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Development of Pressure Control System of Contact Transducer for Measurement of Ultrasonic Nonlinear Parameter

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Abstract Ultrasonic nonlinearity has been considered as a promising method to evaluate the micro damage of material; however, its magnitude is so small that its measurement is not easy. Especially, when we use contact PZT transducer, if the contacting pressure is not kept in constant during the measurement then there exists extraneous fluctuation in the measured nonlinearity caused by the unstable contact condition. In this paper, we developed a pneumatic control system to keep the contacting pressure of transducer in constant during the measurement and analyzed the effect of contacting pressure to the ultrasonic nonlinearity measurement. As a result, we found that the pressure of transducer in our measurement system should be greater than 170 kPa to measure the ultrasonic nonlinear parameter in stable with no dependency on the contacting pressure.

Keywords: Ultrasonic Nonlinear Parameter, Ultrasonic Transducer, Contacting Pressure, Pneumatic Control

1. Introduction

In recent years, there is a growing interest in using nonlinear effects in the ultrasonic wave propagation for nondestructive evaluation of micro damage in materials (Na et al, 1996; Berndt and Green, 1998; Jhang and Kim, 2001 and Jhang et al, 2004). The distinguished phenomenon in nonlinear ultrasonics is the generation of higher-order harmonic waves during the propagation. Therefore, in order to quantify the nonlinearity, we use to measure a parameter β defined as the amplitude ratio of a second-order harmonic component and a fundamental frequency component included in the propagated ultrasonic wave signal (Jhang, 2000).

This parameter is the relative value rather than the absolute value of material nonlinearity. In spite of that, this parameter makes the evaluation of material degradation available by monitoring the change from the initial value. Only the point that we have to pay attention in the measurement of this parameter is to hold all conditions of measurement in consistent. Especially, when we use contact transducer, if the contacting pressure is not kept in constant during the measurement, then there exist extraneous fluctuation in the measured nonlinearity caused by the unstable contact condition.

In order to overcome this problem, we developed a pneumatic control system to keep the contacting pressure of transducer in constant during the measurement and analyzed the effect of contacting pressure to the ultrasonic nonlinearity measurement. The performance of the pneumatic control system was verified by

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showing that the contacting force between transducer and specimen is linearly dependent on the input pressure. Next, with this system, we investigated the change in the amplitude of transmitted wave and in the measured nonlinear parameter, when the input pressure is changed. These results can be provided as a reference for the guideline in the experimental system construction to measure the nonlinear parameter by using a contact transducer.

2. Nonlinear Acoustic Effect

To explain the generation of higher order harmonic waves, we now consider the case where a single frequency ultrasonic wave (longitudinal) incident upon one end of a block specimen propagates through the medium and is detected on the other end, as shown in Fig. 1.

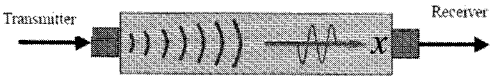

Fig. 1 One-dimensional wave propagation

Then, we begin with the one-dimensional nonlinear stress-strain relation as shown in eqn. (1) (Jhang, 2000).

$$\sigma = E\varepsilon(1+\beta\varepsilon+\cdots) \tag{1}$$

Where σ is stress, ε is strain, E is Young's modulus, and β is the 2nd order nonlinear parameter. If we now assume that the attenuation can be neglected, then the equation of motion for longitudinal waves in the medium can be represented as follows:

$$\rho\frac{\partial^2 u}{\partial t^2} = \frac{\partial \sigma}{\partial x} \tag{1}$$

Where, ρ is the density of the medium, and u is the displacement. Using eqns. (1) and (2) and the relationship between strain and displacement, $\varepsilon(x,t) = \frac{\partial u(x,t)}{\partial x}$, we can obtain the nonlinear wave equation for displacement $u(x,t)$ as follows:

$$\rho\frac{\partial^2 u}{\partial t^2} = E\frac{\partial^2 u}{\partial x^2} + 2E\beta\frac{\partial u}{\partial x}\frac{\partial^2 u}{\partial x^2} \tag{3}$$

Where, we considered eqn. (1) up to the 2nd order. To obtain a solution, a perturbation theory is applied. For this purpose, the displacement u is assumed as in eqn. (4).

$$u = u_1 + u_2 \tag{4}$$

Where, u_1 is the primary solution and u_2 is the secondary solution. If we set u_1 to a sinusoidal single frequency wave form, or

$$u_1 = A_1\sin(kx-\omega t) \tag{5}$$

then, we can obtain the secondary solution as follows (Cracker, 1997):

$$\begin{aligned} u_2 &= A_2\cos 2(kx-\omega t) = \\ &\frac{\beta}{4}A_1^2 k^2 x \cos 2(kx-\omega t) \end{aligned} \tag{6}$$

Where, A_1 and A_2 are the amplitudes of the primary and secondary solution, k is the wave number, and x is the propagation distance.

