Lasergenerated pseudoRayleigh acoustic wave propagating along the edge of a thin plate

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Laser-generated pseudo-Rayleigh acoustic wave propagating along the edge of a thin plate

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A pseudo-Rayleigh wave traveling along the edge of a thin plate is excited by a pulsed laser and detected by optical interferometry. The field confinement feature at the top of the plate edge is investigated by means of acoustic dilatation measurement. A nearly dispersionless behavior and little diffraction loss are observed during the guided mode propagation which agree with theoretical prediction. The possibility of using this wave for viscosity sensing is also discussed. © *1996 American Institute of Physics.* [S0021-8979(96)01317-5]

I. INTRODUCTION

Since the last decade there is a growing interest in the use of laser techniques for ultrasonic measurements such as material characterization and transducer calibration.[1,2] The noncontact and remote measurements offered by lasers are particularly useful in hostile environments (e.g., hot, corrosive) and awkward geometries where conventional piezoelectric transducers often fail to access. Without disturbing the acoustic field under investigation, pulsed laser generation of ultrasound in conjunction with wideband optical detection provides an ideal means for experimental studies of elastic wave propagation. In addition to bulk waves, laser generation is able to produce excellent surface and guided wave forms since more than 60% energy of the photoacoustic source is transferred into these waves.[3] A number of results relevant to Rayleigh and Lamb waves have been reported in the literature,[2,4] but few concerning guided waves propagating in complex structures have appeared. In a recent work, we have made use of the laser ultrasonic technique to study surface waves in a topographic wedge guide.[5] The antisymmetric flexural (ASF) modes traveling along the wedge tip are of particular interest for signal processing such as nonlinear interactions because of its absence of diffraction and its high concentration of acoustic energy at the tip. Thanks to the high spatial and temporal resolution offered by the laser ultrasonic technique, an anomalous dispersion behavior of these modes produced by the inherent truncation of the wedge guide was revealed in the experiments.

Another interesting topographic waveguide concerns the edge of a thin plate which supports a dominant symmetric mode when the height of the plate from the top edge is much greater in front of acoustic wavelength (semi-infinite plate approximation).[6] As do the ASF wedge modes, this plate edge mode (pseudo-Rayleigh wave) that is also confined at the top edge and free of lateral diffraction, is almost dispersionless, making itself an ideal candidate for nondispersive delay lines. Until now, only measurements of wave velocity have been reported.[7–9] In these experiments, the pseudo-Rayleigh waves were mainly excited by one piezoelectric transducer and detected by another or an optical probe. In designing surface wave devices, detailed knowledge of the propagation characteristics will be desirable. In this article we report the investigation of the pseudo-Rayleigh wave properties using noncontact, pointlike, and wide-band laser ultrasonic technique and discuss also the possibility of viscosity sensing by this wave.

II. THEORETICAL ANALYSIS

The pseudo-Rayleigh wave propagating along the edge of a thin plate ($d \ll \lambda$ with λ the wavelength) exhibits predominantly displacement components in the plate plane *xoz* and decays down from the edge (Fig. 1). Most approaches describing the behavior of this wave made use of the thin plate approximation.[7–9] These models took into account the lowest symmetrical Lamb mode S_0 and shear horizontal mode SH_0 of the plate which are the only propagating modes polarized in the plane of a plate at the low-frequency limit of interest ($fd \ll 1$), below the cut-off frequencies of higher order modes. The SH_0 mode being nondispersive is rigorously a slice of shear plane wave, whereas the Lamb mode S_0 is in general a combination of both longitudinal and shear waves in the sagittal plane of a plate and behaves essentially as a dilatational plate wave at the low frequencies or thin plate limit. These two waves couple together at the top edge of a traction-free plate in a way similar to the case of the longitudinal and shear bulk waves combined to form a Rayleigh wave at the surface of a semi-infinite substrate. By using a two-dimensional concept available for thin plate approximation ($d/\lambda \ll 1$) in which field parameters are considered as uniform across the plate thickness,[7] one obtains the characteristic equation of the symmetrical pseudo-Rayleigh wave along the free plate edge ($z=0$),

$$[2-(V/V_S)^2]^2-4[1-(V/V_P)^2]^{1/2}[1-(V/V_S)^2]^{1/2}=0, \quad (1)$$

which is identical with the equation for the Rayleigh wave on the planar surface of a substrate except that the plate dilatational velocity V_P replaces the bulk longitudinal velocity V_L. In an aluminum plate with respective bulk wave velocities $V_L=6210$ m/s and $V_S=3120$ m/s, the pseudo-Rayleigh wave velocity is calculated as $V_0=2870$ m/s which is less than the Rayleigh wave value $V_R=2910$ m/s in a substrate. Obviously, this edge wave solution is nondisper-

