

NASA SP-299

N73-25540
THRU
N73-25560

HOLOGRAPHY AND OPTICAL FILTERING CASE FILE COPY

A conference held at
MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama
May 24-25, 1971



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

HOLOGRAPHY AND OPTICAL FILTERING

The proceedings of a conference sponsored
by the National Aeronautics and Space
Administration and the Optical Society
of America and held at George C. Marshall
Space Flight Center, Huntsville, Alabama,
May 24-25, 1971



Scientific and Technical Information Office

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C.

1973

For sale by the Superintendent of Documents
U.S. Government Printing Office, Washington, D.C. 20402
Price: \$2.85, domestic postpaid; \$2.50, GPO Bookstore
Stock Number 3300-00496
Library of Congress Catalog Card Number 72-600046

Foreword

The Conference on Holography and Optical Filtering was held on May 24 and 25, 1971, at Marshall Space Flight Center, Huntsville, Alabama. It was sponsored jointly by NASA and the Huntsville Section of the Optical Society of America.

The purpose of the conference was to bring together people interested in the development of holography and optical filtering techniques, in order to discuss current trends and future possibilities. An effort was made to maintain a high level of competence by presenting only invited papers. The 25 papers were heard by approximately 100 attendees representing a wide range of institutions. Their participation indicated the widespread interest in the subject and the importance of this type of conference in establishing lines of communication.

A report on the conference, written by Dr. R. F. van Ligten, can be found in the October 1971 issue of *Applied Optics*. Thanks are due to Dr. van Ligten for this well written, detailed account of the conference.

The conference presented a field of interest for all—from the neophyte to the highly experienced professional. It is with my deepest sincerity and gratitude that I thank all of the many people involved in making this a successful conference.

John R. Williams
Conference Chairman

Page Intentionally Left Blank

Contents

	PAGE
A PULSED RUBY LASER SOURCE FOR PORTABLE HOLOGRAPHY	1
Donald H. Close	
ADVANCES IN PULSED RUBY LASERS DESIGNED FOR HOLOGRAPHY	7
E. Gregor	
HOLOGRAPHIC STUDY OF AN OPERATING COMPACT-ARC LAMP	13
Charles G. Miller	
HOLOGRAPHIC INSTRUMENTATION OF TURBINE BLADES	15
K. R. Overoye and R. Aprahamian	
APPLICATIONS OF HOLOGRAPHY TO WAVE PROPAGATION IN SHELLS AND TO VIBRATION AT HIGH TEMPERATURE	27
D. A. Evensen and R. Aprahamian	
APPLICATION OF HOLOGRAPHIC INTERFEROMETRY TO SHELL STRUCTURES	35
J. C. Chen and R. Badin	
HOLOGRAPHIC TECHNIQUES APPLIED TO THE SOLUTION OF AEROSPACE PROBLEMS	39
Frederick C. Way	
A NOVEL HOLOGRAPHIC TECHNIQUE TO RECORD FRONT- SURFACE DETAIL FROM A HIGH-VELOCITY TARGET	59
Robert L. Kurtz	
LIGHT SCATTERING IN PHOTOGRAPHIC MATERIALS FOR HOLOGRAPHY	75
Howard M. Smith	
THE QUANTITATIVE MEASUREMENT OF SMALL PHASE DIFFERENCES IN HOLOGRAPHICALLY RECONSTRUCTED OPTICAL FIELDS	83
G. S. Ballard	
QUANTITATIVE MEASUREMENT USING HOLOGRAPHIC INTER- FEROMETRY	93
Edwin B. Champagne	
NONDESTRUCTIVE TESTING AND FLOW VISUALIZATION—TWO AERO- SPACE APPLICATIONS OF HOLOGRAPHY	95
R. K. Erf, R. M. Gagosz, and J. P. Waters	
REVIEW OF HOLOGRAPHIC INSTRUMENTATION AT ARNOLD ENGIN- EERING DEVELOPMENT CENTER	121
J. D. Trolinger	
HOLOGRAPHIC DEVICES	129
H. Kogelnik and T. P. Sosnowski	
APPLICATIONS OF OPTICAL PROCESSING	131
A. Vander Lugt	
PHOTOPLASTIC RECORDING MATERIALS IN HOLOGRAPHIC MEMORIES .	137
A. A. Friesem and E. N. Tompkins	

	PAGE
APPLICATION OF COHERENT OPTICAL MATCHED FILTERING FOR DETECTION OF METEOR TRAILS	145
T. H. Gee and C. W. Allen	
HOLOGRAPHIC PATTERN RECOGNITION—NEW THOUGHTS ON OLD PROBLEMS	149
H. J. Caulfield	
SELECTIVITY AND NOISE EFFECTS IN APPLICATION OF OPTICAL CORRELATION	153
R. O. Webb and F. M. Shofner	
ONBOARD OPTICAL DATA PROCESSING FOR SPACECRAFT	163
Akram S. Husain-Abidi	
HOLOGRAPHIC IMAGE DEBLURRING METHODS	173
George W. Stroke	
ELIMINATION OF COHERENT NOISE IN A COHERENT LIGHT IMAGING SYSTEM	175
Gerald B. Grebowsky, Robert L. Herman, Hugh B. Paull, and Arnold Shulman	
OPTICAL CORRELATION EVALUATION OF SURFACE DEFORMATION DUE TO FATIGUE	177
Robert L. Bond	
SOLDER JOINT FATIGUE MEASUREMENT BY OPTICAL CROSS- CORRELATION	183
Rodney B. Jenkins and Melvin C. McIlwain	
AN INVESTIGATION OF THE REAL IMAGE OF AN APERTURE- LIMITED, IN-LINE FRAUNHOFER HOLOGRAM	193
Ronald A. Belz	

A Pulsed Ruby Laser Source for Portable Holography

Donald H. Close

Hughes Research Laboratories

The stability and coherence requirements for hologram recording ordinarily lead to rather large and massive holography systems. We describe a portable, self-contained holocamera, measuring 30.5 by 33 by 15.5 cm and weighing 7.9 kg, that uses a mode-controlled, pulsed ruby laser as the illumination source. Emphasis is placed on the design and operating characteristics of the laser source, which provides a TEM_{00} transverse mode output with a longitudinal coherence length of 25 cm. The small, highly reliable laser was built for a rangefinder system and later modified to provide a high-quality source for holography.

The purpose of the work described here was to demonstrate the feasibility of doing holography on the surface of the Moon. We developed and built a prototype holographic microscope designed to provide high-resolution imagery of the undisturbed lunar surface (ref. 1).^{*} Holography was used to provide a greater depth of field than can be obtained with a conventional photographic microscope. The goal was to make a small, lightweight, reliable instrument that would be insensitive to moderate vibration and would provide resolution of at least $5\ \mu\text{m}$ in images of a diffuse surface with 10-percent reflectivity.

Figure 1 shows schematically the operation of the system. The requirement of immunity to vibration means that the light source must be a pulsed laser. We used a small ruby laser with a normal-mode pulse duration of 100 to 150 μs .

There are several limitations that make it very difficult, even in the laboratory, to achieve the required resolution by direct holography. We therefore used a high-quality magnifying relay lens to reduce the f-number requirements on the hologram (ref. 2). This not only allows the use of film instead of plates to record the holograms, but also makes it possible to reconstruct the holograms with a continu-

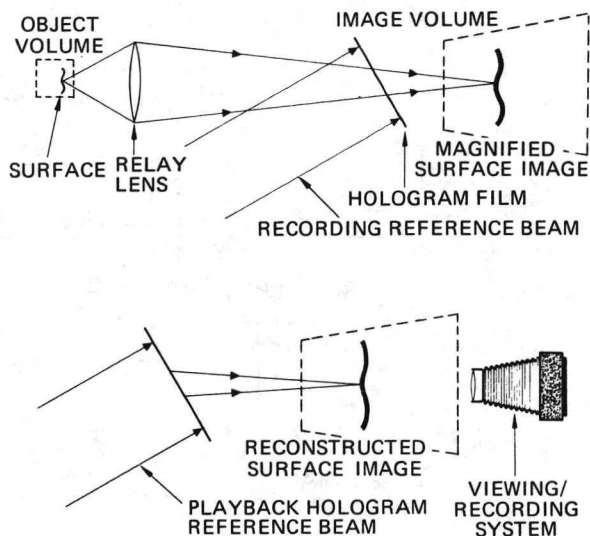


Figure 1.—Schematic diagram of the holographic system. Top: hologram recording step; bottom: hologram reconstruction step.

ous-wave helium-neon laser at 633 nm with no image degradation.

The increased depth of field is achieved by using holography to record the three-dimensional image space of the relay lens. This entire image space can then be studied and focused images can be recorded during the reconstruction step.

^{*}Construction and testing of the system were performed under contract NASW-2092 with NASA Headquarters.

The field of view and depth of field are determined by the characteristics of the relay lens and the system geometry. We use a 6X microscope objective which provides a field of view 4.5 mm in diameter and a depth of field of 4 mm. This depth is about 800 times larger than the calculated depth of focus that would be obtained using the same objective in an ordinary photographic microscope. Resolution in the system is limited by the effects of speckle, which introduce a strong granularity into the image. In order to reduce the speckle effects, the hologram camera is arranged to record an automatic sequence of four holograms of each site, each hologram having an independent speckle pattern. The four images can then be incoherently superposed to average the speckle granularity. We achieve a resolution of about $4\text{ }\mu\text{m}$ in images of diffuse surfaces from a single hologram. Considerably improved contrast and image

quality and a slight improvement in resolution are observed in the superposition of the four images.

