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Non-contact ultrasonic technique for Lamb wave characterization in composite plates

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ABSTRACT

A fully non-contact single-sided air-coupled and laser ultrasonic non-destructive system based on the generation and detection of Lamb waves is implemented for the characterization of A_0 Lamb wave mode dispersion in a composite plate. An air-coupled transducer (ACT) radiates acoustic pressure on the surface of the composite and generates Lamb waves within the structure. The out-of-plane velocity of the propagating wave is measured using a laser Doppler vibrometer (LDV). In this study, the non-contact automated system focuses on measuring A_0 mode frequency–wavenumber, phase velocity dispersion curves using Snell's law and group velocity dispersion curves using Morlet wavelet transform (MWT) based on time-of-flight along different wave propagation directions. It is theoretically demonstrated that Snell's law represents a direct link between the phase velocity of the generated Lamb wave mode and the coincidence angle of the ACT. Using Snell's law and MWT, the former three dispersion curves of the A_0 mode are easily and promptly generated from a set of measurements obtained from a rapid ACT angle scan experiment. In addition, the phase velocity and group velocity polar characteristic wave curves are also computed to analyze experimentally the angular dependency of Lamb wave propagation. In comparison with the results from the theory, it is confirmed that using the ACT/LDV system and implementing simple Snell's law method is highly sensitive and effective in characterizing the dispersion curves of Lamb waves in composite structures as well as its angular dependency.

1. Introduction

Since the rise of composite structures in the aerospace industry, there has been a great need for inspection and evaluation techniques that could monitor and characterize those complex materials and better understand their behavior during operational life. Wide group of analysis techniques have been developed in the last few decades that were categorized as either destructive or non-destructive. Non-destructive techniques are however more attractive in the aerospace field because they do not cause any damage or permanently alter the part being inspected. Some ultrasonic non-destructive inspection (NDI) techniques are Lamb wave based. Lamb waves are resonant acoustic excitations guided by plate-like structure surfaces and are directed along the plate for long distances. Those elastic waves are very dependent on the geometrical and material properties of the propagating medium and thus analyzing and characterizing the Lamb waves propagating in the medium of interest will also help analyze and understand the medium itself.

Lamb wave and bulk wave NDI techniques have been extensively investigated by different researchers worldwide for the purpose of characterizing and evaluating different materials as well as inspecting different structures for any flaws or damages. Green [1] presents a great review of most non-contact ultrasonic techniques that were available till the beginning of the twenty first century including acoustic emission, holographic imaging, electromagnetic acoustic transducers, laser generation and detection, and air-coupled generation and detection. Green has also shown the ability of some of those techniques in inspecting rail roads and wheels and radiation embrittlement monitoring of metals. However, "*the future of non-destructive testing lies in the ability to efficiently generate waves in structures without contact*" [2]. Remillieux et al. [2] offered a review of conventional non-contact sources of ultrasonic waves and air-coupled transduction in NDI using bulk waves. On the other hand Chimenti [3] provided a review article of air-coupled ultrasonics employed for the characterization and NDI of industrial materials. The construction and function of capacitive

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film transducers is briefly examined by Chimenti including capacitive film transducers, piezoelectric plate and piezocomposite transducers used for the generation and detection of ultrasonic waves. A complete section of his work [3] reports the air-coupled generation and detection of Lamb and plate waves in solids from sound waves in the surrounding air, which was investigated by different researchers for material characterization by measuring material stiffness, investigating through-thickness resonance, reconstructing wave dispersion curves and studying the aging of carbon epoxy-plates, to defect detection based on Lamb waves criteria in adhesively bonded aluminum lap shear joints, plastic reinforced composite plates, composite-aluminum laminates, honeycomb structures, and high pressure composite tanks.

Ultrasonic Lamb waves generated by an acoustic wavefield impacting a small region of a plate's surface remain confined inside the plate, can propagate over a long distance within, and are produced by the repeated reflections at the top and bottom surfaces resulting in a traveling wave guided by the plate surfaces. While the guided waves travels along the plate, a small part of the wave energy disturbs the air causing the acoustic field radiated in the air. This will allow the detection of Lamb waves using air coupled transducers. Those guided waves can interrogate the entire thickness of a thin structure and carry important information about the material. As is known that due to the wave interference between surfaces Lamb waves propagating along a plate made of a homogeneous, isotropic material shows dispersive effects; that is, the velocities both depend on the mode type, on the mode order, and on the frequency. In plates made of composite material these velocities become dependent on the propagation direction, as a consequence of the distribution of the laminate layup. The dispersion relations for an elastic isotropic plate was first derived by Lamb [4]. In anisotropic composite plates there are two theoretical approaches to investigate Lamb waves being 3-D elasticity theory and approximation solutions by plate theories. Using the following approaches, investigators have obtained the phase velocity dispersion relation and dispersion curves in composite lamina [5] and laminates [6] as well as group velocity dispersion relation and dispersion curves [7].

