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Single mode Lamb wave excitation in thin plates by Hertzian contacts

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We present novel techniques to selectively excite the lowest order symmetric (S_o) and antisymmetric (A_o) Lamb wave modes in thin solid plates. Hertzian contacts are formed between the plates and the end of specially designed quartz rods which guide extensional waves generated by PZT-5H transducers bonded at their other end. Mode selectivity is achieved by applying shear and/or longitudinal traction at the edge or the surface of the plates according to the results of a two-dimensional normal mode theory. In aluminum plates, mode selectivity is measured as a function of frequency for different traction forces. With normal forces, A_o mode selectivity of more than 46 dB is obtained for $fd<0.4$ MHz mm. With antisymmetric shear traction at the edge of the plate, a selectivity exceeding 55 dB is achieved for single mode S_o operation. © *1996 American Institute of Physics.* [S0003-6951(96)02328-5]

Lamb waves are commonly used to measure the elastic properties of platelike structures.[1,2] These measurements provide crucial information for nondestructive testing and process monitoring. One of the problems associated with Lamb waves is the coexistence of many undesired modes in the plate, resulting in difficulties in data interpretation.[2] All Lamb wave modes except the lowest order symmetric (S_o) and antisymmetric (A_o) modes have lower cutoff frequencies. When the thickness of a plate increases and becomes comparable to the longitudinal and shear wavelengths, the higher order modes begin to propagate. To increase mode selectivity either wedge transducers[2] or interdigital transducers are used.[3,4] Both of these methods, however, cannot be used at high temperature or in clean environments. Instead, small aperture Hertzian contacts[5] or tightly focused laser beams[6] are used to excite the lowest order Lamb waves.

At low frequency-thickness product (fd) values, the only propagating Lamb wave modes are the lowest order A_o and S_o modes. In order to understand the excitation of these modes, we use the 2D normal mode theory for free plates, which gives the mode amplitudes of Lamb waves as a function of applied surface traction components and the characteristics of the propagating mode.[7] According to this theory, the particle velocity field in the plate can be expressed as a sum of the normal modes as

$$v(x_0,z)=\sum_n a_n(x_0)v_n(z), \tag{1}$$

where the amplitude of a particular mode propagating in $+x$ direction with propagation constant β_n can be written as

$$a_n(x_0)=\frac{1}{4P_{nn}}e^{-j\beta_n x_0}\int_0^{x_0} f_{sn}(\zeta)e^{j\beta_n\zeta}d\zeta. \tag{2}$$

Here, P_{nn} is the total power flowing in the propagation direction at the plane $x=x_0$. The function $f_{sn}(\zeta)$ is the forcing function and it extends over the region from $\zeta=0$ to $\zeta=x_0$. This function can be written explicitly in terms of the surface traction and particle velocity components at the surface of the plate as

$$f_{sn}(x)=v_{nx}^*(d)T_{xz}(x,d)+v_{nz}^*(d)T_{zz}(x,d)$$
$$-v_{nx}^*(0)T_{xz}(x,0)-v_{nz}^*(0)T_{zz}(x,0), \tag{3}$$

where the plate is assumed to have a thickness d in the z direction and is infinite in the y direction as shown in the inset in Fig. 1. Therefore, T_{zz} corresponds to normal traction at the surface and T_{xz} corresponds to the shear traction applied on the x-y plane in the x direction. For surface traction sources with dimensions satisfying the condition $\beta_n x_0 \ll 1$, the phase factor in the integrand in Eq. (2) becomes negligible. In this case, the mode amplitude is determined by the ratio of particle velocity components to the total power carried by the mode. Thus, knowing the particle velocity field for particular modes, one can use Eq. (3) as a guide for mode selection through the application of appropriate surface tractions. In Fig. 1, the variation of the normal particle velocity amplitudes at the surface of an aluminum plate are plotted as a function of *fd* for the A_o and S_o modes. In this case, only normal traction is applied on the top surface of the plate so that $T_{zz}(z=d)$ is the only nonzero term in Eq. (3). The amplitudes are normalized to the value for the A_o mode at $fd=0.05$ MHz mm. It should be noted that the results correspond to relative rather than absolute values. The variations

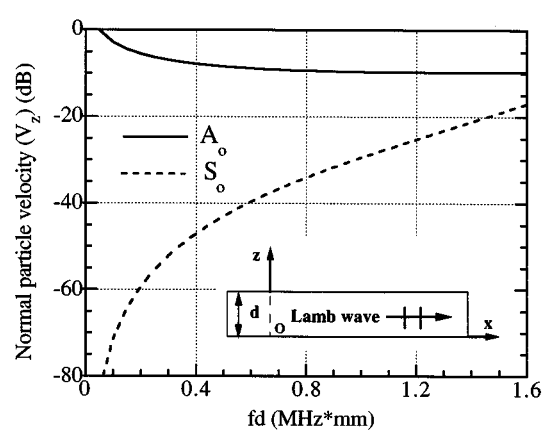

FIG. 1. The normal (z) component of particle velocity for the A_o and S_o modes excited by a normal traction force on the surface of an aluminum plate as a function of *fd*. The inset indicates the coordinate system.

