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Ultrasound imaging of immersed plates using high-order Lamb modes at their low attenuation frequency bands

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ABSTRACT

This paper focuses on the use of a Lamb wave-based methodology for ultrasound imaging of immersed plate structures. In these cases Lamb waves can be strongly attenuated due to leaky waves and viscous losses in the liquid, but there are low attenuation frequency bands that may be used for NDT applications. Experimental measurements were conducted to validate the existence of these low attenuation frequency bands, which were also theoretically predicted for some propagation modes, between the frequencies-thickness products of 0.5 MHz mm and 9.0 MHz mm. Using a 5 MHz linear-array and phased-array techniques, A1 and S1 modes are used to obtain images of an immersed aluminum plate with artificial defects. The signals are post-processed in order to select the desired propagation mode and to obtain an image with dynamic focusing in reception. While the A1 mode is strongly attenuated, the S1 mode, at 3.4 MHz mm, can be used to detect and localize defects in the immersed plate.

1. Introduction

Lamb waves are appealing for non-destructive testing (NDT) of plate and pipe structures, and structural health monitoring (SHM) in the aerospace and civil engineering industries, due to their characteristic to propagate relatively long distances (in dry conditions), allowing inspection of a significant large area without having to move the transducers [1–3]. Lamb wave techniques can be used to detect and monitor corrosion [4,5], cracks [6], and/or delaminations [7] in fiber and reinforced carbon composite materials. Other applications include oil, water and food pipes [8]; off-shore immersed structures [9]; or medical diagnostics [10]. Different modes can propagate simultaneously, each one with a particular frequency-velocity relationship, given by the dispersion curves. The possibility of multimode propagation provides more information in a measurement process when compared to ultrasonic systems based on monomode longitudinal or shear waves. On the other hand, the attenuation and dispersion characteristics must be taken into account for correct interpretation of results, since they may interfere with each other.

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Most NDT applications with Lamb waves are focused on air-coupled or dry structures. For example, Zhu and Rose [11] study the generation of Lamb waves by using periodic linear arrays, in contact with a dry plate. When one or both sides of a plate are in contact with a liquid, there is an important mechanical coupling at the solid-liquid interfaces and strong attenuation can occur due to leaky waves and viscous losses in the fluid [12,13]. This attenuation significantly reduces the propagation range of the waves and limits its practical application in NDT.

When dealing with leaky waves, analytical approaches appropriate for gas-coupled plates and pipes are no longer valid, because fluid-solid coupling must be considered and, as a consequence, multidimensional systems arise. Different methods and numerical tools have been described in the literature to deal with this problem: the transfer-matrix method and the global-matrix method [14,15] the last being used in the software DISPERSE [16]; the semi-analytical finite element (SAFE) method [17–19], based on the coupling of harmonic function to a finite element method; the distributed point source method (DPSM) [20], based on the interface discretization to solve the coupling equations. The effect of a viscous loading layer on the attenuation of Lamb modes and shear horizontal modes were studied by Simoneti [21].

In spite of the acoustic coupling between the solid structure and the fluid, low attenuation frequency regions can be found for some guided modes. The attenuation drops when the out-of-plane oscillations at the solid-fluid interfaces tend to zero. In the case of cylindrical structures, these bands of minimal attenuation were investigated by Pavlakovic et al. [22], and can also be appreciated in the attenuation vs. frequency plots of many other works [23–25]. In plates, such bands have been studied, for example, by Zernov et al. [9] and Sharma and Mukherjee [26], although these attenuation plots are not shown as often as the sound velocity dispersion curves.

A variety of emitter/receiver configurations and propagation modes are reported in the literature when considering the inspection of immersed structures. Leinov et al. [25] analyzed the propagation through buried pipes to detect corrosion using a pulse-echo configuration, where the wave was excited by a ring of transducers around the pipes; Djili [27] analyzed immersed copper tubes using a similar pulse-echo arrangement, but exciting the tube with a single transducer; Mijarez et al. [28] used a pitch-catch configuration with a pair of transducers for SHM of sub-sea tubular structures. The Time-Reversal technique [29] has also been used in the detection of cracks in a hollow cylinder immersed in water [30].

Chen et al. [5] used the A0 mode for analyzing liquid layers in contact with the plate using two immersion transducers operating in pitch-catch mode. Rizzo et al. [31], used a laser to excite the A0, S0 and quasi-Scholte modes and two immersion transducers were used for reception. In [32], a similar technique was used to detect Leaky Lamb waves by using an array of ultrasonic receivers. Immersed fiber reinforced carbon plates were analyzed by Chimenti and Martin [33] using leaky waves, but performing C-scans with a pair of immersion transducers. Recently, Sharma and Mukherjee [26] analyzed the mode propagation and defect detection in immersed plates exciting S0, A1 and S1 modes with a pair of immersed transducers. Zhang et al. [34] used a single transducer in a pulse-echo configuration with varying angle to detect cracks in immersed plates by means of lower order Lamb waves. Propagation of guided waves in plate structures was used to characterize fluids in contact with them [35], as well as in pipes [23].

This work is motivated by the industrial interest on NDT tools for the analysis of immersed structures. A linear array can be directly coupled to the structure under inspection, or by using wedges of appropriate geometries to excite the desired propagation modes. The use of Lamb wave arrays reduce the scanning requirements, as fast images of a given area can be obtained by placing the array at a fixed position. Special attention is given to mode selection and bandwidth limitation imposed by the low attenuation bands, as well as by employing an experimental inspection system with no moving parts. Such moving parts would not be practical in some applications, for example those involving difficult access to the structure. Depending on the desired range, the array can be moved, but even so the mechanical scanning requirements would be reduced in comparison with B- or C-Scan techniques, for example, which have been described in several works.

The underlying theory and mathematical models involving the propagation of Lamb waves in immersed plates are described in Section 2, along with experimental verifications of the low attenuation frequency bands. The model and associated theoretical curves are employed in Section 3 to properly select frequency bands and modes to propagate waves in immersed plates for NDT purposes. Low and high attenuation Lamb modes are excited by a linear array coupled to an aluminum plate with artificial defects. After signal acquisition and post-processing, an image of the structure is obtained for both dry and immersed conditions, showing the application of the proposed methodology. To the authors' knowledge, it is the first time that phased array technology combined with Lamb waves is used for imaging defects in immersed plate structures. Practical issues related to the use of this technology to NDT are discussed in Section 4.

2. Dispersion and attenuation curves in immersed plates

2.1. Theoretical description

Consider a $2d$-thick isotropic solid plate immersed in a fluid, as illustrated in Fig. 1. The structure is unlimited along the x and y axes and wave propagation occurs in the x direction. A geometrical discontinuity (plate-fluid) occurs only in the z direction.

For fluid modeling, the equation of motion for a Newtonian viscoelastic fluid can be described by the Navier-Stokes equation [36], where shear and bulk viscosity coefficients were considered in the model. The shear viscosity of the liquid is