THE ULTRASONIC MEASUREMENT OF STRESS ON FERROUS PLATE

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INTRODUCTION

It has recently been shown that one can measure stress, in the presence of texture, or other metallurgical variables, by comparing the velocities of horizontally polarized (SH) ultrasonic waves propagating in orthogonal directions [1,2]. The prediction of stress depends on the formula

\[ \sigma_{11} - \sigma_{22} = 2\rho V(V(0^\circ) - V(90^\circ)) \]  

(1)

where \( V(\theta) \) is the velocity of a SH wave propagating in the plane of a metal surface, \( \theta \) is the angle of the propagation measured with respect to the "1" direction, \( \rho \) is the density, \( V \) is an average horizontally polarized shear wave velocity, and \( \sigma_{11} \) and \( \sigma_{22} \) are components of a biaxial stress state. The major importance of Eq. (1) is that all of the quantities on the right-hand-side are accessible to nondestructive measurement. The only exception is the density, which is generally known to sufficient accuracy for particular components. This technique is not influenced by the degradations in accuracy due to competing microstructurally induced velocity shifts that plague most acoustoelastic techniques. It thus offers the possibility of realizing the sampling of bulk stresses that is the motivation for most acoustoelastic work.

The capability of precisely measuring the SH velocity with a previously developed texture measurement apparatus has allowed it to be reprogrammed for the measurement of stress [3]. During 1988, stress measurements were made on aluminum, stainless steel, and ferritic steel sheets. It was found that an improved velocity precision with respect to the texture measurement problem was required, and this was realized with a modified zero-crossing measurement approach. Good comparisons between applied and ultrasonically predicted stresses were obtained on aluminum, as shown in Figure 1, and stainless steel. However, uncontrolled EMAT liftoff introduced significant scatter. Moreover, in some cases, it was difficult to select the corresponding zero-crossings as the propagation distance changed. In addition, much poorer performance was obtained on ferritic steel as shown in Figure 2. The major emphasis of this paper is to report on efforts to reduce these problems.
Fig. 1. Comparison of ultrasonically measured stress versus actual stress for Aluminum 6061-T6 using permanent periodic magnet EMATs (after Ref. 3).

Fig. 2. Comparison of ultrasonically measured stress versus actual stress for ASTM A-569 (cold rolled steel) using permanent periodic magnet EMATs (after Ref. 3).
The SH waves are generally excited by periodic permanent magnetic EMAT's [4]. In the complex static field patterns established by these EMAT's both Lorentz forces and magnetostrictive mechanisms contribute to the generation process. However these tend to launch waves with different phases. It has been speculated that microstructurally induced fluctuations in the strength of the magnetostrictive component leads to shifts in the phase of the generated wave. Such an effect would account for errors in the measured velocities and hence in the predicted stresses.

One way to overcome this problem would be to use an EMAT which only exhibits one transduction mechanism. Such an improved EMAT configuration for stress measurement on ferrous materials has been designed, and integrated into our breadboard system. This EMAT configuration [5] incorporates a meander coil consisting of a series of parallel conductors through which the current flows in a serpentine path. In the usual meander coil EMAT [6], a static magnetic bias field normal to the part is utilized. The Lorentz force $f_\omega$ on the eddy currents is given by the right-hand law $f_\omega = j_\omega x B_0$, where $j_\omega$ is the dynamic induced eddy current density and $B_0$ is the static magnetic bias field. Thus a periodic surface stress is established parallel to the surface and in the sagittal plane (in the plane of propagation). Such a force provides an efficient excitation of Rayleigh waves, but does not couple to the SH waves needed for the stress measurement. In the new EMAT configuration, the static magnetic field is rotated $90^\circ$ so that it is in the plane of the surface, parallel to the elements of the serpentine coil [5]. The Lorentz forces, discussed above, thus vanish since $j_\omega \parallel B_0$. However, in ferromagnetic materials, a magnetostrictive mechanism exists which couples to the desired SH waves. This appears to be a very desirable configuration since the absence of the Lorentz force mechanism precludes any velocity errors that might be produced by interference of Lorentz force and magnetostrictively generated signals.

LIFT-OFF COMPENSATION

It was noted in last years proceedings [3] that, "the [stress measurement] results are very sensitive to grit and dust on the surface of the samples. It is believed that this causes small, lift-off induced changes in EMAT impedances, which in turn induce small phase shifts in the signals. Further study will be required to develop techniques to compensate for this problem." This brief comment can be understood by considering an analogy between an EMAT coil and an eddy current coil. It is well known that the impedance of the latter changes with lift-off, so it is not surprising that similar changes would occur for EMAT coils. If the EMAT were driven from a current source, these small impedance changes would be expected to have little effect on the phase of the generated signal. However, real systems often utilized tuned, resonant circuits so that the phase of the current delivered to the EMAT is influenced by small shifts in the EMAT impedance. Recalling that we wish to measure delay shifts as small as one nsec and that these correspond to a few hundredths of a degree of electrical phase shift at the measurement frequency of 500 kHz, the existence of the difficulty is not surprising.

