The Measurement of Acoustoelastic Constant to evaluate Stress by Using Ultrasonic Waves

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Abstract. This experimental study aims to investigate the capability of the ultrasonic method by using critically refracted longitudinal (LCR) wave for measuring welding stress in elastic limits. Ultrasonic technique is based on the linear relation between the ultrasonic wave velocity and the stress, known as the acoustoelastic effect. To determine acoustoelastic constants, different amounts of stress were applied to the specimens by using uniaxial tensile testing machine. The outcome of the study showed a linear relation between time-of-flight (TOF) measured and the tensile stress in the samples and provided the acoustoelastic constants of Q345. This paper also analyzed the measurement influence factors including the thickness of couplant, temperature and residual stress.

1. Introduction
The stress plays a significant role in the strength and service life of structures. It is quite important to quantify the levels of residual stress in critical components and welding such as those high-level vessels in petrochemical plants, since they can deeply impact in-service performance.

The measurement of stress can be achieved by destructive methods (e.g., the contour method), semi-destructive methods (e.g., hole-drilling) or nondestructive methods (e.g., ultrasonic techniques [1, 2, 3], X-Ray diffraction, magnetic Barkhausen noise). The high industry request for stress measurement techniques expects development of nondestructive methods. Ultrasonic technique is based on the acoustoelastic effect, the linear relation between the ultrasonic wave velocity and the stress. The longitudinal critically refracted (LCR) wave which travels near to the surface, shows the most strain sensitivity among all other types of ultrasonic waves when the wave travels parallel to the stress [1].

In this study, based on the acoustoelastic effect, acoustoelastic constants of two orthogonal directions were measured, which were employed to measure the stress in the three-point bending test.

2. Theoretical backgrounds
Within the elastic limit, the ultrasonic stress evaluation technique relies on the acoustoelastic law. Figure 1 shows elements of a bar under tension where the ultrasonic wave propagates in two perpendicular directions. Left in Figure 1, the wave propagates parallel to the load and $V_{||}$ represents the velocity of the particles in the same direction (longitudinal wave), while right in Figure 1, the $V_{\perp}$ velocity is for longitudinal waves propagating perpendicular to the stress direction.
The waves with particle motion in the direction of the stress fields showed the greatest sensitivity to stress. The most considerable variation in travel time with the strain was found for longitudinal waves, followed by the shear waves when the particles vibrate in the direction of the applied stress. The velocities of the longitudinal plane waves can be related to the strain (\(\sigma\)) by the following expressions.

\[
\rho_0 \frac{V_{//}}{c^2} = \lambda + 2\mu + \sigma \left[ \frac{3\lambda + 2\mu}{\mu} \right] (3\lambda + 2\mu)^{-1} \\
\rho_0 \frac{V_{\perp}}{c^2} = \lambda + 2\mu + \sigma \left[ 2l - \frac{2\lambda}{\mu} (\lambda + 2\mu + m) \right] (3\lambda + 2\mu)^{-1}
\]

In equations (1) and (2), \(\rho_0\) is the initial density; \(V_{//}\) is the velocity of waves travelling parallel to load; \(V_{\perp}\) is the velocity of waves travelling perpendicular to load. \(\lambda, \mu\) are the second order elastic constants (Lame’s constants); \(l, m, n\) are the third order elastic constants. The relative sensitivity is the variation of the velocity with the strain and can be calculated by equation (3,4)(\(V_{//}\)instead of \(V_{//}\), \(V_{\perp}\)instead of \(V_{\perp}\)).

\[
V_{//}^2 = V_{//0}^2 (1 + k_{//} \sigma) \\
V_{\perp}^2 = V_{\perp0}^2 (1 + k_{\perp} \sigma)
\]

where:

\[
k_{//} = \left[ \frac{3\lambda + 2\mu}{\mu} \right] (3\lambda + 2\mu)^{-1} \\
k_{\perp} = \left[ 2l - \frac{2\lambda}{\mu} (\lambda + 2\mu + m) \right] (3\lambda + 2\mu)^{-1}
\]

The LCR technique uses a special longitudinal bulk wave mode, as shown in figure 2. When the ultrasonic longitudinal wave reaches an interface between two media at the first critical angle, wave mode conversion occurs, and the LCR wave is produced (\(\beta_L = 90^\circ\)), which travels parallel to the surface, particularly propagating below the surface at a certain depth, about twice of its wavelength.

In this study, the structural Q345 material is assumed to be isotropic and homogeneous. Moreover, it is assumed to be in its elastic range. After a derivation from equation (3,4), the relationship between the measured wave time-of-flight (TOF) and corresponding uniaxial stress can be written as follows.

In equations (9, 10), \(k_{//}\) and \(k_{\perp}\) are separately two directional acoustoelastic constant for LCR waves.

\[
dV = -\frac{L}{t^2} \, dt \\
\frac{dt}{d\sigma} = -\frac{kV_{//0}t^2}{2L} = -\frac{kL_0}{2}
\]
\[ k_{//} = -\frac{2}{t_0} \frac{d t_{//}}{d \sigma} \]  
\[ k_{\perp} = -\frac{2}{t_0} \frac{d t_{\perp}}{d \sigma} \]  

3. Experimental procedures

3.1 Sample description
A 10mm thick Q345 experimental sample was shown in figure 3. This specimen would be used for acoustoelastic constant evaluation and three-point bending test. Also, the annealing process was done at 600°C in vacuum to give the specimen a uniform fine-grained structure and a stress-free state.