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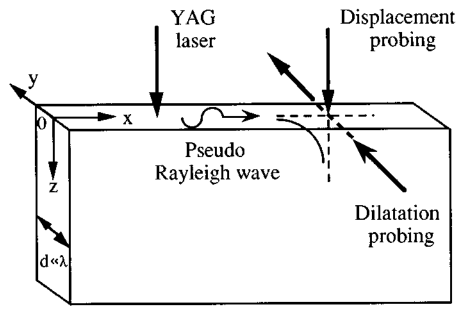

FIG. 1. Schematic diagram of the laser ultrasonic study of the pseudo-Rayleigh wave travelling along the edge of a thin plate.

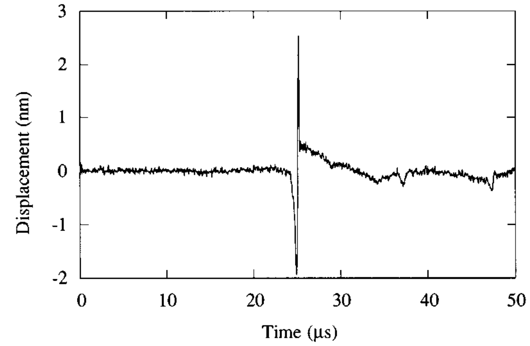

FIG. 3. Displacement waveforms detected at the edge surface of 0.5-mm-thick aluminium plate.

sive. When the frequency increases over a range between the zero limit and the cut-off of the first high-order mode, the velocity of the Lamb mode S_0 is, however, known as being frequency dependent. As a result, the velocity of the resulting pseudo-Rayleigh wave should be expected also to be frequency dependent. Replacing V_P by the Lamb mode S_0 velocity in Eq. (1) gives the phase velocity (solid line) of the pseudo-Rayleigh wave versus d/λ_0 (plate thickness to wavelength) with $\lambda_0 = V_0/f$, as illustrated in Fig. 2. The apparently slight dispersion agrees with calculations using an effective Poisson's ratio for the material[8] and a microwave network approach.[9]

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

A. Dispersion behavior of phase velocity

Topographic guides investigated in our experiments were elastic plate edges made of aluminum or glass. The thickness of these plates were 0.5 mm, much smaller than the typical wavelength of ~3 mm, which allows the approximate thin plate analysis to be applied. The dimensions of the plates were large enough to avoid acoustic reflections. The YAG laser used for acoustic excitation emits an optical pulse of 5 mJ energy and of 6 ns duration and is focused into a spot of 0.2 mm on the edges of plates. The resulting power density induces slight material ablation, creating essentially a stress normal to the edge surface. Normal displacements associated with excited plate edge waves were then detected by a wideband optical heterodyne interferometer (Fig. 1).[10] Typical wave form recorded at the edge of an aluminum plate is shown in Fig. 3. The arrival time of the signal corresponds to a mean velocity of 2750 m/s. In order to quantify the velocity dispersion of pulsed plate edge modes, a phase analysis method was utilized.[5] If $\phi_1 = \phi_1(x_1, f)$ and $\phi_2 = \phi_2(x_2, f)$ are assumed as the phase spectra of Fourier transforms of the signals detected at x_1 and x_2, respectively, the phase velocity is given by $V_p(f) = 2\pi f \Delta x/\Delta\phi$ where $\Delta x = x_2 - x_1$ and $\Delta\phi = \phi_2 - \phi_1$. Figure 2 illustrates experimental phase velocities for the pseudo-Rayleigh wave versus d/λ_0. The result demonstrates that the pseudo-Rayleigh wave exhibits very little dispersion over a wide frequency range. The deviation between theory and experiment at high frequencies, in particular, is likely due to the behavior of the Lamb mode S_0 whose fields are not uniform across the plate thickness when the frequency is increased. In this range, the thin plate approximation is no longer adequate and second-order equations involving additional high-order modes shall be taken into account to describe edge wave propagation.[11] Nevertheless, the almost nondispersive feature over a wide frequency range together with the good lateral confinement offered by the guide makes the pseudo-Rayleigh wave very suitable for long delay applications. Figure 4 presents the

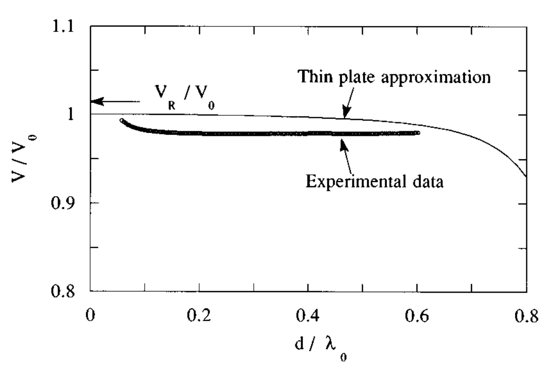

FIG. 2. Phase velocity dispersion of the pseudo-Rayleigh wave vs the product d/λ_0. Theoretical curve and experimental data.

