SCANNING HETERODYNE MICRO-INTERFEROMETER
FOR HIGH RESOLUTION CONTOUR MAPPING

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INTRODUCTION

Previous studies [1] described a sample scanning heterodyne interferometer which produced contour plots of parameters derived from ultrasonic time domain waveform measurements. Subsequent studies [2] described an alternative design that produced similar contour plots by scanning the image of a stationary sample. This enhancement eliminated the need to continuously realign the system, and increased resolution by providing a stable sample plane. This paper describes a further enhanced system that uses a large aperture, long distance microscope to produce a magnified image with higher resolution than previously obtainable. This image scanning micro-interferometer has been developed for imaging small static and dynamic displacements with high resolution and is particularly useful for studying interfaces in fiber reinforced composites.

The technique used in this study enables the measurement of average displacements within regions approximately one micron in diameter, with a sensitivity of about fifty angstroms for static displacements, and one angstrom for dynamic displacements. It also produces profiles and contour maps of these displacements.

The apparatus uses a heterodyne interferometer in which one of the mirrors is a sample to be mapped. A long distance microscope is used to project a magnified image of the sample onto a scanning detector that produces a signal for which the phase shift is proportional to the normal displacements of the sample surface.
IMAGING INTERFEROMETER

The detection apparatus has two main components, the optical or imaging interferometer portion, and the detection or phase comparator portion. The optical portion is shown in fig. 1 and is described below. The detection portion is detailed later.

The linearly polarized light beam (wavelength = 514.5nm) from an argon laser is split into two diverging beams by an Acousto-Optic Modulator. The first beam is incident upon the reference mirror (M1) of the interferometer. The second beam, which is frequency shifted by 40 MHz is incident upon the sample, which serves as the other mirror in the interferometer. The initial mirror (M0) reflects the modulated beam toward the sample.

The combination of the polarizing cube and the quarter wave plate allows the sample to be illuminated at normal incidence without excessive light loss. This permits the sample surface being imaged to lie within the object plane of the microscope. The polarizing cube reflects vertically polarized light, and transmits horizontally polarized light. The vertically polarized light incident upon the cube is reflected through the quarter-wave plate (W/4), which circularly polarizes the light. After reflecting from the sample, the beam passes back through the quarter-wave plate, producing a horizontally polarized beam that passes through the polarized cube toward the beam splitter.

For maximum coherence, the modulated and un-modulated beams should traverse equivalent paths to the image plane of the microscope. However, for certain samples, the light loss that would be incurred by placing a polarizing cube in the

![Figure 1. Imaging Interferometer](image-url)
reference arm would result in greater loss of sensitivity than does the existing difference in pathlength between the two arms. A polarizing cube must, however, be used in the sample arm due to the need for the sample to lie in the object plane of the microscope.

The half-wave plate (W/2) in the reference arm rotates the polarization of the un-modulated beam to match the beam from the sample at the beamsplitter. The system is aligned so that both beams travel a colinear path through the microscope.

The long distance microscope images both the sample, and an equidistant plane within the reference arm, onto a scanning photodetector. The light that forms the sample image differs in frequency by 40 MHz from the light that forms the reference image, creating a 40 MHz beat signal. The phase of this beat signal at any particular point across the image is proportional to the path difference between the sample signal and the reference signal at this same point. Therefore, the phase of the beat signal throughout the image is proportional to the z-axis displacement of the sample surface from the object plane of the microscope.

One corner of this image plane is reflected by a mirror (M2) onto a second photodetector. The reflected portion of the image is from an area of the sample that is of no interest. The signal at this stationary photodetector is used as a phase reference signal. As the scanning photodetector moves across the image, the phase of the 40MHz image signal is compared to the phase of the reference signal. As a result, dynamic disturbances, such as air turbulence, mechanical vibration, and thermal drift, that occur within the interferometer but away from the sample do not effect the readings. That is, the resultant out-of-plane displacements are with respect to the one corner of the image that is used as the reference.

Since the sample serves as a mirror, it is necessary that its surface be relatively specular. For the results reported here it was necessary to polish the sample surfaces, and sputter a thin, gold coating (approximately 500 angstroms) onto the area to be measured.

Through the use of lenses placed between the long distance microscope and the image plane, magnifications from 1x to 100x are possible. However, light intensity drops below acceptable levels with magnifications of 50x and more, for all but the most reflective of samples.

The use of the one watt argon laser provides light level advantages over the previously used HeNe lasers, which typically output ten milliwatts or less. This added power allows for measurements on samples with reflectances much lower than in previous studies.

The large numerical aperture of the long distance microscope increases light gathering power and permits high
resolution imaging. It incorporates an eight inch diameter primary mirror, and operates with a working distance of 13 to 21 inches. Consequently, samples can be imaged as far as 15 inches from an optimally designed interferometer. As a result this device is non-contact, and allows a reasonable working distance without the need for position detectors to avoid sample contact, as is necessary for other high magnification devices.

