Numerical and Experimental Evaluation of Ultrasonic Wave Propagation Characteristics at Contact Interface*

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As a background of the ultrasonic characterization of contact interfaces, ultrasonic wave propagation characteristics at contacting solid surfaces have been studied numerically and experimentally. The wave propagation along the contact interface has been simulated by the two-dimensional finite difference method, assuming a spring-type interface with normal and tangential stiffnesses. The analysis has verified that the antisymmetric-mode interface wave can be generated by the shear excitation at one end of the interface, and its phase velocity can be evaluated with good accuracy from the waveform received at the other end. Measurement of the phase velocity of the interface wave has been carried out for contacting PMMA surfaces under different contact pressures, together with the shear-wave reflection measurement to evaluate the interface tangential stiffness. The measured relation between the phase velocity and the tangential stiffness has been shown to agree well with the theoretical relation for the antisymmetric-mode interface wave.

Key Words: Ultrasonic Wave, Contact Interface, Phase Velocity, Interface Stiffness, Contact Pressure, Finite Difference Method, PMMA, Nondestructive Evaluation

1. Introduction

Ultrasonic waves offer useful tools to characterize the contact condition between solid components in non-destructive and noninvasive manners^{(1)–(5)}. It has been shown that the transmission and reflection coefficients of the ultrasonic wave are sensitive to the contact pressure or other contact parameters. Theoretically, the normal and tangential stiffnesses of the contact interface govern the transmission/reflection coefficients^{(3), (5)} and serve as parameters to characterize the contact condition.

In addition to the transmission/reflection characteristics, the stiffnesses of contacting surfaces can be evaluated by the elastic wave that propagates along their interface. Pyrak-Nolte and co-workers^{(6)–(9)} investigated the elastic

wave propagation along fracture surfaces in geophysical media, and found that the propagation velocity changed with the pressure acting on the fracture interface. Recently, Biwa et al.⁽¹⁰⁾ have examined the propagation of this wave mode, which is referred to as the contact interface wave (CIW) hereafter, for a contact interface between poly(methyl methacrylate) (PMMA) blocks, and experimentally demonstrated the overall contact-pressure dependence of its phase velocity between those of the Rayleigh wave and the bulk shear wave.

Theoretically, Gu et al.⁽⁹⁾ have shown that there exist two distinct modes of steady-state wave propagation along a spring-type interface between two elastic half-spaces, that is, the symmetric mode (referred to as S-mode hereafter) and the antisymmetric mode (A-mode). From a practical point of view, however, it is important to recognize how the CIW can be generated from a finite-size wave source (ultrasonic transducer) located at one end of the interface, or which of the above two modes is generated in the particular excitation condition. Clarification of such issues requires the numerical analysis incorporating essential factors involved in the CIW propagation.

In the present study, numerical simulation of the generation and propagation of the CIW is carried out using the two-dimensional finite difference method. For two elastic solids bonded by finite interface stiffnesses, the exci-

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tation of the ultrasonic wave at one end of the interface and its detection at the other end by shear-wave transducers are numerically simulated, in order to clarify the wave mode that is excited or detected in the experimental setup used in the above-mentioned work⁽¹⁰⁾. The spectral analysis is carried out for the computed waveforms in order to simulate the procedure to extract the phase velocity of the CIW from the received signal. Furthermore, experiments are also carried out to measure the phase velocity of the CIW for PMMA-PMMA contact interface under different contact pressures, for which the tangential stiffness is independently measured using the shear-wave reflection technique. The experimentally obtained relation between the CIW phase velocity and the tangential stiffness is then compared with the theoretical as well as numerical results.

2. Numerical Model

A two-dimensional computational model of two elastic blocks in contact is shown in Fig. 1, with length $L = 40$ [mm] and height $H = 10$ [mm] for each. The domain of each block is discretized into 400×100 Cartesian grids, with the equal interval of 0.1 mm for the horizontal and vertical directions. The two-dimensional Navier equations for the displacements u and v in homogeneous and isotropic elastic solids under the plane-strain condition are solved using the finite difference method⁽¹¹⁾. The second-order-accurate centered finite differences are employed to replace the derivatives with respect to spatial as well as temporal coordinates. The time step is taken to be small enough (1.0 ns) in order to assure the stability of the numerical scheme.

