EFFICIENT EXCITATION AND DETECTION OF LAMB WAVES FOR PROCESS MONITORING AND NDE

F. Levent Degertekin, B.V. Honein and B.T. Khuri-Yakub

E.L. Ginzton Laboratory, Stanford University
Stanford, CA 94305

ABSTRACT

Lamb waves are currently used in many nondestructive testing applications to determine or monitor elastic properties of plate-like structures using various excitation methods. The methods vary from point-like dry contact transducers and laser ultrasound techniques in hostile environments to wedge transducers for inspection of immersed structures. In this paper, we analyze the excitation of Lamb waves in 2-D geometry by surface sources, as in the case of many applications. To calculate the coupling characteristics to various Lamb waves, we use the mode orthogonality principle and utilize the angular spectrum approach to find the field distributions on the surface excited by non contact transducers with finite dimensions. We present theoretical results related to Hertzian contact transducers at low frequencies along with some measurements in agreement with theory. We also investigate the wedge transducers exciting different Lamb wave modes in immersion mode.

INTRODUCTION

Since the Lamb waves are the natural ultrasonic modes of solid plates with free or slightly perturbed boundaries, they are commonly used for measuring various physical properties of these structures. Depending on the parameter of interest, one of the many possible modes can be excited and used for measurement. For example, the lowest order anti-symmetric mode (A0) is preferable for thickness measurements due to strong dispersion especially at low frequency*thickness (**fd**) values. For material characterization purposes, the whole spectra of Lamb waves is more useful to invert the elastic properties [1]. To excite different modes selectively, wedge transducers are used at particular frequencies with proper incidence angles. Using the mode conversion from a longitudinal or shear wave, it is possible to excite different Lamb wave modes efficiently by these transducers [2]. Although the transducers are optimized for a particular mode, some other modes are also excited due to the finite transducer size. Other methods of Lamb wave excitation include mainly point-like sources such as direct transducer bonding or pencil-breaking for material property determination. In hostile environments such as high temperature, low pressure conditions, laser excitation and dry-contact transducers with buffer rods are utilized [3]. In all cases, the desired properties of Lamb wave transducers can be stated as selective single mode operation and high efficiency. To achieve these goals with different transduction schemes, we investigate the dependence of these properties on transducer parameters, such as frequency, nature of excitation and geometry, for both small aperture sources and wedge transducers.

THEORETICAL MODELING

Application of complex acoustic reciprocity theorem to acoustic wave guides as shown in Figure 1 results in powerful analytic methods for wave guide excitation problems. Assuming no variation along the y-axis, and stress-free boundaries enables us to write the following relations for arbitrary velocity and stress fields with $e^{j\omega t}$ time variation as,

$$\mathrm{v}(x,z) = \sum_n a_n(x)\,\mathrm{v}_n(z) \qquad (1)$$

$$\mathrm{T}(x,z)\cdot\hat{\mathrm{x}} = \sum_n a_n(x)\,\mathrm{T}_n(z)\cdot\hat{\mathrm{x}} \qquad (2)$$

where the fields $\mathrm{v}_n(z)$ and $\mathrm{T}_n(z)$ are the particle velocity and the stress field distributions of the propagating orthogonal modes along the cross-section of the wave guide [4,5].

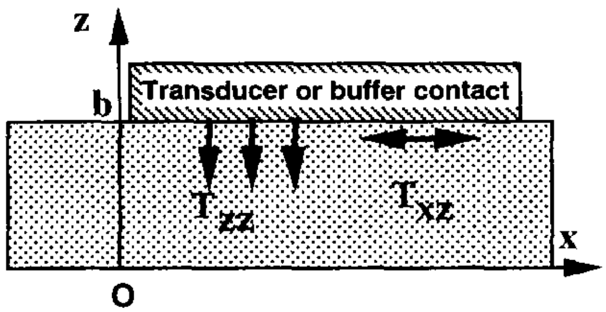

Figure 1. The plate geometry with coordinates. The plate is an unbounded anisotropic solid and has a thickness b.