After considering several alternative solutions, a relatively simple one was selected - utilizing two transmitters driven in series. The receiver would then detect two pulses, delayed by the time $\Delta t = L/V$ where $L$ is the separation of the transmitting EMAT's and $V$ is the horizontally polarized shear wave speed to be determined. Because the current must have the same phase in the two EMAT's by virtue of their series connection, any lift-off induced variations in this phase should cancel in the determination of time difference. Experimental measurements of stress in aluminum have shown this technique to be much less sensitive to lift-off than the previous ones [3].
AUTOMATIC ZERO-CROSSING PROCEDURE

It was also noted in last year's proceedings, [3] that "some further effort is required to allow the [corresponding] zero-crossing to be selected" in the determination of the relative time shift of two waveforms. This is a potential problem because the narrow band pulses excited by the meander coils contain many cycles of comparable amplitude. It is sometimes difficult, for example, to select a zero-crossing corresponding to the "largest" cycle. An apparent solution to this problem has been developed as part of a related program. The Center for Advanced Technology Development (CATD) is supporting the further development of a previous version of the EMAT instrument for texture measurement applications. As a part of that project, the Fourier transform-phase technique for measuring time delays [7,8] has been modified in a way which overcomes both the zero-crossing selection problem and the previously reported high-sensitivity to noise [3]. Therefore, that technique is being incorporated in the stress measurement apparatus.

Without going into great detail, the basic idea is as follows [9]. In the simplest implementation of the Fourier transform-phase technique, one first computes the Fourier transform of the two received signals. The phase of the ratio of the transforms is then plotted versus frequency. The slope is expected to be equal to \( 2\pi \nu / V \), thereby allowing the determination of velocity. In our previous implementation of this technique, it was found that noise could easily induce tens of nanoseconds of error, which was more than could be tolerated in stress measurement applications. What has now been recognized is that these uncertainties are still small with respect to a period of the ultrasonic signal. We effectively use the original technique to determine the proper zero-crossing. We then find that addition of the constraint that the graph of phase versus frequency must pass through the origin or a multiple of \( 2\pi \), as determined by the zero-crossing selection, greatly reduces noise sensitivity to a level comparable to theoretical bounds. Detailed theoretical simulations of the performance of this technique have been performed. The expected improvement facilitated by the new technique is highlighted by recalling from our paper last year [3] that 0.5% noise produced a standard deviation of 18.7 nsec. This is an order of magnitude greater than the predicted improved performance [9]. Early experimental data are consistent with these predictions, with errors of a few nanoseconds observed under typical experimental conditions.

EVALUATION OF APPARATUS FOR STRESS MEASUREMENT OF FERROUS MATERIALS

At the time of this preparation of this paper, the apparatus has been available for only a few weeks and check-outs are not complete. Results of a preliminary test of stress measurements on ferritic steel, shown in Figure 3, indicate reduced scatter in the ultrasonic estimation of stress. The scatter is still greater than the target error bounds of plus and minus 2KSI; however, we expect to achieve better results with sufficient time to "fine tune" the system. Received RF signals from the two series driven transmitter EMATs shown in Figure 4 have excellent signal-to-noise. Transit time difference versus angular rolling direction shown in Figure 5 is in reasonably good agreement with the expected four-fold symmetry due to the plate's texture and the signal amplitude decrease as a function of increasing lift-off shown in Figure 6 as is expected.

Figure 7, presenting the transit time variation in nanoseconds as a function of lift-off, shows little or no change when the receiver EMAT is lifted. However there appears to be a substantial change upon lifting one of the transmitter EMATs. This is not the expected result based on the design analysis and will be the subject of further study.
Fig. 3. Comparison of ultrasonically measured stress versus actual stress for ASTM A-569 (cold rolled steel) using pulsed magnetostrictive EMATS.

**EMAT Signals in 0.10" Plate**

\[ f = 637 \text{ kHz} \quad \lambda = 0.2" \]

Transmitter Separation 4.50"

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**Receiver Output**

(Two Transmitters in Series)

0.5 v/\text{div.}  
20\text{µsec/\text{div.}}

**First Signal**

(expanded sweep)

0.5 v/\text{div.}  
1.0\text{µs/\text{div.}}

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Fig. 4. Received RF signal from two series driven transmitter EMATs in 0.10" steel plate.
Fig. 5. Comparison of measured angular dependence of transit time difference with the \( \cos(4\theta) \) behavior expected for textured media in the absence of stress.

Fig. 6. Air Gap Effect - Signal amplitude (Vpp) versus lift-off in thousandths of an inch.
CONCLUSIONS

We have finished the design and adaptation our present semi-automatic velocity measurement system to the prediction of stress in textured ferritic steel. Magnetostrictive EMATs, which have no driving forces generated by Lorentz forces, are used on ferrous alloys since the absence of the Lorentz force mechanism precludes any velocity errors that might be produced by interference of Lorentz force and magnetostrictively generated signals. Phase shifts due to lift-off are suppressed by driving a pair of transmitting EMAT's in series. To make reliable wave-speed measurements in an industrial environment with an economical sampling period of 100 nanoseconds, a Fourier transform-phase-slope technique has been implemented which not only solves the zero-crossing problem, but achieves theoretical accuracy. Initial data are improved over last year's work. Further improvements are expected as we investigate the effects of lift-off compensation in greater detail and take into account corrections such as temperature variations over the duration of the measurement process.

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