LASER DESCRIPTION

The ruby laser on which we based the hologram microscope design was developed at the Hughes Aircraft Company for a military rangefinder system. We obtained the unit from a production run of 300 systems. The rangefinder laser has passed extensive and severe environmental testing (ref. 3).

Figure 2 shows a schematic layout of the rangefinder laser and a photograph of the laser as used in the hologram camera. The basic mechanical structure of the laser is a T-section of aluminum approximately 19 by 6 by 4 cm with appropriate fixtures for mounting the components. This configuration provides a very rigid structure and excellent alignment stability. The pathlength of the optical cavity is about

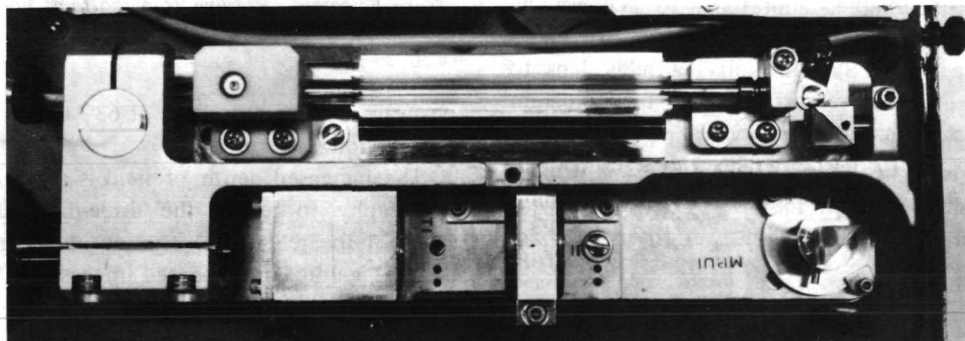
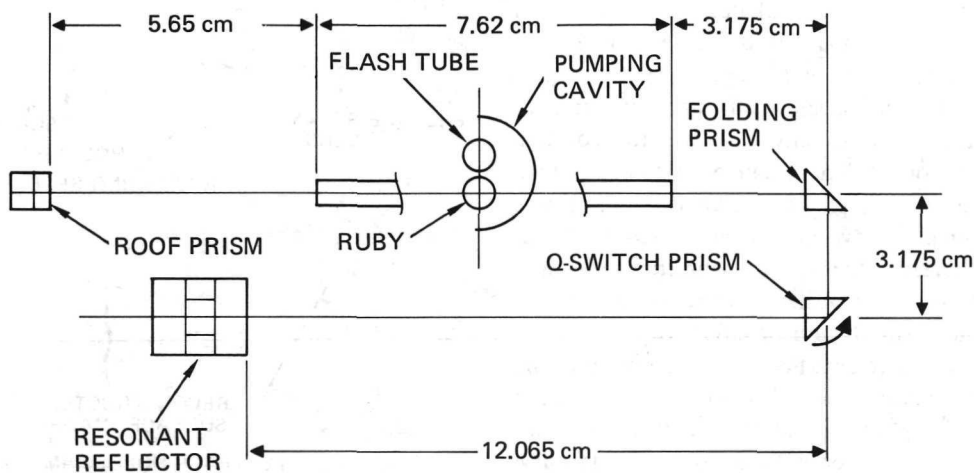


Figure 2.—Top: schematic of rangefinder laser head; bottom: photograph of the modified laser in the hologram camera.

36 cm. The cavity extends from a resonant reflector output coupler through two folding prisms and the ruby crystal to a roof prism reflector. In the rangefinder system the roof prism provides alinement in the vertical direction and one of the folding prisms is rotated to provide Q-switching and alinement in the horizontal direction. The ruby rod is 6.4 mm in diameter and 76.2 mm long. It is pumped by a single linear xenon flashlamp through a high-reflectivity, semielliptical pump cavity. The ruby is clamped in an aluminum block that holds it securely and provides rapid heat transfer to the external structure.

The resonant reflector is made from three disks of SK-14 glass with a refractive index of 1.6. Each disk is 7.5 mm thick and is polished flat and parallel. One disk is bored out to form a cylindrical spacer and the other disks are optically contacted to either side of the spacer. This unit was originally incorporated into the laser design to provide a damage-resistant output coupler, but it also provides good longitudinal mode control.

Modification of the laser head for holographic use was straightforward. We fixed the rotating prism in permanent alinement to provide normal-mode operation, replaced the roof prism with a high-reflectivity flat dielectric mirror, and inserted a 1.0-to-1.5-mm-diameter aperture inside the optical cavity. The two latter modifications provided transverse mode control.

With these modifications the laser operates in a TEM_{00} transverse mode and in a single mode of the resonant reflector. The TEM_{00} mode operation was verified by making near-field and far-field photographs of the laser output. These photographs showed that the output was diffraction-limited to the accuracy of the measurement. The longitudinal mode structure was studied with a Fabry-Perot interferometer and a Michelson interferometer. Figure 3 shows some examples of mode structure data obtained from this laser. The free spectral range of the Fabry-Perot interferometer was 2.1 cm^{-1} with a resolution of about 0.1 cm^{-1} . These data show that the oscillation bandwidth is less than 0.1 cm^{-1} and is very reproducible from shot to shot. In order to determine the longitudinal coherence length, we observed fringe visibility versus pathlength difference in a simple Michelson interferometer. The fringe visibility dropped by a factor of two at about 25 cm. These measurements were made at an output level of about 50 mJ.

We also Q-switched the laser with a solution of cryptocyanine in methanol. The TEM_{00} mode was maintained and the longitudinal coherence length was extended to at least 1 m, the limit of the measurement. Pockels cell Q-switching was not attempted, but experience with other lasers indicates that the excellent output characteristics should be maintained.

SYSTEM DESCRIPTION

A schematic diagram of the hologram microscope optical system is shown in figure 4. The output of the ruby laser is split to form an object illumination beam and a collimated reference beam. The use of a collimated reference beam reduces the effective point

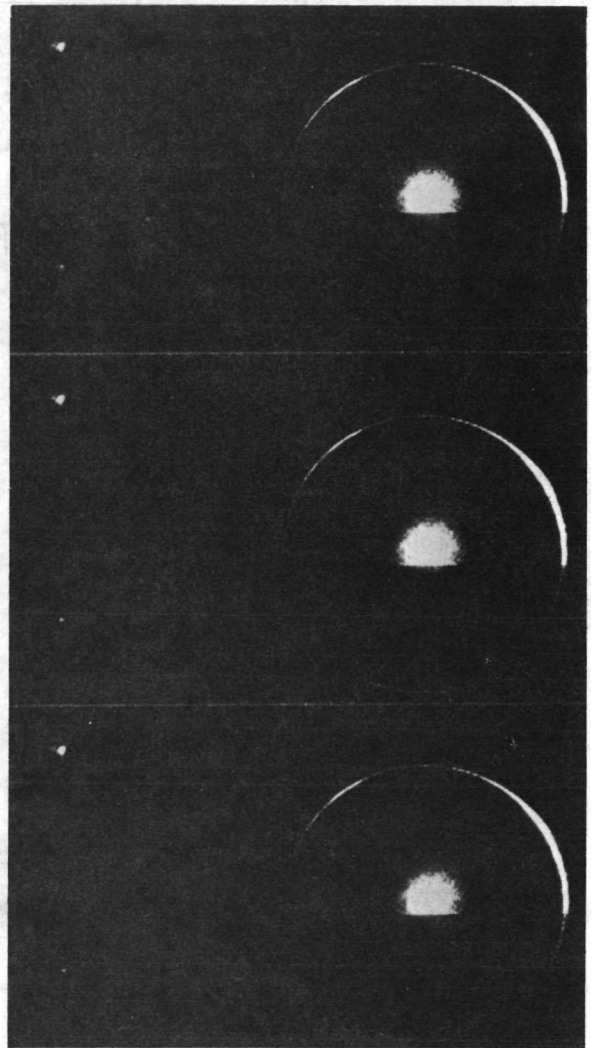


Figure 3.—Mode structure data from a sequence of three firings of the laser.

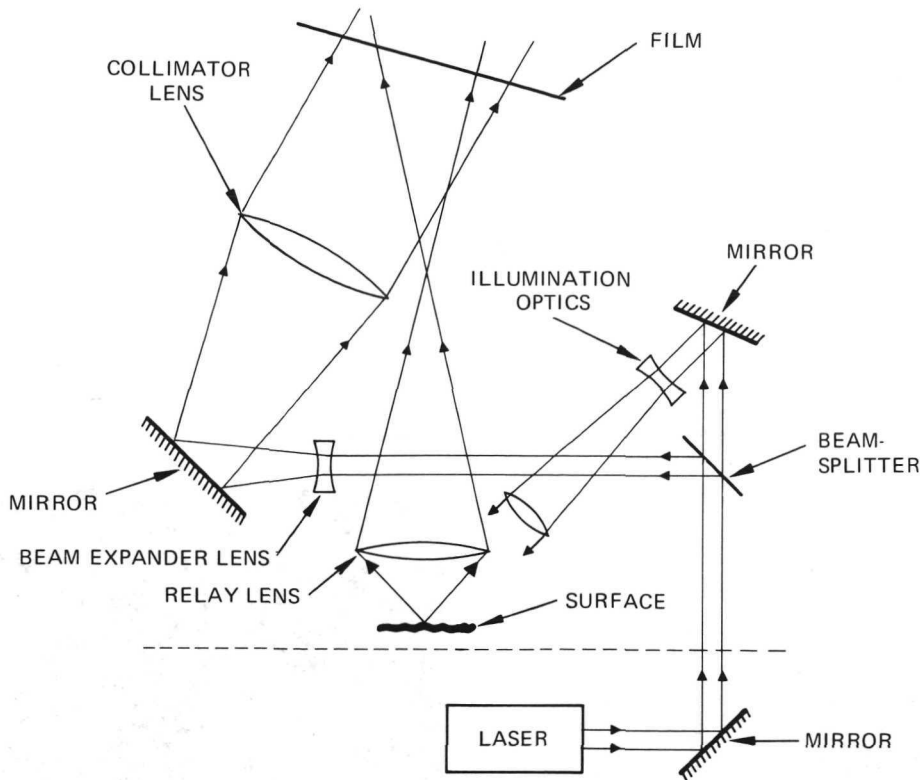


Figure 4.—Schematic diagram of the hologram microscope optics.

source size and provides simple access to both the primary and the conjugate images during the reconstruction step. With this system the resolution of a single holographic image is limited by the effects of speckle (ref. 4), which produces a random granularity in the image. We decided after considerable study and experimental evaluation to make a sequence of four holograms of each surface site, with each hologram recording an independent speckle pattern. The four resulting images can then be incoherently superposed to reduce the speckle granularity.