Using mode orthogonality along with the complex reciprocity, in a non-piezoelectric free plate with no volume sources, we can evaluate the mode amplitudes

$a_n(x)$, due to surface sources $f_s(x)$ as

$$a_n(x) = \frac{1}{4P_{nn}} e^{-j\beta_n x} \int_0^x f_s(\zeta) e^{j\beta_n \zeta} d\zeta \qquad (3)$$

assuming $a_n(0)=0$ and where P_{nn} is the average power flow in the x-direction, i.e. the integral of the real part of the Poynting vector along the cross-section of the wave guide [6]. The source function can be related to the applied stresses on the top and bottom surfaces of the plate explicitly by the relation

$$f_s(x) = v_{nx}^*(b)T_{xz}(x,b) + v_{nz}^*(b)T_{zz}(x,b) - v_{nx}^*(0)T_{xz}(x,0) - v_{nz}^*(0)T_{zz}(x,0) \qquad (4)$$

where the superscript * denotes complex conjugate and the subscripts denote the relevant components of stress and particle velocity. Eqs 3 and 4 will be the basis of our discussion for 2-D Lamb wave excitation problems in this paper, since in a free solid plate, Lamb waves constitute an orthogonal set of propagating modes. To evaluate the mode amplitudes, the particle velocity, stress fields, and the Poynting vector for Lamb wave modes are calculated solving the Christoffel's equation and imposing the stress free boundary conditions for general anisotropic plates.

LAMB WAVE EXCITATION BY SMALL APERTURE TRANSDUCERS

Small aperture, point-like transducers either directly bonded or temporarily contacting to the surface are frequently used for Lamb wave excitation, especially for accurate wave velocity measurement and applications in hostile environments. Because of the small size, these transducers excite waves in the plates uniformly in all directions. This results in excitation of all possible modes in the frequency spectrum of the transducer. In Figure 2, the phase velocity dispersion curve for a (001) silicon plate in <100> is depicted. Inspection of this dispersion spectra reveals that, for **fd** > 3 MHz*mm, there are a number of modes available. A small transducer will excite a plurality of Lamb wave modes which is not desirable for many process monitoring and NDE applications. For that reason, we investigate the excitation efficiency of these modes for small values of **fd** (< 2), where only the lowest order symmetric (S0) and anti-symmetric modes can be excited. Although the analysis is in 2-D which neglects the effects of diffraction, the relative excitation efficiency figures are approximately valid for the point-like transducers, since the different modes experience similar diffraction processes as a function of frequency.

Observing that in Eq 4, the contributions of different surface source components to the mode amplitude can be isolated, we can evaluate the Lamb wave mode excitation efficiency for normal and tangential surface stresses separately. To include normal tractions on top surface we let all the stresses except $T_{zz}(x,b)$ be zero. In Figure 3, the calculated relative mode amplitudes for A0 and S0 modes with normal stress source on the top surface of a silicon plate are plotted. The amplitudes are normalized to A0 mode amplitude at **fd**=0.025. The source dimension is 20μm, which is typical for a Hertzian contact transducer with 100μm tip radius which applies normal forces on the samples from one side. On

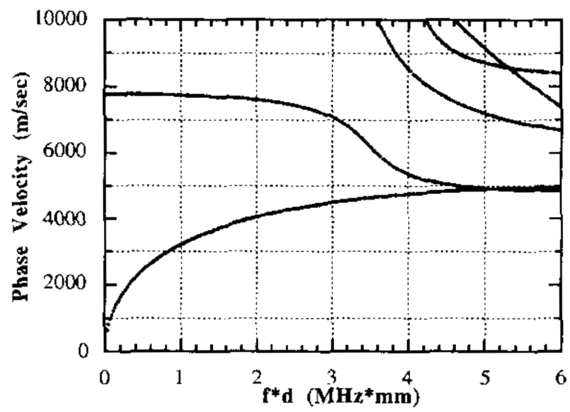

Figure 2. The Lamb wave dispersion curve for (001) silicon plate. Propagation is in <100> direction.

the same graph, the experimental results are also indicated. The data around **fd**=0.25-0.35 are obtained from a Hertzian contact transducer at 500 kHz using silicon plates of 0.532 and 0.724 mm thickness. At that frequency S0 mode amplitude is lower than the detection limit. The data at **fd**=0.735 shows that at f=1.47 MHz, the same transducer can excite both modes in a 0.5 mm silicon plate at detectable levels. The agreement with the calculations is excellent. It should be noted that the graph indicates the one way relative difference. Hence, for **fd** < 0.25, assuming detection by a similar transducer, the relative amplitude for A0 is nearly 70 dB higher than of the S0 mode, and the system virtually operates with a single mode.

In many applications, small aperture shear wave transducers or contact transducers using the flexural mode in the buffer medium can also be utilized for Lamb wave excitation. The efficiency of these methods can be examined by the same methodology, assuming that the only stress component in Eq 4 is $T_{xz}(x,b)$. The results of this calculation are shown in Fig. 4. Again the amplitudes are normalized to the same value. The interesting feature is the fact that the tangential stress excites both modes with at most 10 dB two way difference, in contrast to the normal force case. Closer examination of Eq. 4 indicates that the A0 and S0 modes can be selectively excited with similar amplitudes by selectively applying tangential stress fields on both surfaces of the plate.

