INTERFACE CHARACTERIZATION BY TRUE GUIDED MODES

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INTRODUCTION

Guided acoustic waves along interfaces are especially sensitive to specific properties associated with boundary conditions and bond quality since their energy is effectively confined to the region of interest. On the other hand, this inherent advantage turns out to be a significant drawback for generation and detection of such guided waves. There are two basic types of propagating interface modes, which are shown schematically in Figure 1. First, there are leaky modes with higher phase velocity than at least one of the bulk velocities in the surrounding media. These modes "leak" their energy into one or more phase-matching bulk modes as they propagate along the interface and they can be readily excited by these mode-coupled bulk modes at the same incidence angle. In other words, the energy of leaky interface modes is not strictly confined to the boundary region therefore they are relatively easy to generate and detect. Because of their relatively short propagation length, leaky interface modes provide localized information on boundary properties and possible imperfections, which can be taken advantage of in ultrasonic NDE of bonded structures [1].

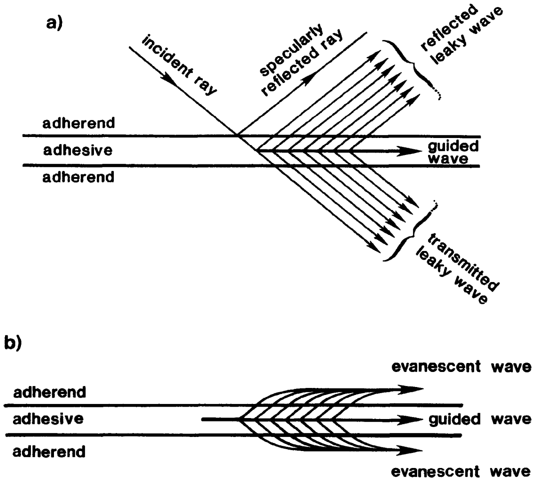

Fig. 1. Schematic diagram of a leaky (a) and true (b) guided mode propagation along an adhesively bonded interface.

True guided modes of lower phase velocity than any of the bulk velocities in the surrounding media are much more difficult to generate and detect since they produce evanescent fields only in the bonded materials as they propagate along the interface. Such guided modes are especially sensitive to overall boundary properties averaged along the interface to by inspected, but their NDE application is badly limited by their poor accessibility. Figure 2 shows the most commonly used geometrical arrangement for guided interface wave inspection of bond properties. Wedge transducers are used to generate Rayleigh waves on the free surface of one of the joining parts, which are coupled to one or more vertically polarized interface modes over the bonded area. This technique works for true guided modes [2,3] as well as for slightly leaky ones, [4,5] but the awkward geometry required for positioning the surface wave transducers renders this technique useless in many NDE applications.

DIRECT EXCITATION OF INTERFACE WAVES

Figure 3 shows an alternative geometrical configuration for direct generation and detection of interface waves between two bonded half-spaces [6-8]. A contact ultrasonic transducer is placed directly over the boundary region so that it can generate both bulk and interface waves. A vertically polarized symmetric mode produces identical transverse, but opposite normal displacements on the two sides of the boundary, therefore it can be excited by a longitudinal transducer which generates only parallel vibration relative to the interface. In a similar way, a vertically polarized antisymmetric mode produces identical normal, but opposite transverse displacements on the two sides of the boundary, therefore it can be excited by a vertically polarized shear transducer which generates only normal vibration relative to the interface. Finally, a horizontally polarized symmetric mode polarized symmetric mode produces identical transverse vibrations on the two sides of the boundary without any normal components, therefore it can be excited by a horizontally polarized shear transducer.

Figure 4 demonstrates the main concept of energy partition between the generated bulk and interface waves. That part of the transducer, which lies directly over the interface region within approximately one wavelength generates mostly interface wave while the remaining part radiates mostly into the bulk mode. Since the transducer diameter-to-wavelength ratio is proportional to frequency, the two frequency spectra are complementary with the low frequency components carried by the interface mode and the high-frequency ones by the bulk mode. Figure 5 shows the geometrical arrangement used in direct interface excitation experiments. A contact ultrasonic transducer is used to generate the ultrasonic waves as well as to detect the reflected signals from the back wall of the specimen. If the sample is long enough and the interface mode is not too dispersive, two separate signals can be detected independently. In most cases, however, these signals are not fully separated and we have to use spectrum analysis to get velocity and amplitude information on the more interesting interface wave component. In the following, we are going to present two typical examples of direct interface wave generation by contact shear transducers.

