Measurement of Stress Profiles by Phase Contrast Techniques

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MEASUREMENT OF STRESS PROFILES BY PHASE CONTRAST TECHNIQUES

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ABSTRACT

An acoustic wave passing through a material has its velocity changed when stress is applied. This is due to changes in the third order elastic constant and the density of the material. By using a small diameter beam or a focused beam incident on a metal and reflected from both its front and back surfaces, it is possible to measure the difference in phase of the two reflected waves; the beam itself can be scanned over the surface of the material. Three kinds of measurements will be shown. The first relates the change of velocity of a compressional wave to the applied stress taken in an MTS testing system. The second shows a scan of the profile of the velocity change around a circular defect. The third is an image of the stressed region around a circular defect obtained with a scanned electronically focused system operating in a phase contrast mode.

A system has been implemented to make ultrasonic measurements of the state of stress in a metal sample. The basic technique determines the change in velocity of an acoustic wave passing through a sample when it is stressed. Scanned acoustic beams of small diameter are used also to determine the variation of the stress in an inhomogeneously stressed sample. One system uses mechanical scanning and is extremely accurate but slow in operation; the second system uses an array of transducers and is electronically scanned in one direction and mechanically scanned in the other. It is fast in operation but less accurate.

A block diagram for the accurate system is shown in Fig. 1. An acoustic transducer approximately 3 mm diameter is used to excite two rf tone bursts in water which are reflected from the front and back faces, respectively, of the sample so that the two received echoes from the front and back faces coincide. We measure the phase difference between the carriers of these tone bursts to determine the change in velocity of waves in the material. The advantage of this technique is that it eliminates errors due to the time delay of the wave in the water path between the transducer and the sample, for only the difference in time delays between waves reflected from the front and back face of the sample is determined. The output is gated so that only the coincident pulses are observed.

The phase relationship of the two echoes is a function of transit time through the sample and the carrier frequency of the tone burst. Thus, the frequency may be adjusted to create the minimum condition. It can be shown that if the transit time through the sample changes by $\Delta T$, the required change in frequency $\Delta f$ is given by the relation:

$$\Delta f = -\frac{\Delta T}{T}$$

where $f$ is the frequency and $T$ is the transit time.

The experimental accuracy is 5 parts in 10$^6$ in a 20 mm thick aluminum sample. The measurement of the transit time of the pulse can be related to the stress state in the sample through nonlinear elasticity. The transit time is a function of the thickness of the sample and the acoustic velocity of the material. Thickness changes with stress can be accounted for by Poisson's ratio and can be measured independently by the use of strain gauges. Velocity changes with stress can be accounted for through use of third order terms in the strain energy function.

For plane stress, changes in velocity and longitudinal wave speed are both proportional to the first stress invariant $\sigma_1 + \sigma_2$. Measurements have been made for calibration purposes in an MTS loading system with acoustic measurement apparatus attached to it. A stress strain curve for aluminum 6061-T6 is shown in Fig. 2. Corresponding values of relative velocity change are shown in Fig. 3. As far as we are aware, these are the first results of this type that have been obtained for both compression and tension; the curves are symmetric about the origin up into the plastic range.

Another sample tested was an aluminum disc which had a hardened steel punch pressed into it. The punch was removed and the surfaces of the disc were ground parallel. Acoustic scans were then taken over the region shown in Fig. 4. The disc was scanned in straight lines and then the results interpolated on the computer to give plots of lines of constant frequency change, which are approximately circular.

Another set of measurements were taken of an inhomogeneous state of plane stress in a plate with a circular hole drilled in it. The plate was loaded to produce a stress state which is predictable theoretically. Acoustic scans were made in one quadrant of the sample. Scan points were spaced 3 mm apart in one direction in the plots, the $x$ and $y$ dimensions are scaled with respect to the width of the plate so the edges are at $x = \pm 1$. An illustration of the plate used is given in Fig. 5. The system was calibrated using the results obtained originally on the MTS testing system. Tension was applied to the sample using a special tension testing machine made for use in a small water tank; this is illustrated in Fig. 6. A set of results taken with a scan in the $x$ direction was seen to compare closely to the theory. The calibration appears to be within 10% of the results obtained on the MTS testing rig. A second set of results, obtained with
a scanning system controlled by a computer and with scanning points only 1 mm apart, is shown in Fig. 7. Again, it is seen that the agreement between theory and experiment is excellent. Furthermore, the region of negative stress, i.e., compression on the top of the hole is measured experimentally, and it can also be seen that the stress near the side of the hole is approximately three times that of the uniform region far from the hole, as would be expected from the theory.

Another system for stress measurements has also been set up. This employs a 100 element electronically scanned and focused system with a long strip horizontal transmitting transducer. Again, two rf pulses are generated, and the resultant phase changes in the sample are measured. The receiver focuses on a point near the surface of the sample and operates in a transmission mode. A block diagram of the system is shown in Fig. 8.

The advantage of this system is the ability to rapidly scan a stressed sample. Changes in phase are now displayed as a change in amplitude of the output signal. The results for the entire sample can be displayed on an oscilloscope, thus giving immediate visual information on the stress state. The scan rate is approximately 100 times that of the purely mechanically scanned system, but the system is somewhat less sensitive to phase change than the first system. A photograph of an image of the disc sample, shown in Fig. 4, is illustrated in Fig. 9 using two different contrast levels. The stress region near the center of the sample can be clearly seen although the results are relatively crude as yet.

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Figure 1. Block diagram of the precision phase measurement system.

Figure 2. Stress strain curve for aluminum 6061-T6.

Figure 3. Relative velocity change versus longitudinal strain for aluminum.

Figure 4. Results obtained by scanning a disk.
Figure 5. Geometry of the plate with a circular hole in tension.

Figure 6. Tension testing machine made for use in small water tank.

Figure 7. Scanned quadrant of plate with hole.

Figure 8. Block diagram of the electronically scanned and focused system.

Figure 9. Photographs of stress state images of disk sample of Fig. 4 taken using the electronically scanned focusing system.