The independent speckle patterns are provided by changing the object illumination between exposures. The illumination optics shown schematically in figure 5 provide an independent, random phase distribution in the object illumination for each exposure, without appreciably changing the illumination direction. This is done by rotating the wedge plate through an angle of 90° about the optical axis between exposures. The wedge plate deviates the beam by only 3 mrad.

Figure 6 is a photograph of the hologram microscope. The instrument weighs 7.9 kg and measures

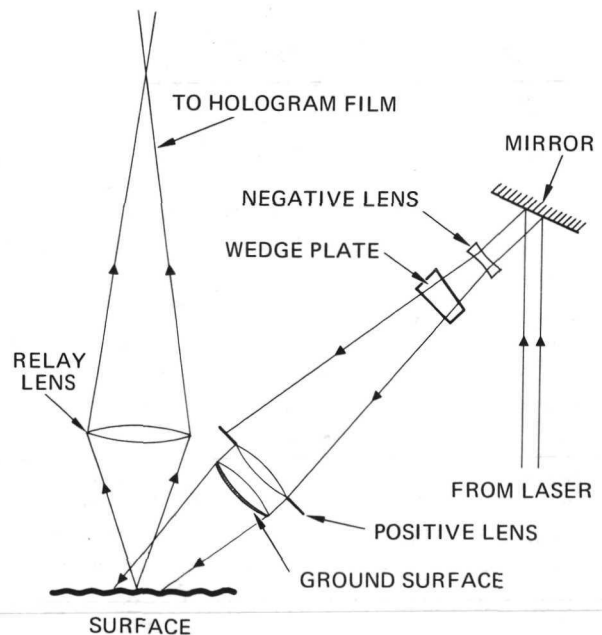


Figure 5.—Schematic diagram of the object illumination optics.

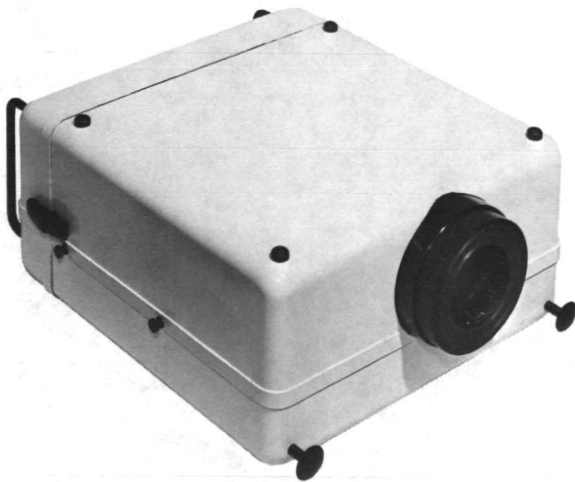


Figure 6.—Exterior view of the hologram microscope.

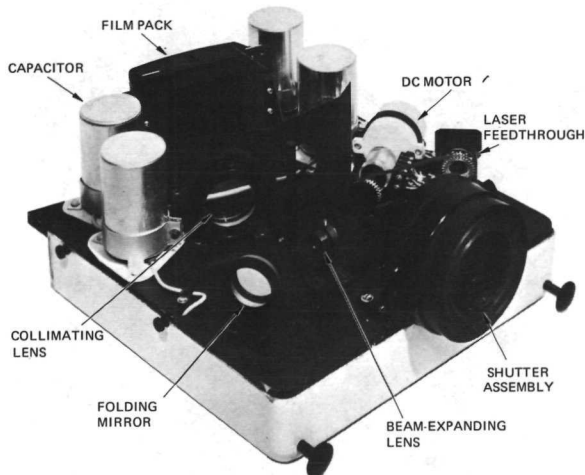


Figure 7.—Interior view, showing the hologram optics.

30.5 by 33 by 15.5 cm. It is completely self-contained, operating from rechargeable storage batteries.

The interior of the instrument is shown in figure 7. The hologram optics and the laser energy storage capacitors can be seen in this view, while the relay lens and part of the object illumination optics are hidden by the shutter assembly. The reference beam diameter is 50 mm, and the angle between the reference and object beams is 30° . Figure 8 shows the battery pack and the compact ruby laser system. The capacitor-charging electronics used here are also part of the laser rangefinder system; a few modifications

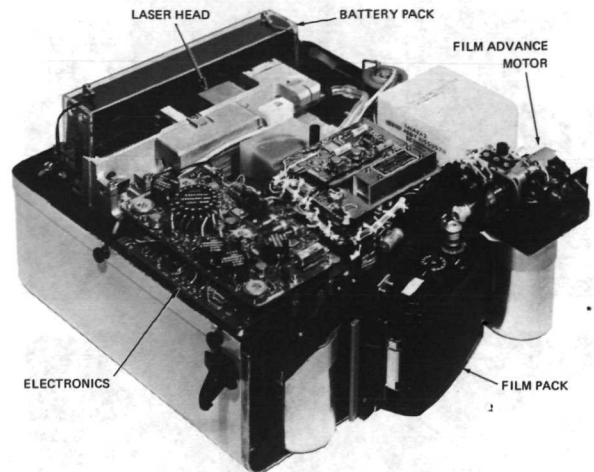


Figure 8.—Interior view, showing the ruby laser system.

have been made and some control circuitry has been added.

Figure 9 illustrates the type of imagery produced by the instrument. A conventional photograph of an integrated circuit assembly is shown at the top. Below it is a photographic recording made from a single hologram of the microcircuit. The latter picture was taken with a camera focused on the face of the silicon chip in the three-dimensional holographic image. It shows about one-half the total field of view of the instrument; the silicon chip is 1.0 mm square. The overall magnification in the lower photograph is 29 times larger than in the top photograph.

The instrument provides a resolution of $1.8 \mu\text{m}$ for a specular point, and about $4 \mu\text{m}$ for diffuse image detail. The image signal-to-noise ratio is 30:1 to 35:1 for the range of reference-to-object-beam intensity ratios normally encountered. The resolution is within a factor of 2 to 3 of that achieved using the same objective in a conventional photographic microscope, while the effective depth of field is increased by some 800 times through the use of holography.

REFERENCES

1. Close, D. H.: Lunar Surface Holography—Equipment Feasibility Demonstration, NASA Report No. N71-16574, Dec. 1970.
2. van Ligten, R. F.; and Osterberg, H.: Holographic Microscopy. *Nature*, Vol. 211, 1966, p. 282.
3. Claar, D.: Acceptance Test Report AN/VVS-1(), Laser Rangefinder for M60A1E2 Tank—Serial Number 3. Hughes Aircraft Company, Research and Development Division, Aerospace Group, Culver City, California; prepared under Contract No. DAAA25-67C-0112.
4. Gabor, D.: Laser Speckle and its Elimination. *IBM J. Res. Develop.*, Vol. 14, 1970, p. 509.

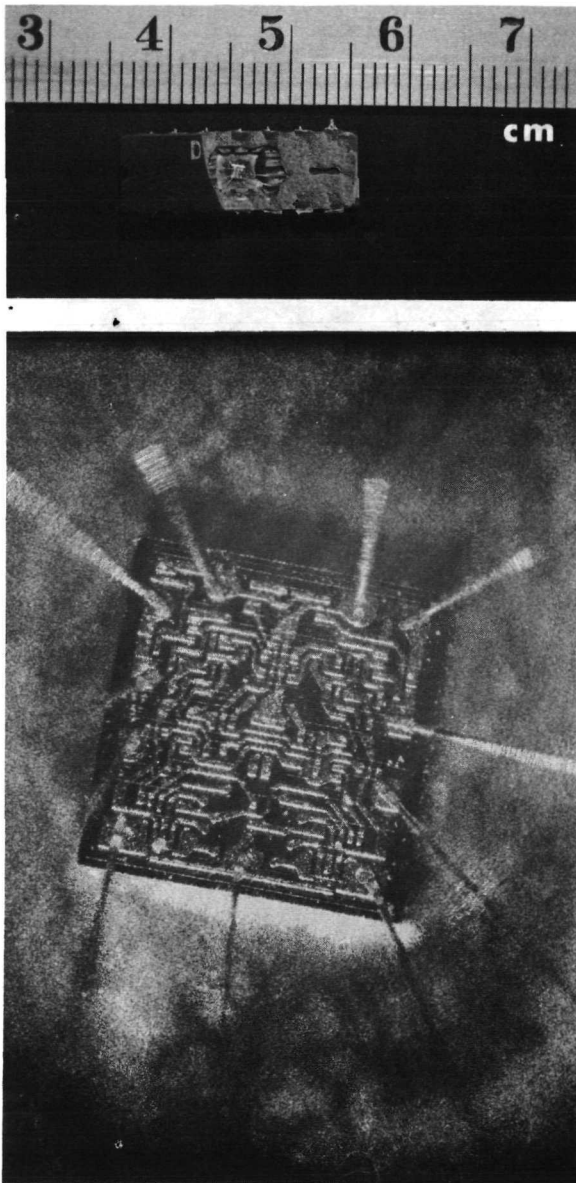


Figure 9. Top: ordinary photograph of an integrated circuit assembly. Bottom: photograph of a single holographic image showing the face of the silicon chip at an overall magnification 29 times larger than in the top photograph.