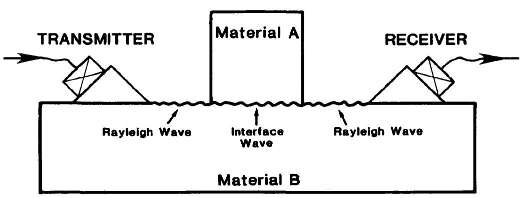

Fig. 2. Guided interface wave inspection by Rayleigh wave coupling.

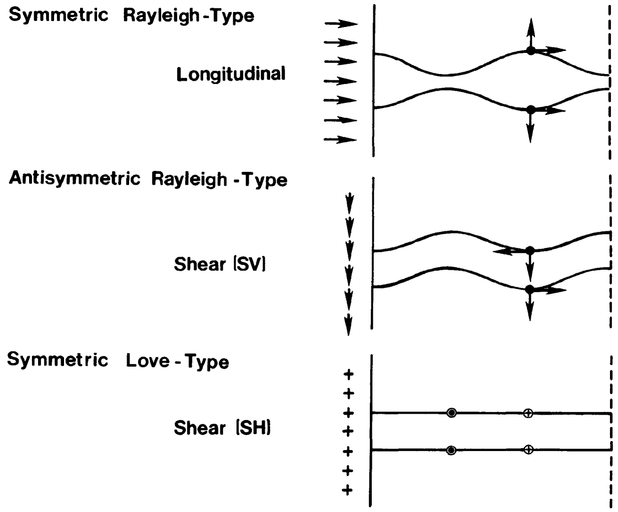

Fig. 3. Direct generation of guided interface modes.

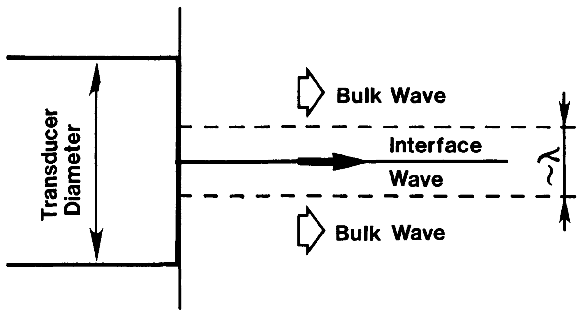

Fig. 4. Energy partition between interface and bulk modes.

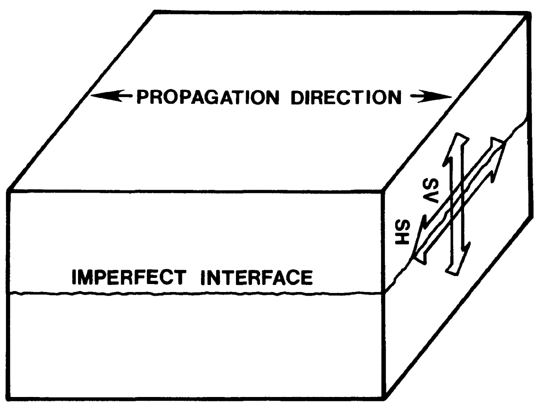

Fig. 5. Geometrical arrangement for direct interface wave excitation.

KISSING BOND WITH FINITE INTERFACIAL STIFFNESS

Many essentially two-dimensional interface imperfections can be modeled by the finite interfacial stiffness technique. According to this model, both tangential and normal components of the stress must be continuous at the interface, but there is a local discontinuity in the displacement components, which is proportional to the interfacial stiffness. The characteristic equation of a guided interface wave propagating along a boundary with finite interfacial stiffness can be separated into symmetric and antisymmetric terms [8-10]

$$\Delta_s = D - \frac{2S_L}{\mu} \frac{\sqrt{k^2 - k_L^2}}{k_T^2} \tag{1}$$

and

$$\Delta_a = D - \frac{2S_T}{\mu} \frac{\sqrt{k^2 - k_T^2}}{k_T^2} , \tag{2}$$

where μ is the rigidity of the substrate and

$$D = \frac{(2k^2 - k_T^2)^2 - 4k^2\sqrt{k^2 - k_T^2}\sqrt{k^2 - k_L^2}}{k_T^2} . \tag{3}$$

Here k, k_T, and k_L are the wave-numbers of the guided interface mode, and the shear and longitudinal bulk modes in the substrate, respectively. It is interesting that the symmetric mode depends on the extensional spring constant (S_L) only, since it does not generate any shear stress at the interface. On the other hand, the antisymmetric mode depends on the transverse spring constant (S_T) only, since it does not generate any normal stress at the interface. At zero boundary stiffness, both modes degenerate into a simple Rayleigh mode on the free surface of the substrate, since the numerator of D is the well-known Rayleigh wave characteristic equation. The same thing happens at very high frequency when the second terms in Eqs. 1 and 2 diminish as ω^{-1}, and the dispersive interface wave velocity approaches the Rayleigh velocity.

