46th Annual Review of Progress
in Quantitative Nondestructive Evaluation
QNDE2019
July 14-19, 2019, Portland, OR, USA

QNDE2019-6854

MEASUREMENT OF ACOUSTIC NONLINEARITY PARAMETER IN STAINLESS STEEL USING ACOUSTOELASTIC EFFECT

Juyoung Ryu, Dong-Gi Song
Department of Mechanical Convergence Engineering,
Hanyang University
Seoul, Korea

Sungho Choi[1], Kyung-Young Jhang[1]
School of Mechanical Engineering,
Hanyang University
Seoul, Korea

ABSTRACT

The measurement of the acoustic nonlinearity parameter of stainless steel has been investigated using the acoustoelastic effect in which the elastic wave velocity changes depending on stress conditions. The stress-dependent coefficient, which is an index quantitatively representing the acoustoelastic effect, was measured and was used to calculate the acoustic nonlinearity parameter. In experiments, stainless steel 304 and stainless steel 316L were used, and the stress-dependent coefficients of the materials were measured from the velocity changes of longitudinal and transverse waves under various compressive stress conditions. From the measured stress-dependent coefficients, the second and third-order elastic constants were calculated, and then the calculated values were converted to the acoustic nonlinearity parameter. The acoustic nonlinearity parameters measured from the acoustoelastic effect approximated the reference values. Consequently, it would be effective to use the acoustoelastic effect when measuring acoustic nonlinearity parameter of stainless steel.

Keywords: acoustoelastic effect, acoustic nonlinearity parameter, stress-dependent coefficient, third-order elastic constants

NOMENCLATURE

E	linear elastic modulus
V	elastic wave velocity
$l,\ m,\ n$	Murnaghan's constants
t_0	time-of-flight of elastic waves under stress-free condition
α	stress-dependent coefficient
β	acoustic nonlinearity parameter
Δt	time-of-flight variation of elastic waves under stress condition
$\lambda,\ \mu$	Lamé constants
v	Poisson's ratio
ρ	density
σ	stress

1. INTRODUCTION

The nonlinear ultrasonic technique highly sensitive to microstructural degradation of materials has been actively studied. In this technique, the acoustic nonlinearity parameter (β) is used as an index that quantitatively indicates the microstructural characteristics of materials. The parameter β is a function of the second-order and third-order elastic constants and can be measured using the acoustoelastic effect [1,2].

In this study, the acoustic nonlinearity parameters of stainless steel 304 and 316L, widely used in industry, were measured by using the acoustoelastic effect. First, the stress-dependent coefficients were measured from the velocity changes of ultrasonic waves under various compressive stress conditions. Then, the third-order elastic constants were calculated using the measured Lamé constants and stress-dependent coefficients. Lastly, the acoustic nonlinearity parameter under uniaxial stress condition (β_l) was estimated using the calculated second-order and third-order elastic constants.

2. ACOUSTOELASTIC EFFECT

The acoustoelastic effect results in the slight changes of elastic wave velocity depending on the stress condition. The elastic wave velocity under uniaxial compressive stress can be expressed as [3]

$$V_{ij} = V_0\left(1 + \alpha_{ij}\frac{\sigma_{11}}{E}\right) \tag{1}$$

where V_{ij} is the elastic wave velocity under the applied stress condition, and the subscript i and j indicate the wave propagation direction and the particle movement direction of the wave, respectively. V_0, σ_{11}, and E mean the wave velocity under stress-free condition, the uniaxial stress, and the linear elastic modulus,

[1] Contact authors: sunghochoi@hanyang.ac.kr, kyjhang@hanyang.ac.kr

 © 2019 by ASME

respectively. α_{ij} indicates the stress-dependent coefficient, and can be expressed as

$$\alpha_{ij} = 1 + \frac{E}{\sigma_{11}}\left(\frac{\Delta t_{ij}}{t_0}\right) \tag{2}$$

where Δt_{ij} and t_0 are the time-of-flight (TOF) variation of the elastic wave and the TOF of the wave under stress-free condition, respectively.