Advances in Pulsed Ruby Lasers Designed for Holography

E. Gregor

*Korad Department
Union Carbide Corporation*

Many technical advances have been made recently to increase the coherence length with temperature-controlled multiple etalons and to improve the beam uniformity by growing better ruby crystals. The pulsedwidth obtainable has been reduced to 2.5 ns without loss of coherence, thus providing shorter holographic exposure times. Large-diameter ruby crystals now available have made it possible to obtain higher energy outputs without reaching the damage threshold. The ruby laser can be readily pulsed with pulse separations down to 2 μ s. Environmentally sealed enclosure designs have allowed it to be used in severe industrial environments.

Since the early use of a pulsed ruby laser in holography around 1965, by Jacobson and McClung at Hughes; Brooks, Hefflinger, and Woerker at TRW; and Silverman, Thompson, and Ward at Tech/Ops, significant technical advances have been made to improve the performance parameters (refs. 1, 2, and 3):

1. The coherence has been extended to beyond 1 m.
2. The pulsedwidth (pulse duration) has been reduced to less than 1 ns.
3. The energy output has been increased to more than 10 J.
4. Double and multiple pulsing have been obtained down to 2 μ s pulse separation.
5. Environmentally sealed enclosures have been designed so that the ruby laser can leave the air-conditioned environment of the R&D laboratory and be used in a severe industrial environment.

The coherence length of the laser limits the depth of field in holography. Therefore considerable effort has been concentrated recently on improving this important characteristic of the ruby laser. The coherence of a laser is commonly divided into temporal

and spatial coherence. Temporal coherence is expressed as either spectral width measured with a Fabry-Perot interferometer or coherence length measured with a Michelson interferometer (ref. 4).

To increase temporal coherence, three major methods are used to obtain longitudinal mode selection:

1. Intercavity etalons
2. Resonant reflectors
3. Bleachable absorbing dye cells

In the ruby laser, the resonant cavity is created by the two mirrors (see fig.1). The ruby crystal and the flashlamp are contained in the laser head. The Q-switch consists, in this example, of a Pockels crystal and a polarizer. The tilted etalon is added to improve the coherence length. Tilted etalons have

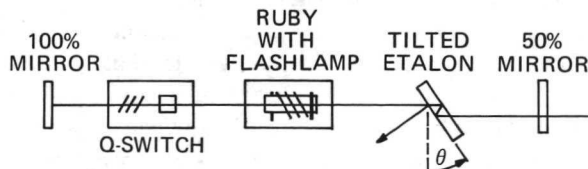


Figure 1.—Ruby laser system using tilted etalon.

been used since 1963 (refs. 5 and 6). However, one of their drawbacks is the need for stability and accuracy of angular alignment. When the etalon is aligned perpendicular to the laser beam ($\theta=0^\circ$), it creates a resonant reflector with a 50-percent mirror. The use of resonant reflectors has been suggested in the literature as early as 1962 (refs. 7 and 8). Results recently obtained demonstrate the effectiveness of this technique, especially when used in a ruby laser and when the design can be optimized with the aid of computers (refs. 9 and 10).

Figure 2 shows a computer plot of a resonant reflector which was found to give a linewidth of less than 0.001 nm in a ruby laser. The resonant reflector has a reflectivity which is dependent on wavelength. This example exhibits two reflectivity peaks, each showing 50-percent reflectivity, separated by 0.085 nm. This separation is needed because a ruby laser without mode selection has a total spectral width of about 0.06 nm.

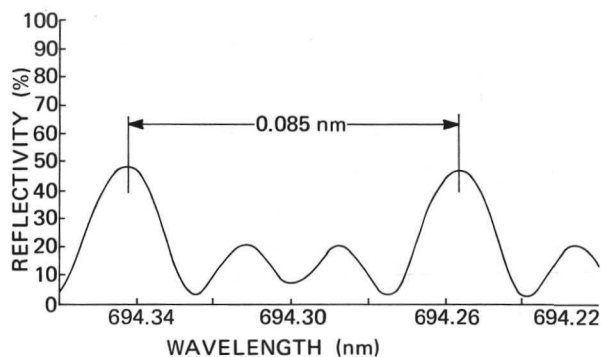


Figure 2.—Reflectivity of a resonant reflector in a ruby laser plotted as a function of wavelength.

Figure 3 shows a photograph from a Fabry-Perot interferometer. A ruby laser without mode selection was used. The interorder spacing is about 0.1 nm. Three distinct spectral lines are visible, separated by about 0.03 nm, representing the ruby output. Using the resonant reflector represented by figure 2, we can select one of the three spectral lines. By changing the temperature, the ruby fluorescent spectral line was adjusted to coincide with one of the high-reflectivity peaks of the resonant reflector. The result is shown in figure 4. Using the same Fabry-Perot interferometer, we observe only one spectral line in the ruby output.

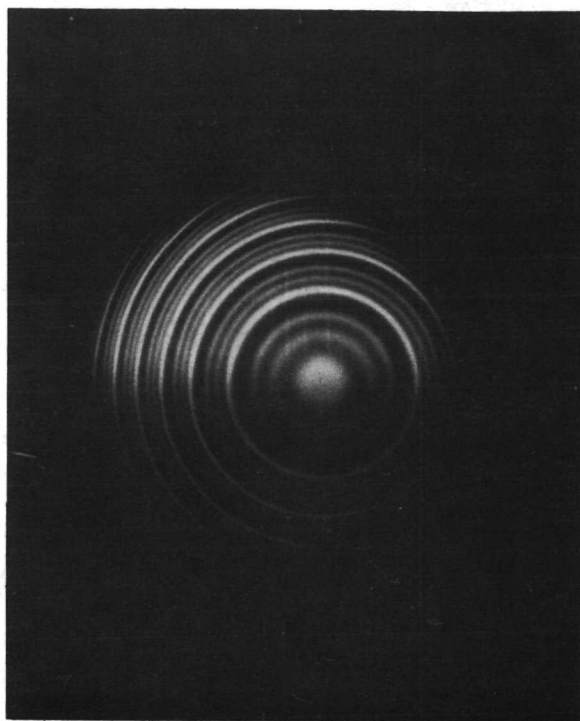


Figure 3.—Fabry-Perot interferogram showing the output of a ruby laser without mode selection.

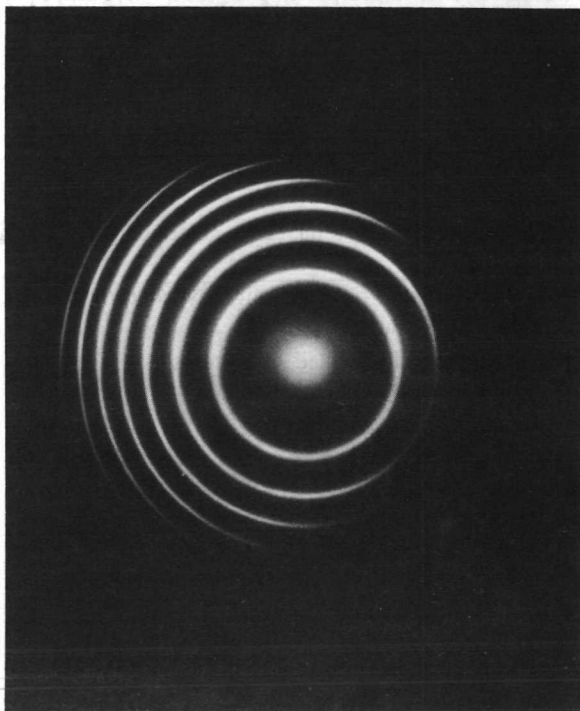


Figure 4.—Interferogram showing only one spectral line in ruby laser output.

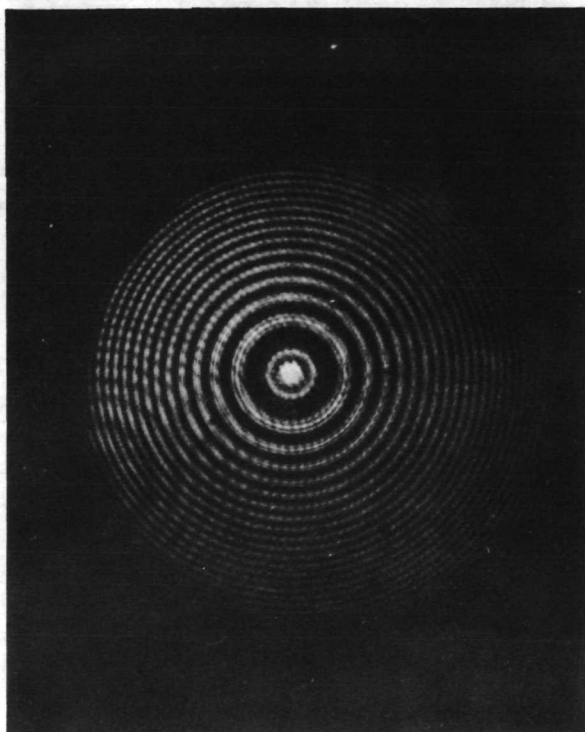


Figure 5.—Interferogram showing 0.001-nm linewidth of ruby laser output.

