Laser-based ultrasonic generation and detection of zero-group velocity Lamb waves in thin plates

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A novel laser-based ultrasonic technique for the inspection of thin plates and membranes is presented, in which a modulated continuous-wave laser source is used to excite narrow bandwidth Lamb waves. The dominant feature in the acoustic spectrum is a sharp resonance peak that occurs at the minimum frequency of the first-order symmetric Lamb mode, where the group velocity of the Lamb wave goes to zero while the phase velocity remains finite. Experimental results with the laser source and receiver on epicenter demonstrate that the zero-group velocity resonance generated with a low-power modulated excitation source can be detected using a Michelson interferometer coupled to a lock-in amplifier. This resonance peak is sensitive to the thickness and mechanical properties of plates and may be suitable, for example, for the measurement and mapping of nanoscale thickness variations. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2128063]

Quantitative nondestructive evaluation of thin plates and membranes through the analysis of guided Lamb wave propagation in these structures is well established. Laser-based ultrasonic inspection of thin plates has been studied both theoretically and experimentally.[1–5] A pulsed laser source can be used to generate broadband Lamb waves that are detected, after some propagation distance, with an optical probe. The phase velocity dispersion characteristics are subsequently used to determine the physical or mechanical properties of the plate. Narrow bandwidth techniques have also been developed to generate Lamb waves at a single phase velocity, such as the phase velocity scanning technique,[6] or at a single wavelength, as in impulsive stimulate thermal scattering.[7,8] In this letter, we explore an alternative approach to laser-based characterization of thin plates and membranes. We have observed that a high-quality factor (Q) resonance peak with a large out-of-plane displacement component can be excited in thin plates using a low-power amplitude-modulated laser source and detected using an optical interferometer. This resonance peak is sensitive to the thickness and mechanical properties of the plate, and may be suitable for the measurement of nanometer-scale thickness variations in plates.

Lamb waves exhibit interesting behavior at specific frequencies where the group velocity vanishes while the phase velocity remains finite. This phenomenon is observed in homogeneous isotropic materials at the minimum frequency of the first symmetric s_1 mode, and can also be observed for higher modes. Figure 1 shows a phase velocity dispersion curve over a limited frequency range in a material with a Poisson's ratio of 0.355. The s_1 mode, above the minimum frequency f_{s1}, appears to be double valued over a small frequency range. However, as discussed in detail in the literature,[9,10] the upper portion of this curve, above the zero-group velocity (ZGV) point, is classified as part of the s_2 mode and is labeled s_{2b} in Fig. 1, where the b stands for "backward wave" and indicates that the phase velocity and group velocity of this mode are of opposite sign. The s_1 mode, on the other hand, starts at the ZGV point and continues out to higher frequencies. Just above the minimum frequency f_{s1}, the s_1 and s_{2b} modes interfere, having very close phase velocities and near ZGV. Due to the fact that both modes have ZGV at the ZGV point, energy coupled into the plate is not transmitted away from the excitation point and a resonance, sometimes referred to as a thickness quasi-resonance,[11] occurs. The frequency of this resonance is slightly lower (roughly 2% to 10%) than the well-known longitudinal or shear thickness resonance associated with the s_{2b} cut-off frequency. While the topic of backward wave propagation, and its effect on the scattering of sound by shells, has been discussed extensively in the literature,[9,10,12] it is only recently that the ZGV resonance has been utilized for materials characterization applications. Holland and Chimenti[13] observed strong transmission through a plate using air-coupled ultrasound transducers at the minimum frequency of the s_1 mode, and went on to use this resonance for imaging thickness variations in millimeter scale plates. We have found that a thermoelastic laser excitation source couples very efficiently into the ZGV resonance, leading to a large out-of-plane displacement that is measured using an optical interferometer. This has some advantages over the air-coupled approach in that it is not limited in frequency range due to sound attenuation in the air, and is thus suitable for the inspection of micron scale thin plates and membranes.

The experimental setup is shown in Fig. 2. The laser ultrasonic system has two paths that lead to the sample surface through a single microscope objective. In the first path, the detection laser light enters the system though a single-mode optical fiber, is collimated, and directed to the sample surface. The reflected light is collected from the sample and sent to a stabilized Michelson interferometer where the acoustic signal of interest is detected. The detection laser is a 200 mW frequency-doubled Nd:YAG, and it is attenuated

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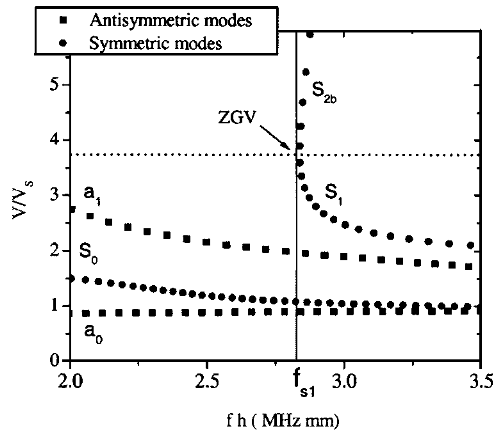

