AN IMAGE SCANNING HETERODYNE MICROINTERFEROMETER

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INTRODUCTION

Previous studies\(^1\) have described a scanning heterodyne microinterferometer which produced contour plots from parameters derived from ultrasonic time domain waveform measurements. These plots were able to resolve ultrasonic displacements on the order of angstroms perpendicular to the plane of the specimen. Spatial resolution comparable to the wavelength of the ultrasonic pulses being detected was obtainable in the plane of the specimen. This level of resolution was adequate to provide details of wave propagation phenomena near large fibers (diameters greater than one tenth of a millimeter) or within groups of similar plies in a laminated composite.

The device worked by precisely scanning a specimen through the beam of a heterodyne interferometer in which the sample served as one mirror. The dimensions of the regions being scanned were on the order of a fiber diameter or a few ply thicknesses. For optimum resolution and signal to noise ratio the interferometer beam was kept normally incident upon the specimen within milliradians and was focused to a diffraction limited spot size on the surface of the sample. In order to maintain these conditions during the scanning process, five degrees of freedom in sample manipulation were required. In addition, several lenses were required for producing a near diffraction limited spot size, which was more difficult than producing an image of comparable resolution.

In this paper an alternatively designed instrument is described in which an image is formed at a detector face in a plane of interference within an interferometer (see Figure 1). By using a scanning detector window with a diameter smaller than the obtainable resolution of the image, detailed displacement contour plots can be made without the necessity of continuous realignment.

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Figure 1. shows a schematic diagram of the scanning imaging heterodyne interferometer used in these studies. The frequency stabilized beam from single mode 1 mw HeNe laser (633nm) is incident upon a 40 MHz acousto-optic modulator producing two beams which are sent along different arms of the interferometer. The reference beam (path A in Figure 1) propagates with the same frequency as the incident beam. The second beam, shifted in frequency by 40 MHz, (path B in Figure 1) illuminates the sample surface. The sample serves as a mirror in this arm of the interferometer.

The beams in both arms of the interferometer are recombined at a diagonal mirror and are then incident upon an avalanche photodiode detector. The beams interfere on the surface of the detector producing a 40 MHz beat frequency signal.

A magnified image of the sample surface produced at the plane of the detector is formed by the lenses on either side of the diagonal mirror. The third lens in path A serves to produce equivalent optical paths in both arms. Displacements on the sample surface result in a phase variation in this 40 MHz carrier received by the photodiode. These can be demodulated by a Phase Locked Loop circuit as described in reference 1. The demodulated signal takes the form of an ordinary ultrasonic time domain waveform. This waveform is further processed by a digitizing oscilloscope which extracts parameters such as the arrival times of various extrema, and their amplitudes.

A distinguishing feature between this design and that of previous work1 is that an image of the specimen surface is being scanned with a photodetector rather than focusing a beam onto the surface of a moving specimen. This results in a relaxation in the precision of the scanning
mechanism necessary to image the specimen. Further considerations of optical resolution, acoustic resolution, and signal to noise ratio associated with this instrument will be discussed below.

When specifying the resolution of the interferometer, two resolution figures are important, the resolution in the plane of the image and the resolution perpendicular to the image plane. Factors affecting the in-plane resolution include the diffraction limited resolution of the lens system used to focus the specimen image onto the plane of the detector, the size of the detector window and the wavelength of the stress waves for which surface displacements are being detected.

In the studies reported here this in-plane resolution was limited by the wavelength of the ultrasonic waves interrogating the specimen. A broadband ultrasonic transducer with a nominal center frequency of 10 MHz was used for these samples. However, Fourier analysis of the actual waveforms showed peak amplitudes at a frequency of 2.0 MHz. The velocities and corresponding wavelengths for the materials in these fiber reinforced composites are shown in Table 1.

Resolution enhancement from higher frequency waves was limited by the bandwidth of the phase lock detector which cut off rapidly above 10 MHz. The lens system in the interferometer provided a magnification of 10X with a detector window size of 0.1 millimeter. This was more than sufficient to provide optimum resolution at these acoustic wavelengths.

The maximum in-plane resolution at higher acoustic frequencies would be determined by limitations of the optical system, such as depth of field and diffraction effects.

Out of plane resolution for apparatus is the same as the displacement sensitivity of the interferometer and is independent of the scanning process. Rudd concluded that sensitivity for interferometers of this type was limited by the ratio of the shot noise to the saturation current for the avalanche photodiode-amplifier combination, the phase noise in the system being equal to the square root of this ratio.

