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CLASSICAL PROBLEMS OF LINEAR ACOUSTICS AND WAVE THEORY

Ultrasonic High Frequency Lamb Waves for Evaluation of Plate Structures[1]

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Abstract—The potentials of high frequency Lamb wave modes are investigated in the inspection of plate-like structures. The wave propagation characteristics of higher order wave modes and the corresponding sensitivity and detectability are studied. Finite element simulations are carried out using infinite elements to model the ultrasonic wedge transducer and the inspection system. Experimental pulse–echo measurements are conducted to verify the influence of different modes characteristics predicted from the finite element simulations. The experimental measurements show a good agreement with the obtained numerical results for the fundamental modes, S_0 and A_0, and the higher order modes, S_1 and A_1, at 4 MHz mm of frequency–thickness.

Keywords: ultrasonic Lamb waves, high frequency modes, finite element, infinite element

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1. INTRODUCTION

Ultrasonic Lamb wave inspection of plate structures generally involves propagating a selected wave mode and measuring the time-of-flight response from an inhomogeneity. Large areas of plate structures can be inspected and monitored from a single, remote access point using Lamb waves. These are often used in a low frequency–thickness range below the cut-off frequency of the higher wave modes to simplify data interpretation [1]. In long range inspection systems, a systematic procedure for mode selection and transducer design should be used based on the properties of the structures under inspection and the inspection system [1]. However, the resulting large wavelengths limit the inspection sensitivity. The basic concepts and some applications of ultrasonic Lamb wave inspection have been reviewed by Rose [2] for isotropic plates and by Kuznetsov [3] for anisotropic plates.

The application of the high frequency Lamb wave modes (higher frequency–thickness range) has more recently been investigated for nondestructive evaluation. In the higher frequency–thickness ranges the sensitivity improvement is predicted for the detection and localization of small surface defects [4]. Terrien et al. [5] used a numerical hybrid method for corrosion detection using the S_0 Lamb wave mode at 5 MHz mm of frequency–thickness. High-frequency longitudinal Lamb modes were employed by Greve et al. [6] for plate inspection. The resulting wavelengths are comparable to the conventional ultrasonic testing to improve the sensitivity for small defects detection [6]. Masserey et al. [4] detected and monitored fatigue crack growth experimentally using high frequency Lamb modes. Fundamental S_0 and A_0 modes were excited above the cut-off frequencies of higher modes for monitoring fatigue crack growth in a multilayered plate structure by Chan et al. [7]. Employing a 90°-angle beam wedge transducer for experiments and FE-simulations, Masserey et al. [8] used the superposition of high frequency S_0 and A_0 Lamb modes to detect a hidden small notch in an aluminum multilayered structured. The experimental estimates and analyzing the sources of errors were performed for the distances necessary for the formation of the symmetric zero modes of the Lamb wave in thin strips at frequencies of 1.8 and 2.5 MHz by Chuprin [9]. Using the finite element method, Hong-xing et al. [10] studied the laser-generated lower order Lamb waves in periodic thin plates within the frequency bandwidth up to 2 MHz. In this paper, the potentials of Lamb wave modes within high frequency ranges are investigated in a plate structure. Finite element simulations are carried out using contact wedge transducer excitation, and the numerical results are compared to the experimental measurements. The wave propagation characteristics of high frequency modes and the corresponding sensitivity and detectability are studied. The measurement errors of different wave modes from a stand-

