DEVELOPMENT OF A BREADBOARD INSTRUMENT FOR THE ULTRASONIC MEASUREMENT OF STRESS

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INTRODUCTION

The measurement of stress is a generic problem which constantly occurs in nondestructive evaluation applications. X-ray diffraction provides the most successful approach, but suffers from the limitation that only a very near surface layer is sensed. Ultrasonic measurements, based on the stress dependence of the wave speed, have the capability of sampling bulk material. However, they suffer from some practical problems, including degradations in accuracy due to competing sources of wave speed shifts and difficulties of making measurements in complex geometries. The former problem has, in principle, been overcome by an approach recently developed as discussed below.

Consider a component having a texture (preferred grain orientation) or unknown magnitude and orientation, but exhibiting the orthrotropic symmetry characteristic of many engineering materials such as rolled plate. In general, this texture will influence the ultrasonic wave speeds, so that it will be impossible to infer stress from the measurement of a single velocity shift. However, it has been found that stress induced velocity shifts vary with angle in a fashion that is fundamentally different from texture induced shifts. Thus, it is possible to differentiate stress from texture by a measurement of the angular variation of the wave speed[1,2]. In particular, consider a biaxial stress state in the plane of a metal plate. In an arbitrary coordinate system, let the principle stresses have values σ_a and σ_b, inclined at an angle Ω with respect to the coordinates selected. Suppose that one measures the velocity of a horizontally polarized ultrasonic shear wave propagating at an angle Θ with respect to the selected coordinates and then subtracts from this the velocity measured at an angle $\theta + 90°$. Then theory shows that

$$2\rho\vec{V}[V(\theta)-V(\theta+90°)] \cong (\sigma_a-\sigma_b)\cos[2(\theta-\Omega)] \tag{1}$$

where $\vec{V}$ is an average shear velocity. This formula, which has been verified experimentally, has two important practical consequences. First, it says that the velocity difference, $[V(\theta)-V(\theta+90°)]$ will be maximized when the ultrasonic propagation directions are aligned with the principle stress axes. Second, it says that the magnitude of this difference, along with the density and mean velocity, can be used to predict the principle stress difference. It is particularly noteworthy that no acoustoelastic constants or other nonlinear properties of the material are needed for the stress prediction, which distinguishes this approach from other ultrasonic stress measurement techniques. The nonlinear material characteristics have been suppressed by the process of taking the velocity difference.

APPROACH

The approach is to employ the EMAT velocity measurement system, previously developed for characterizing metal texture[3,4], to implement the stress measurement technique. It is anticipated that the velocity precision will have to be improved over that used in the texture measurement problem. Our present precision is limited by the sampling rate of the digitizer. However, researchers at the NDT Centre in Harwell have shown how to use Fourier transform techniques to improve accuracy[5,6]. These will be evaluated in the context of the constraints of the present system. Given the capability of the system to precisely measure the SH velocity, the coupled computer will be reprogrammed for the measurement of stress based on Eqn. (1). Initially, the system will be tested by measurements made on aluminum plates. Measurements will next be made on ferritic steel plates. In this case, experience at several laboratories has shown that phase shifts associated with magnetostrictive contributions to the EMAT transduction process produce unacceptable measurement errors. An alternative approach, which has produced favorable initial results at the IZFP in Saarbrucken, West Germany, makes use of a different probe configuration which operates solely in ferromagnetic materials. Such probes are to be constructed and incorporated in the system. They will then be evaluated in terms of the ability of the system to measure stress in ferritic steel plates.

Significant progress has been made in the development of a stress measurement system. Included is construction of an apparatus for applying controlled loads, determination of the necessary time resolution and selection of the appropriate experimental procedure to realize this goal, development of system software, and demonstration of performance. Details of these topics are given in the following sections, along with a discussion of remaining problems.

