Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

Evaluation of contact stiffness between solid-solid interfaces using dual-frequency ultrasound

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PACS: 43.35.+d, 43.25.+y, 81.70.Cv

ABSTRACT

Acoustical methods are playing an important role for nondestructive evaluation (NDE) of adhesive-bonded composites and components in industrial applications. A dual-frequency ultrasonic technique is proposed for the quantitative evaluation of contact strength between pressed solid surfaces. An ultrasonic excitation consists of two primary frequency components is applied perpendicular to the interface, and the transmitted wave is examined. Theoretical study is based on a perturbation analysis of contact acoustic nonlinearity (CAN) model, predicting the generation of difference and sum frequency waves, together with the second harmonics. Nonlinear parameters are defined to describe the nonlinearity generation efficiencies. Experiments are performed for three types of interfaces, i. e. the interfaces of two aluminum alloy blocks with and without couplant and two glass blocks. The difference frequency wave component has bigger generation efficiency than other nonlinear components, which offers an advantage of high SNR and good detection capability of contact stiffness (interfacial stiffness). For each interface, the first and second-order interfacial stiffness are measured with contact pressure increasing from near zero to about 0.8 MPa with the aid of a laser interferometer. Finally, numerical simulations are also carried out, and a consistency is found between measurements and calculations. The dual-frequency ultrasound sent to the interface generates at least four second-order nonlinear components, which enriches the CAN technique for interface quality examinations. Both measured and simulated results indicate an increase of interfacial stiffness and decrease of nonlinear parameters with growing contact pressure. Moreover, measured results show that couplant between interfaces influences the contact stiffness evaluations in an enhanced manner, while the contact pressure determined by measured interfacial stiffness values are underestimated due to the couplant. The main problem comes from the contact between the transducer-sample interfaces, which brings extra nonlinearity to the detected signals and affect the accuracy of measuring.

INTRODUCTION

In the nondestructive evaluation (NDE) of adhesive-bonded composites and components, ultrasonic methods have attracted much interest. In industrial applications such as electronics, aerospace, and shipbuilding etc., ultrasonic evaluations allow the detection of potential fracture risks, such as delaminations and debondings. The state of the art of contact evaluations includes pulse-echo, resonant ultrasound spectroscopy and acoustic imaging techniques [1]. However, quantitative evaluations have not been achieved yet.

For cracks or defects, a high level nonlinearity might be induced by their contact behaviours, which is known as the contact acoustic nonlinearity (CAN) and has promising potential applications for discriminating flaws and inhomogeneities in samples. Theoretical [2] and experimental [3] studies conducted by Richardson *et al* revealed that CAN is caused by passage of a longitudinal acoustic wave across the interface, and the harmonic amplitude is a function of the pressure applied normal to the interface. However, the hypothetical perfect smooth interface, which is the base of their works, does not exist in real applications. In reality, contact surfaces have certain roughness, and are accounted for by several models. Representitive works carried out by Pecorari [4] and Gusev *et al* [5-7] indicate that nonlinearity is generated at the interface. However, the pressure-dependent characteristics of generated nonlinearity require further investigations.

To describe the topology and ultrasonic response of rough interfaces, various statistical models are developed. The first concern is the pressure dependent contact stiffness (interfacial stiffness) between solid interfaces, which is linked to the roughness topology by Rudenko *et al* [8], Drinkwater *et al* [9] and then Kim *et al* [10, 11]. The interaction of interfaces could be described using a spring boundary or other models such as a relaxator, and the interfacial stiffness changes sensitively with the contact pressure [11]. In the theoretical [12] and experimental [13] studies by Biwa *et al*, the interfacial stiffness was obtained from measured ultrasonic reflection/transmission coefficients together with nonlinearity coefficients. However, it is impossible to directly compare the theoretical and experimental results in a quantitative manner, as there is a lack of absolute calibration of the measured wave amplitude [13].

This study aims at quantitative evaluation of the interfacial stiffness of contacting interfaces by using a dual-frequency ultrasonic technique. A theoretical analysis using a perturbation method indicates that difference- and sum-frequency waves, together with second harmonics, are generated from contacting interfaces irradiated by dual-frequency ultrasound. Theoretical analysis is testified by numerical simulations and experiments performed on different samples. The first- and second-order interfacial stiffness values are obtained from measured spectral amplitudes calibrated with a laser interferometer. The pressure dependences of defined nonlinearity parameters are also examined.