The two blocks are both assumed to be PMMA, which acoustic properties⁽¹²⁾ are given in Table 1. At the boundary between two blocks, a spring-type interface is assumed, which enforces the continuity of the normal and tangential tractions as well as the following conditions for the displacement discontinuities.

$$[v] \equiv v_+ - v_- = \frac{\tau_{yy}}{K_N}, \quad [u] \equiv u_+ - u_- = \frac{\tau_{xy}}{K_T}. \quad (1)$$

In Eq. (1), τ_{yy} and τ_{xy} denote the normal and tangential tractions, and $[v]$ and $[u]$ are the differences of the vertical

and horizontal displacement components, respectively, of the upper (+) and the lower (−) sides of the interface.

The parameters K_N and K_T represent the interface stiffness for the normal and tangential directions, respectively. Although these stiffnesses depend on the contact pressure giving rise to a nonlinear acoustic effect⁽¹³⁾, the present analysis only deals with small-amplitude ultrasonic waves so that K_N and K_T are assumed to be constants. In order to evaluate the influence of the contact conditions on the wave propagation characteristics, the normal stiffness K_N is varied in the range of 0 to 4×10^{13} Pa/m. Since it has been found theoretically and experimentally⁽⁵⁾ that the tangential stiffness K_T changes approximately in proportion to the normal stiffness K_N , the present simulation assumes $K_T = 0.5K_N$ as a representative case.

The left and right boundaries of the two blocks are assumed traction-free, except the central portion of the left boundary of width d (taken to be 5 mm presently) representing the excitation area. Since the precise simulation of the transducer-medium coupling is an intractable task, the surface tractions on this part are prescribed to be the functions of time as explained below. In the aforementioned study⁽¹⁰⁾, it has been found experimentally that the use of shear-wave transducers for both transmission and reception is a feasible way to measure the CIW. Therefore, in order to simulate the wave excitation by a shear-wave transducer, the uniform shear traction is assumed on this part as a single-period sinusoidal function of time, i.e.

$$\tau_{xy}(t) = \begin{cases} \tau_0 \sin(\omega_0 t), & 0 < t < 2\pi/\omega_0, \\ 0, & t \leq 0, t \geq 2\pi/\omega_0, \end{cases} \quad (2)$$

while this area is assumed free from normal tractions. In the above expression, ω_0 is the angular frequency of excitation, presently set as 2π MHz, and τ_0 is a constant.

The upper and lower boundaries of the whole system are assumed to be an absorbing boundary, in order to suppress the reflected waves that are of less interest. These boundaries are subjected to the conditions⁽¹⁴⁾

$$\tau_{yy} = a\rho c_L \dot{v}, \quad \tau_{xy} = b\rho c_T \dot{u}, \quad (3)$$

where the dots denote the time derivatives, and ρ , c_L and c_T are the mass density, the longitudinal wave speed and

Fig. 1 Numerical simulation model

Table 1 Acoustic parameters for PMMA

Longitudinal wave velocity	Shear wave velocity	Density
c_L [m/s]	c_T [m/s]	ρ [kg/m ³]
2743	1381	1180

the shear wave speed, respectively. The numerical parameters a and b are both taken to be unity.

3. Results of Numerical Simulation

3.1 Wave motion on the interface

The displacement components, $u_{\pm}$ and $v_{\pm}$, on the upper (+) and lower (-) sides at the right end $x = L$ of the interface are plotted as function of time in Fig. 2, for the interface stiffness $K_N = 2K_T = 2 \times 10^{12}$ [Pa/m]. Owing to the linearity of the problem at hand, the plotted displacements are in arbitrary units.

It is found from Fig. 2 that $[v] = v_+ - v_- = 0$ and $u_+ = -u_-$ on the interface. Therefore, the wave motion corresponds to the so-called antisymmetric mode (A-mode) in the terminology by Gu et al.⁽⁹⁾ Figure 3 shows the resulting trajectories of the transient particle displacement at different locations on the interface. At the right end ($x = L = 40$ [mm]), the traction-free condition gives rise to a larger motion than at other locations. The demonstrated trajectories resemble the elliptic motion that would be found in the steady-state condition⁽⁹⁾. Figure 4(a) and (b) schematically illustrate the wave motion on the interface and the associated particle motion, for the A-mode and the S-mode, respectively, in the steady-state propagation⁽⁹⁾.