CONSTRUCTION OF A LOADING APPARATUS

In order to experimentally evaluate a stress measurement instrument, it is necessary to perform the velocity measurements on samples under controlled loads. A small load frame was constructed and dedicated to this project and is shown in Figure 1. This incorporated a manually controlled hydraulic pump to develop loads of up to 60,000 pounds. Using the same size metal sheet samples that were employed in our texture project, having a 1 in. cross-section, tensile loads of up to 60KSI could be applied. Construction of the apparatus was completed in January at a modest cost (≈ $2K). The apparatus has performed satisfactorily since then.

ESTIMATION OF REQUIRED TIME MEASUREMENT

From Eqn. (1), one can estimate the velocity precision required to achieve any specified precision in stress measurement. The corresponding precision required for the time measurement follows from the relationship

$$\Delta V = -(L/T^2)\Delta T \qquad (2)$$

where L is the ultrasonic path length and T is the time delay. We have selected as a goal a stress measurement accuracy of ±2KSI averaged over a path length of 8 cm (a factor of 2.7 improvement in resolution over our previous work). Based on Eqns. (1) and (2), this translates into a required time measurement accuracy of 6.5nsec in aluminum. In steel the number is reduced to 2.3nsec due to the increased density (see Eqn. (1)). Thus better accuracy is required than the ±10nsec precision of the texture apparatus which was fixed by the sampling rate of the digitizer.

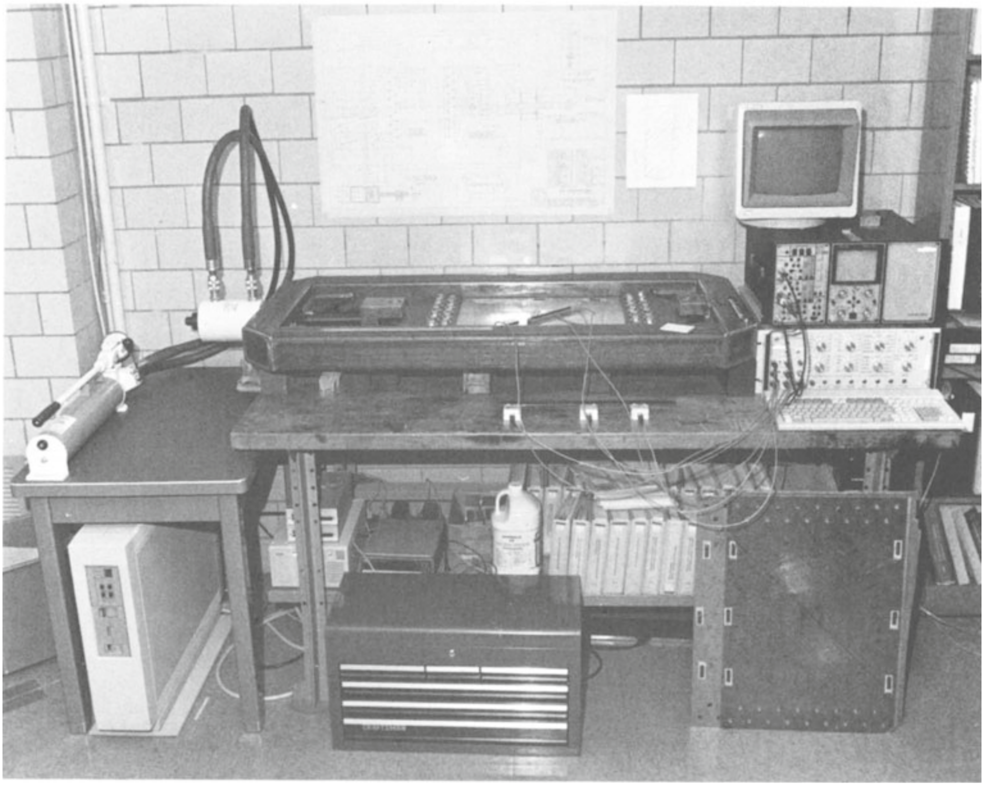

Fig. 1. Load frame and equipment for the ultrasonic measurement of stress in the presence of texture on metal plate.