By changing the spacer in the Fabry-Perot to 100 mm, we obtain an interorder spacing of 0.0024 nm and can readily observe the 0.001-nm linewidth in figure 5.

This same result can be obtained using a bleachable absorbing dye cell as a Q-switch. The bleachable absorbing dye cell has inherent mode-selecting properties which are due to its nonlinear absorption characteristics. The most common dye in ruby lasers is cryptocyanine in methanol (ref. 11). For the best coherence, a combination of resonant reflector and bleachable dye cell is used.

Good spatial coherence or TEM_{00} performance can be readily obtained today in a ruby laser. This is due mainly to advances in crystal growth technology, which have virtually eliminated the problems of multiple transverse-mode performance due to scattering centers and index variations inside the ruby crystal (ref. 12).

Figure 6 shows an example of a good-quality ruby crystal. The Twyman-Green interferogram indicates a minimum of fringes across the central aperture.

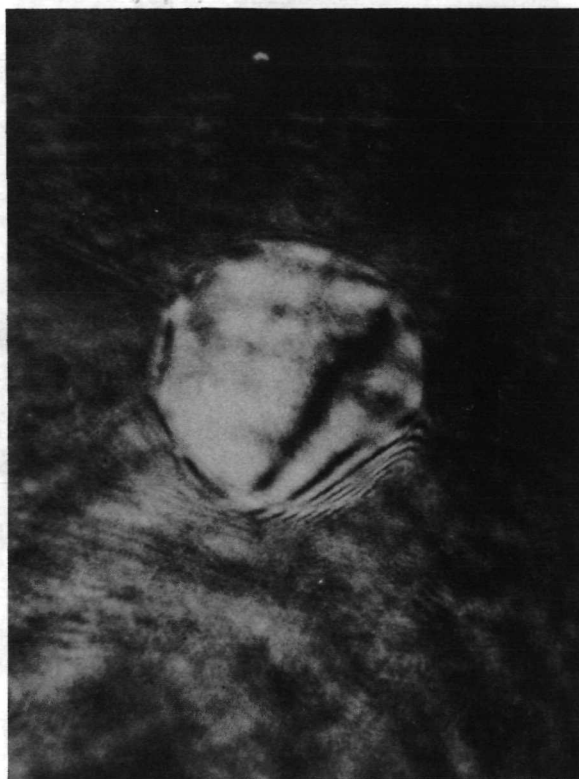


Figure 6.—Twyman-Green interferogram of a good ruby crystal.

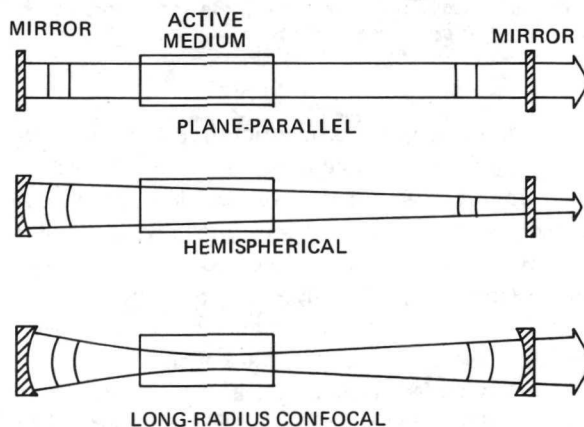


Figure 7.—Three types of resonators used with ruby lasers.

Starting with such a ruby crystal, the well established resonators can be used to obtain TEM_{00} performance. All three resonators shown in figure 7 have been used to obtain TEM_{00} output from a ruby laser. The

majority of commercially available ruby lasers, however, use the long plane-parallel resonator, aided by an aperture (ref. 13). This resonator has the largest mode volume inside the active medium, thus providing potentially the optimum output.

The pulsewidth of the ruby laser determines the exposure time in holography. In the Q-switched ruby laser, the pulsewidth ranges from 10 to 100 ns. Rotating mirror and Kerr cell Q-switches provide pulsewidths of 50 to 100 ns. Pockels cell and bleachable absorbing dye Q-switches both give pulsewidths of 10 to 30 ns.

Figure 8 shows an oscilloscope trace of a Pockels cell Q-switched pulse. The time scale is 20 ns per division.

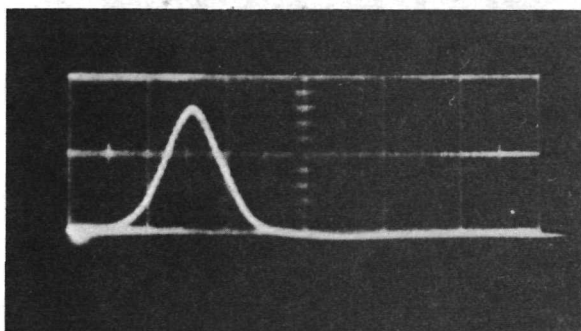


Figure 8.—Pockels cell Q-switched pulse (each division on horizontal scale equals 20 ns).

All three Q-switches mentioned can be double-pulsed and multipulsed with varying degrees of difficulty (ref. 14). The Pockels cell has been multipulsed down to 2 μ s pulse separation and is popular because of its low jitter, good reproducibility, and low driving voltage (ref. 15). To obtain pulsewidths of less than 10 ns, more elaborate methods have been used recently. The pulse transmission mode, or "cavity dumping", technique has reduced the pulsewidth to 2.5 ns (refs. 10 and 16). The shortest pulses (less than 1 ns) are obtained using mode locking (fig. 9). To single out one subnanosecond pulse from a mode-locked train, an external Pockels or Kerr cell is used as a shutter (refs. 17 and 18).

Since the coherence length is ultimately limited by the pulsewidth, a coherence length of 15 cm is the best that can be expected from a 1-ns pulse.

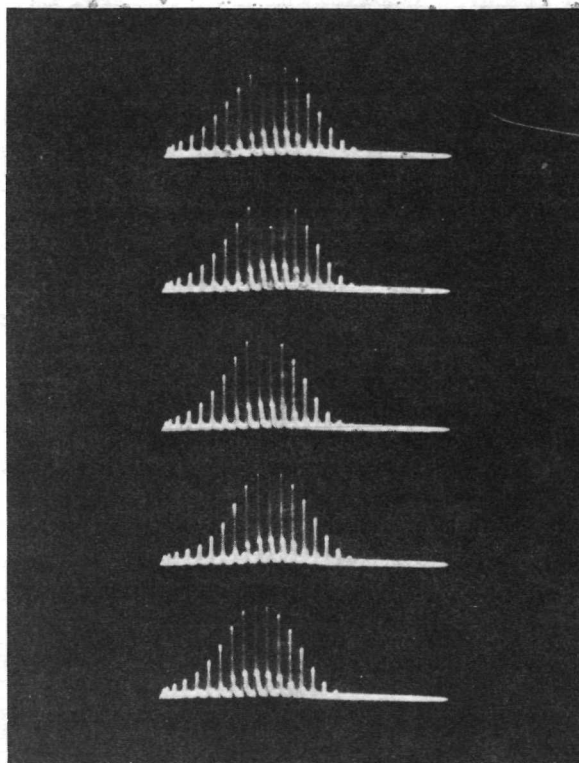


Figure 9.—Pulses obtained using mode locking (each pulse less than 1 ns).

The energy contained in one pulse limits the size of the object in holography. A ruby laser without an amplifier typically has an output of 30 to 100 mJ at about a 20-ns pulsewidth. This energy is sufficient for transmission holography, where most of the energy is recombined at the holographic plate, and for diffuse reflection holography of small objects. Figure 10 depicts a typical transmission holography optical arrangement. Figure 11 shows a diffuse reflection holography arrangement. With a 10-cm-long ruby crystal as an amplifier, a gain of 4 to 5 is obtained. Diffuse reflection holography of a 50-by-50-cm object can be readily performed, as shown in figure 12.

Recent advances in ruby crystal growth technology have produced ruby crystals of up to 2.5-cm diameter and 30-cm length. These crystals are obtained from 6-cm bulls. The crystal diameter determines the ultimate limit of the energy from a ruby laser. The highest operating energy density level commonly used is 6 J/cm² or 300 MW/cm². At

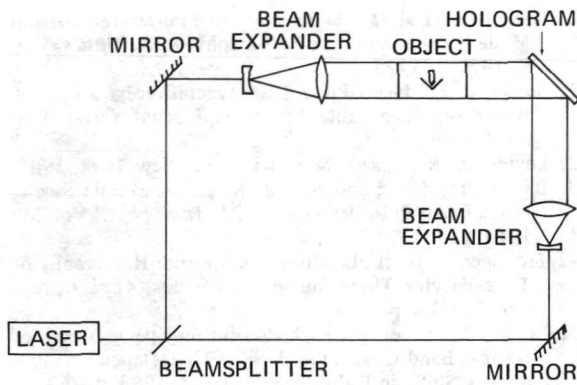


Figure 10.—Optical arrangement for transmission holography.