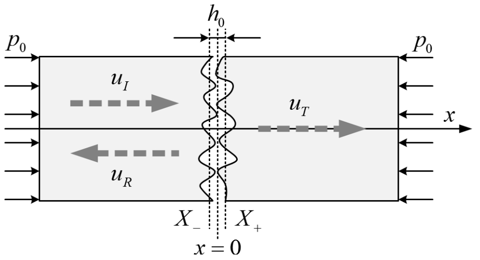

Figure.1 Geometrical sketch of the considered model.

METHODS

Theoretical Analysis

A geometrical sketch of the considered model is illustrated in Figure 1. As has been considered by other researchers [2, 11, 12], two elastic solids of identical material are pressed together by an external pressure p_0. The contacting surfaces are considered as flat with certain roughness, while their average height in x-direction are defined as the reference planes at X_- and X_+, which leads to a gap distance of $h = X_+ - X_-$. Actually, the gap distance is a function of the dynamic pressure p and has an initial equilibrium distance h_0 at the contact pressure p_0. Assuming that u_I, u_R and u_T are the displacement fields of the incident, reflected and transmitted waves, $X(t)=[u(X_-, t)+u(X_+, t)]/2$ is introduced as the "center of gravity" of the contacting interfaces, while $Y(t)= u(X_+, t)-u(X_-, t)$ is the dynamic gap distance. The vibration of the gap could then be described by,

$$\dot{X} = -cu_I(-ct) \quad (4a)$$

$$\dot{Y} = 2cu_I'(-ct) + 2\left(-K_1Y + K_2Y^2\right)/rc \quad (4b)$$

The incident dual-frequency ultrasound is composed of two monochromatic sinusoidal components with zero initial phase angles, while w_1 and w_2 are the two primary angular frequencies (assuming that $w_1>w_2$), A_1 and A_2 are the corresponding displacement amplitudes. A perturbation method is therefore applied for analytical nonlinear solutions of equation (4b). The gap distance Y is composed of linear component Y_1 and second-order perturbation Y_2, determined by,

$$\dot{Y}_1 + \frac{2K_1}{rc}Y_1 = 2A_1w_1\sin w_1t + 2A_2w_2\sin w_2t \quad (6a)$$

$$\dot{Y}_2 + \frac{2K_1}{rc}Y_2 = \frac{2K_2}{rc}Y_1^2 \quad (6b)$$

The transmitted waves are hence obtained,

$$u_T(-ct_2) = A_T^{(0)} + \sum_{i=1}^{2} A_T^{(i)}\cos\left(w_it_2 + \Phi^{(i)}\right) + \sum_{j=3}^{6} A_T^{(j)}\sin\left(w_jt_2 + \Phi^{(j)}\right) \quad (7)$$

in which $t_2=t-x/c$, $w_3=w_1+w_2$, $w_4=w_1-w_2$, $w_5=2w_1$ and $w_6=2w_2$. The amplitudes $A_T^{(i)}$ are expressed as,

$$A_T^{(0)} = K_2/K_1\left(\hat{A}_1^2 + \hat{A}_2^2\right) \quad (8a)$$

$$A_T^{(1)} = -2\hat{K}_1\hat{A}_1, \qquad A_T^{(2)} = -2\hat{K}_2\hat{A}_2 \quad (8b)$$

$$A_T^{(3)} = -4k_3\hat{A}_1\hat{A}_2K_2/K_1, \qquad A_T^{(4)} = -4k_4\hat{A}_1\hat{A}_2K_2/K_1 \quad (8c)$$

$$A_T^{(5)} = -k_1\hat{A}_1^2\,K_2/K_1, \qquad A_T^{(6)} = -k_2\hat{A}_2^2\,K_2/K_1 \quad (8d)$$

in which the following symbols are introduced,

$$\hat{K}_i = K_1/rcw_i, \quad k_i = \hat{K}_i\Big/\sqrt{1+\hat{K}_i^2}, \quad i=1,2,3,4, \quad (10a)$$

$$\hat{A}_j = -A_j\Big/\sqrt{1+4\hat{K}_j^2}, \quad j=1,2, \quad (10b)$$

The phase angles of each wave component are not concerned, and are omitted here. The analytical results indicate the second harmonics, sum- and difference-frequency waves and "DC" components are contained in the transmitted waves. The second harmonic amplitudes are proportional to the square of corresponding primary wave amplitudes; while the amplitudes of difference- and sum-frequency waves are linear functions of both primary wave amplitudes.