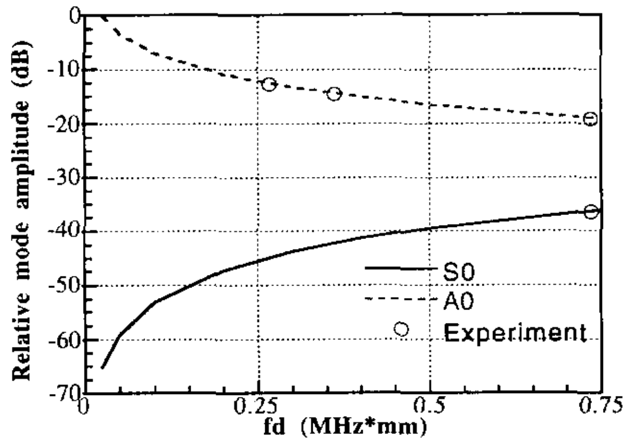

Figure 3. Relative Lamb wave amplitudes for A0 and S0 modes in (001) silicon for normal traction source on top surface. Circles indicate the experimental measurements.

Figure 5 depicts the similar calculations with the same parameters for a steel plate. Since the assumption of stress free plate surface holds very closely in case of fluid loading, the relative amplitudes can be assumed valid for inspection of fluid carrying pipe-like structures by dry Hertzian contact transducers contacting from outside.

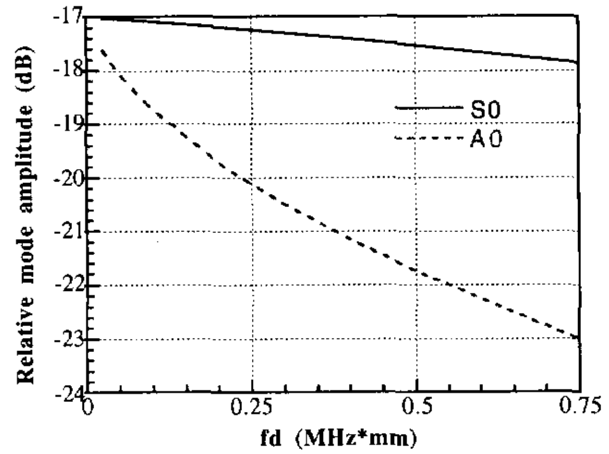

Figure 4. Relative mode amplitudes for A0 and S0 modes for tangential traction on top surface.

APPLICATION TO WEDGE TRANSDUCERS

Leaky surface waves on solid halfspaces can be excited very efficiently by mode conversion from longitudinal or shear waves incident at the critical angle of the particular mode [5]. Wedge transducers with optimized parameters considering the leak rates are widely used for NDE and material characterization by surface waves. In case of solid halfspaces, surface waves are the dominant leaky modes, however, in a plate, many Lamb wave modes can be excited at a particular frequency at different incidence angles. The dispersion curves as in Fig 2, can be used to determine the angle and frequency for the wedge transducer to excite a particular Lamb wave mode. By changing the incidence angle θ and using various thickness plates, different modes can be phase matched to obtain the Lamb wave dispersion curves. Although most of the incident energy is coupled to the desired mode, the angular spectrum of the incident beam has components at other critical angles due to the finite width of the transducer. This results in excitation of spurious modes preventing the single mode operation. The energy leak rate of the mode, which is a critical parameter for wedge transducer efficiency also varies among the different modes and for a particular mode it depends on the **fd** product.

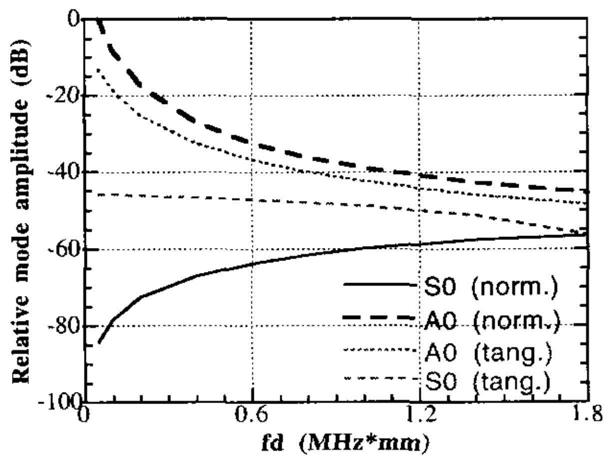

Figure 5. Relative mode amplitudes for A0 and S0 modes in steel plate normalized to A0 mode at **fd**=0.05 MHz*mm.