The easiest way to study an imperfect interface with controlled interfacial stiffness is to consider the simple case of dry contact between slightly rough aluminum counterparts under compressive pressure. At zero compressive pressure, two separate signals can be observed. The first arrival is a shear-type bulk wave while the second one is a Rayleigh-type interface wave. At higher compressive pressure, the two signals are not separated sufficiently to directly measure their respective time delays, but frequency analysis can still readily reveal the sought separation. Distinct minima occur as a result of destructive interference between the two principal modes, and the periodicity of the observed frequency modulation can be readily used to determine the sought interface wave velocity as a function of either frequency or compressive pressure. Figures 6 and 7 show the received ultrasonic signals and their corresponding frequency spectra for a dry interface between aluminum surfaces at zero and 4000 psi compressive pressure. Figure 8 shows the measured interface wave velocity as a function of compressive pressure. Naturally, the separation between the observed minima in the spectrum is not quite constant since the interface wave is slightly dispersive. This phenomenon will be discussed in more detail in connection with the next example. In this case, we simply measured the average separation between the minima over the whole frequency range from 1 to 9 MHz, and related the resulting average interface wave velocity to the center frequency of 5 MHz. Lee and Corbly were the first to experimentally observe this kind of gradual transformation of a Rayleigh wave into a Stonely wave due to strong pressing together of two solids [4]. Between similar materials, the interface wave degenerates into a vertically polarized shear mode as the boundary stiffness increases with increasing compressive pressure. The slight discrepancy between the theoretical prediction and the measured experimental data is due to the limitations of Haines' model used to calculate the boundary stiffness of the interface [11].

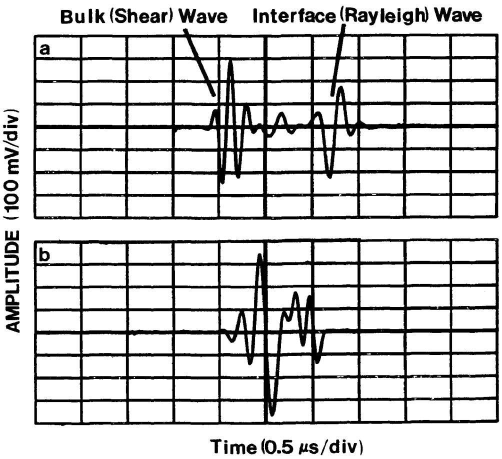

Fig. 6. Received ultrasonic signals along a dry interface between aluminum surfaces under (a) zero and (b) 4000 psi compressive pressure.

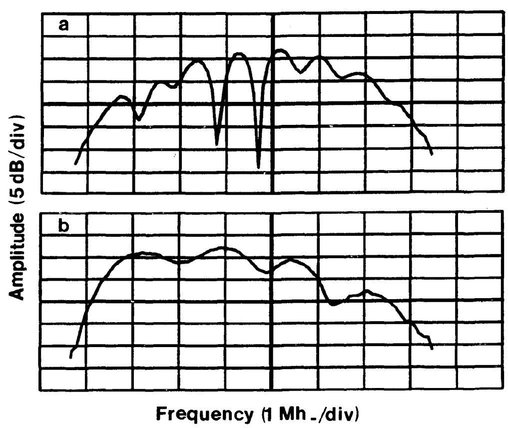

Fig. 7. Frequency spectra of the detected ultrasonic signals.

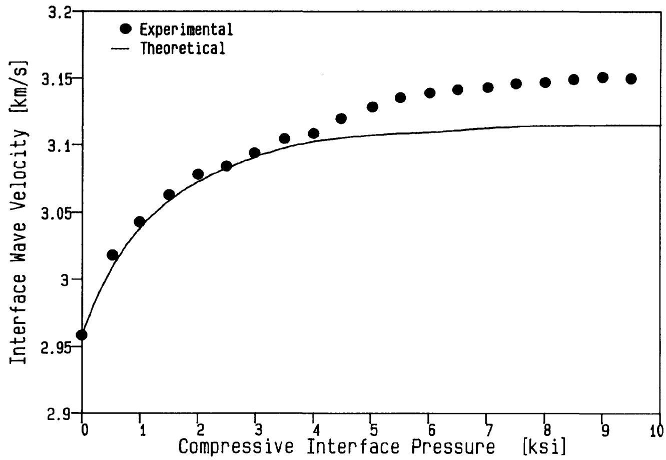

Fig. 8. Measured and calculated interface wave velocity as a function of compressive pressure between aluminum counterparts at ~5 MHz.