Since this is an image scanning device, there is no need to move the sample. Vibration and focusing problems usually encountered with sample scanning devices, are therefore completely eliminated.

Thermal and mechanical disturbances within the interferometer do not effect the results, since the reference and sample signals are similarly affected by any such disturbance. By placing the reference detector near the scanning detector, only in-plane disturbances at the image plane itself affect the results.

PHASE COMPARISON

The scanning process is fully automated. Once the system is properly aligned, a host computer controls the scanner which drives the detector across the image in a raster pattern. Phase data are continuously obtained during each single line. A phase map is generated from the compilation of a series of such single line scans, to produce a three dimensional plot of the illuminated portion of the sample surface.

A lock-in amplifier is used to compare the phase of the 40 MHz signals from the reference and the scanning detector. As the detector scans across the image the lock-in amplifier produces a signal proportional to this phase. This output is monitored by a digital oscilloscope for which the sweep rate is synchronized to the scan so that one scan line corresponds to one 1024-point waveform on the oscilloscope screen. Each waveform is then transferred to the host computer and stored for later processing.

MODES OF OPERATION

Using various configurations, this device is capable of four different types of measurements. Both static and dynamic measurements are possible with varying sensitivities.

Map of Static Surface Contours

The static surface contours of an area as large as one square millimeter can be mapped, and displacements as small as fifty angstroms can be measured. Fig. 2 is a phase map of the end of a single carbon fiber embedded in an epoxy matrix. The circular indentation in the center of the plot is the cross section of the carbon fiber viewed end on, and the raised area surrounding it is the matrix.
Map of Surface Displacements Due to Stress

By making static surface contour plots of a sample before, and during an applied stress, such as mechanical or thermal loading, a contour plot of the resulting displacements due to the stress can be obtained by subtracting the plot of the initial surface from the plot of the surface after the application of stress. Since there is no realignment between scans, the distortions caused by imperfections in the optical components are identical for both scans, and therefore are factored out of the resultant plot. Using this method, it is possible to measure absolute displacements as small as ten angstroms, since the dominant system noise is eliminated. Fig. 3 is a single line plot of the resulting displacements caused by the heating of the carbon-epoxy specimen. The specimen is heated by inducing a current through the carbon fiber, and the current is maintained until the specimen temperature reaches equilibrium.

Figure 2. Phase map of a 30 micron diameter fiber embedded in an epoxy matrix. 200 micron x 150 micron area.

Figure 3. Single line scan across the diameter of the carbon fiber showing the resulting matrix displacements caused by heat induced stress. The fiber is in the well near the left one third of the plot. Width of scan is 650 microns.
Slow Dynamic Displacements at a Single Point

By fixing the scanning photodetector in place, the real time displacements at a particular point on the specimen can be obtained. This particular configuration can detect changes as fast as ten milliseconds in duration, with the response of the lock-in amplifier being the limiting factor. With the use of a photodetector array, the dynamic displacements at many points could be obtained simultaneously. Fig. 4 is a time dependant plot of the epoxy matrix expansion at a single point due to rapid cooling. This plot was obtained by heating the sample to equilibrium, then shutting off the current supply.

Fast Dynamic Displacements at a Single Point

The apparatus is easily convertible to a Doppler velocity detector. By substituting an FM discriminator for the lock-in amplifier, frequency shifts due to surface motion are detectable. Acoustic disturbances on the order of one angstrom, and as fast as one hundred Megahertz can be detected.

Resolution

Surface features on each mirror, and in-homogeneous density variations in each cube and wave plate serve to distort the phase plane of the laser beam that is incident upon it. Fig.5 is a contour plot of an optical flat, scanned using this device. These results are an indication of the distortions caused by the various optical components within the interferometer. The plot shows approximately 50 angstroms of out of plane background distortion for single, static plots. However, for plots of surface displacements

![Graph](image)

Figure 4. Time dependent displacement of a single point 400 microns from the fiber center, on the surface of a cooling epoxy sample.
Figure 5. Phase map of an optical flat indicating the distortion caused by the various optical components in the interferometer. 200 micron x 200 micron area.

due to stress, the background distortion is subtracted out of the resultant plot, since the identical distortions are present in both the initial and final plots. In this case, the resolution is limited by the inherent noise in the light source and the detection electronics.

Typically, the in-plane resolution is limited by the size of the detector window. At present, the detector window is .75mm in diameter, which at a magnification factor of 50x, yields an in-plane resolution of approximately 15 microns.

CONCLUSION

An instrument has been developed which measures surface displacements of specimens at large working distances. Static contour maps, stress induced displacement maps, and single point dynamic displacements waveforms are all possible without system realignment, and are virtually unaffected by mechanical or thermal noise.

REFERENCES
