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NASA Technical Memorandum 103252

Fiber-Optic Projected-Fringe Digital Interferometry

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Prepared for the
1990 Fall Conference on Halogram Interferometry and Speckle Metrology
sponsored by the Society for Experimental Mechanics
Baltimore, Maryland, November 4–7, 1990

NASA

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ABSTRACT

A phase–stepped projected–fringe interferometer has been developed which uses a closed–loop fiber–optic phase–control system to make very accurate surface profile measurements. The closed–loop phase–control system greatly reduces phase–stepping error, which is frequently the dominant source of error in digital interferometers.

Two beams emitted from a fiber–optic coupler are combined to form an interference fringe pattern on a diffusely reflecting object. Reflections off of the fibers' output faces are used to create a phase–indicating signal for the closed–loop optical phase controller. The controller steps the phase difference between the two beams by $\pi/2$ radians in order to determine the object's surface profile using a solid–state camera and a computer.

The system combines the ease of alignment and automated data reduction of phase–stepping projected–fringe interferometry with the greatly improved phase–stepping accuracy of our closed–loop phase–controller. The system is demonstrated by measuring the profile of a plate containing several convex surfaces whose heights range from 15 to 25 μm high.

INTRODUCTION

Surface profile measurements are required in industrial applications such as automated parts inspection, calibration standards testing, and materials research such as the detection of cracks and surface layer debonding. Profiles are sometimes determined by measuring the deflection of a stylus dragged across the surface, but non–contact optical methods have been developed for applications in which the object can not tolerate even slight contact or can not be directly accessed. Among the optical techniques are several which can measure an entire surface profile at once instead of point by point or line by line; these include holographic interferometry, speckle interferometry, moire, and projected fringe techniques. Phase–stepped versions of each of these techniques increase both the speed and accuracy of the profile measurement.

Phase–stepped holographic interferometry[1] and phase–stepped speckle interferometry[2] provide surface measurements accurate to 1/100 of a wavelength of light, but are extremely sensitive to environmental disturbances. A disadvantage inherent in holographic interferometry is the need for a high resolution device to record a reference hologram. Photographic emulsions are typically used; these require processing which increases the data acquisition time, especially when many different objects are to be tested. Speckle interferometry requires a small aperture to generate speckles large enough to be recorded with a solid–state camera; this makes inefficient use of available light. Phase–stepped moire[3] and projected fringe topography[4] are much less sensitive to environmental disturbances than are holographic or speckle interferometers, and can use fast optics to reduce optical power requirements. Measurement sensitivity is still 1/100 of a fringe, but the fringe width, which is variable, is several orders of magnitude larger than a wavelength of light.

The accuracy of each of these phase–stepping techniques can be limited by the following types of phase–stepping errors: calibration errors involving transducer nonlinearity and hysteresis[5], drifts in the phase modulator's sensitivity caused by both temperature variations and changes in the optical layout, and non–uniform transducer motion, which causes the magnitude of the phase steps to vary as a function of position. Open–loop phase–stepping systems are also subject to errors caused by random phase variations produced by vibration, temperature fluctuations and air currents. Additional disadvantages of conventional phase–stepping interferometers result from their use of bulk–optic components such as mirrors, lenses, beam splitters and spatial filters; such interferometers are generally inflexible with respect to their layout, difficult to align, and environmentally sensitive.

This paper describes a new method of measuring surface profiles of diffusely reflecting objects. It uses an accurate optical–fiber–based phase–controller in conjunction with projected interference fringes. Two beams travelling nearly collinearly form an interference pattern on the surface of an object under study. The object's topography is determined by measuring the phase of the interfering beams where they intersect the object and comparing this phase distribution to that of a reference flat[4]. The closed–loop phase controller uses a phase–stabilization technique described by Corke et.al.[6] together with a method of phase stepping developed by Mercer and Beheim[7]. This paper describes the use of this novel phase–controller as it is applied to surface profilometry.