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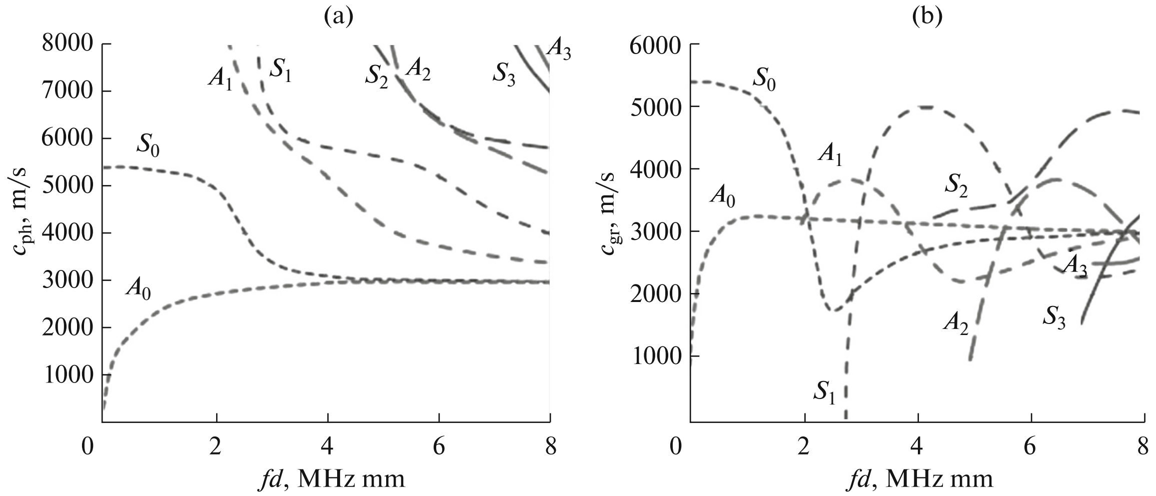

Fig. 1. Dispersion curves for a 2 mm thick steel plate: (a) phase velocity, (b) group velocity.

off distance are demonstrated using pulse–echo measurements.

2. ULTRASONIC LAMB WAVE MODES

Two types of ultrasonic waves can propagate in an elastic plate, Lamb wave and shear horizontal wave. The Lamb wave solution and the corresponding frequency equation are derived assuming plane-strain conditions. The well-known Rayleigh–Lamb frequency equation is written as [11]:

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2pq}{\left(q^2-k^2\right)^2} \quad \text{for symmetric modes,} \tag{1}$$

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{\left(q^2-k^2\right)^2}{4k^2pq} \tag{2}$$

for antisymmetric modes,

where

$$q^2 = \left(\frac{\omega}{c_T}\right)^2 - k^2, \quad p^2 = \left(\frac{\omega}{c_L}\right)^2 - k^2. \tag{3}$$

The wave number k is numerically equal to ω/c_{ph}, where c_{ph} is the phase velocity, ω is the circular frequency and c_L and c_T are longitudinal and transverse wave velocity, respectively. The group velocity can also be expressed as

$$c_{gr} = c_{ph} + k\frac{dc_p}{dk}. \tag{4}$$

Equations (1), (2) and (4) can be considered as relating the phase velocity, c_{ph}, or group velocity, c_{gr}, to the frequency, f, or frequency–thickness parameter, resulting in the dispersion curves [11]. The phase velocity and group velocity for a steel plate are shown in Fig. 1. It is observed that for a given frequency–thickness, multiple symmetric and antisymmetric modes with different phase and group velocities are propagated in the plate. Increasing the frequency–thickness parameter increases the likelihood of realization of higher order modes. In an ultrasonic Lamb wave inspection, either a pulse–echo or pitch–catch configuration, it is necessary to operate using a single mode over a definite frequency range. Many factors affect the mode and frequency selection, including dispersion, sensitivity, detectability, attenuation etc., that are classified into two categories, properties of the plate-like structure and the inspection system [1].

3. NUMERICAL SIMULATIONS

To investigate the wave propagation characteristics of high frequency modes, the finite element method (FEM) is employed. The wave propagation in a plate-like structure is simulated based on an explicit dynamic formulation, using the commercially available software ABAQUS/Explicit. The numerical investigations are performed with a two-dimensional model assuming plane-strain wave propagation. For this purpose, a structured mesh is generated using 4-node plane-strain, CPE4R elements. Temporal and spatial resolution of the finite element model is important to the convergence of the results. To avoid numerical instability, ABAQUS/Explicit recommends a stability limit for the integration time step as [12]

$$\Delta t \le L_{\min}/cL, \tag{5}$$

where $L_{\min}$ is the smallest dimension of the elements. The maximum frequency of the dynamic problem, $f_{\max}$, limits both the integration time step and the ele-