those waves can interrogate the entire thickness of a thin structure and carry important information about the material.

Different ultrasonic probes using contact or non-contact techniques have been suggested over the years to enhance generation and detection of Lamb waves in structures. All direct ultrasonic techniques require a method of coupling the transducers to the test specimen to ensure efficient transfer of energy from the transmitter to the structure. Air-coupled ultrasonic inspection emerged as a promising non-contact method for rapid, non-contact inspection and characterization of materials. The main advantages of this technique are the absence of any contact and the ability to generate a relatively pure Lamb wave mode with appropriate incident angle. However, due to the high impedance mismatch between air and solids, the air-coupled ultrasonic inspection nowadays still faces great challenges. Little research work was done in air-coupled ultrasonic testing in the past decade. With recent advancements in highly efficient transducers and ultrasonic transmitting and receiving instruments [1], air-coupled ultrasonic testing is emerging as a powerful technique in non-destructive inspection

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(NDI) [2–5]. Other non-contact methods for ultrasonic waves and Lamb waves in particular, are laser based. Non-contact laser ultrasonic technique using Nd:YAG lasers, Q-switched lasers, interferometer, and Doppler-shift-based laser vibrometers, are being used for the generation and detection of Lamb waves [6,7].

Lamb wave dispersion is the most important feature for waves guided by the plate-like structures. Determination of dispersive curves in materials using non-contact ultrasonic techniques has received much attention recently [8]. Experimental studies have fused multiple non-contact mechanisms to overcome different challenges [9] or to meet conditions needed for non-destructive inspection (NDI) of specific structures.

In order to discern different wave propagating modes in a plate and accurately locate a defect, Pohl and Mook [10] and Pohl et al. [11] experimentally determined the dispersion relation of Lamb waves in carbon-fiber-reinforced polymer (CFRP) using PZTs as actuators and LDV as out-of-plane velocity and displacement scanning sensor. Their results have shown good agreement with the theoretical dispersion curves. Kohler [12] obtained the dispersion curve for Lamb waves in an isotropic aluminum plate using contact actuator (PZT) and non-contact sensor (LDV). He also extracted phase velocity dispersion curves directly from the measured dispersive curves and compared them with numerical results of the A_0 mode. However, when applying the same method to anisotropic glass fiber reinforced polymer (GFRP) plates, inconsistency appeared in the measured dispersion curves when the line length used for generating the dispersion map was changed. Schopfer et al. [13], using the former excitation and reception method by Kohler, also investigated an accurate determination of dispersion curves by applying the matrix pencil method. They were able to extract automatically smooth curves of different symmetric (S) and anti-symmetric (A) Lamb wave modes from experimentally measured data on an aluminum plate and compared to theoretical values.

Using couplant broadband transducers (B1025 and B225 Digital Wave), Samajder et al. [14] measured the dispersion relations of group velocity for S_0 and A_0 modes in an aluminum plate as well as a woven composite plate, which have shown good agreement with theoretical results in a frequency range (100–500 kHz). However, in studying the aluminum honeycomb composite plate, the group velocity dispersion curve for A_0 mode was only discussed. The results matched the values predicted through a numerical model they developed using ABAQUS. Hora and Cervena [15] obtained the dispersion curve for a steel plate by means of Fourier transform using a non-contact laser source of excitation and couplant miniature transducers (VP-1093 Pinducer) to scan the displacements on the plate surface. The experimental results were compared with FEA performed in COMSOL Multiphysics and found a good match for multiple S and A modes for frequencies from 20 kHz to 1 MHz.

Regarding the characterization of Lamb wave dispersion using complete non-contact methods; Ann et al. [16] generated Lamb waves in an aluminum plate using Q-switched Nd:YAG laser with a mask of a linear array of slits to control its wavelength and an ACT as a receiver. Applying wavelet transform to the time-frequency analysis, the dispersion curves of group velocity of S_0 and A_0 modes were detected, which agreed with the theoretical curves. Liu et al. [17] and Castaings et al. [18], using ACTs for excitation and reception of Lamb waves in composite structures obtained the phase velocity dispersion curves for certain modes in a narrow frequency range (160–240 kHz).

This paper presents a fully, non-contact hybrid configuration that comprises air-coupled and laser ultrasound in a new method for characterizing the dispersion curves for A_0 Lamb wave mode. The technique permits measurements of the phase velocity and group velocity dispersion curves for A_0 Lamb wave mode in

isotropic materials rapidly using Snell's law concept. This paper is organized as follows. Section 2 details the theory of Lamb waves in isotropic plates, the use of ACT as ultrasonic transducers, and LDV as ultrasonic receiver. In Section 3, the experimental setup and methods used for characterizing dispersive behavior of A_0 mode of Lamb wave are presented and a comparison is drawn between different experimental results and theoretical predictions for aluminum plate. Finally, in Section 4 some conclusions are drawn.

2. Theory

2.1. Lamb wave generation using air-coupled transducer

Lamb waves are resonant acoustic excitations guided by plate boundaries and composed of coupled bulk longitudinal and transverse waves. For thin plate-like structures, the longitudinal and shear waves experience repeated reflections at the upper and lower surfaces alternately and the resulting disturbance propagation from their mutual interferences is guided by the plate surface and is directed along the plate. Lamb waves can be modeled by imposing traction-free surface boundary conditions on the equations of motion and can effectively describe the wave behavior. However, this approach introduces dispersion phenomenon, i.e. the velocity of propagation of a wave along the plate is a function of frequency, or equivalently, wavelength. Therefore, the dispersion in the case of an elastic medium is simply an interference phenomenon rather than a physical property of the material. The Lamb wave dispersion relation for a linear, homogenous, and isotropic elastic plate, placed in vacuum, bounded by the surfaces $z = \pm h/2$ and of infinite extent in the x and y directions is given by

$$\frac{\omega^4}{c_T^4} = 4k^2 q^2 \left[1 - \frac{p \tan(ph/2 + \gamma)}{q \tan(qh/2 + \gamma)} \right] \quad (1)$$

where $\gamma = 0$ and $\pi/2$ represent S and A Lamb wave modes, respectively,

$$p^2 = \frac{\omega^2}{c_L^2} - k^2 \quad \text{and} \quad q^2 = \frac{\omega^2}{c_T^2} - k^2 \quad (2)$$

k is wavenumber, ω is angular frequency, c_L and c_T are longitudinal and transverse velocities of the bulk material, respectively. Here, the time-harmonic wave motion is in plane strain in the (x, z) plane of the given plate and the guided wave field is represented by a propagating wave in the x direction and a standing wave in the z direction.

However, when using an ACT to generate Lamb waves in a thin plate, the problem is treated as an infinite plate immersed in non-viscous fluid (air). The plate is thus excited by a longitudinal ultrasonic wave traveling in air and striking an interface between air and plate at angle θ as shown in Fig. 1.

The bulk longitudinal wave in air striking the plate is partially reflected and carried away by the air half-space above the plate and partially refracted into the plate. The refracted longitudinal and transverse bulk waves generated in the plate will be reflected by the top and bottom surfaces of the plate and couple together to form Lamb waves. The acoustic energy is no longer trapped inside the plate and it leaks into the surrounding medium and called the *leaky Lamb wave*. Viktorov [19] studied the effect of the presence of two half-spaces, a solid plate immersed in a fluid, on the generated plate waves inside the solid. It was found that the dispersion equations found in this case named *leaky Lamb wave* dispersion equations have one additional root that appears at every frequency for a phase velocity value that is less than the longitudinal bulk wave speed in the surrounding fluid or the shear wave speed in the solid. This wave mode is referred to as Scholte wave, which

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