A fiber–optic coupler delivers two spatially filtered beams of light to a beamsplitter where they are recombined. An object placed in the path of the beams is illuminated by a sinusoidally varying intensity pattern generated by the interference of the two beams. The relative phase of these beams is stepped by $\pi/2$ rad using a closed–loop phase–control circuit and fiber–optic phase–modulators. Each phase step is produced by a combination of open–loop adjustment followed by closed–loop fine tuning; the closed–loop mode of operation is then used to stabilize the resultant interferogram while it is electronically recorded.

This phase–control technique compensates for both phase–modulator errors and random phase shifts caused by environmental disturbances of the optical fibers. The use of single–mode optical fibers provides the measurement system with increased flexibility, easier alignment, greater safety, and spatially uniform phase steps. The fibers provide a simple way of obtaining a feedback signal for closed–loop phase control without constraining the layout of the interferometer, and allow for the instrument's sensitivity to be readily readjusted.

The phase–stepped projected–fringe profilometer is described in the first section of this paper, followed by a brief review of how surface profiles can be determined from a series of phase–stepped images. A demonstration of the system as it is used to measure a plate containing small convex surfaces is then presented, followed by concluding remarks.

SYSTEM DESCRIPTION

The projected–fringe profilometer is shown schematically in Figure 1. Laser light is coupled through a lens (L_1) into one leg (F_{in}) of a single–mode non–polarization–preserving fiber–optic coupler (FC). The laser beam is split into two equal intensity beams which are guided through the 10 m long output fibers F_1 and F_2. The lengths of these output fibers are matched to within 0.5 cm, allowing the use of a short coherence length laser. The two beams emitted from output fibers F_1 and F_2 are combined with a beamsplitter (BS), collimated with a lens (L_2), and used to illuminate a test object (OBJECT) placed in the path of the beams. The interference between the two beams causes the object to be illuminated with a sinusoidally varying intensity distribution, known as the projected fringe pattern. The orientation and spacing of these fringes is determined by the relative location of the ends of the output fibers.

A profile of the object's surface can be determined by using phase stepping to measure the relative phase of the projected fringe pattern at each point on the surface. A closed–loop phase–control system (PHASE CONTROLLER) accurately steps the relative phase θ between the light at the output face of fiber F_1 relative to that at the face of fiber F_2. This controller is briefly described here; additional information is available in reference [8].

Light reflected off of the output faces of fibers F_1 and F_2 travels back through the fiber coupler and recombines interferometrically in the remaining leg of the coupler (F_{out})[6]. The light emitted from F_{out} is monitored by a photodiode (PD). A piezoelectric cylinder (PZT_1), around which fiber F_1 is tightly wrapped, is used to sinusoidally modulate the output of PD at a frequency much greater than video frame rates. This output is demodulated and filtered to extract a signal which is proportional to $\sin(2\theta)$; this phase–indicating signal is then integrated, amplified, and applied to a second fiber–optic phase modulator (PZT_2) to close the feedback loop. The relative phase θ is stepped by $\pi/2$ rad by alternating the polarity of the signal sent to PZT_1 and applying an open–loop phase adjustment, followed by closed–loop control for fine–tuning.

SURFACE PROFILE MEASUREMENT

The interference fringe pattern projected on to the test object is recorded by a solid–state camera (CAMERA) and digitally stored on a computer (COMPUTER). Four images of the fringe pattern are acquired, with the relative phase θ between the two illumination beams stepped by $\pi/2$ radians between each exposure. The relative phase φ of the fringe pattern at each pixel (x,y) is computed from the four images by:[9]

$$\varphi(x,y) = \tan^{-1}\left[\frac{I_4(x,y) - I_2(x,y)}{I_1(x,y) - I_3(x,y)}\right]. \qquad (1)$$

The object is replaced with a reference flat in order to determine the phase of the projected fringes. The reference flat is placed in nominally the same position that the object held; the camera's focus should not need readjustment. The reference profile is then subtracted from the object profile and any slight angular mismatch between the reference and object surfaces is digitally removed, leaving a phase map which represents the surface profile of the object.