Meanwhile, dispersion curves for isotropic and anisotropic plates have been investigated experimentally using different NDI techniques. Ann et al. [8] 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 group velocity dispersion curves of S_0 and A_0 modes were detected, which were in agreement with the theoretical curves. Liu et al. [9] and Castaings et al. [10], using ACTs for excitation and reception of Lamb waves in composite structures obtained the phase velocity dispersion curves for certain modes in a 160–240 kHz frequency range. Draudviliene and Mazeika [11] have applied a spectrum decomposition technique using finite element analysis (FEA) model for measuring group velocity dispersion curves in carbon fiber reinforced plastic (CFRP) composite plate for A_0 and S_0 Lamb wave modes in the frequency range from 218 up to 584 kHz and from 280 to 477 kHz, respectively. Garcia-Rodrigues et al. [12] experimentally demonstrated the viability of Lamb wave generation and detection in metallic plates using ultrasonic air-coupled concave array transducers and the measurement of A_0 mode phase velocity dispersion curve using Snell's law and group velocity dispersion curve using time-of-flight technique, and also compared with theoretical values.

This work presents a fully, non-contact hybrid system that employs air-coupled and laser ultrasound in a methodology for characterizing the dispersion curves for A_0 Lamb wave mode in a composite plate. The technique permits measurements of the frequency–wavenumber, phase velocity and group velocity dispersion curves for A_0 Lamb wave mode in an anisotropic material rapidly using Snell's law and time-of-flight concept. This paper is organized as follows. Section 2 details the theory of Lamb wave dispersion and characteristic wave curves. In Section 3, the hybrid NDI system setup and methods used for characterizing dispersive behavior of A_0 mode of Lamb wave are presented. The experimental results and theoretical predictions for the composite plate are discussed in Section 4. Finally, in Section 4 some conclusions are drawn.

2. Lamb wave dispersion

Lamb waves can be modeled by imposing traction-free surface boundary conditions on the equations of motion and can effectively describe the wave behavior. This approach introduces dispersion phenomenon, i.e. the velocity of propagation of a wave along the plate is a function of frequency. 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

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

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

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

k is wavenumber, ω is angular frequency, c_L and c_T are longitudinal and transverse velocities inside the plate, 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, for waves propagating in multi-layered composites, the wave interactions depend upon the constituent properties, geometry, direction of propagation, and frequency. In a previous work done by the corresponding author, Wang and Yuan [7] the exact dispersion relations of symmetric and anti-symmetric wave modes in a lamina are formulated from 3-D elasticity theory. Then the formulation was extended to a composite laminate with an arbitrary stacking sequence. In a single lamina, a closed-form dispersion relation relating ω and $\mathbf{k}$ in a fixed direction of propagation was derived and formulated by Wang and Yuan as follows,

$$\begin{aligned} &H_{11}(H_{22}H_{32} - H_{23}H_{32})\tan(\xi_1 h/2 + \varphi) \\ &\quad + H_{12}(H_{23}H_{31} - H_{21}H_{33})\tan(\xi_2 h/2 + \varphi) \\ &\quad + H_{13}(H_{21}H_{32} - H_{22}H_{32})\tan(\xi_3 h/2 + \varphi) = 0 \end{aligned} \tag{3}$$

where $\varphi = 0$ and $\pi/2$ represent anti-symmetric and symmetric Lamb wave modes, respectively. h is the thickness of the single lamina. ξ_j $(j = 1,2,3)$ is an unknown variable and H_{ij} $(i = 1,2,3)$ are

$$\begin{aligned} H_{1j} &= C_{13}k_x + C_{23}k_yR_j + C_{33}\xi_jS_j + C_{36}(k_y + k_xR_j) \\ H_{2j} &= C_{44}(\xi_jR_j + k_yS_j) + C_{45}(\xi_j + k_xS_j) \\ H_{3j} &= C_{45}(\xi_jR_j + k_yS_j) + C_{55}(\xi_j + k_xS_j) \end{aligned} \tag{4}$$

C_{ij} $(i,j = 1,\ldots,6)$ being the elements of the stiffness matrix, k_x and k_y are $(k\cos\phi)$ and $(k\sin\phi)$, respectively, where ϕ is the direction of wave propagation in the composite. R_j and S_j are real-valued coefficient related to the displacement coefficients, elements of stiffness matrix, wavenumbers, frequency and material density. For detailed derivation of the following dispersion relation and all variables, the reader is referred to the derivations in Section 2 of Wang and Yuan's article on the formulation of Lamb waves in composites.