FIG. 1. Phase velocity dispersion curve for a material with a Poisson's ratio of 0.355. *Vs* is the shear velocity of the plate, f is the Lamb wave frequency, h is the plate thickness, and ZGV is the location of the s_1 ZGV resonance occurring at the frequency f_{s1}.

such that approximately 3 mW is incident on the photodiode. The generation laser is a 1550 nm electroabsorption modulated distributed feedback diode laser with a 1 W erbium-doped fiber amplifier (EDFA). In the second path, the light from the EDFA is collimated, directed to a mirror on a gimbal mount, sent though a relay lens system, and directed to the sample. A maximum of 500 mW of average generation power makes it through the lens system to the sample surface. The gimbal mount is used to control the generation point within the field of view of the microscope. The diode laser is amplitude modulated using a signal generator. The output signal from the optical detector is sent to a radio-frequency lock-in amplifier where the magnitude and phase of the signal are recorded. A small fraction of the generation beam is directed to a second photodiode, the output of which serves as a reference to the lock-in amplifier. The sample used is a tungsten plate with a nominal thickness of 50 μm. The bandwidth used for all measurements was 0.7 Hz.

The system was used to first measure the phase velocity dispersion characteristics of the plate in the vicinity of the ZGV point. The excitation and detection laser spot sizes were approximately 5 μm and 0.6 μm, respectively. The laser source-to-receiver distance was scanned from 10 μm to 600 μm in steps of 10 μm. At each source-to-receiver distance, the real and imaginary components of the acoustic field were recorded in the frequency range from 40 to 48 MHz in steps of 0.1 MHz. At each temporal frequency, the data taken over all spatial steps were collected and a spatial Fourier transform was applied. The spatial frequencies of the laser generated acoustic modes were then determined by identifying the peaks in the power spectrum, and the dispersion curve constructed by dividing the excitation frequency by the measured spatial frequency of each mode to yield the phase velocity.[14] The result is shown in Fig. 3. Note that the phase velocity of the s_{2b} mode was found to be *negative* and that the magnitude is taken to give the plot shown. The theoretical dispersion curve is overplotted in the figure. For the theoretical curve, literature values were taken for the density and elastic properties of tungsten.[15] The simplex optimization routine was used to determine the best-fit plate thickness, using only the first two Lamb wave modes (a_o and s_o), and this gave a plate thickness of 50.8 μm, in good agreement with the manufacturer's

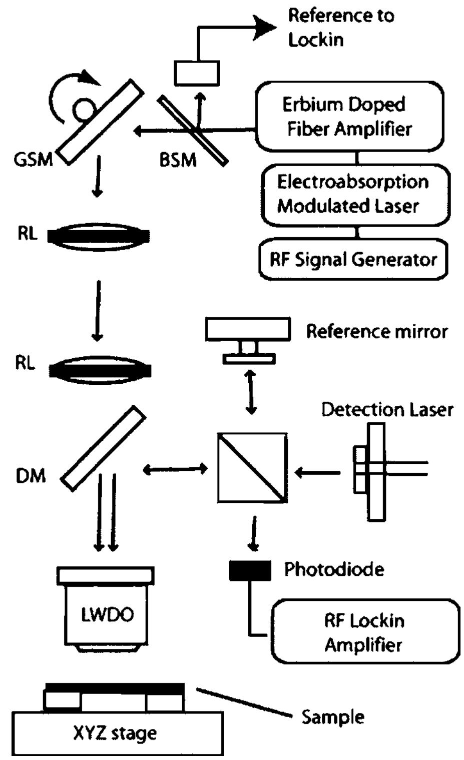

FIG. 2. Schematic of laser ultrasonic system with the component labels given as: BSM—beam sampling mirror, RL—relay lens, LWDO—long working distance objective, DM—dichroic mirror, and GSM—gimbal scanning mirror.

specification of 50 μm. A total of five modes were detected over this frequency range. The first three modes show excellent agreement with theory, while the s_1 and s_{2b} are shifted by approximately 7%. The reason for this shift is unclear, but similar results (2%–8% discrepancy) were obtained on other samples, and it is postulated that this may be due to processing induced anisotropy. It is also interesting to point out that the s_1 and s_{2b} modes do not converge at the ZGV point in the experimental measurement, but rather follow a more horizontal path toward the lower frequencies. A purely complex mode exists in this region and it is believed that this feature in the experimental data can be attributed to the detection of this nonpropagating mode.[16]

In order to evaluate the ZGV resonance, the source and detector were aligned on the epicenter and the excitation la-

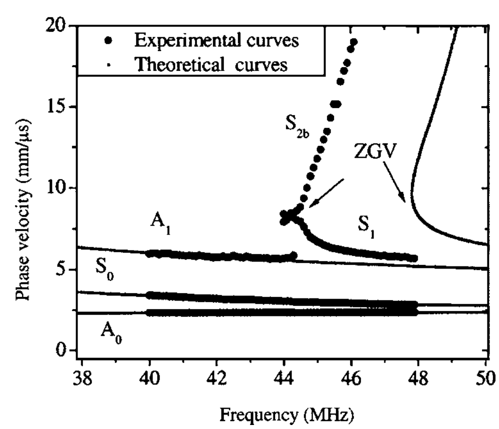

FIG. 3. Theoretical and experimental phase velocity dispersion curves in the vicinity of the ZGV point.