For collimated illumination beams and with the camera aligned along the normal to the object's surface, the relationship between the surface height and the calculated phase map is described by:[4]

$$h(x,y) = \frac{p_0}{2\pi} \tan(\alpha)\, \varphi(x,y) \qquad (2)$$

where p_0 is the separation of the projected fringes as seen on the reference flat, α is the angle which the incoming light makes with the surface, and φ is the difference between the phase of the object and that of the reference flat at point (x,y) (Figure 2).

The sensitivity of the measurement can be easily changed by repositioning the end of one of the fibers F_1 or F_2, thereby changing the fringe spacing p_0 and/or the fringe orientation. The sensitivity is also dependent on α; smaller angles increase sensitivity but may also produce surface shadows.

The size of the illuminated area can be easily altered by using zoom lenses for both the collimating lens and the camera's imaging lens. The common–path design and active phase stabilization produce an optical configuration which is relatively insensitive to environmental disturbances.

DEMONSTRATION

The profile of a diffusely–reflecting plate with convex surface protrusions was measured with this system. A 6.35 x 6.35 mm^2 section of the plate recorded with oblique white–light illumination (Figure 3) shows three single protrusions on the upper part of the plate, and two arrays of protrusions on the lower part. The individual bumps have diameters of 2.0, 1.0, and 0.4 mm, each element in the array on the left has a diameter of 0.4 mm and is separated from its neighbor by roughly 0.46 mm, and the elements in the other array each have a 0.1 mm diameter and a separation of about 0.18 mm.

Interference fringes were projected onto the plate using a 1.2 watt Argon–ion laser operating single–line without an etalon at 514.5 nm. Images from a 240x240 pixel CID camera set at f/4 were digitized with an 8–bit analog–to–digital converter and processed by a mini–computer. Each of the camera's detector elements were 28 μm square. The plate intersected the collimated beam of projected fringes at an angle α of 20°, and the camera was aligned along the perpendicular to the plate's surface. The fringes were oriented vertically with a separation of $p_0 = 0.279$ mm. A vibration–isolation table was used for the data presented here, although one is not required. An air baffle around the output fiber faces and the beamsplitter is required and was used.

A diffusely–reflecting silicon wafer was used as the reference flat; its rms surface roughness was about .035 μm. Phase maps were made of both the object and reference surfaces as previously described, then the difference between the two was boxcar averaged over 9 pixels in both the horizontal and vertical directions to smooth out the effects of laser speckle and video noise. The phase map was converted to a surface map by using Eq. 2, and is shown in Figure 4 where differences in gray scale indicate differences in surface height. The three single convex surfaces are clearly visible in the top of Figure 4, as is the array of larger convex surfaces on the lower left. The boundary of the small–surface array is indicated, but the individual peaks have been lost by the averaging. The raw and averaged surface profiles along nominally the center lines of the three single peaks are shown in Figure 5; the rms deviation of the raw data from the smoothed curve was 10.3°. This data shows that the heights of the three individual convex surfaces are 24.0, 19.4, and 12.8 μm. A 3–D plot of the smoothed data is shown in Figure 6 where, again, each of the peaks are clearly defined except for the array of small diameter protuberances. The heights of the individual peaks in the larger array could not be determined because the averaging filled in the valleys between the peaks.

A contact profilometer was used to verify the measurements made with the optical profilometer. A stylus was dragged across the surface near the center of each peak to determine the heights of each; the uncertainty in these measurements is about 10%. A summary of the measurements made by both the contact profilometer and the phase–stepping projected–fringe profilometer is given in Table 1. Both sets of data agree within 10%.