To quantitatively measure the generation efficiencies of sum- and difference-frequency waves, following nonlinear parameters are definded,

$$b_T^{(sum)} = \left|A_T^{(3)}\Big/\left(A_T^{(1)}A_T^{(2)}\right)\right| = 4k_3\,K_2/K_1 \quad (11a)$$

$$b_T^{(diff)} = \left|A_T^{(4)}\Big/\left(A_T^{(1)}A_T^{(2)}\right)\right| = 4k_4\,K_2/K_1 \quad (11b)$$

which are correlated to the contact pressure p_0 and independent on the amplitudes of the incident ultrasonic waves A_1 and A_2. In the previous studies by other researchers [11, 12], nonlinearity parameters were defined as the ratio of the second harmonic amplitude to the squared primary wave amplitude,

$$b_T^{(1)} = \left|A_T^{(5)}\Big/\left(A_T^{(1)}\right)^2\right| = 4k_1\,K_2/K_1 \quad (12a)$$

$$b_T^{(2)} = \left|A_T^{(6)}\Big/\left(A_T^{(2)}\right)^2\right| = 4k_2\,K_2/K_1 \quad (12b)$$

which reflect the generation efficiencies of second harmonics and are also independent of the amplitude of excitation.

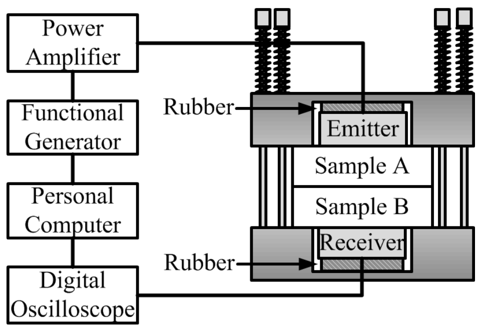

Figure. 2. Experimental setup.

Experimental setup

In experiments, two pieces of sample blocks were pressed together by a mechanical system as is shown in Figure 2. The emitting and receiving transducers were pressed towards the samples using Vaseline as couplant medium, while rubber pads were placed at their backs to maintain constant pressure at the transducer-sample interfaces. Two kinds of sample materials were used. One was aluminum alloy, with its density and sound velocity measured to be 2708.3 kg/m^3 and 6030.5 m/s; the other was glass, whose density and sound velocity were measured to be 2517.2kg/m^3 and 5916.3m/s, respectively. For the aluminum alloy samples, the contacting interface with and without Vaseline as couplant were examined. All samples used had a rectangular contact surface of dimensions 30 mm × 30 mm; the length along the wave propagation direction was 5 mm. Before the measurements, the contacting surfaces of aluminum alloy samples were polished with No. 1000 sand-paper, all samples were subjected to three loading/unloading cycles to flatten the contact asperities, which ensured that pressure-dependent hysteresis was eliminated [9, 12].

A function generator (Agilent 33250A, USA) was used to produce repeating dual-frequency electric pulses (500 and 800 kHz) at a repetition frequency of 0.1 kHz and the pulse length was 80 μs. The signal was windowed with a Hanning function, and amplified by a broadband 55 dB RF power amplifier (ENI 150A, USA), then used to drive the emitter. The emitter was a broadband piezoelectric transducer with a nominal frequency of 500 kHz (Panametrics V413-SB). Two piezoelectric transducers were chosen as receivers: receiver #1 (Panametrics V413-SB) was used to detect wave components that have frequencies less than 1 MHz and receiver #2 (Panametrics V401-SB, nominal frequency 1 MHz) for higher frequency wave packets. The detected signals were sent to a digital oscilloscope (Agilent 54830B, USA) at a sampling frequency of 250 MHz. A personal computer was used to control the waveform generator and the oscilloscope.

Prior to all other measurements, the vibration amplitudes produced by the emitter at the angular frequencies of w_i (i=1, 2, 4, 6) were measured with a laser interferometer (Polytec OFV-505/5000, Germany), when the excitation voltage (peak-to-peak value) was 248V. Consequently, measured voltage values produced by the receivers in experiments were calibrated to displacement amplitudes.