Then, Murnaghan's constants can be obtained from the stress dependent coefficients in Eq. (2) and Lamé constants as follows [3]

$$l = \frac{[(-2\alpha_{11} + 5)(\lambda + 2\mu) + 4m] - 2\nu\lambda}{2(2\nu - 1)} \tag{3}$$

$$m = \frac{(\alpha_{11} - \alpha_{22})(\lambda + 2\mu)}{2\nu + 1} - \frac{\mu}{2} \tag{4}$$

$$n = \frac{2}{\nu}[-(\lambda + 4\mu + m) + 2\nu(\lambda + \mu + m) + 2\mu\alpha_{12} \tag{5}$$

Lastly, the acoustic nonlinearity parameter under uniaxial stress condition (β_t) can be determined using the Lamé constants and the Murnaghan's constants.

$$\beta_t = -\frac{1}{E}[2\lambda(\nu - 1)^2 + \lambda + 6\mu + 2l + 4m - 8\nu l + 2\nu^2(4l - 2m + n)] \tag{6}$$

3. EXPERIMENTS

The experimental setup is shown in Fig. 1. Stainless steel 304 and 316L specimens were prepared in 25 mm x 25 mm x 20 mm (width × length × thickness) sizes. The pulse-echo method was used to measure the TOF of longitudinal and transverse waves. In order to monitor the compressive stress in real time, the load cell was placed under the specimen and the hydraulic system was located at the top of the transducer holder, as shown in Fig. 1. Compressive force was increased by 1000 kg intervals from 1000 kg (≒ 14 MPa) to 4000 kg (≒ 56 MPa). The auto-correlation function was used to calculate the TOF of the received echo signals.

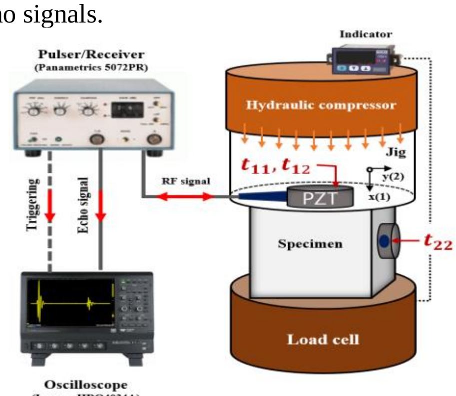

FIGURE 1: EXPERIMENTAL SETUP FOR PULSE-ECHO MEASUREMENTS

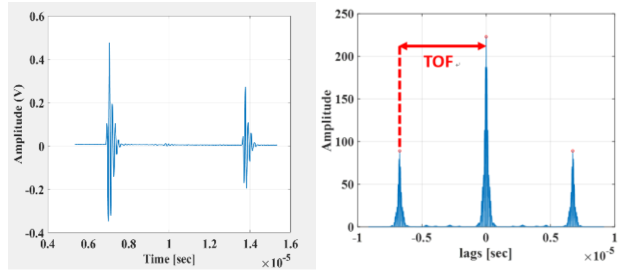

FIGURE 2: TYPICAL PULSE-ECHO SIGNAL AND ITS AUTO-CORRELATION RESULT

Typical pulse echo signal and its auto-correlation result are shown in Fig. 2. The measured second-order and third-order elastic constants, and the acoustic nonlinear parameters are summarized in Table 1.

TABLE 1: MEASURED SECOND-ORDER AND THIRD-ORDER ELASTIC CONSTANTS AND ACOUSTIC NONLINEARITY PARAMETER

	Acoustic nonlinearity parameter	Elastic properties		Second & Third-order elastic constant				
	β_t	ν	E [GPa]	λ [GPa]	μ [GPa]	l [GPa]	m [GPa]	n [GPa]
SUS316L	2.42 ± 0.11	0.285	197.8	102.8	76.9	-224.1	-390.8	-901.9
SUS304	2.86 ± 0.13	0.289	201.3	106.7	78.1	-200.1	-473.3	-714.9

4. CONCLUSION

The acoustic nonlinearity parameters of stainless steel 304 and 316L were measured using the acoustoelastic effect. The second-order elastic constants were obtained from the longitudinal and transverse wave velocities, and the third order elastic constants were obtained using the stress-dependent coefficients measured with increasing stress. The measured results approximated the reference values of stainless steel.

ACKNOWLEDGEMENTS

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (NRF-2013M2A2A9043241).

REFERENCES

[1] Jhang, Kyung-Young. "*Nonlinear ultrasonic techniques for nondestructive assessment of micro damage in material: a review*," International journal of precision engineering and manufacturing, Vol.10 No.1 (2009): pp.123-135. 10.1007/s12541-017-0018-3.

[2] Kim, Jongbeom, Lee, KyoungJun, Jhang, Kyung-Young and Kim, ChungSeok. "*Evaluation of Ultrasonic Nonlinear Characteristics in Artificially Aged Al6061-T6,*" Journal of the Korean Society for Nondestructive Testing, Vol.34 Issue 3 (2014): pp.220-225. 10.7779/JKSNT.2014.34.3.220.

[3] Takahashi, Sennosuke and Takahashi, Kiyoko. "*Third Order Elastic Constants of Semi-Continuous Casting Ingot A3004 Aluminum Alloy and Measurement of Stress,*" Journal of Materials Science, Vol.42 (2007): pp.2070-2075. 10.1007/s10853-006-1470-0

© 2019 by ASME