These results show that the non–contact, non–destructive projected–fringe profilometer can measure surface height changes of nominally 15 μm with an accuracy of about ± 3 μm. The accuracy in the surface height measurement can be affected by uncertainty in the measurement of α and p_0, the difficulty in determining the peak and base of each convex surface, electronic video noise, and speckle effects. There are approximately 185 speckles per detector element, which produce a 7.3% intensity error in each pixel[10]. It can be shown that for the four–step algorithm shown in Eq. 1 this intensity error corresponds to an error of 1.6 μm in the un–smoothed surface profile. The rest of the observed error is probably caused by video noise. The video noise can be greatly decreased, and the speckle effect can be reduced by averaging across pixels, increasing the camera's aperture, increasing the size of the detector elements, or perhaps by employing a speckle averaging technique such as reviewed in reference [11].

CONCLUSION

A new optical profilometer has been developed for measuring remote surfaces. The sensitivity of the instrument to environmental disturbances is reduced by a combination of a common path optical design with closed–loop phase control. Optical fibers, integral to the design of the phase controller, simplify installation and enhance safety. The phase controller provides accurate, stable phase steps. The preliminary results presented in this paper indicate that video noise and speckle effects are the primary contributors to the measurement uncertainty. These problems will be addressed so that the benefits of closed–loop phase control may be realized.

A wide variety of objects can be measured with this instrument, with the main constraint being that the object must remain stationary during the time it takes to acquire four video images. The measurement sensitivity is easily changed from a resolution of a few micrometers to several hundred millimeters, and the surface area that is measured is likewise variable. Surface heights ranging from 15 to 24 μm were measured with an accuracy of about 3 μm.

This non–contact, full–field surface profilometer has many potential applications, including the inspection of machined and ceramic parts, printed circuit boards, and large machinery. The system is rugged and compact, and can measure surfaces having a wide variety of sizes and surface finishes.

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TABLE 1.

Peak heights of three surface protrusions measured with the contact and optical profilometers.

Protrusion Diameter	2.0 mm	1.0 mm	0.4 mm
Contact Profilometer	24.0 μm	17.5 μm	15.6 μm
Projected Fringe Profilometer	24.0 μm	19.4 μm	12.8 μm
Differences	+0.0 μm	+1.9 μm	−2.8 μm

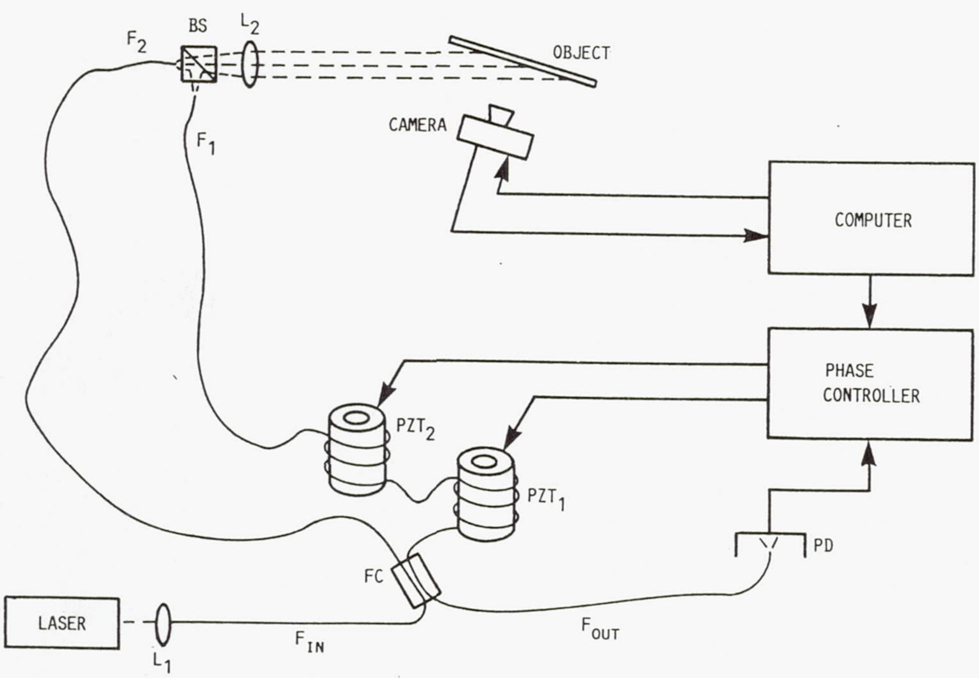

FIGURE 1. - PHASE-STEPPED PROJECTED-FRINGE PROFILOMETER.

