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CLASSICAL PROBLEMS
OF LINEAR ACOUSTICS AND WAVE THEORY

Asymmetric Propagation of the First Order Antisymmetric Lamb Wave in a Tapered Plate Based on Time Domain Analysis[1]

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Abstract—The asymmetric propagation of the first order antisymmetric (A_1) Lamb wave in a tapered plate respectively carved with sharp bottom corner and round bottom corner is theoretically investigated. Through numerical simulation of A_1 Lamb wave in time domain, we find that when the thickness of the waveguide abruptly decreases to below the cut-off thickness, about half of the A_1 mode is converted into the fundamental symmetrical S_0 and antisymmetrical A_0 modes to pass through the defected region. Furthermore, the transmitted modes A_0 and S_0 are completely apart from each other and can be quantitatively evaluated. Conversely, when the thickness change is very smooth, most of the energy of A_1 Lamb wave is reflected back. It is the unique mode conversion behavior that leads to great transmission difference value of A_1 Lamb wave along the opposite directions. Finally, the influence of geometrical parameters on the transmission coefficient is also studied. The higher efficiency and proper working frequency range can be realized by adjusting the slope angle θ, height h_1 and h_2. The simple asymmetric systems will be potentially significant in applications of ultrasound diagnosis and therapy.

Keywords: asymmetric transmission, first order antisymmetric Lamb wave, mode conversion, time domain analysis

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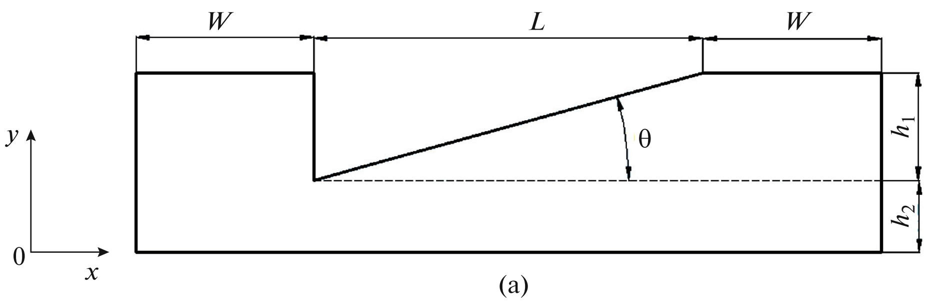
1. INTRODUCTION

Inspired by the extensive applications of diode (such as rectifier, switch, or trigger in the circuit), the asymmetric acoustic transmission has become a hot research topic in recent years. The realization of one-way transmission of acoustic waves requires either broken time-reversal symmetry or broken spatial inversion symmetry. Due to the low energy conversion efficiency and the difficulty in fabrication for the broken time-reversal symmetry case, considerable effort has been dedicated to breaking the spatial inversion symmetry. Li et al. [1] have theoretically and experimentally investigated "asymmetric acoustic wave propagation" by breaking the spatial inversion symmetry in the composite square rods structure. With the related structure, asymmetric acoustic wave propagation has been realized by asymmetric acoustic grating [2, 3], acoustic grating composed of asymmetric units [4–6], and asymmetric modulation of phononic crystals [7, 8]. Previous numerical works are based on the excitation of the bulk acoustic waves and the fundamental symmetric and antisymmetric Lamb modes (S_0 and A_0) [9–13]. However, acoustic rectification systems in the above researches are seldom concerned about high-order Lamb waves, which have been widely applied to nondestructive evaluation and ultrasonic devices due to higher sensitivity to plate thickness, such as the fatigue evaluation of plate [14], ultrasonic sensors [15], or oscillators [16].

In this paper, we have studied the propagation of the first order antisymmetric (A_1) Lamb wave in a tapered plate, which can obtain the acoustic unidirectional transmission. Throughout this paper, the eigenmode matching theory (EMMT) method is adopted to gain the transmission spectra, and the finite element (FE) method (COMSOL MULTIPHYSICS) is employed to confirm the results. By numerical simulation and analysis in time domain, we study the physical mechanism of the unidirectional transmission of A_1 Lamb wave incident from two opposite directions. When the thickness of the waveguide abruptly decreases to below the cut-off thickness, the corresponding transmitted modes S_0 and A_0 are also quantitatively evaluated. Further, the influence of geometrical parameters on the transmission coefficient is also discussed, which is fairly helpful to design highly efficient ultrasonic devices.

