Measurement of Ultrasonic Nonlinear Parameter for Fused Silica using Piezo-electric method

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Abstract

Nonlinear ultrasonic technique (NUT) is one of the promising non-destructive methods to evaluate the variation of elastic properties induced by material degradation such as thermal aging, creep, and fatigue [1-3]. The NUT is based on nonlinear elastic interaction between a propagating ultrasonic wave and nonlinear behavior of a material. When a single frequency ultrasonic wave propagates through a material, harmonic frequency components are generated by the nonlinear elastic interaction. The NUT uses this nonlinear ultrasonic effect to evaluate variation of elastic properties of a material by measuring an ultrasonic nonlinearity parameter. The ultrasonic nonlinear parameter $\beta$ is defined by the ratio of the second harmonic displacement amplitude to the squared fundamental displacement amplitude as follows [1-4]:

$$\beta = \frac{8A_2}{k^2xA_1^2}$$  \hspace{1cm} (1)

where, $A_1$ is the displacement amplitude of the fundamental component, $A_2$ is the displacement amplitude of the second harmonic component, $k$ is the wave number and $x$ is the propagation distance.

Keywords: Ultrasonic Nonlinear Parameter, Fused silica, Nonlinear Ultrasonic Technique

1 Introduction

Nonlinear ultrasonic technique (NUT) is one of the promising non-destructive methods to evaluate the variation of elastic properties induced by material degradation such as thermal aging, creep, and fatigue [1-3]. The NUT is based on nonlinear elastic interaction between a propagating ultrasonic wave and nonlinear behavior of a material. When a single frequency ultrasonic wave propagates through a material, harmonic frequency components are generated by the nonlinear elastic interaction. The NUT uses this nonlinear ultrasonic effect to evaluate variation of elastic properties of a material by measuring an ultrasonic nonlinearity parameter. The ultrasonic nonlinear parameter $\beta$ is defined by the ratio of the second harmonic displacement amplitude to the squared fundamental displacement amplitude as follows [1-4]:

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Only a few methods such as capacitive, interferometric, and piezo-electric methods have been typically conducted. However, the capacitive transducer and laser interferometer have low sensitivity, since they are easily affected by surface roughness. In contrast, the piezo-electric transducer can overcome the effect of the surface conditions by using couplant; furthermore, it has higher signal to noise ratio than the other methods [6].

The ultrasonic nonlinear parameter measurement using a surface ultrasonic wave is conducted in changing a propagation distance to measure pure nonlinearity of a material because system nonlinearity does not change regardless of the propagation distance [7]. However, it is difficult to measure the ultrasonic nonlinear parameter using a bulk wave for a solid in changing the propagation distance though it is possible to change the propagation distance in fluid such as water [8]. Hence, the ultrasonic nonlinear parameter measurement was conducted in fixed propagation distance in many studies [2, 5-6].

In this study, the ultrasonic nonlinear parameter using the bulk wave is measured in changing the thickness of the material comparing with the measurement in increasing the incident wave amplitude in the fixed thickness. The stability of the ultrasonic nonlinear parameter measurement is verified from the results of two measurements.

2 Piezo-electric method

The piezo-electric method developed by Dace et al [9] measures displacement amplitude of an ultrasonic wave propagating through a material in a roundabout way from electric signal obtained by a piezo-electric transducer. This technique obtains a transfer function $H(\omega)$ that converts received current signal into displacement of propagating wave as follow [10]:

$$H(\omega) = \frac{\left| V'_{\text{in}}(\omega) \frac{V'_{\text{out}}(\omega)}{I'_{\text{out}}(\omega)} + V'_{\text{in}}(\omega) \right|}{2\omega^2 \rho v a |I'_{\text{out}}(\omega)|}$$

(2)
where $I'_{\text{in}}$ and $V'_{\text{in}}$ are the current and voltage signal in the input signal, and $I'_{\text{out}}$ and $V_{\text{out}}$ are the current and voltage signal in the output signal, $\omega$ is the angular frequency, $\rho$ is the density of the material, $v$ is the sound velocity of the material and $a$ is the radius of the transducer. Then, an uncalibrated electric current signal $I(\omega)$ which is the received tone-burst signal is measured in harmonic measurement. From the transfer function $H(\omega)$ and current signal $I(\omega)$, the displacement of ultrasonic wave $A(\omega)$ is expressed as follows [10]:

$$|A(\omega)| = |H(\omega)||I(\omega)|$$

(3)

That is, the obtained electric signal in the harmonic measurement can be converted into displacement amplitude via the transfer function.

3 Experiments

The calibration measurement and harmonic measurement were conducted to measure the ultrasonic nonlinear parameter. At first the calibration measurement was conducted to obtain the transfer function. Then, the harmonic measurement was conducted to measure the second harmonic components after ultrasonic wave propagated through a specimen.

To verify the stability of the ultrasonic nonlinear parameter measurement, experiment was conducted for two cases. Firstly, a fused silica specimen with 20 mm thickness was tested for changing the fundamental displacement amplitude in a fixed propagation distance. Secondly, fused silica specimens with various thickness (10, 20, 30, 40 mm) were tested for changing the propagation distance in a fixed incident fundamental displacement amplitude.

3.1 Calibration measurement

Figure 1 shows an experimental setup for the calibration measurement. Pulser/Receiver (PR-5072, Olympus) was used to drive spike pulse and receive a signal. Lithium Niobate crystal with 15 MHz resonance frequency and 0.375 inch diameter was used as a receiver in order to receive the second harmonic component sensitively. Note that the calibration measurement was conducted only for the receiver. A current probe (CP030, Lecroy) and voltage probe (P5550, Tecktronics) were used to obtain input and output signal reflected from the backwall of the specimen. The signals were acquired by an oscilloscope (WaveSuffer452, Lecroy).
3.2 Harmonic measurement

Figure 2 shows the diagram of the harmonic measurement. A 7.5 MHz tone-burst signal was driven by high-power pulser (RAM-5000-SNAP, RITEC Inc). Lithium Niobate crystal with 7 MHz resonance frequency and 0.375 inch diameter was used as a transmitter. The receiver installed in the calibration measurement was used equivalently.

4 Results

Figure 3 shows results of the ultrasonic nonlinear parameter with respect to changing the fundamental displacement amplitude in fixed propagation distance 20 mm. The amplitude of second harmonic component is proportional to the square of the amplitude of the fundamental component. The ultrasonic
nonlinear parameter of fused silica is 9.18. For changing the propagation distance in the fixed incident fundamental displacement amplitude, second harmonic amplitude increases linearly according to propagation distance. The experimental results of ultrasonic nonlinear parameter are 7.21~10.47, which are similar with reported reference values (9 ~ 14) [10, 11-12].

5 Conclusions

In this study, the stability of the ultrasonic nonlinear parameter measurement using the piezo-electric method was verified by comparing the results of two measurements: 1) changing the fundamental displacement amplitude in a fixed propagation distance and 2) changing the propagation distance in a fixed incident fundamental displacement amplitude. The experimental results were similar in both two measurements and reported reference values. This means that the used method is reliable. Meanwhile, if attenuation and diffraction correction apply to experimental results, the more accurate value of the ultrasonic nonlinear parameter can be measured.

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References