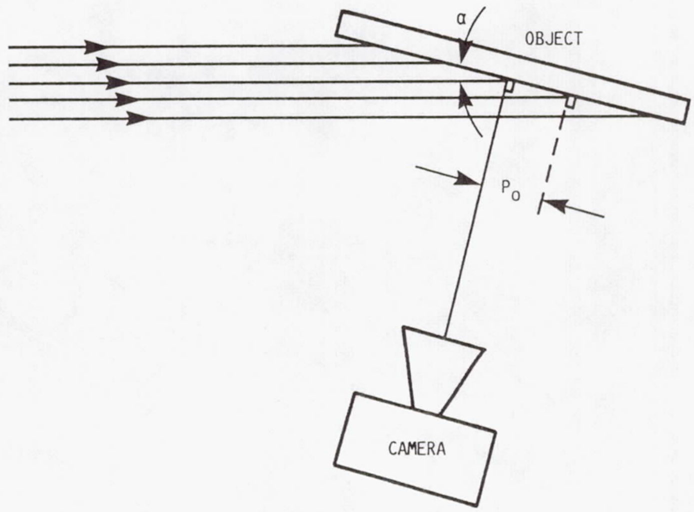

FIGURE 2. - GEOMETRY FOR PHASE MAP ANALYSIS.

FIGURE 3. - VIDEO IMAGE OF PLATE CONTAINING CONVEX SURFACE PROTRUSIONS.