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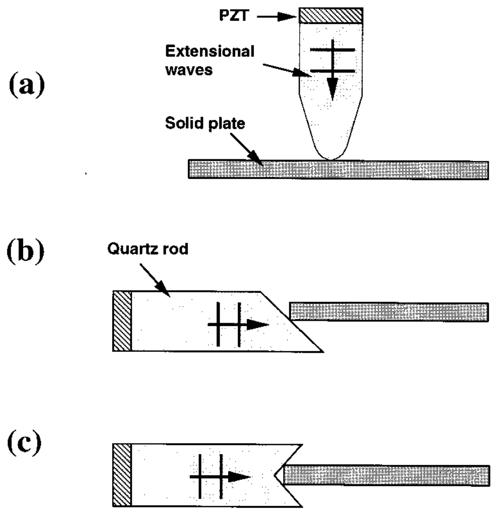

FIG. 2. The Hertzian contact transducer configurations to generate different traction components on the plate surface.

at small *fd* values suggest that due to the antisymmetric nature of the excitation the A_o mode is strongly excited, whereas the S_o mode is suppressed. Thus, a transducer generating normal traction on the surface can be used for single mode A_o operation. The mode selectivity can be further enhanced by applying out of phase normal traction to the opposite surface of the plate. This can be observed by referring to Eq. (3) and noting that in isotropic plates $v_{nz}(d) = v_{nz}(0)$ for the A_o mode and $v_{nz}(d) = -v_{nz}(0)$ for the S_o mode.

Hertzian contact transducers are used to test the predictions of the normal mode theory for several reasons. First, it enables one to apply surface tractions in desired directions and locations. Second, the excitation region is determined by the contact size, which can be adjusted to satisfy the condition $\beta_n x_0 \ll 1$.[5–8] To fabricate Hertzian contact transducers, PZT-5H rods 3 mm in diameter and 2 mm thick were bonded at the end of quartz rods and used to excite extensional waves. This configuration results in a transducer with a 30% fractional bandwidth at a center frequency of 500 kHz. Figure 2 shows the shapes of the tips where the Hertzian contacts are made and the configurations used for Lamb wave excitation and detection. A conical tip with 100 μm radius of curvature [Fig. 2(a)] is used to generate normal traction at the surface and increased sensitivity to normal particle velocity for enhanced A_o mode excitation and detection. A straight grooved tip with an angle of 150° is fabricated to realize the configurations of Figs. 2(b) and 2(c). For the configuration of Fig. 2(b), the edge of the plate is brought into contact with the lower wedge of the tip, and for the configuration of Fig. 2(c) both of the upper and lower edges are contacted by the respective wedges of the tip. These configurations apply shear traction on the surface and increase sensitivity to tangential particle velocity.

In Fig. 3, we plot the measured relative received signal amplitudes for the A_o and S_o modes, when both the transmitter and receiver are used in the configuration of Fig. 2(a). The transmitter and receiver are separated by 10 cm to allow temporal separation between the two Lamb wave modes. The

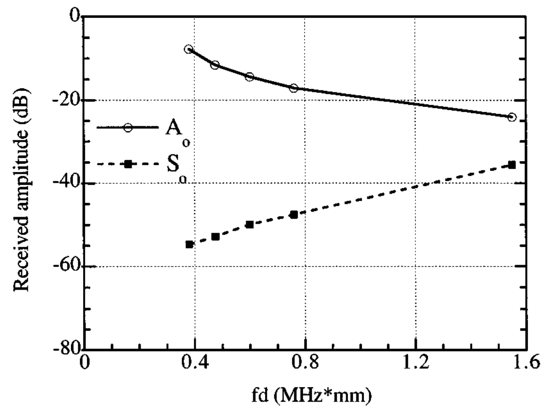

FIG. 3. The measured A_o and S_o mode signal amplitudes as a function of *fd* for Hertzian contact transducers used in the configuration of Fig. 2(a). The normalization is the same as in Fig. 1.

input signal is a 6 cycle toneburst at 500 kHz. The different data points are obtained by applying the same force on the contacts and changing only the thickness of the aluminum sample plates. It is observed that the behavior is similar to the 2D theory depicted in Fig. 1 which ignores diffraction and changes in the acoustic impedance of the plate due to thickness variations. For *fd* values smaller than 0.4 MH mm, the S_o mode suppression is more than 46 dB, so that the single side normal traction excitation scheme can be used for single mode A_o operation with high signal-to-noise ratio (SNR).