![Figure 3. The size of the experimental sample.](image)

3.2 Measurement device
The ultrasonic measurement device includes an Ultrasonic Instrument with integrated pulser, receiver, computer and two transducers assembled on a united wedge. The frequency of transducers was 5 MHz and the diameter of the piezoelectric elements was 6mm. The Ultrasonic Instrument is a 100 MHz ultrasonic testing device which allows precise measurements of the time of flight, even better than 2ns after data process. For the united wedge, the LCR wave travels about 25mm in the specimen.

![Figure 4. The ultrasonic measurement device, united wedge and transducers.](image)

3.3 Acoustoelastic constant evaluation
To evaluate the acoustoelastic constant, the acoustoelastic constant is deduced experimentally from a uniaxial tensile test associated with an ultrasonic measurement.

![Figure 5. Uniaxial tensile testing and the acoustoelastic constant evaluation.](image)
After several tensile tests, the acoustoelastic constant within the elastic limit were got. To be noticed that the acoustoelastic constant might be slightly changed on different specimens, even on the same specimen. The constant cannot be the exactly same since the couplant’s thickness varies. In this study, we have done four times of tensile tests on one single specimen, and took the average value. Acoustoelastic constant represents the slope of the relative variation curve of the $\Delta t/t_0$ and the applied stress, as shown in figure 6.

The key of acoustoelastic constant evaluation is to make sure the thickness of the couplant is fixed, which means a thick gel couplant, such as honey used in this experiment, would get a better result than a liquid one. It will be discussed later. The installation of wedge could make it work stably as well.

Figure 6. Result of tensile test to evaluate acoustoelastic constant.

Three-point bend test of Q345 beam was carried out by using FEM simulation and experiments. Load was applied at the bottom of material at a concentrated point. In order to install the ultrasonic wedge (46mm in length) on the sample, half of the strain gauges had to be taken off, and stresses on only three positions were measured by ultrasonic method. To be noticed that, since the stressing jack cannot keep the strain stable, the strain gauges have to be bonded all the time. Moreover, the ultrasonic result has been corrected. LCR waves give information on the strain that is the average of the through-path with length of 25 mm.

Figure 7. Stress measurement in three-point bending test.

4. Results and discussion
In the case of ultrasonic measurement, the results show great agreement between finite element and ultrasonic stress measurement. Three influencing factors in stress measurement were considered as follows.

4.1 Thickness of couplant
Assuming the velocity of ultrasound in the couplant is 2mm/$\mu$s, if the thickness of couplant modifies about 5μm, TOF would change about 5ns, which is taken in account as stress variation (125Mpa). Tiny
variation could induce obvious error. The experiment where the specimen was positioned vertically and oil was used as couplant was done. Even there was a magnetically installation of wedge, the oil still dropped down slowly because of the gravity. TOF were measured every 20 min, and it obviously changed a lot as seen in figure 8. As time passing, the thickness of couplant decreased which made TOF diminishing. Thus, it is essential to keep the thickness of couplant steady in both acoustoelastic constant measurement and stress measurement.

![Figure 8. TOF variation.](image)

4.2 Temperature

For isotropic metal materials, ultrasonic velocity will decrease as temperature rises up to 500°C, and its trend with the Young’s modulus decreases is consistent with the rise of temperature.[4] To figure out how temperature influence the ultrasound velocity, experimental system was set as shown in figure 9. The system is mainly composed of plate heater, electromagnetic ultrasonic device and transducer, temperature measurement device and cotton insulation.

![Figure 9. Temperature experimental system](image)

Since the velocity of longitudinal wave is proportional of that of shear wave, the relationship between the velocity of longitudinal wave and temperature can be regarded as seen in Figure 7. For example, from room temperature 25 to 100°C, the velocity varies from 3180 m/s to 3145 m/s, which makes TOF for 25 mm increase 0.165 us. From figure 6, stress of 250 Mpa induced the 10ns variation of TOF, and therefore the variation of TOF induced by temperature must be considered in stress measurement by ultrasonic method.

4.3 Residual Stresses

Although the annealing process was done at 600°C in vacuum, the specimen was given nearly, but not absolutely a stress-free state. The more several tensile tests are done, its state is more likely stress-free, and therefore the acoustoelastic constant will fluctuate less and be precise.
5. Conclusions
In this study, tensile tests were employed to measure the acoustoelastic constant of Q345 and LCR based technique could provide a great opportunity for stress evaluation. Based on the achieved results, it can be concluded as follows.

1) The results of the study indicated that there is a significant relation between stress and time of flight wave in elastic limit and provided acoustoelastic constants of Q345.

2) More likely stress-free is the sample’s state, more precise the acoustoelastic constant is measured. Variation of thickness of couplant and temperature would cause less accuracy of measuring stress. The key of measurement is to keep the couplant and temperature stable.

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