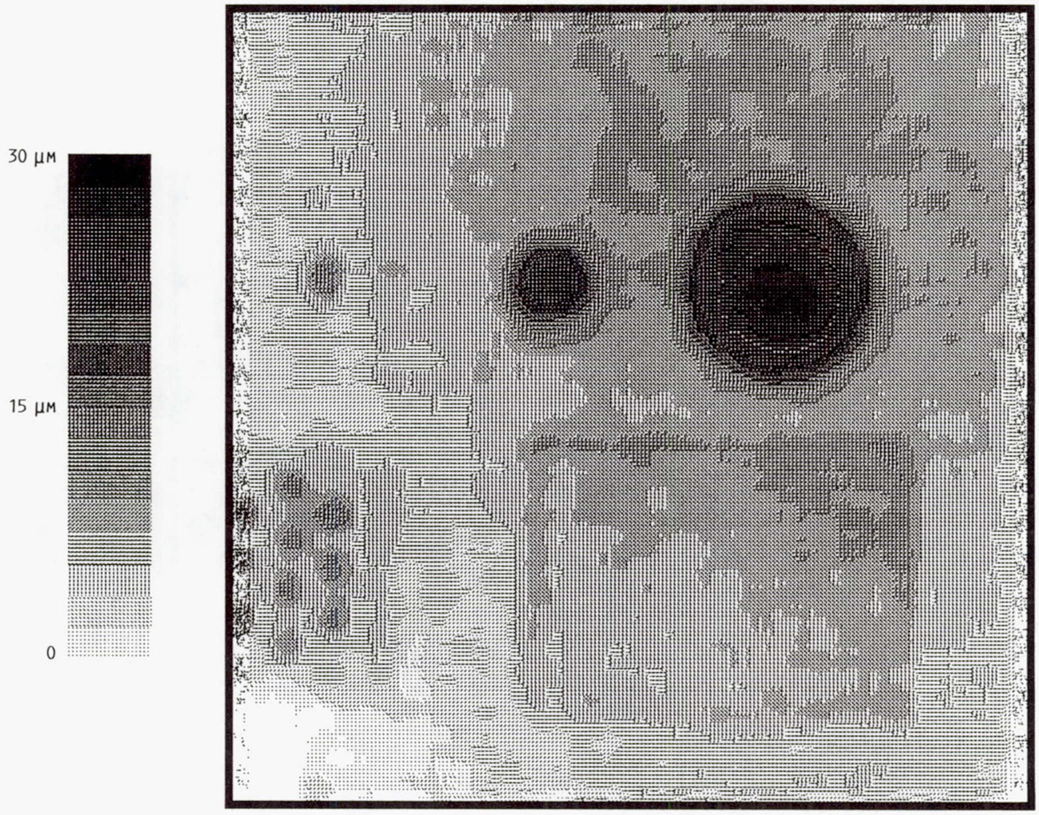

FIGURE 4. - SURFACE MAP OF PLATE. GREY LEVELS INDICATE RELATIVE SURFACE HEIGHT.

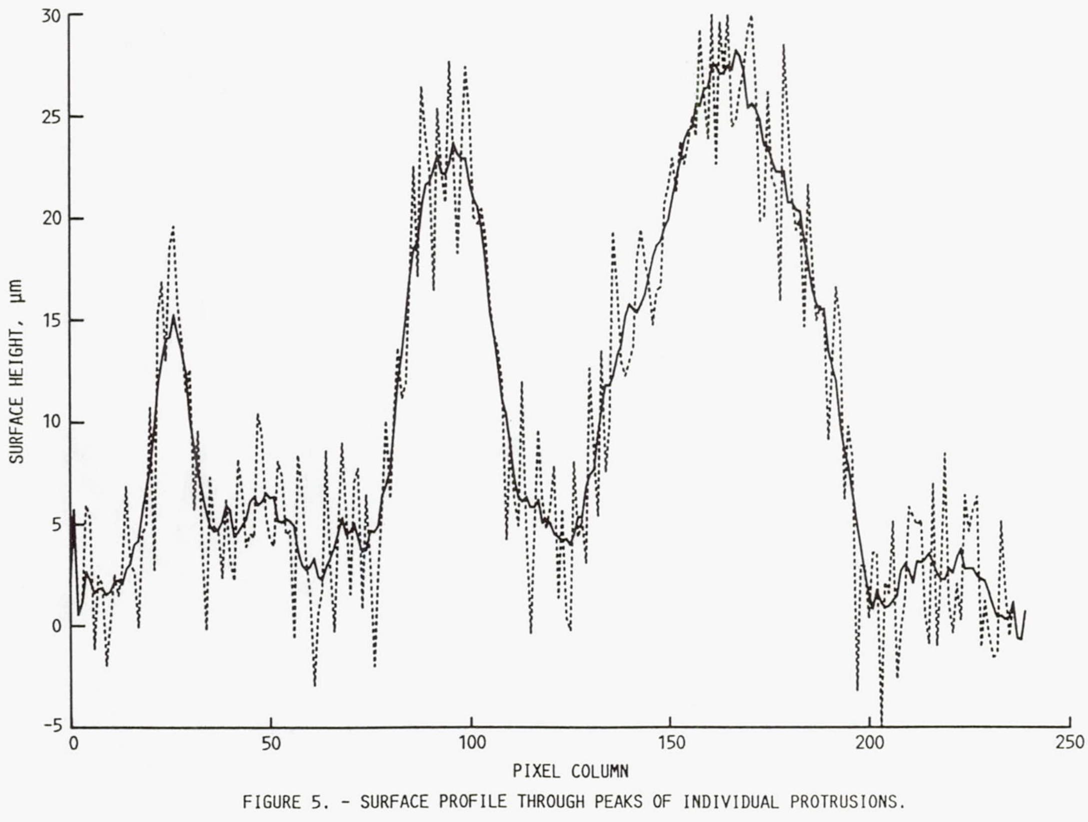

FIGURE 5. - SURFACE PROFILE THROUGH PEAKS OF INDIVIDUAL PROTRUSIONS.