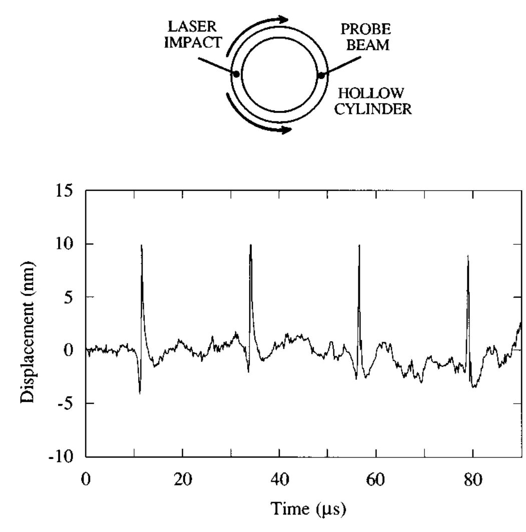

FIG. 4. Repeated circuminavation of the pseudo-Rayleigh wave along the edge of a 0.5-mm-thick and 20-mm-diam aluminium hollow cylinder.

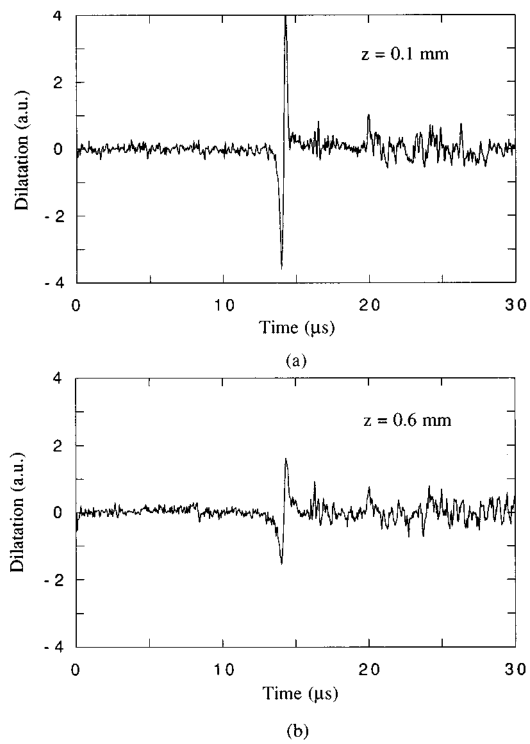

FIG. 5. Dilatation wave forms detected away from the top edge of a 0.5-mm-thick glass plate at depths of $z=$(a) 0.1 mm and (b) 0.6 mm.

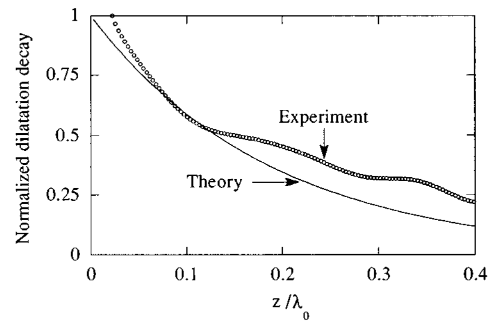

FIG. 6. Comparison between theoretical and experimental dilatation decay vs z/λ_0.

circumnavigation of pseudo-Rayleigh waves along the edge of a 0.5-mm-thick and 20-mm-diam hollow cylinder. No noticeable deformation of pseudo-Rayleigh mode wave forms is observed upon several round trips, which confirms the above discussion.

B. Dilatation field confinement

The field confinement away from the top edge is another important property for an acoustic waveguide in addition to dispersion behavior. As mentioned above, the pseudo-Rayleigh wave has components of displacement parallel to the plate plane. A conventional optical interferometer sensitive only to the normal component of displacement[12] is thus not able to detect this wave on plate surfaces. In order to measure the field confinement of the pseudo-Rayleigh wave from the top edge, we have made use of an optical interferometric method developed by the authors.[13,14] This method, based on interferometric measurement of the induced phase shift of a laser beam crossing an acoustic beam (Fig. 1), permits two-dimensional measurements of the acoustic dilatation associated with guided waves polarized in the plane perpendicular to the laser beam. Unlike previous studies, the in-plane acoustic dilatation ($S_{xx}+S_{zz}$) in a thin plate induces additionally a non-negligible component S_{yy} parallel to the laser beam.[15] Nevertheless, a detailed calculation[16] shows that the phase shift of the laser beam can still be reduced to the in-plane dilatation if a correction term $\alpha=-\lambda/(\lambda+\mu)$ is included,