In the studies reported here we have found that some improvement in this figure is possible by operating the avalanche photodiode in a saturated condition; however, saturation conditions were not approached in the scanning mode. Phase noise under these conditions was still inversely proportional to the square root of intensity as predicted by Rudd's analysis. Intensities of up to 2.5 times saturation were used in these tests.

| TABLE 1 |
|-----------------|-----------------|------------------|------------------|
| CHARACTERISTICS OF LONGITUDINAL STRESS WAVES PROPAGATING THROUGH SELECTED MATERIALS. |
| MATERIAL | PROPAGATION VELOCITY | WAVELENGTH AT 10 MHz | WAVELENGTH AT 2.0 MHz |
| Steel | 5960 M/S | 596 MICRONS | 2484 MICRONS |
| Lucite | 2680 M/S | 268 MICRONS | 1340 MICRONS |
| Boron | 12,600 M/S | 1260 MICRONS | 6300 MICRONS |
| Aluminum | 6400 M/S | 640 MICRONS | 3800 MICRONS |

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Other observed sources of error reported by Rudd\(^2\) are loss of coherence due to reflection from non-specular surfaces and phase errors due to the presence of residual modulation in the two interferometer arms. This latter effect seems to be caused by a small amount of mixing of the shifted and unshifted beams within the acousto-optic modulator. This spurious signal does not distort the ultrasonic waveforms; however, it does alter time domain amplitudes by a constant factor. Since this constant is a function of carrier signal amplitude, the spurious signal can cause significant scan distortions for specimens having nonuniform image intensity.

This problem could be eliminated using a technique suggested by Ringermacher\(^7\) in which the light beams in both the sample and reference arms of the interferometer are frequency shifted by different amounts. In this way the carrier frequency would be different from the frequency of the spurious carrier signal present in either modulator.

The presence of incoherently reflected light at the photodetector is another possible source of noise which has not been fully investigated. It is likely that such noise results in increased DC levels in the detector which will reduce the dynamic range of the carrier; fluctuations in the DC signal may also contribute to phase noise near the carrier frequency.

RESULTS

As a test of the interferometer a model composite composed of a 2 mm diameter steel rod imbedded in lucite was selected. The steel rod was oriented longitudinally with respect to the transducer so that the interferometer illuminated a circular cross section of the rod along with the interface, and matrix. The surface facing the interferometer (shown in Figure 2) was coated with a thin layer of gold to enhance its reflectivity. In Figure 3 the carrier signal strength was mapped at points in an evenly spaced 25x25 lattice in an image scan window of 1.0 mm x 1.0 mm. This scan included a portion of the steel rod, the interface between the rod and matrix, and matrix region. Without realignment of the instrument, the signal strength was maintained throughout the scan.

The shapes of the time domain waveforms for this specimen varied only slightly between the rod and the matrix material the former transmitting some additional low amplitude high frequency features. Contour plots of the arrival time vs position for the higher amplitude features were flat and showed little variation between fiber and matrix regions. Corresponding plots of feature amplitude showed somewhat more definition (see Figure 4).

Figure 4 shows a scan of a boron aluminum sample made using the same ultrasonic transducer as was used for the steel lucite specimen. Considering the size of the fiber relative to the ultrasonic wavelength, its position is very well defined. The time domain waveforms for the fiber and matrix regions on this specimen were almost identical in shape and contour plots of the arrival time vs. position were relatively featureless.

These results are explainable if the contrast in the amplitude scans results from noise which has its source in spurious 40 MHz modulation present in the reference signal. As described above, such noise changes the amplitude of the time domain waveform without changing its shape. Therefore, the presence of such noise would
affect the amplitudes of peaks in time domain waveforms but would not affect the arrival times of those peaks.

Low coherent reflectivity from matrix regions on boron aluminum samples make it likely that the scans would exhibit effects from this type of noise. Scanning electron and optical micrographs of boron fiber surfaces show them to be much more highly polished than the adjacent matrix material. This specular fiber surface tends to reflect much more uniformly and more coherently than does the rougher matrix material. As a result 40MHz carrier signal from the matrix is much weaker, more variable and strongly affected by any spurious modulation in the reference beam.

CONCLUSIONS

Results of these studies have shown that image scanning interferometry is a usable technique for interrogating localized stress waves in materials. This technique is simpler to implement and more stable than techniques which scan the image or scan a focused beam but it may be difficult to calibrate under conditions of low carrier level and high spurious modulation.

Fig. 2. Scan of Steel Rod Embedded in Lucite (25 Angstroms per division vertical scale).
Another difficulty is that the technique may return a smaller fraction of coherent light to the detector than techniques which focus the interrogating beam to a diffraction limited spot size on the sample surface.

Some of these difficulties can probably be overcome by increasing the intensity of the interferometer light source.

REFERENCES

