Acoustoelastic Determination of Residual Stress with Laser Doppler Velocimetry

by L. F. He and S. Kobayashi

ABSTRACT—The main object of this study is to develop a new technique for stress nondestructive measurement. A noncontact measurement technique of ultrasonic wave velocity is proposed. In the measurement system, a laser Doppler velocimeter, which is noncontact, is used to detect wave motions due to Rayleigh waves instead of a piezoelectric transducer. The noncontact measurement technique is applied to determine the stress-acoustic coefficient of Rayleigh waves for aluminum 5052 and a structural steel, and the results are in good agreement with those obtained using knife-edge piezoelectric transducers. The technique is also used to evaluate residual stress existing in an H-section rolled beam of the structural steel. The distribution of residual stress is reasonable.

KEY WORDS—Residual stresses, stress-acoustic coefficient, noncontact measurement, laser Doppler velocimeter, Rayleigh waves

Introduction

It is of fundamental importance to know the residual stress existing in structures and structural elements due to fabrication and welding. To estimate residual stress, several techniques have been developed, including mechanic, diffraction, ultrasonic and magnetic methods.1 In this paper, an acoustoelastic method is applied to estimate residual stress by use of the laser Doppler technique and Rayleigh waves.

Acoustoelastic stress measurement is based on the use of the acoustoelastic effect, in which elastic wave velocities depend on the stress. In acoustoelastic stress measurement, by use of Rayleigh waves, the near-surface stress can be measured.2-7 For example, by operating at a frequency of 2 MHz, the Rayleigh waves' penetration depth is on the order of 1 mm. This may be preferable to the X-ray diffraction method. Because X-ray only penetrates a few microns, the measurements are easily affected by the damage caused by machining effects at the surface.3 Moreover, by measuring the velocity of Rayleigh waves at two different frequencies, the stress gradient can be determined.7

In this investigation, Rayleigh waves are emitted by a wedge transducer and detected by a laser Doppler velocimeter. The advantages of using the laser Doppler technique are that there is no contact with the specimen and that a laser beam can be focused onto a very small area where the velocity is required. Therefore, the operation is not usually seriously affected by temperature, and a higher accuracy can be expected. Another potential advantage is the possibility of a large operational distance.7,8

Acoustoelasticity Formulas of Rayleigh Waves

The theory of acoustoelasticity for Rayleigh waves is reviewed in Ref. 9. Here, only the final result is given.

For an elastic isotropic solid defined by normal plane coordinates (x1, x2) and a half-space x3 < 0, according to the analytic solutions of both Hayes and Rivlin10 and Hirao et al.,11 as first order approximately, the velocities of Rayleigh waves propagating in the principal axes (x1, x2) directions of an initial stress field are expressed as

\[
\frac{V_1 - V_{10}}{V_{10}} = \frac{\Delta V_1}{V_{10}} = K_{11}\sigma_{11} + K_{21}\sigma_{22},
\]

\[
\frac{V_2 - V_{20}}{V_{20}} = \frac{\Delta V_2}{V_{20}} = K_{12}\sigma_{11} + K_{22}\sigma_{22},
\]

where \(V_{10}, V_{20}\) are the Rayleigh wave velocities in an unstressed medium in the \(x_1\) and \(x_2\) directions, respectively; \(V_1, V_2\) are the Rayleigh wave velocities in the presence of \((\sigma_{11}, \sigma_{22})\) in the \(x_1\) and \(x_2\) directions, respectively; \(\sigma_{11}, \sigma_{22}\) are the principal stresses; and \(K_{ij}\ (i, j = 1, 2)\) are the stress-acoustic coefficients due to Rayleigh waves.