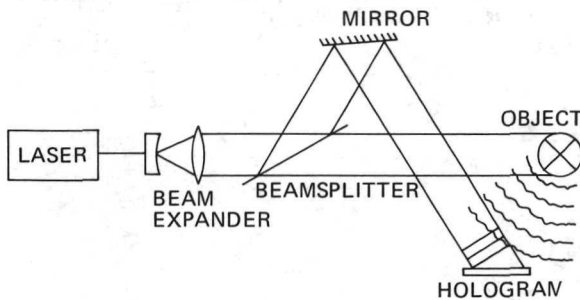


Figure 11.—Arrangement for diffuse reflection holography.



Figure 12.—Photograph of diffuse reflection holograph.

higher energy density levels, damage to the ruby crystal can result after only a few pulses. The present-day practical limit from a 2.5-cm-diameter ruby is 30 J.

In order to move the ruby laser from the R&D laboratory to the industrial environment, advanced packaging had to be developed. Sealed enclosure designs combined with semipermanently aligned shock-resistant mirror mounts have simplified the operation and maintenance of the commercially available ruby laser. An example of a present-day holographic ruby laser is shown in figure 13. The laser rail assembly is hermetically sealed in an environmental enclosure. The power supply, the Q-switching electronics, and the water cooling system are contained in a single compact cabinet.

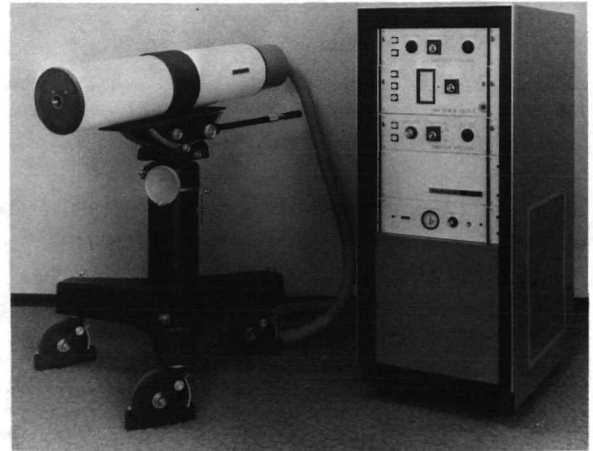


Figure 13.—A commercial holographic ruby laser system.

In summary, significant advances have been made to adapt the ruby laser for holography since it was first used in 1965. The coherence has been extended to beyond one meter. The energy has been increased to exceed 10 joules. The pulsewidth has been reduced to less than one nanosecond. Double and multiple pulsing has been reliably obtained. Finally, the new environmental enclosures are enabling the ruby laser to perform as a valuable pulsed light source in many holographic applications.

REFERENCES

1. Jacobson, A. D.; and McClung, F. J.: Holograms Produced with Pulsed Laser Illumination, *Appl. Optics*, Vol. 4, 1965, pp. 1509-1510.
2. Brooks, R. E.; et al.: Interferometry with Holographically Reconstructed Comparison Beam, *Appl. Phys. Letters*, Vol. 7, 1965, pp. 92-94.
3. Silverman, B. A.; Thompson, B. J.; and Ward, J.: A Laser Fog Disdrometer, *J. Appl. Met.*, Vol. 3, 1964, p. 792.
4. Smith, W. V.; and Sorokin, P. O.: *The Laser*, McGraw-Hill, New York, 1966.
5. Collins, S. A.; and White, G. R.: Interferometer Laser Mode Selector, *Appl. Optics*, Vol. 2, 1963, p. 448.
6. Manager, H.; and Rothe, H.: Selection of Axial Modes in Optical Masers *Phys. Letters*, Vol. 7, 1963, p. 330.
7. Kleinman, D. A.; and Kislink, P. O.: Discrimination against Unwanted Orders in Fabry-Perot Resonators, *Bell Sys. Tech. J.*, Vol. 41, 1962, p. 453.
8. Kogelnik, H. and Patel, C. K. N.: Mode Suppression and Single Frequency Operation in Gaseous Optical Masers, *Proc. Inst. Radio Engrs.*, Vol. 50, 1962, p. 2365.
9. Watts, J. K.: Theory of Multiplate Resonant Reflectors, *Appl. Optics*, Vol. 7, 1968, p. 1621.
10. Gregor, E. et al.: Mode Selection in a Pulse Transmission Mode Ruby System for Holography, *Appl. Optics*, Vol. 9, 1970, p. 1723.
11. Soffer, B. H.: Giant Pulse Laser Operation by a Passive, Reversibly Bleachable Absorber, *J. Appl. Phys.*, Vol. 35, 1965, p. 2551.
12. Levine, A. K.: *Lasers*, Marcel Dekker, New York, 1965.
13. Bjorkholm, J. E.; and Stolen, R. H.: A Simple Single-Mode Giant-Pulse Ruby Laser, *J. Appl. Phys.*, Vol. 39, 1968, p. 4043.
14. Trolinger, J. D. et al.: Multiple-Exposure Holography of Time-Varying Three-Dimensional Fields, *Appl. Optics*, Vol. 7, 1968, p. 1640.
15. Bradley, D. J. et al.: High-Resolution Spectroscopy of Narrow-Band Giant-Pulse Lasers: Time-Dependent Frequency Shifts in Ruby, *Phil. Trans. A*, 1968, p. 263.
16. Rundle, W. J.: A Ruby Laser Modified for Pulse-Transmission Mode Cavity Dumping, *J. Appl. Phys.*, Vol. 39, 1968, p. 5338.
17. DeMaria, A. J. et al.: Picosecond Laser Pulses, *Proc. of the IEEE*, Vol. 57, 1969, p. 2.
18. Gregor, E.; and Davies, J. H.: Design Considerations for Nanosecond Holography, *Electro-Optical Systems Design*, July-Aug. 1969, p. 48.

Holographic Study of an Operating Compact-Arc Lamp

Charles G. Miller

Jet Propulsion Laboratory

Flash holograms have been made of a xenon compact-arc discharge while in operation. With the anodes used, the holograms showed laminar flow at the interface of the arc stream and anode surface. No evidence of gas density variation in the vicinity of the center core of the arc was found. Electron densities in the arc stream were shown to be too low to introduce significant refraction in looking through the arc.

The data presented are the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS 7-100, sponsored by the National Aeronautics and Space Administration.

Page Intentionally Left Blank

Holographic Instrumentation of Turbine Blades

K. R. Overoye and R. Aprahamian

*Advanced Technology Staff
TRW Systems Group*

The applicability of laser holographic interferometry to the determination of stresses in turbine blades was investigated. Experiments included continuous-wave holographic interferometry of a statically loaded blade at both room and elevated temperatures (760 °C) and a vibrating blade at room temperature. A finite-element computer model of the blade was used to calculate deflections, strains, and stresses in the blade in response to the experiment loads. The holographically measured deflections were compared to the computed deflections and were found to be in good agreement. Actual stresses were then taken to be those calculated by the computer program. The feasibility of obtaining holograms of blades rotating at high speed was investigated analytically and experimentally. Analysis showed that certain optical arrangements or shortened laser pulses were required. Experiments were performed in which holograms were successfully recorded, confirming the analysis and demonstrating that high rates of rotation do not necessarily degrade holographic images.

TRW recently has completed a contract* with the Naval Air Systems Command in which the objective was to determine the feasibility of applying holographic techniques to the study of stresses in operating turbine blades. Jet engine designers now rely on high-temperature strain and stress gages, connected through slipring contacts, to measure strains and stresses in blades in an operating engine. The desirability of using holography as a noncontacting displacement measurement technique is evident. Toward this end, TRW has performed a number of experiments designed to measure deflections in turbine blades at elevated temperatures and to establish methods of obtaining holograms of turbine blades rotating at 10 000 rpm.

Four of the experiments conducted dealt with the measurement of deflections in stationary turbine blades. For these experiments, continuous-wave (CW) holography was employed. Experiments were performed on a blade both at room temperature and at

about 760 °C (1400 °F). Deflections of the blade were measured holographically in response to (1) a bending load, (2) a torsion load, (3) a thermal gradient, and (4) vibration mode excitation. A numerical model of the blade was used to compute deflections, strains, and stresses in the blade. The holographic data was used to verify the model. An evacuated enclosure around the blade eliminated the adverse effects of air convection currents over the heated blade on the holographic recording process. A fifth experiment investigated the feasibility of recording a hologram of a turbine blade rotating at high speed. For the last experiment, pulsed ruby laser illumination was used.

The methods developed and the results achieved are presented in the following descriptions of each of the experiments.

STATIC STRESS DETERMINATION IN TURBINE BLADES

For the static load experiments, the objective was to measure whole surface deflections of a turbine

*N00019-70-C-0590

blade using holography and a known applied static load. The technique described by Aleksandrov and Bonch-Bruevich (ref. 1) was employed to relate the holographic data to the displacement fields. Two loading conditions were investigated. One type of loading was the application of a point load near the tip so as to cause chiefly bending in the turbine blade. The other was the application of a two-point couple to produce primarily static torsion of the blade. These experiments were performed both at room temperature and near the operational temperature of the turbine blade. The holographic data was interpreted to provide the deflections of the blade surface. A finite-element technique, described below, was used to determine stresses and strains. The data obtained holographically was used to verify the finite-element technique.