3.2 Influence of the interface stiffness

Keeping in mind the detection by a shear-wave transducer, attention is now paid to the transient vertical displacement at the right end of the contact interface. The simulated waveforms are plotted in Fig. 5 for different levels of the interface stiffness. In Fig. 5, the case of

Fig. 2 Displacement waveforms at the right end of the contact interface, when $K_N = 2K_T = 2 \times 10^{12}$ [Pa/m]

Fig. 3 Displacement trajectories at different locations on the interface, when $K_N = 2K_T = 2 \times 10^{12}$ [Pa/m]

$K_N = 2K_T = 0$ corresponds to the free surface, where the Rayleigh wave pulse is observed. As the interface stiffness increases from zero, the arrival of the pulse is shown to shift to an earlier time. Figure 5 includes the extreme case of the “intact” interface, where the displacement components are continuous at the interface. This case then reduces to a bulk solid with no interface, and it is a pulse of the bulk shear wave that reaches the observation point.

3.3 Wave field

The wave field in the two solids connected by the stiffness $K_N = 2K_T = 2 \times 10^{12}$ [Pa/m] are shown in Fig. 6 for two different time elapses, where the contour plots of

Fig. 4 Schematic wave motion and particle trajectory of (a) the antisymmetric mode and (b) the symmetric mode

Fig. 5 Influence of the contact stiffness on the simulated waveform on the contact interface

Fig. 6 Shear wave field in the blocks at time elapses of (a) 10 μ s and (b) 20 μ s, when $K_N = 2K_T = 2 \times 10^{12}$ [Pa/m]

the rotation $\nabla \times \mathbf{u}/2$ of the displacement vector $\mathbf{u} = (u, v)^T$ are illustrated in order to demonstrate the shear (equivolumetric) wave field. In Fig. 6, quiescent regions are colored in gray, while the values of $\nabla \times \mathbf{u}/2$ with opposite signs are demonstrated in black and white. It can be readily seen in Fig. 6 that the bulk shear wave propagates in the blocks. It is also seen that the CIW at the interface is somewhat delayed from the bulk wave, as the propagation velocity of the CIW is lower than that of the bulk wave.

4. Phase Velocity of the Contact Interface Wave

4.1 Evaluation of phase velocity

In this section, the numerical waveforms at the right end of the contact interface are used to simulate the phase velocity evaluation in experimental situations. In realistic situations using a piezoelectric transducer, the detected waveform is an integrated electric signal over the surface area of the transducer. Since it is out of the scope of the present analysis to incorporate the actual transducer-medium coupling, the vertical displacement waveform on the interface is simply considered to be the detected signal.

The procedure to obtain the phase velocity of the CIW is as follows⁽¹⁰⁾. The fast Fourier transform (FFT) of the CIW pulse simulated with finite interface stiffness is computed to obtain its spectrum $V(\omega)$ as a function of the angular frequency ω . This is divided by the corresponding spectrum $V_0(\omega)$ of the pulse simulated for the interface with zero stiffness. Then the phase difference between the two pulses is computed. If the phase velocities of the two pulses are denoted by $c(\omega)$ and $c_0(\omega)$, respectively, the fol-

lowing relation holds.

$$\text{Arg} \left[\frac{V(\omega)}{V_0(\omega)} \right] = L \left\{ \frac{\omega}{c(\omega)} - \frac{\omega}{c_0(\omega)} \right\} + 2n\pi, \quad (4)$$

where L is the travel distance, n is an integer and $\text{Arg}[\cdot]$ denotes the argument of a complex quantity. Since the pulse with null stiffness corresponds to the Rayleigh wave, its phase velocity $c_0 = c_R$ can be computed from the following characteristic equation⁽¹⁵⁾ based on the acoustic properties of PMMA.

$$\left(2 - \frac{c_R^2}{c_T^2} \right)^2 - 4 \sqrt{1 - \frac{c_R^2}{c_L^2}} \sqrt{1 - \frac{c_R^2}{c_T^2}} = 0. \quad (5)$$

With c_R given as above, the CIW phase velocity $c(\omega)$ can be obtained as

$$c(\omega) = \frac{c_R}{1 - \frac{\text{Arg}[V(\omega)/V_0(\omega)] + 2n\pi}{\omega L}}, \quad (6)$$

where the integer n can be determined by unwrapping the phase of each spectrum appropriately.