As we can see, the secondary solution has 2nd harmonic frequency component and its magnitude depends not only on A_1, k, x, but also on β. Thus, for the quantitative representation of nonlinearity, parameter β is defined as eqn. (7).

$$\beta = \frac{8A_2}{A_1^2 k^2 x} \tag{7}$$

This parameter is a material constant, thus if the elastic property of material varies with the degradation, then the value of β also varies. Therefore, we can evaluate the degradation of material by measuring the value of β and comparing it with the value at the virgin state.

Since the parameter β depends on the ratio of the amplitude of the 2nd order harmonic component and the power of fundamental component when other variables, k and x, are constant, the normalized parameter β' as shown in eqn. (8) is usually measured instead of β.

$$\beta' = \frac{A_2}{A_1^2} \tag{8}$$

Only the point that we have to pay attention in the measurement of nonlinear parameter is to hold all conditions of measurement in consistent for different specimens to be measured and compared. This is because experimental equipments and set-up conditions may cause extra harmonic components in the waveform.

In addition, when we use contact transducer, however, we have to consider the contacting pressure of transducer, because the unstable contact condition between transducer and specimen may cause undesirable fluctuation in the measured nonlinearity. Firstly, insufficient contact of transducer will greatly reduce the efficiency in the acoustic energy transfer from the transducer to the specimen, and the amplitude of A_1 will be down. In this case, A_2 depending on A_1^2 will be much smaller as comparable to the level of background noise and it will be difficult to measure. Secondly, if the transducer contact condition is not sufficient, then the incident waveform may be partially rectified, which produces extra harmonics in the incident waveform itself. This can be explained by the contact acoustic nonlinear effect (Kawashima, 2007). Once this extra harmonics are mixed up with the harmonics caused by the material nonlinearity, it is difficult to identify the harmonics by material nonlinearity.

Resultantly, the transducer should be contacted at sufficient and constant pressure. For this, we developed a pneumatic control system to keep the contacting pressure of transducer at constant during the measurement. Also we will experimentally verify the effect of transducer contacting pressure to the measurement of nonlinear parameter and find out a reasonable minimum pressure.

3. Automatic Contacting Pressure Control System

Fig. 2 shows the schematic diagram of whole measurement system including the developed pneumatic controller, which is designed to hold ultrasonic transducer and specimen, and deliver a constant pressure to them. Test specimen is Al6061 and its length is 50 mm.

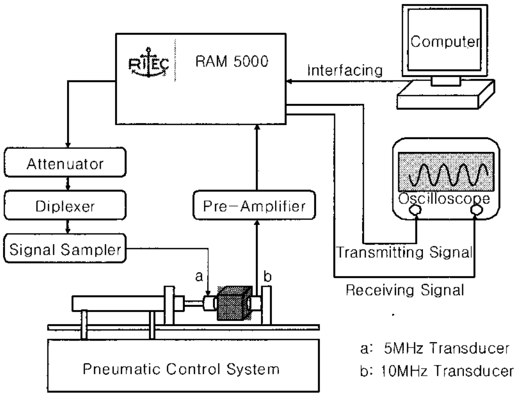

Fig. 2 Automatic contact-pressure control system for ultrasonic transducer

Signal control is mainly based on RAM-5000 (RITEC, USA) equipment that transmits and receives ultrasonic wave. In this system, primary frequency is 5 MHz, so that a 5 MHz narrowband transducer is used as transmitter and a 10 MHz broadband transducer is used as receiver to detect secondary wave sensitively. 5 MHz tone burst signal is transferred to the transmitter from RAM-5000. The burst size is 10 cycles. From the received signal we estimate the amplitude of primary wave and 2nd harmonic component by spectral analysis to calculate the nonlinear parameter β'. For one measurement of β', 100 signals were averaged to reduce the additive random noise.