For each pair of samples, total of 12 measurements were performed at different pressure levels as contact pressure increases from 0.03 MPa to 0.8 Mpa. In each measurement, the excitation voltage applied to the emitter (peak-to-peak value) was kept to be 248V. The detected transmitted signals were averaged over 32 traces to enhance the signal noise ratio, and then analyzed in the frequency domain using a Fast-Fourier-Transform program, finally converted to absolute displacement amplitudes.

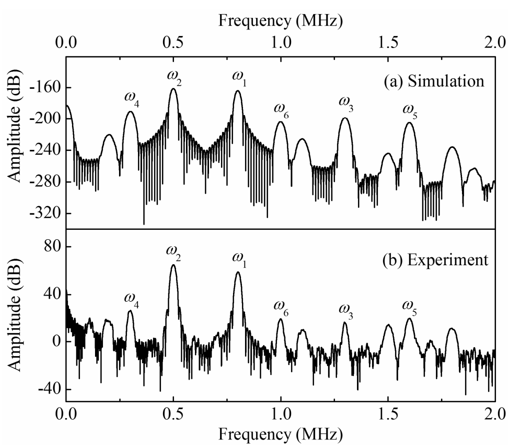

Figure. 3. Frequency spectrum of transmitted waves for uncoupled aluminum interfaces.

Numerical simulations

The ordinary differential equation 4(b) was directly solved with fourth-order Runge-Kutta algorithm to provid a comparison with the analytical solutions and measured results. In the simulations, the pressure dependent interfacial stiffness values were determined by the power-law model [12],

$$K_1 = C p_0^m \tag{13a}$$

$$K_2 = \frac{1}{2} m C^2 p_0^{2m-1} \tag{13b}$$

in which C and m are positive constants correlated to the material and topology of the interfaces, such as the radius of asperities and their height distributions [9, 11]. In this study, C and m used in numerical simulations were determined from the measured pressure dependence of linear interfacial stiffness K_1 fitted by equation (13a); and K_2 was therefore obtained using equation (13b).

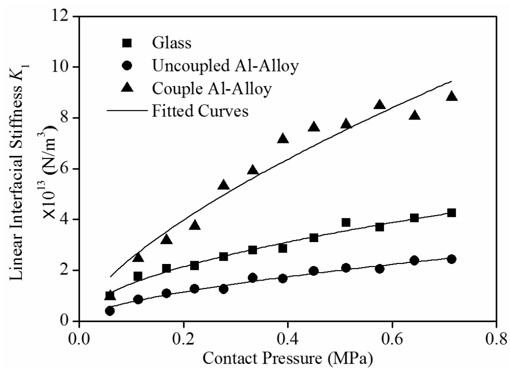

Figure. 4 Measured linear interfacial stiffness K_1.

RESULTS AND DISCOSSIONS

Generation of nonlinearity

As is described in equation (7), nonlinearities generate from the interaction between the dual-frequency ultrasound and the contacting interface. Figure 3 shows the spectrum of the measured transmitted ultrasonic signal through the aluminum alloy interface under the contact pressure of 660 kPa. Result of numerical simulation is also provided in this figure. Obviously, both simulation and experiment indicate the generation of difference- and sum-frequency waves, second harmonics and the zero-frequency "DC" component. The difference-frequency wave is found to have bigger generation efficiency than other nonlinear components in both cases, which offers an advantage of high SNR and good detection capability of contact stiffness. Noted that the "extra" spectral components at other frequencies, such as 200 kHz, 1.1 MHz and 1.5 MHz, etc, are not predicted in the theoretical analysis but observed in both simulations and experiments. The reason is that the used governing equations only contain the first- and second-order perturbations of the dynamic gap distance Y. Consideration of higher order perturbation equations is unnecessary, as the amplitudes of the "extra" waves are relatively low.

The interfacial stiffness

The ratio of either two nonlinearity parameters defined in equations (10) and (11) is a function of linear interfacial stiffness K_1 and independent on K_2, thus could be an effective evaluation of the linear interfacial stiffness. In this study, $b_T^{(diff)}/b_T^{(2)}$ is adopted for the calculations.

For all three tested interfaces, the pressure dependences of K_1 were presented in Figure 4. In all the cases, the first-order interfacial stiffness increases monotonously with the contact pressure, which indicates a decrease of nonlinearity in the transmitted ultrasonic waves. Furthermore, the aluminum alloy interfaces coupled by Vaseline show the strongest contact and the uncoupled aluminum alloys is the weakest. The measured pressure dependences of K_1 were fitted by equation (13a), and the interface constants C and m were thus determined as: a) C=2.89×10^{10} and m=0.54 for the glass interface, b) C=6.85×10^{9} and m=0.61 for the uncoupled aluminum alloy interface and c) C=9.72×10^{9} and m=0.68 for aluminum alloy interface with couplant.