To find the optimized parameters for wedge transducers for Lamb wave excitation, the same theoretical approach can be used with slight modifications. Since the plate is immersed in a fluid, the tangential stresses should vanish at the surface of the plate, leaving the normal stress as the only surface source. The stress distribution on the plate surface is calculated using the angular spectrum approach starting with uniform velocity potential at the transducer surface. The angular spectrum is then propagated and projected on the surface of the sample and the normal traction $T_{zz}(x,b)$ is obtained by summing the fields at the liquid-solid interface due to individual plane wave components. The leak rates of particular Lamb wave modes are included by changing the real propagation constant β_n to $\beta^l n = \beta_n - j\alpha_n$. Although the orthogonality principle for propagating modes requires real propagation constants, the loading of the fluid can be assumed a small perturbation since $\alpha_n << \beta_n$. The leak rates of the modes are calculated using the plane wave reflection coefficients at the fluid solid plate interface.

The mode amplitudes are obtained by using Eq. 4, by integrating the source function in the region insonified by the transducer. The output power is then calculated using the mode amplitudes at the end of the insonified section. To find the coupling efficiency, the output power is normalized to the input power at the sample surface. Since the wedge problem is inherently a 2-D problem, the absolute efficiency can be calculated by the present analysis. As an example, an aluminum plate immersed in water is considered at **fd** = 6 MHz*mm. The two Lamb wave modes (labeled M1 and M2) with critical angles of θ_1=26.2 and θ_2=18.89 degrees are selectively excited by wedge transducers with varying widths in the range of 0.2 to 4 cm. Figure 6 shows the variation of coupling efficiency of the Lamb wave modes when the sample is insonified with a wedge at the respective critical angles. It can be seen that using the same transducer results in different efficiencies due to the change in the leak rates.

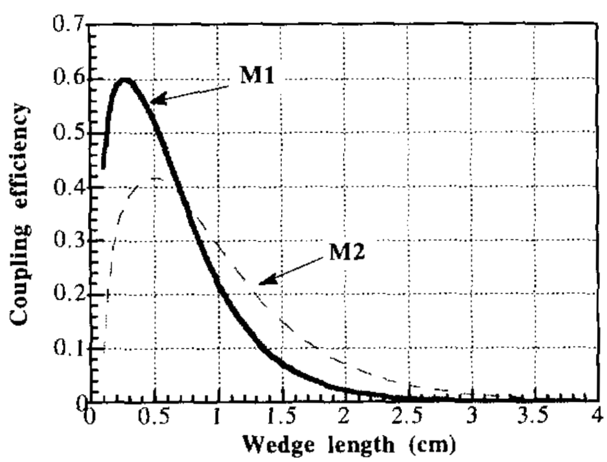

Figure 6. The excitation efficiency as a function of wedge width for two Lamb wave modes in aluminum plate in water, **fd** = 6 MHz*mm.

In Fig. 7, the signal levels are shown for both modes while the incidence angle is θ_1. Although the angle is not matching to the M2 mode, the level of spurious signal is only 18 dB below of the desired M1 mode. The finite wedge width results in side lobes in the angular spectrum, which in turn excite the undesired modes at a significant level. Using the methodology described, different wedge widths and apodization schemes can be easily simulated to minimize the unwanted side lobes in the angular spectrum.

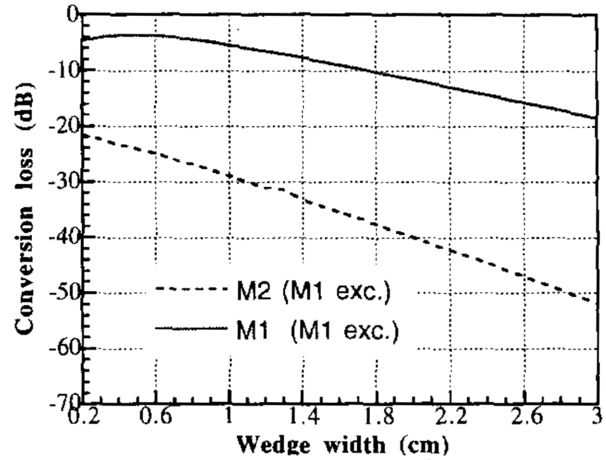

Figure 7. Conversion loss for two different Lamb wave modes showing the effect of side lobes in angular spectrum.

CONCLUSION

Different Lamb wave excitation methods are evaluated in terms of single mode operation and efficiency. A simple theoretical model is used to predict the relative excitation efficiency of A0 and S0 modes at low frequencies. The results indicate that small sources imposing normal surface traction can be used for single mode A0 mode excitation, and by shear wave transducers bonded on both surfaces of thin plates, one can selectively excite the A0 and S0 modes with comparable efficiency figures. The multi-mode Lamb wave excitation by wedge transducers and their efficiency dependence on the leak rate is also investigated, showing that a proper design using apodization or optimization of wedge width with a cost of efficiency is required for better single mode operation.

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