Fig. 3 shows the pneumatic part in detail. This part consists of 6 components; double acting pneumatic cylinder, solenoid valve, lubricator, digital pressure gauge, filter regulator and nitrogen gas tank. Once nitrogen gas gets out of tank, the pressure of gas is controlled by filter regulator and we check the pressure level with digital pressure gauge (Simen Tech, SMT-RS 1000). After fixing a specific pressure, nitrogen gas moves through lubricator and operates double acting pneumatic cylinder in back and forth. Solenoid valve actuated by on/off switch controls the moving directions of pneumatic cylinder.

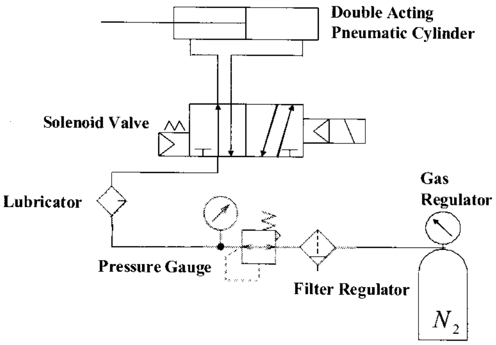

Fig. 3 Construction of pneumatic control system

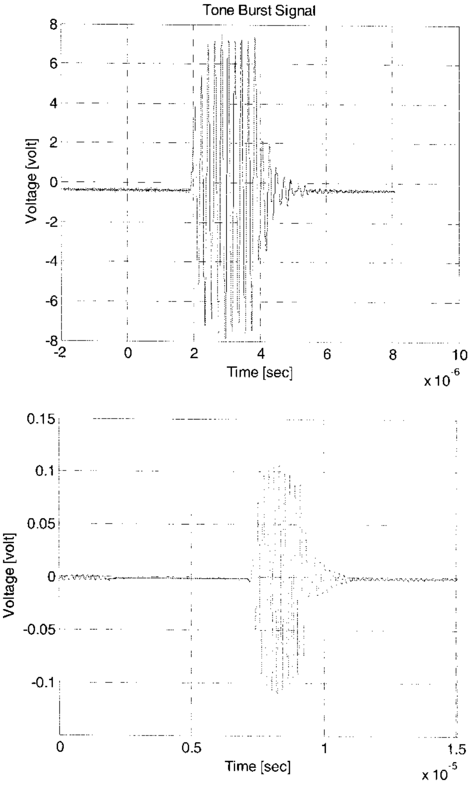

Fig. 4 Example of transmitted signal (upper) and received signal (lower)

Fig. 4 shows examples of signals transmitted and received. Fig. 5 is the power spectrum of the received signal shown in Fig. 4. We can see the 2nd harmonic frequency component (10 MHz) beside fundamental frequency component (5 MHz).

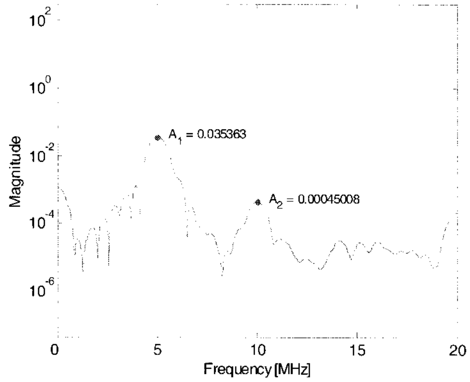

Fig. 5 Power spectrum of the received signal shown in Fig. 4

4. Experimental Results

4.1 Performance of Pressure Control

In order to verify the performance of the pressure control system, we have investigated the relationship between the input pressure and the output force acting at the transducer. The force was measured at the interface of transducer and specimen by the force transducer (IMADA DPS-0.5 kgf & HALDA, HALMSTAD-4 kgf). In general, the relationship between

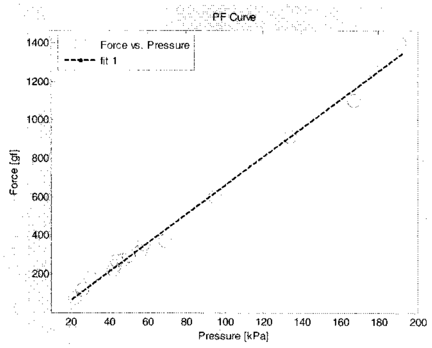

Fig. 6 Force measured at the interface of transducer and specimen as increasing the input pressure of pneumatic system

pressure and force should be linear. Fig. 6 shows the result of experiment, which has good linear correlation between them.

From this result, we can assure that the transducer contacting force (or pressure) is controlled in stable by the input gas pressure. With this system, we will be able to carry out experiments in stable condition of transducer contacting pressure.