4.2 Comparison to theoretical relation

According to the theoretical analysis by Gu et al.⁽⁹⁾, the phase velocity of the CIW is given by the following characteristic equations derived on the assumption of steady-state propagation. Namely,

$$(1 - 2\xi^2)^2 - 4\xi^2 \sqrt{\xi^2 - \zeta^2} \sqrt{\xi^2 - 1} - 2\bar{K}_N \sqrt{\xi^2 - \zeta^2} = 0 \quad (7.a)$$

for the S-mode, and

$$(1 - 2\xi^2)^2 - 4\xi^2 \sqrt{\xi^2 - \zeta^2} \sqrt{\xi^2 - 1} - 2\bar{K}_T \sqrt{\xi^2 - 1} = 0 \quad (7.b)$$

for the A-mode, where

$$\xi = \frac{c_T}{c}, \quad \zeta = \frac{c_T}{c_L}, \quad (8)$$

and the normalized interface stiffnesses are

$$\bar{K}_N = \frac{K_N}{\rho c_T \omega}, \quad \bar{K}_T = \frac{K_T}{\rho c_T \omega}. \quad (9)$$

Therefore, the phase velocities of the S-mode and A-mode are separately governed by the normal and tangential stiffness, respectively.

It is now checked if the phase velocity computed by the procedure in section 4.1 agrees with that for the A-mode predicted by Eq. (7.b). The comparison is made in Fig. 7 as the plots of the normalized phase velocity c/c_T against the normalized interface stiffness $\bar{K}_N = 2\bar{K}_T$ used in the numerical simulation. The theoretical predictions are drawn as solid curves and the simulated results are plotted as circles. Since the simulated waveforms have relatively narrow frequency bandwidths, the phase velocities at a fixed frequency of 0.6 MHz are shown. The theoretical curves and the numerical results agree favorably, indicating that the phase velocity of the CIW can be extracted from the waveforms recorded at the terminal of the contact interface.

Fig. 7 Comparison between the normalized phase velocity obtained from the simulated waveform and the theoretical relation as a function of the normalized interface stiffness

In the present numerical analysis, the ratio between the tangential and the normal stiffnesses of the contact interface has been set as $K_T/K_N = 0.5$. In order to examine the influence of this stiffness ratio, simulations with different K_T/K_N ratios have been also carried out. As a result, however, no essential differences have been observed in the results shown above, as long as the tangential stiffness K_T is regarded as a governing parameter. This is a natural consequence of the fact that the characteristics of the A-mode CIW are governed by the tangential stiffness, as mentioned above based on the theoretical relations.

5. Experimental Verification

5.1 Experimental setup

It has been shown in the numerical analysis that the excitation at one end of the contact interface by a shear-wave transducer enables generation of the A-mode CIW. This finding is examined here from an experimental point of view. The experimental configuration is shown in Fig. 8, where two PMMA blocks (length 40 mm, height 25 mm and width 25 mm) are mated and pressed to each other. An ultrasonic wave pulse is transmitted from the left end of the contact interface and received at the right end by the piezoelectric shear-wave transducers with the aid of a Panametrics 5072PR pulser/receiver. The polarization directions of the transducers are both arranged perpendicular to the interface. The ultrasonic waveforms are recorded as digital data into a personal computer via a Tektronix TDS340AP digital oscilloscope after averaging over 256 synchronized signals.