ADHESIVE BOND

The second example is a thin adhesive layer between aluminum adherends. Although, in this case, there exist an infinite number of both vertically and horizontally polarized guided modes [1,12], the strongest one is always the zero order mode which has the most even phase distribution along the face of the contact transducer. The 1/4" - 1"-long samples were made of aluminum plates bonded with a 140 μm thick FM300 adhesive layer. Figures 9 and 10 show the received ultrasonic signals and their corresponding frequency spectra for a 1/2"-long sample. The time domain signals are obviously too confused by the dispersive nature of the guided interface wave to directly evaluate. On the other hand, the observed minima in the frequency spectra of these signals can be readily used to calculate the phase velocity of the interface wave. Figure 11 shows the measured velocity as a function of frequency along with theoretical predictions for phase velocities of the two lowest order modes at vertical and horizontal polarizations.

Both interface waves approach the pure shear mode at very low frequencies. At vertical polarization, the interface velocity quickly drops to approximately the Rayleigh wave velocity as the frequency increases and exhibits but very small dispersion up to 0.8 MHz mm. At horizontal polarization, the interface wave has negligible dispersion up to approximately 0.3 MHz mm, where it sharply drops from the shear velocity of the adherend to the much lower shear velocity of the adhesive. Due to this strong dispersion, all we can detect is basically the turning point of the dispersion curve, but this point is a very sensitive measure of bond properties.

CONCLUSIONS

A new experimental technique was introduced to generate and detect interface waves along otherwise unaccessible plane boundaries. Theoretical and experimental results for the phase velocities of propagating guided modes along different solid-solid interfaces were found to be in good agreement. The suggested simple technique may found numerous applications in ultrasonic assessment of bond properties requiring guided mode inspection.

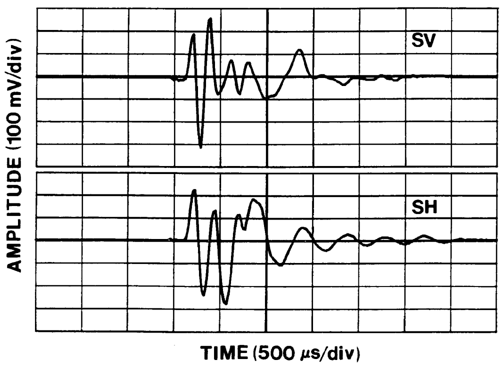

Fig. 9. Received ultrasonic signals along a 1/2"-long, 140 μm-thick aluminum-FM300 adhesive bond.

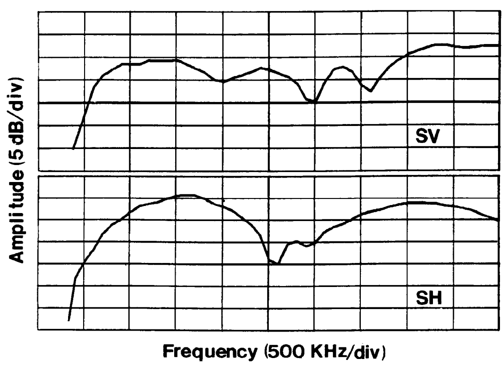

Fig. 10. Frequency spectra of the ultrasonic signals shown in Fig. 9.

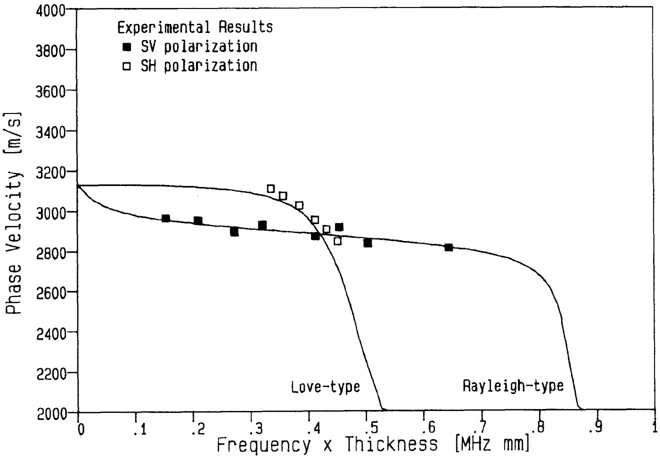

Fig. 11. Phase velocity versus frequency curves for the lowest order interface modes at different polarizations.

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