IMPLEMENTATION AND EVALUATION OF IMPROVED TIME MEASUREMENT TECHNIQUES

The texture velocity measurement technique was based on a cross-correlation procedure. The signals were detected at two receiver positions, their cross-correlation was computed digitally, and their relative time shift was determined from the peak in this cross-correlation. Since the position of this peak could be determined to no better than the sampling rate (5nsec), an error of ±10nsec is possible when taking the difference in the velocities obtained at two propagation angles. Although adequate for texture characterization (see FY87 annual report), these values are inadequate for the stress measurement problem as discussed above.

To overcome this limitation, three alternate ways to improve the time delay measurement precision were considered. These were a) interpolation between the discrete cross-correlation points produced by the FFT based digital implementation, b) a digital implementation of a zero crossing time measurement technique, and c) a deconvolution phase technique. Approach a) appears feasible and has been used with success at other laboratories. However, its implementation appeared awkward in our particular computer system and its implementation was deferred pending the evaluation of the other techniques.

Technique c) involves taking the ratio of the Fourier transform of the signals received at two propagation distances. Neglecting attenuation and beam spread effects, it can be shown that the ratio is equal to exp $[-j\omega L/v]$ where ω is the angular frequency, L is the transducer separation and v is the phase velocity. A plot of the phase of this ratio versus frequency should be a straight line of shape $2\pi L/v$. An attractive feature of this technique is that a form of interpolation occurs automatically, as has been demonstrated by researchers at the NDT Centre at the AERE Harwell Laboratories in England. Suppose that one obtains N digital samples at an interval Δt. Then, after applying the FFT algorithm, one will have evaluated the Fourier transform at a set of frequencies spaced by $\Delta f = 1/2N(\Delta t)$ from 0 to fmax $= 1/2\Delta t$. For a signal with a given spectral content, this suggests that one wishes to increase the sampling period, Δt, to obtain as many spectral components as possible within the bandwidth of the transducer and hence improve the precision of the determination of the slope of the phase versus frequency plot. In our implementation of this technique, we chose N = 512 and $\Delta t = 100 nsec$, (a factor of 20 slower than the sampling rate used in the correlation technique). Using synthetic data, the above theoretical expectations were validated with time shifts of a few psec being resolvable, limited only by the numerical accuracy of the computations. Application of the technique to real experimental data yielded somewhat poorer results, with errors measured in nanoseconds rather than picoseconds with occasional outliers of significantly poorer accuracy. Examination of the results led to an analysis of the sensitivity of the technique to noise. In simulation studies, the same signal was assumed to be detected at the two receiver positions with a certain amount of superimposed noise. When the signals were shifted by 92nsec, the algorithm made the predictions summarized in Table 1.

This data suggests that noise greater than 0.1% would produce an unacceptable error. Since it would be difficult to routinely achieve the implied 60dB signal-to-noise ratio experimentally, attention was turned to technique b).

In principle, a digital zero-crossing technique is trivial. One only needs to 1) select the appropriate zero-crossing, 2) pick the samples between which the waveform crosses zero, and 3) estimate the zero-crossing by interpolation. In practice, we found that clock-noise in our digitizer led to unacceptable errors when the zero-crossing was estimated from two points, but that excellent results were obtained when the waveform was sampled at a rate of 2nsec and the zero-crossing time was estimated from 100 points in the vicinity of the zero-crossing. Simulation studies indicated a standard deviation of 0.7nsec. Thus, this technique was chosen for implementation in the stress measurement system.

Table 1. Noise Sensitivity of FFT Algorithm.

% Noise	Mean Predicted Shift (nsec)	Standard Deviation (nsec)
0.00	92.0	0.0
0.01	92.0	0.4
0.1	93.7	2.2
0.5	94.0	18.7

DEVELOPMENT OF SYSTEM SOFTWARE

The zero-crossing technique was integrated with Eqns. (1) and (2) to form an algorithm for stress prediction. The software took the form of a menu-driven code which instructed the operator regarding initial set-up of the digitizer and manual rotation of the probes. The remainder of the digitizer operations were under computer control.