[1] The article is published in the original.



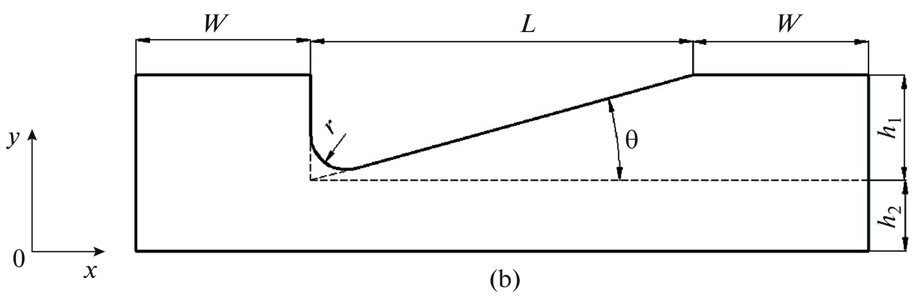


Fig. 1. Schematic representations of the homogeneous tapered plates: (a) with a sharp bottom corner and (b) with a round bottom corner.

2. MODEL AND METHODS OF CALCULATION

The physical models, as schematically illustrated in Figs. 1a and 1b, consist of the homogeneous plate engraved with tapered structure, which is surrounded by vacuum. The geometric parameters of the two samples are $W = 5$ mm, $h_1 = 3$ mm, $h_2 = 2$ mm, $\theta = 15°$, and $L = h_1/\tan(\theta)$. The material used in the calculations is steel, whose parameters are $\rho = 7800$ kg/m^3, $E = 205$ GPa, $\nu = 0.3$, $c_l = 5950$ m/s and $c_t = 3180$ m/s, where the symbols ρ, E, c_l, c_t represent mass density, elastic modulus, Poisson's ratio, longitudinal wave velocity, and transverse wave velocity, respectively. Different from the model with a sharp bottom corner shown in Fig. 1a, the other model with a round bottom corner is described in Fig. 1b and the circle radius is 0.8 mm. We consider both samples are finite in the x- and y-direction and infinite in z-direction. And an imaginary system can be constructed by stacking the considered system and vacuum layers along the y-direction periodically. Owing to the high calculation efficiency and convergence, the transmission spectra can be obtained by the EMMT method, which details are given elsewhere [17]. The high-order Lamb wave (A_1 mode) is taken as the incident wave in the transmission coefficient calculation and all calculations satisfy the energy flow conservation $T + R = 1$.

In order to verify the results calculated by the EMMT method, the FE method in time domain is also employed. In our simulation and analysis, the pure A_1 Lamb mode can be gained by loading an excitation displacement in the incident end of the plate, whose displacements are given by relations [18]

$$u_x = Aiq\left(\frac{\sin(qy)}{\sin(qh)} - \frac{2k^2\sin(py)}{(k^2-q^2)\sin(ph)}\right)e^{i(kx-\omega t)}, \quad (1)$$

$$u_y = Ak\left(\frac{\cos(qy)}{\sin(qh)} + \frac{2pq\cos(py)}{(k^2-q^2)\sin(ph)}\right)e^{i(kx-\omega t)}, \quad (2)$$

where $q^2 = \omega^2/c_t^2 - k^2$, $p^2 = \omega^2/c_l^2 - k^2$, $k = \omega/c_p$, k is wavenumber, ω is angular frequency, A is constant ($A = 10^{-5}$ m^2), and h is half-thickness of the plate. It is noted that c_p is the phase velocity of A_1 mode, which can be gained from the phase velocity dispersion curves as shown in Fig. 3a. We can see from the Fig. 3a that the value of c_p is 8121 m/s when giving the excitation frequency of 0.4351 MHz and the plate thickness of 5 mm. Usually, the signal will be not periodic within the temporal and spatial sampling windows, and leakage will occur. Therefore, the Hanning window function is employed to avoid the leakage and get a smooth pulse signal, which is described by

$$f(t) = \frac{1}{2}\left[1-\cos(\omega_0 t/N_c)\right], \; t \in [0, N_c/f_0], \quad (3)$$

where f_0 is excitation frequency, N_c is number of cycles ($N_c = 5$), and ω_0 is the excitation angular frequency [19]. Once a frequency is chosen to be excitation frequency, the corresponding phase velocity can be obtained from the Lamb wave dispersion relations [20,