A fixture was constructed to clamp a small turbine blade (from stage 4 of the T-64 engine) rigidly across its root. A pushrod mechanism was designed to apply a measured point load near the tip of the turbine blade. A two-fingered mechanism was devised to apply a static torsion load to the blade. To heat the blades, a thin molybdenum foil was placed near the blade on the side facing away from the holographic apparatus. The foil was resistively heated and the blade in turn was radiantly heated by the foil. The final temperature distribution in the blade approximated the distribution in the blade under operational conditions in an engine (approximately 540°C at the root and 815°C at the tip). Heating led to an experimental problem. Convection currents over the blade caused optical pathlength shifts during the recording of holograms using CW laser illumination. To overcome this difficulty, the blade and its heating and loading fixture were placed in a metal vacuum bell jar. A large port provided a view of the blade for holographic purposes. To insure a valid comparison between the room-temperature case and the heated case, both sets of the experiments were performed with the bell jar in place and evacuated. Figure 1 shows a typical holographic interferogram of the blade heated to 760°C with an applied bending load. Figure 2 shows an interferogram with an applied torsion load and the blade at room temperature.

A number of interferograms were recorded both at room and elevated temperatures over the ranges from 0 to 4.5 kg (0 to 10 lb) for the applied bending load and from 0 to 88.5 N-m (0 to 10 in.-lb) for the applied torsion load. The measured deflections of the

blade were normalized to a unit applied for all interferograms. For each experimental condition, the normalized deflections at the two corners of the blade tip were found to agree within experimental error.

As indicated above, special analytical techniques were required to determine internal strains and stresses within the blade. An analytical model of the blade was formulated and then used to compute the deflections of the blade in response to the experimentally applied loading forces. Provided the deflections measured holographically and those computed analytically were in agreement, it was assumed that the stresses and the strains in the blade were accurately given by the computational procedure itself. It should be noted that the holographic technique measured only one of three components of the deflection of the blades. Although holography is a three-dimensional process and holographic interferometry is capable of measuring all components of a given deflection (ref. 1), sophistication beyond the scope of this program would have been required to measure more than a single component. Hence, the comparison between the experimental and theoretical results was made only for a single component.

The analytical computations for the static bending and static torsion experiments (and vibration mode experiments discussed below) were performed using a finite-element technique (refs. 2 and 3). The finite-element model divided the blade into 14 sections, or elements. Each section was represented by a curved surface with somewhat idealized shape. The process was analogous to representing a complicated surface by a set of flat platelike sections. However, the sections for this model were allowed to possess curvature in two directions and variable thickness (ref. 4). The elastic constants and mass density of the blade material were included in the model. Through standard matrix algebra the strains, stresses, and deflections of the turbine blade were calculated for each of the conditions treated experimentally. Deflections were calculated in three orthogonal directions and then combined to give the component measured by the holographic experiments.

Figures 3 through 6 show comparisons of the computed and measured deflections for each of the static loading experiments along the leading and trailing edges of the turbine blade. As can be seen, the comparison is quite good. The discrepancy that does exist may be attributed to a few factors. One possible

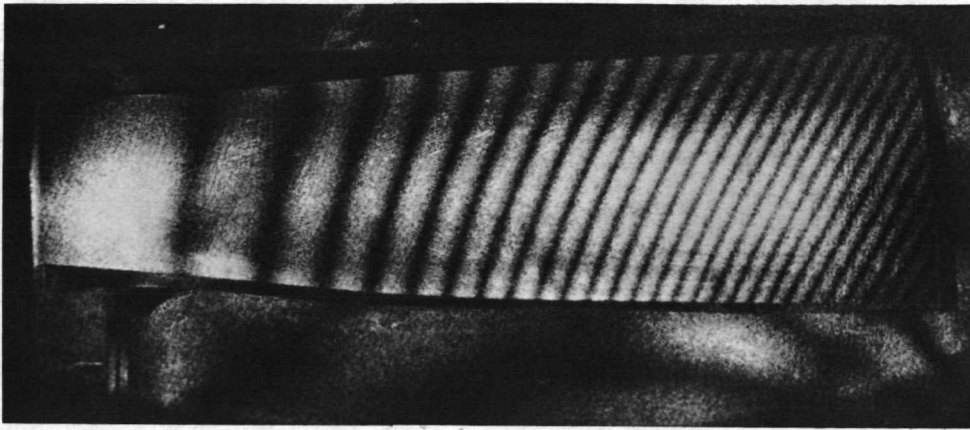


Figure 1.—Double-exposure interferogram of turbine blade heated to 760°C with an applied bending load of 0.028 kg.

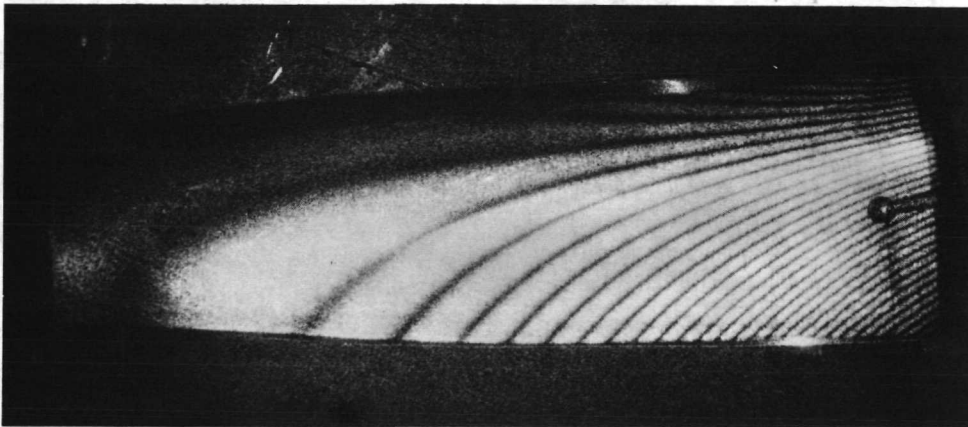


Figure 2.—Holographic interferogram of a turbine blade with an applied torque at room temperature.

cause was the use of too idealized boundary conditions in the finite-element model. Experimentally, the blade bent and rotated slightly at the clamp across its root, whereas the analytical model assumed perfectly rigid clamping at the root. A second possible factor was the fact that the finite-element model represented the blade by a limited number of degrees of freedom. Such a model is typically found to be stiffer than the object itself, which possesses infinitely many degrees of freedom. In the case of the torsion experiments (in which the discrepancy was somewhat larger than for the bending experiments), it is thought that there might be some problem in correctly modeling the applied torsion load for the computer analysis.

Since the experimental and analytical results were in good agreement, it was assumed that the stresses and strains calculated by the computer program well represented the actual stresses and strains within the turbine blade. Figure 7 shows typical plots of a component of strain along the leading edge for the blade under an applied bending load. Figure 8 shows a plot of a component of stress within the turbine blade for an applied torsion load with the blade at room temperature.

It is felt that two aspects are of significance in the above experiments. One aspect is that the computer program was used to model completely the structure being tested experimentally. The correctness of this model was verified using holography to compare

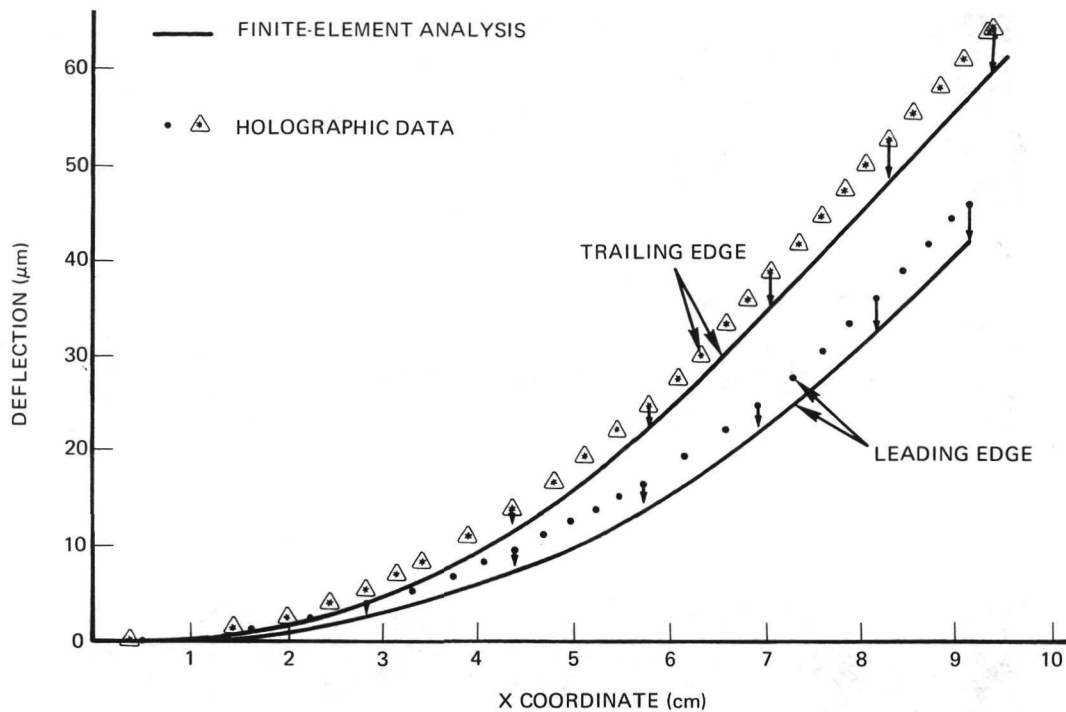


Figure 3.—Deflection of the blade surface vs position along the span for a static point load of 0.4536 kg (1 lb) applied near the tip with blade at room temperature.