In applications where a differential measurement is desired, it is advantageous to have more than one mode in the structure with different sensitivities to the parameter of interest. Theoretical calculations show that with a line source applying shear traction at the surface, it is possible to excite both the A_o and S_o modes with comparable efficiency. However, in the 3D case, a small source of shear traction will act like a dipole, which is not an efficient radiator in the far field. To circumvent this inadequacy, we apply shear traction to one of the surfaces at the edge of the sample as in configuration of Fig. 2(b). Using both the transmitter and receiver in this configuration results in the signal shown in Fig. 4. In this case the thickness of the plate is 0.77 mm and the transmitter–receiver distance is 13 cm. The figure shows the

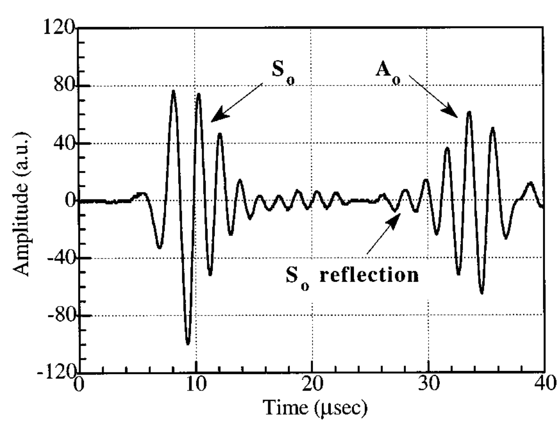

FIG. 4. Digitized output signal when the transmitter and receiver are used in the configuration of Fig. 2(b) and a high voltage spike is applied to the transmitter. The S_o multiple signal is due to reverberations in the sample.

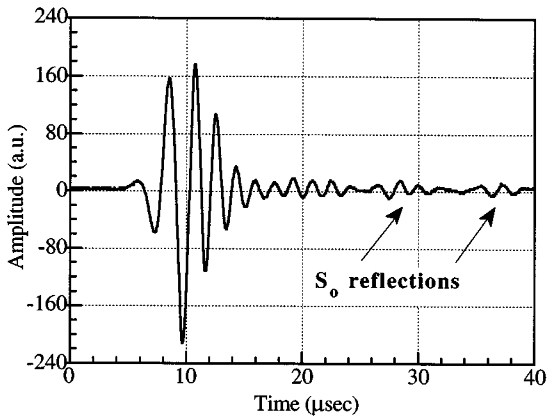

FIG. 5. Digitized output signal when the transmitter and receiver are used in the configuration of Fig. 2(c). The same signals except the A_o mode signal are observed as in Fig. 4.

impulse response of the system. The first signal is due to the S_o mode, which has a group velocity of around 5400 m/s. The dispersion of this mode is evidenced in the signal since the lower frequency components arrive earlier. The A_o mode signal comes later due to lower group velocity, and it has a dispersion in the opposite direction as compared to the S_o mode. The signals from both modes are similar to each other in amplitude, a desired property for differential measurements. This measured amplitude ratio remains nearly constant over a wide range of *fd* values.

According to Eq. (3), for enhanced S_o mode selection, shear traction in the opposite directions should be applied to the opposite surfaces of the plates since $v_{nx}(d)=v_{nx}(0)$ for the S_o mode and $v_{nx}(d)=-v_{nx}(0)$ for the A_o mode. This is achieved by using both transducers in the configuration of Fig. 2(c). Figure 5, which shows the received signals in this case, can be compared directly to Fig. 4, since all the parameters except the transducer configurations are the same. The S_o mode signal is enhanced whereas the A_o signal is below the noise, showing the single mode S_o operation. The SNR, calculated here as the ratio of averaged peak signal voltage to the peak noise voltage, is around 56 dB. The small spurious signals are due to multiple reflections of S_o mode in the sample. The same spurious signals are also present in Fig. 4.

In summary, we have developed several methods using Hertzian contacts for selective excitation of Lamb waves in thin plates. Especially the S_o mode, which is difficult to excite by mode conversion, is excited and detected with high SNR. It is also possible to excite both modes with similar efficiency, enabling independent measurements of important parameters such as thickness and temperature. The SNR values obtained, permit accurate measurements required for quantitative nondestructive testing and process monitoring. Since no coupling medium or permanent bonding is necessary, these methods can be easily used in environments where the standard techniques are of limited use.

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