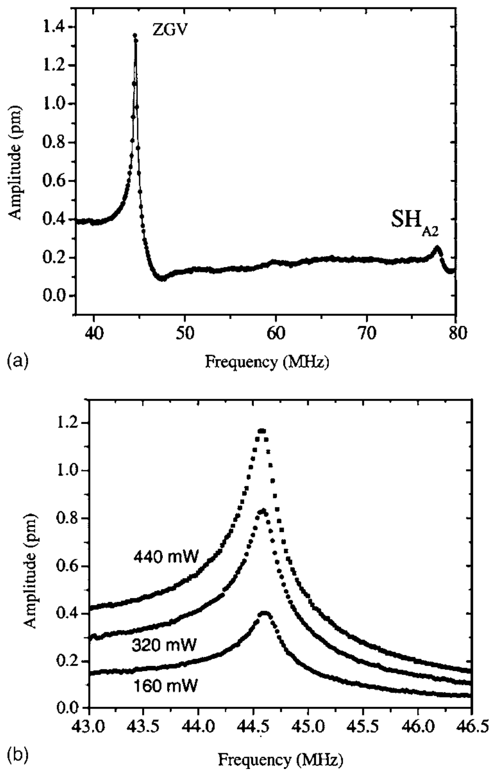

FIG. 4. The magnitude of the acoustic response (a) over a broad frequency band showing both the ZGV resonance and a shear thickness resonance peak and (b) showing the ZGV resonance for average power levels in the excitation source of 160 mW, 320 mW, and 440 mW.

ser was expanded to a spot size of 25 μm by adjusting the position of the relay lens to slightly defocus this beam on the sample surface. The reason for defocusing the excitation source was to reduce background thermal effects. The laser excitation frequency was then scanned between 38 MHz and 80 MHz in steps of 0.1 MHz, and at each frequency the magnitude of the acoustic signal was recorded. The result is shown in Fig. 4(a). The prominent feature in the spectrum is a sharp resonance occurring at approximately 44.6 MHz. Returning back to Fig. 3, it can be seen that this occurs very near the ZGV point in the dispersion curve, and is clearly not associated with a conventional longitudinal or shear thickness resonance. The only other feature in the spectrum is a small somewhat broader peak observed at about 77.8 MHz. This peak, labeled SH_{A2} is the thickness mode shear resonance that occurs at the cut-off frequency of the a_2 mode. For a plate thickness of 50.8 μm and a transverse wave speed of 2.64 mm/μs, this resonance is expected to occur at 77.9 MHz, which is in good agreement with the measured value. Figure 4(b) shows the ZGV resonance peak measured at several incident average powers of the generation beam, and with a frequency step size of 20 kHz. The full width at half maximum of the peak is approximately 390 kHz giving a Q of approximately 114. It is seen that the ZGV resonance generated with a low-power generation source in this experimental configuration can be effectively detected. This is a result of a high signal-to-noise ratio obtained through the narrow bandwidth nature of the measurement,[17] and efficient coupling of the generation laser source into this mode at the ZGV point. These results are in qualitative agreement with the theoretical findings of Liu *et al.*[18] who showed that the ZGV peak dominates the spectral response of a thin plate subjected to shear loading at the surface. Similar results have been obtained on a 100 μm tungsten plate and several aluminum plates of varying thicknesses. On these materials, the resonance appears to be localized and is insensitive to the presence of plate boundaries. Measurements on nickel and zinc plates of similar thickness showed some distortion in the ZGV resonance peak that can most likely be attributed to grain-boundary scattering.

One potential application of the ZGV resonance is precision mapping of thickness variations in thin plates. Figure 4(b) indicates that we have sufficient sensitivity to measure frequency shifts in the resonance peak of less than 0.1 MHz. A frequency shift δf corresponds to a thickness variation $\delta h = (h\delta f)/f$. For a ZGV resonance frequency of 44.6 MHz and a plate thickness of 50.8 μm, this allows for thickness changes of less than 114 nm (approximately 0.2%) to be observed. Further experiments are required to determine the damping mechanism responsible for limiting the quality factor and to quantify the effects of, for example, surface roughness, material attenuation, and nonparallel plate boundaries.

In conclusion, an amplitude-modulated continuous-wave laser source was used to excite narrow bandwidth Lamb waves in thin plates. It was shown that the dominant feature in the spectrum is a sharp resonance peak that occurs close to the ZGV point. The narrow-band nature of the inspection system allows for excellent sensitivity and it is proposed that the ZGV resonance has potential applications in precision thickness measurements in micron-scale plates and membranes. Experiments on a 50.8 μm thick tungsten plate demonstrate the potential for measuring thickness variations on the order of 0.2%. Further work is required to evaluate the loss mechanisms that are responsible for limiting the Q value and to quantify the effects of, for example, material damping and surface roughness.

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