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Numerical investigation of the excitability of zero group velocity Lamb waves

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Abstract

We numerically investigate the excitability of Zero Group Velocity modes by pulsed laser excitation. Within the numerical simulations we solved the coupled heat and wave equations using the finite difference method and studied the influence of the ratio of the laser spot diameter (D) to plate thickness (h). Transient and steady-state responses were obtained in the time domain. In the simulations we have studied the transient response of tungsten plates with Fourier-transforms. The obtained numerical results show how the ratio D/h influences the coupling of the excitation into the Zero Group Velocity modes.

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Keywords: ZGV Lamb wave, negative group velocity, backward propagation

1. Introduction

Within the dispersion relations of plates, the slope of the dispersion curve, and hence the group velocity of the wave mode, becomes zero tt Zero Group Velocity (ZGV) points [Prada et al. (2005b)]. Hence, energy cannot be carried away from a given excitation source, leading to a strong and easily detectable resonance of the plate. This behavior is observed for the second symmetric branch of the Lamb wave dispersion curve [Tassoulas and Akylas (1984)] but also some other modes of the Lamb wave spectrum exhibit ZGV points.

Laser based ultrasonics has been found to be well-suited for experimental studies of Lamb wave propagation [Prada et al. (2005b); Clorennec et al. (2006); Veres et al. (2014); Clorennec et al. (2006)]. Experiments on metallic plates with a pulsed laser source have shown that the S_1 ZGV mode oscillates particularly long and dominates the plate response. Exceptional sensitivity to thickness has been demonstrated and by taking advantage of the slowly decaying ZGV resonance, also the thickness of a thin deposited layer on a thick plate has been evaluated [Ces et al. (2011)].

In previous works [Balogun et al. (2007); Prada et al. (2005a)] a numerical technique, based on an integral-transform method, was pursued to investigate the optimal optical spot size for exciting the S_1ZGV resonance. The

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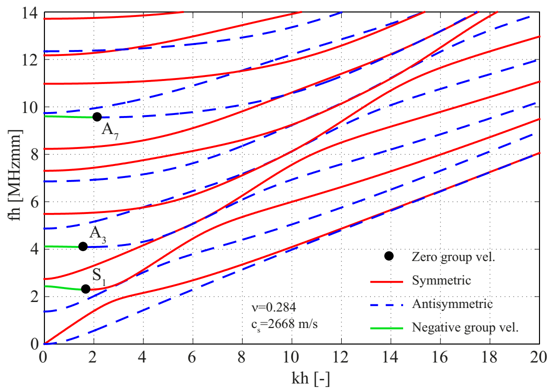

Fig. 1. Dispersion relation of Lamb waves with $\nu = 0.284$. ZGV points are visible for the S_1, A_3 and A_7 modes.

optimal diameter was found as approximately the half the wavelength of the ZGV mode. In this paper, we perform time domain finite difference simulations of the thermoelastic generation of ultrasound.

2. Excitability of ZGV Lamb waves

2.1. ZGV modes in Lamb waves

A typical Lamb wave spectrum determined by symmetric and antisymmetric modes is plotted on Fig. 1. For the corresponding Poisson's ratio of $\nu = 0.284$ three ZGV points exist in the presented range: in the S_1, A_3 and A_7 mode.

2.2. Numerical simulation of the excitability of ZGV-modes

Time and frequency domain FEM simulations are powerful means to investigate wave propagation problems [Veres and Berer (2012); Veres et al. (2012)]. We simulate the excitation of elastic waves by a thermoelastic source, similarly to the time-domain finite-difference scheme presented in [Veres et al. (2013); Veres (2010)]. We assume isotropic thermophysical properties with density ρ and bulk wave velocities (c_l, c_s) given as $\rho = 193000$ kgm^{-3}, $c_l = 4858$ ms^{-1} and $c_s = 2668$ ms^{-1}. The thermal properties are given as $\alpha = 4.5 \times 10^{-6}$ K^{-1}, $K = 173$ W(mK)$^{-1}$, $c_v = 134$ J(kgK)$^{-1}$ [Every et al. (2013)]. The thickness and the length of the plate are 50 μm and 5.6 mm, respectively, corresponding to a discretisation of 6559×119 cells, or 1.56×10^6 DOF, with cell dimensions of $\Delta r = 0.85$ μm and $\Delta z = 0.42$ μm. The simulations were carried out in the time domain with a duration of 2 μs.

The generation of ultrasound by laser-irradiation is described by the coupled heat conduction and wave equations. First, the heat equation must be solved which is given in polar coordinates (r, z) as:

$$-\frac{1}{r}\frac{\partial}{\partial r}(rq_r) - \frac{\partial q_z}{\partial z} = \rho c_v \dot{T} - q_0, \qquad q_r = -K\frac{\partial q_r}{\partial r}, \qquad q_z = -K\frac{\partial q_z}{\partial z}, \tag{1}$$

where T denotes the temperatures, K the thermal conductivity, c_v the specific heat of the material at constant deformation, q_0 the external surface heat flux, ρ the density, and q_r, q_z are the heat flux densities. The presented formalism with first order differential equations allows an efficient, staggered-grid solution using finite differences [Every et al. (2013); Veres et al. (2013)]. The wave equations in polar coordinates are given as:

$$\rho\ddot{u}_r = \frac{\partial\sigma_{rr}}{\partial r} + \frac{\partial\sigma_{rz}}{\partial z} + \frac{\sigma_{rr} - \sigma_{\theta\theta}}{r}, \qquad \rho\ddot{u}_z = \frac{\partial\sigma_{rz}}{\partial z} + \frac{\partial\sigma_{zz}}{\partial z} + \frac{\sigma_{rz}}{r}, \tag{2}$$