The calculated K_1 values were then used for the determination of second-order interfacial stiffness K_2 via equation (11b) and (12b), which was selected as the average of that determined by both equations. The obtained contact pressure dependences of K_2 are illustrated in Figure 4. The case of a coupled aluminum alloy interface has the largest second-order stiffness while the same uncoupled interface has the smallest. Besides, K_2 shows no obvious increasing or decreasing with the growing contact pressure.

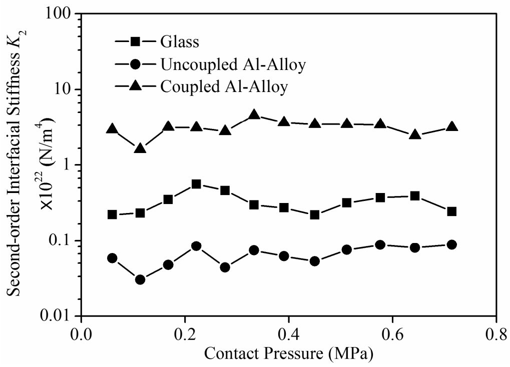

Figure. 5 Measured second-order interfacial stiffness.

Other discussions

In this study, the interfacial stiffness values are derived from measured nonlinearity parameters, which are obtained after a calibration using the optical interferometer. In traditional studies using monochromatic excitations, linear/nonlinear reflection/transmission coefficients were utilized to acquire K_1 and K_2. In one of the experimental studies by Biwa *et al* [13], the measured pressure dependences of K_1 were fitted by a polynomial expression and then used to determine K_2. To some extent, the use of reflection/transmission coefficients is more reasonable in the determination of interfacial stiffness, as it covers the influence of measuring system more or less. However, it demands the measurements of both reflected and transmitted waves, as in the representative works by Pecorari et al [14] and Biwa *et al* [13].

For the choice of ultrasonic nonlinearity parameters, there are two options: a) second harmonic amplitude to fundamental amplitude and b) second harmonic amplitude to squared fundamental amplitude. The latter is preferred in our view, because it's independent on the amplitude of excitation, as is predicted in equations (11), (12) and the work of other researchers [11, 12]. The latter choice also keeps formal consistence with the two additional nonlinearity parameters defined for difference- and sum-frequency waves. With the adopted nonlinearity parameters, quantitative comparison between theoretical and corresponding experimental results become possible, which makes the dual-frequency technique more valuable in the NDE of apparently closed cracks or imperfect bonds.

In measurements, errors come from the contacting at transducer-sample interfaces and multi-reflections inside the sample blocks, which generates extra nonlinearities. Since the calculation regards all the nonlinearities in detected signals to be generated from the sample-sample interface, the contact between investigated surfaces are mistaken as "softer" than they really are. Accurate evaluation of the contact strength requires an approach of all three involved interfaces.

CONCLUSION

Inspection of the quality of interfaces by examination of the contact strength is of great significance in modern NDE technology. A dual-frequency ultrasonic technique has been studied in this work for the quantitative prediction of linear and nonlinear interfacial stiffness. The interaction between irradiated dual-frequency ultrasound and the interfaces generates not only harmonic waves, but also difference- and sum-frequency components, which has been testified by both theoretical and experimental studies. According to the measurements from three types of interfaces, it is found that generated nonlinearities decrease with the growing contact strength, while couplant between interfaces enhances the strength of contact. The main problem comes from the contact between the transducer-sample interfaces, which brings extra nonlinearity to the detected signals and affect the accuracy of measuring. For a better interpretation and evaluation of the contacting behavior of solid interfaces, the nonlinearity caused by the contact-type measurement should be taken into account. More accurate measurements require a combined study of the reflection/transmission technique and quantitative methods, such as the dual-frequency evaluation.

AKNOWLEDGEMENTS

This work is supported by the China Postdoctoral Science Foundation (Contract No. 20090450146), National Natural Science Foundation of China (Grant No. 10974098), and National Basic Research Program 973 (Grant No. 2010CB732600) from Ministry of Science and Technology of China.

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