4.2 Relationship between Pressure and V_{p-p}

Next, we tested the relationship between pressure and V_{p-p} (peak-to-peak) of transmitted wave, because V_{p-p} of the received signal is a confidential index to verify the contact condition between transducer and specimen. The value of V_{p-p} at good contact would be higher than other imperfect contact condition.

Fig. 7 shows the result. We have obtained V_{p-p} as increasing the pressure up to 200 kPa by 10 kPa step, and it was measured three times at each pressure. The measured values of V_{p-p} showed big deviation in low-pressure range, of which deviation was caused by the insufficient contact condition of transducer. While, when the pressure is over 170 kPa it comes stable, and hence we can decide that the contact pressure of transducer should be at least 170 kPa in this experimental set-up.

4.3 Relationship between Pressure and Nonlinear Parameter

As a next stage, we have investigated the relationship between pressure and measured nonlinear parameter β', because we want to know how this nonlinear parameter is dependent on the contact pressure of transducer. In the similar way as previous experiment, we have made experiments by increasing the pressure and obtained data three times at each pressure.

Fig. 8 shows the result. In the low-pressure range, deviation of nonlinear parameter is very high. Meanwhile, in the pressure range over 140 kPa, the nonlinear parameter is settled down. This result shows that we have to measure the signal when the contact pressure is over 140 kPa to get nonlinear parameter in stable.

Then, this pressure limit is slightly different from the pressure limit in the previous experiment. This would be explained as follows. The amplitude of second harmonic wave, A_2, is quadratically dependent on the amplitude of fundamental wave, A_1, as represented in eqn. (7). Thus, if the detected signal satisfies this relationship even when there are deviations in V_{p-p}, then any deviation would not be appeared in the measurement of nonlinear parameter. That is, there is no requirement that

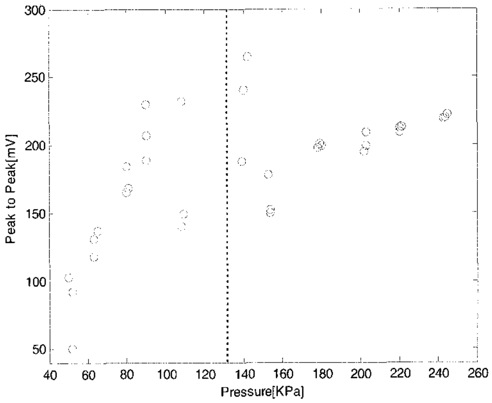

Fig. 7 Measured peak-to-peak value (V_{p-p}) of received signal as increasing the input pressure of pneumatic system

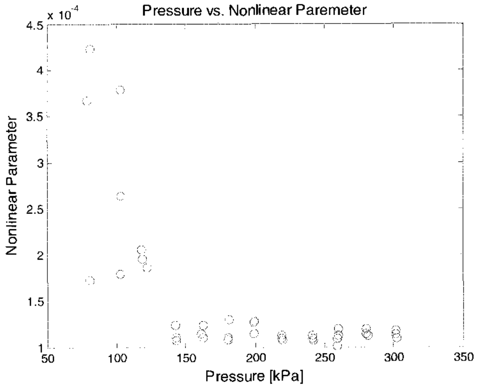

Fig. 8 Measured nonlinear parameter as increasing the input pressure of pneumatic system

the minimum pressure levels to get stable signal amplitude and to get stable nonlinear parameter should be identical. Since our goal is to measure nonlinear parameter in stable, not to measure V_{p-p}, the minimum pressure level can be determined as 140 kPa. However, in order to ensure the fully stable contact condition of transducer, we recommend the pressure level larger than 170 kPa in our system.

5. Conclusions

With all design and experiments, we can conclude as below:

1) Our automatic contact-pressure control system can supply a specific constant pressure on the transducer. Operation gas pressure has good linear correlation with the force acting on the interface between transducer and specimen. This system enables the transducer to contact on the specimen at constant pressure during the measurement.
2) With the developed transducer contact-pressure control system, we could show the dependency of the nonlinear parameter measured by using contact transducer upon the contact condition between transducer and specimen. In order to ensure the reliability in the measurement of nonlinear parameter, the contact pressure should be greater than 170 kPa in our system. In this contact pressure range, the nonlinear parameter was measured in constant regardless of pressure change.
3) In this paper, however, we did not discuss on the upper limit of contact pressure. We are expecting that too high contact pressure may affect to the nonlinear behavior of ultrasonic wave. This problem should be studied furthermore.

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