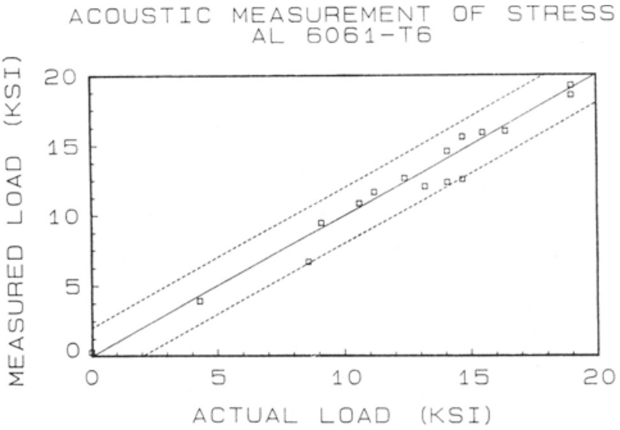

Fig. 2. Comparison of ultrasonic and actual determination of stress. Error bars indicate ± 2KSI.

PERFORMANCE

The most detailed evaluation of the system has been made on aluminum samples, for which we have achieved the design goal of an accuracy of ±2KSI over a range of applied stress from 0 to 20KSI (see Fig. 2). Measurements have also been on stainless steel, with the error being 2 to 3 times larger. Although somewhat greater than the design goal, this performance is still judged to be satisfactory in view of the higher strength of steel. Measurements on ferritic steel have not yet been satisfactory. Errors are often on the order of 20-30 KSI and the data is not highly reproducible. These problems are believed to be associated with the magnetostrictive properties of the material which contribute to the phase of the signal in a fashion that varies due to hysteresis effects.

REMAINING PROBLEMS

Two aspects of the system require further attention. First, although not discussed above, the results are very sensitive to grit and dust on the surface of the samples. It is believed that this causes small lift-off changes in the EMAT's which in turn induce small phase shifts in the signals. Using a current probe to monitor phase shift of the transmitting EMAT and applying correction to the time measurement process initial experiments show hat this technique can in principle be applied in some range of lift-off. Further studies will determine that range. Initial comparisons are shown in Figure 3.

Second, although not as fundamental, some further effort is required to allow the correct zero-crossing to be selected in the algorithm discussed above. Several candidate procedures are on hand which should make this possible.

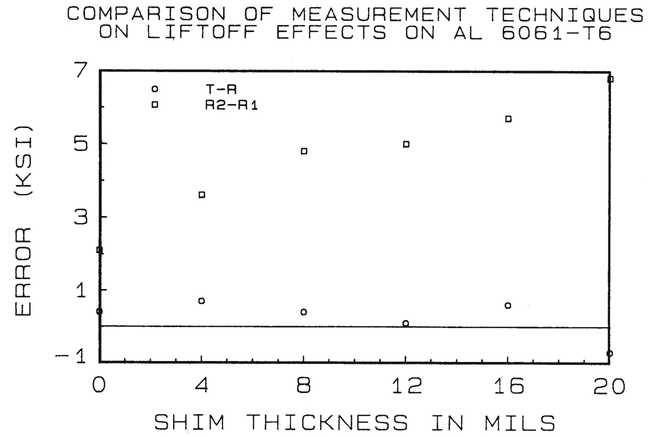

Fig. 3. Comparison of measurement error in KSI between lift-off compensation (T-R) using the transmitter EMAT current waveform and (R2-R1) and no lift-off compensation.

SUMMARY

The measurement of stress in the presence of texture on orthrotropic symmetric plate has been demonstrated on aluminum samples by use of orthogonal measures of the velocity of horizontally polarized ultrasonic shear wave. Velocity measurement techniques were compared with a zero-crossing technique being implemented resulting in an acceptable error of ±2KSI. Work continues on alternative measurement techniques suitable for both texture and stress as well as adaptation of the system to ferrous steels.

ACKNOWLEDGEMENTS

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