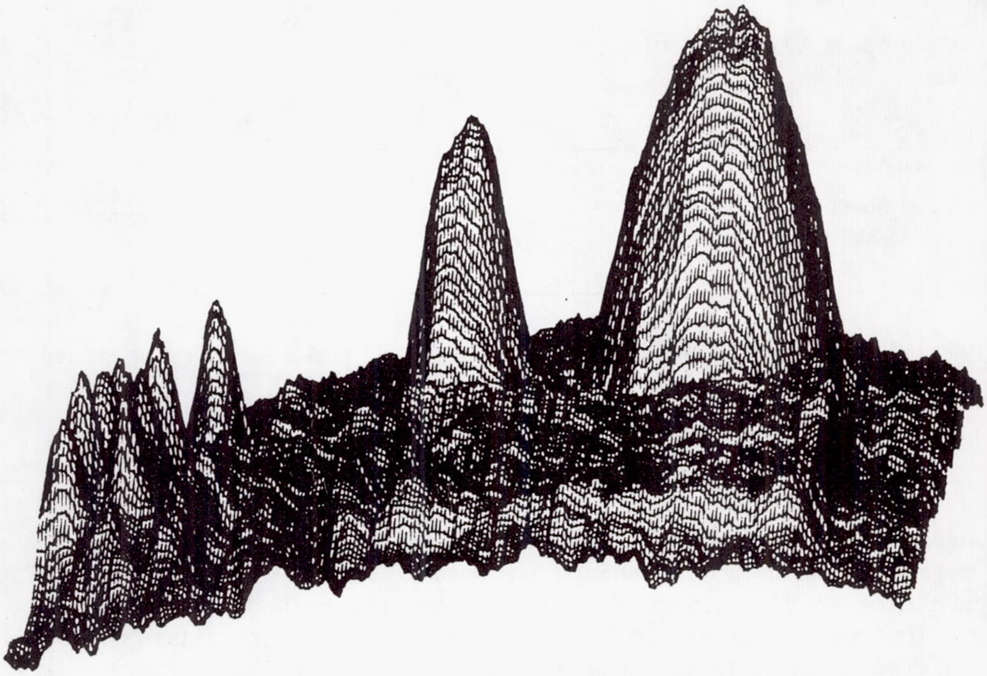

FIGURE 6. - 3-D SURFACE PLOT OF PLATE.

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Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-103252		

4. Title and Subtitle	5. Report Date
Fiber-Optic Projected-Fringe Digital Interferometry	
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Carolyn R. Mercer and Glenn Beheim	E-5681
	10. Work Unit No.
	590-21-11
9. Performing Organization Name and Address	11. Contract or Grant No.
National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191	
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Technical Memorandum
National Aeronautics and Space Administration Washington, D.C. 20546-0001	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the 1990 Fall Conference on Hologram Interferometry and Speckle Metrology sponsored by the Society for Experimental Mechanics, Baltimore, Maryland, November 4-7, 1990.

16. Abstract

A phase-stepped projected-fringe interferometer has been developed which uses a closed-loop fiber-optic phase-control system to make very accurate surface profile measurements. The closed-loop phase-control system greatly reduces phase-stepping error, which is frequently the dominant source of error in digital interferometers. Two beams emitted from a fiber-optic coupler are combined to form an interference fringe pattern on a diffusely reflecting object. Reflections off of the fibers' output faces are used to create a phase-indicating signal for the closed-loop optical phase controller. The controller steps the phase difference between the two beams by $\pi/2$ radians in order to determine the object's surface profile using a solid-state camera and a computer. The system combines the ease of alignment and automated data reduction of phase-stepping projected-fringe interferometry with the greatly improved phase-stepping accuracy of our closed-loop phase-controller. The system is demonstrated by measuring the profile of a plate containing several convex surfaces whose heights range from 15 to 25 μm high.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Topography; Nondestructive testing; Phase measurement; Fiber-optics; Interferometry	Unclassified – Unlimited Subject Category 35

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	8	A02

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161