The compressive force is measured with a load cell to calculate the nominal contact pressure. In order to evaluate the tangential contact stiffness in an independent man-

Fig. 8 Experimental setup

ner, the shear wave pulse is sent from the normal direction, and the amplitude spectrum of the reflected shear wave is evaluated through the FFT procedure. Then the reflection coefficient is calculated at the same frequency as in the CIW measurement. From the shear wave reflection coefficient $R_T(\omega)$, the tangential stiffness K_T can be obtained as⁽³⁾

$$K_T = \frac{\rho c_T \omega}{2} \sqrt{\frac{1 - R_T^2}{R_T^2}}. \quad (10)$$

The present experiment uses contact-type normal-incidence shear-wave transducers (nominal diameter 0.5 inches) by Panametrics, Inc. for both CIW and reflection measurements. The nominal frequencies of the transducers for the CIW transmission, CIW reception, and the normal reflection (transmission and reception) are 2.25 MHz, 5 MHz, and 1 MHz, respectively. These nominal frequencies have been chosen after preliminary trials so as to assure that the received CIW and the reflected shear-wave pulses have overlapping frequency bandwidths, around 0.7 MHz in the present experiment.

5.2 Recorded waveforms

Figure 9 shows the recorded ultrasonic signals for different nominal pressures applied to the contact interface. It shows that the CIW pulse arrives at the receiver earlier in the case of higher pressure, while the arrival time of the bulk shear wave appears to be insensitive to the applied pressure. Since increasing pressure gives increased contact stiffness, the result in Fig. 9 qualitatively corresponds to the simulation result in Fig. 5. It is considered to be due to the finite area of the transducer that the measured waveforms in Fig. 9 contain the bulk shear wave pulse for any pressure levels.

It is noted that the direct comparison between the

Fig. 9 Experimental waveforms received for different contact pressures

transient waveforms in Figs. 5 and 9 is not meaningful, because of the different excitation waveforms assumed in the numerical simulation and the experiment. Since the numerical and experimental waveforms have different spectra of frequency components, the present study focuses on the correspondence between the phase velocities at the same frequency that are obtained through the FFT procedure. Furthermore, although the transducer of nominal frequency 2.25 MHz was used for the CIW transmission, the center frequency of the received CIW waveforms was as low as about 0.5 MHz, due to the frequency-dependent attenuation that is not explicitly modeled in the numerical simulation.

5.3 Relation between phase velocity and tangential stiffness

From the experimental waveforms in Fig. 9, the phase velocity of the CIW has been calculated in the procedure described in section 4.1. Figure 10 shows the relation between the measured CIW phase velocity and the contact pressure, in the loading/unloading cycle up to 1.25 MPa. It can be observed that the change of the CIW phase velocity exhibits hysteric behavior in the loading/unloading of the contact interface⁽¹⁰⁾.

In Fig. 11, the CIW phase velocities (normalized by c_T) are plotted against the tangential stiffness K_T evaluated by the shear-wave reflection coefficient by Eq. (10), where the theoretical curve and the present numerical results are also shown for comparison. The measured CIW phase velocity is in reasonable agreement with the theoretical as well as numerical results, which confirms that it is indeed the A-mode CIW that has been experimentally generated and detected.

Since the shear-wave reflection measurement is based on the amplitude information of the echo from the interface, it is difficult to quantify a small change of the contact condition accurately. For this reason, the discrepancy of

Fig. 10 Variation of the phase velocity with the contact pressure in the loading/unloading cycle

Fig. 11 Relation between the normalized phase velocity and the tangential stiffness of the contact interface

the experimental plots from the theoretical curve in a low-pressure range in Fig. 11 is to some extent ascribed to the inaccuracy of the reflection coefficient used to calculate the tangential stiffness. In addition, at such low contact pressures the contact interface may not be in a uniform contact condition, which causes a discrepancy between a local condition measured by the normal reflection and the overall condition measured by the CIW.

In summary, the measurement of the CIW phase velocity using shear-wave transducers is considered to be a promising alternative to the transmission/reflection methods for quantitative evaluation of contacting interfaces.

6. Conclusion

In this paper, the generation, propagation and detection of the contact interface wave (CIW) have been studied numerically and experimentally. The two-dimensional finite difference method has been employed to simulate the propagation of the CIW from a shear-wave source of finite width located at one end of the interface. The resulting wave field and the character of the wave motion

at the contact interface have been examined based on the present simulation. It has been verified that the spectrum analysis based on the FFT procedure can be used to extract the phase velocity of the CIW from the received signal.

The present analysis has shown that the antisymmetric-mode CIW can be generated on the contact interface and detected using shear-wave transducers with polarization normal to the interface. From the phase velocity of the CIW obtained by the spectrum analysis, the tangential stiffness of the contact interface can be evaluated quantitatively.

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