For an uniaxial stress field, eq (1) can be expressed as follows:

\[
\frac{V_1 - V_{10}}{V_{10}} = \frac{\Delta V_1}{V_{10}} = K_{11}\sigma_{11}.
\]

In the unstressed medium, the propagating distance and time for Rayleigh waves are \(L_0\) and \(T_0\), respectively. Then, the following expression can be obtained:

\[
\frac{\Delta V_1}{V_{10}} = \frac{\Delta L}{L_0} - \frac{\Delta T}{T_0}.
\]

With eq (3), eq (2) can be rewritten as

\[
\frac{\Delta T_1}{T_{10}} = K_{11}\sigma_{11} - \frac{\Delta L_1}{L_{10}}.
\]

Equation (4) is mainly used to obtain the stress-acoustic coefficient in which the last term indicates the strain between measured points (i.e., average strain between measuring sensors). It cannot be neglected in general contact measurement.

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However, in this investigation, by use of the laser Doppler velocimeter, two laser beams are used as receivers and are fixed on the sensor head of the velocimeter. Of course, this term will become zero; that is, eq (4) is simplified as

\[ K_{11} \cdot \sigma_{11} = \frac{\Delta T_1}{T_{10}}. \]  

(5)

From eq (5), it is known that for a certain stress field if the change in propagating time can be measured, the stress-acoustic coefficient can be obtained. On the contrary, based on measuring the change of propagating time, the stress field can be determined with the corresponding coefficient.

**Experimental Technique**

*Detection of Rayleigh Waves with a Laser Doppler Velocimeter*

In this investigation, Rayleigh waves are emitted by a wedge transducer and detected by an LV-1300 laser Doppler velocimeter (Ono Sokki Company, Japan). In the Doppler velocimeter, an interferometer is installed in the sensor head. The laser interferometer is an ideal probe for detecting the wave velocity field generated by various ultrasonic sources because it is both noncontact and a broadband point detector. A typical configuration of an interferometer using an electro-optic frequency shifter is shown in Fig. 1.

To measure wave velocity at two points, the laser Doppler velocimeter was improved using a beam divider. Two laser beams emitted by the sensor head of the velocimeter are interchangeably selected as receiving sensors. Figure 2 shows the composition of the laser Doppler velocimeter system. The distance between the two beams is fixed at about 4 cm. The sensor head is mounted on a specially designed adjustable jig, which is supported vertically on a tri-direction (xyz-axis) stage with a resolution of 0.001 in. per micro-step. The stage is fixed on an anti-vibration table. The focus of the laser beam is first adjusted by z-axis micro-stage and then fine adjusted manually by the jig mentioned above with a 0.002 mm precision micrometer head.

**Experimental Setup**

Figure 3 shows the noncontact measurement experimental setup. In this system, two instruments with different measuring methods are used to measure the propagating time through the specimen for a Rayleigh wave. One is a UVM-2 sing-around unit (Cho-Onpa Kogyo Company, Japan), which uses the sing-around method. The sing-around method is one of the first high-resolution wave speed-measuring techniques, which was developed by Cedrane and Curran. The sing-around unit is connected to a computer, and data acquisition is automatically carried out. The other is the digital oscilloscope (LeCroy 9384TM), which measures time of flight (TOF) by reading the images of waves at zero-cross on the cathode ray (CR) display directly. The oscilloscope is simultaneously used to monitor received waveforms and pulse. The accuracy of measurement by the sing-around unit is about 0.1 nanoseconds for 10,000 trigger signals, whereas that by the oscilloscope is about the same when the waveforms are averaged over 500 times.

**Specimens and Experimental Procedure**

The specimens for determining stress-acoustic coefficients due to Rayleigh waves are cut from rolled plates of aluminum 5052 and a structural steel, respectively, whose size is 200 mm length × 20 mm width × 5 mm thickness. The longitudinal axis is parallel to rolling direction.

To obtain the stress-acoustic coefficient, uniaxial tensile tests are performed with these specimens at a frequency of 1 MHz. The measurements are carried out continually under a loading and unloading procedure.

The H-section rolled beam for evaluating residual stress is shown in Fig. 4. To make the surface smooth enough for good reflection of laser beams, the surface is ground in the laboratory with 1200-grit emery paper and cleaned with acetone.

The measurements are made continuously along the measuring trace. The emitting transducer is moved from one measuring point to another manually with a spacing of 10 mm, and the laser beams are moved by turning the micro-stage with the same spacing. Special attention is paid to focusing...