$$\Delta\phi \sim [p_{11}+(1+2\alpha)p_{12}](S_{xx}+S_{zz}), \tag{2}$$

where p_{11} and p_{12} are the photoelastic constants. Figure 5(a) and 5(b) display measured dilatations at $z=0.1$ and 0.6 mm away from the edge top of a glass plate, respectively. The dilatation decay versus z/λ_0 (depth/wavelength) in Fig. 6 deduced from the magnitude ratio of fast Fourier transforms (FFT) shows a strong field confinement of the pseudo-Rayleigh wave at the plate edge, agreeing well with the theoretical calculation. Such a direct visualization of field confinement may also be helpful for determining the portion of energy contained in the guide and choosing appropriately the structure parameters of a topographic rectangular ridge.[6]

C. Wave interaction with viscous materials

An attempt was also made to consider the plate edge wave for use in viscosity sensing. When a viscous material is present on the plate surface close to the top of edge, the pseudo-Rayleigh wave having displacement components parallel to the plate plane couple viscously to the material, causing shear motion of the latter in a layer adjacent to the plate surface and thereby dissipating wave energy. Therefore, the propagation loss of the edge mode depends strongly upon the material viscosity. Figure 7(a) shows a typical temporal wave form when the edge guide is in contact with a viscous film (e.g., an adhesive tape). A high attenuation of the plate edge mode caused by viscous coupling is observed, and the following low-frequency fluctuation is likely associated with Lamb modes. Furthermore, unlike Rayleigh wave or Lamb waves used in conventional sensor devices,[17] the pseudo Rayleigh wave by its in-plane polarization is free of the energy dissipation resulting from compressional wave radiation and therefore has a low attenuation when immersed in liquids [Fig. 7(b)]. This feature should permit low-loss operation of an immersed sensor, often required in chemical and biological sensing.[18] In comparison with a viscosity sensor utilizing SH plate modes,[19] the plate edge mode is free of lateral diffraction and tightly confined at the top of the guide, providing probably a higher sensitivity. It shall also be possible to excite and receive the plate edge wave, as in most applications of surface acoustic waves (SAW) sensors, by developed piezoelectric techniques such as point contact transducer,[20,21] surface wave wedge,[9] coated piezoelectric film,[22] and interdigital electrodes if the waveguide is made of piezoelectric material.[19] Further study of potential viscosity sensors employing plate edge mode is in progress.

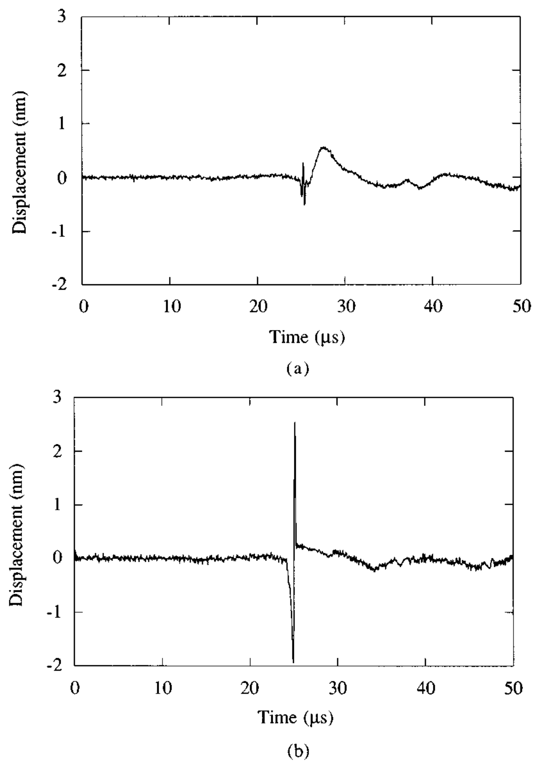

FIG. 7. (a) An adhesive tape causes a high wave attenuation, while (b) a water loading has almost little effects, except slightly on the following low-frequency signal of Lamb modes.

IV. CONCLUSION

The laser technique has provided a wide-band, point-like, and noncontact tool for generating and receiving pseudo-Rayleigh waves along the edges of solid plates. Associated displacement and dilatation fields were both measured by optical heterodyne interferometer. Properties of the plate edge mode such as diffraction loss, dispersion behavior, and field confinement have been investigated, confirming the theoretical predictions. Preliminary results relevant to viscosity sensing via the plate edge mode show interesting potentials for future works.

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