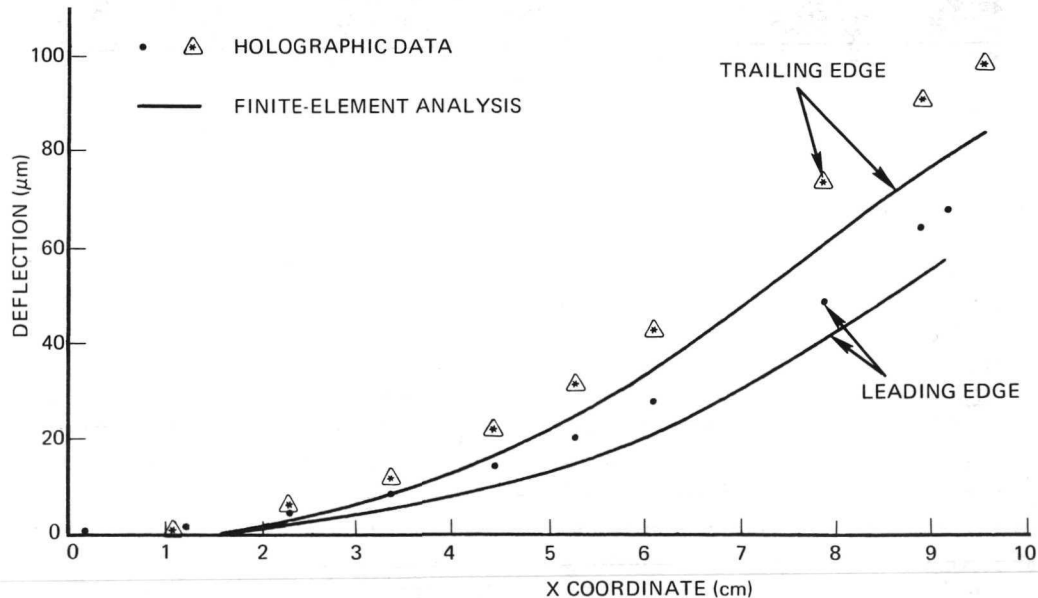


Figure 4.—Deflection of the blade surface vs position along the span for a static point load of 0.4536 kg applied near the tip with blade heated to 760 °C.

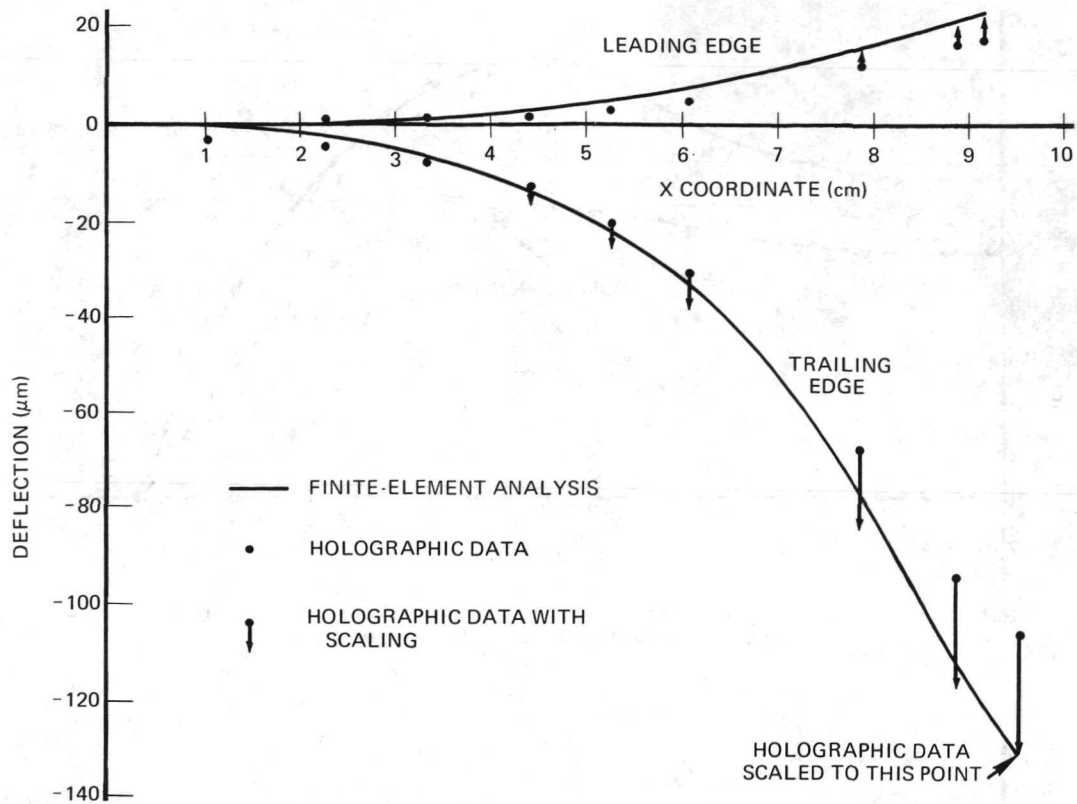


Figure 5.—Deflection of the blade surface vs position along the span for a torsion load of 8.85 N-m (1 in-lb) applied near the tip with blade at room temperature.

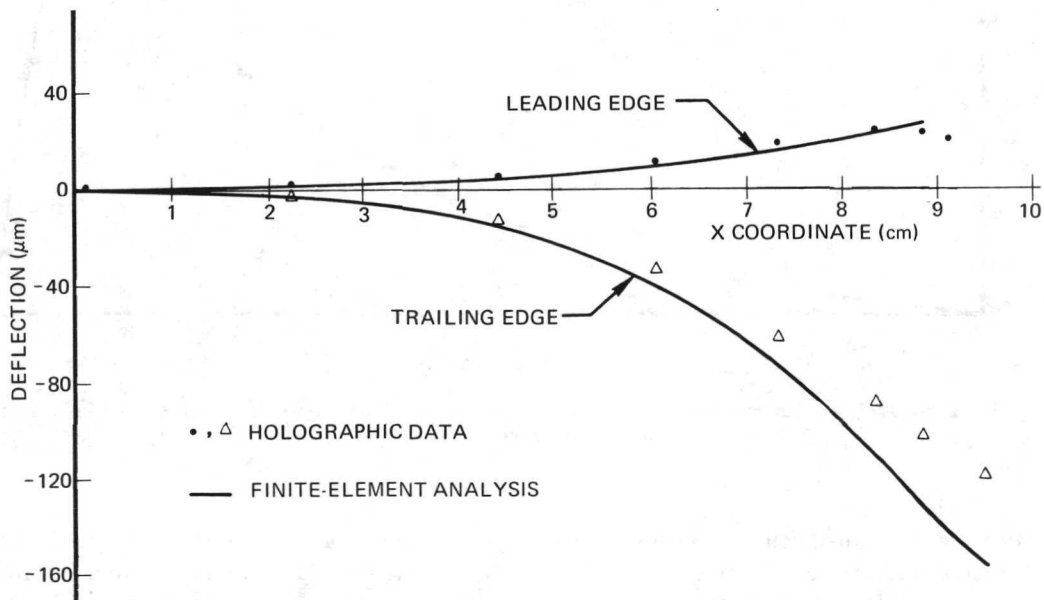


Figure 6.—Deflection of the blade surface vs position along the span for a torsion load of 8.85 N-m applied near the tip with blade heated to approximately 677 °C.

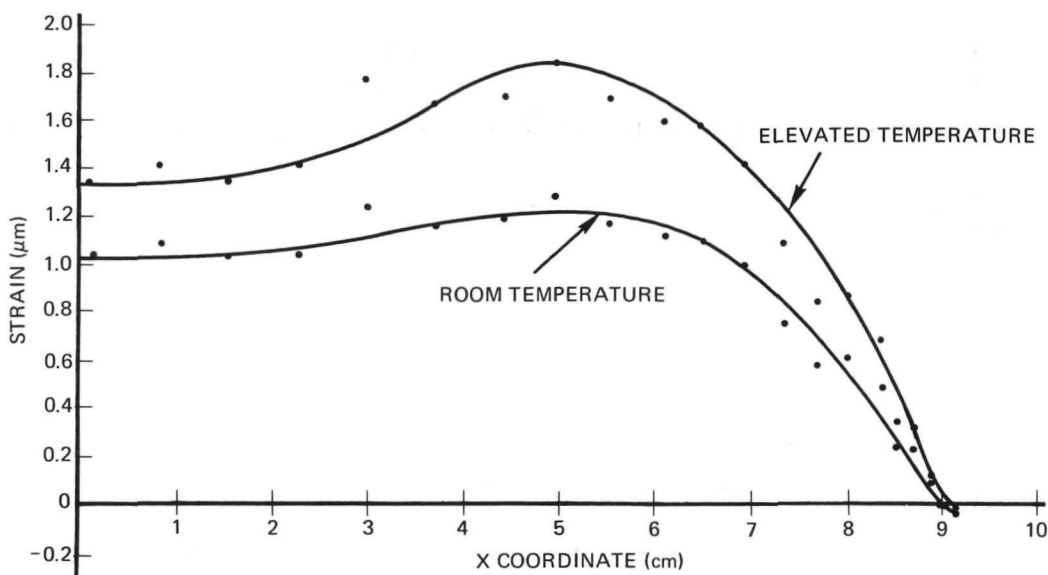


Figure 7.—Midsurface strain parallel to the span along the leading edge vs position along the span for a static point load applied near the tip of the blade.

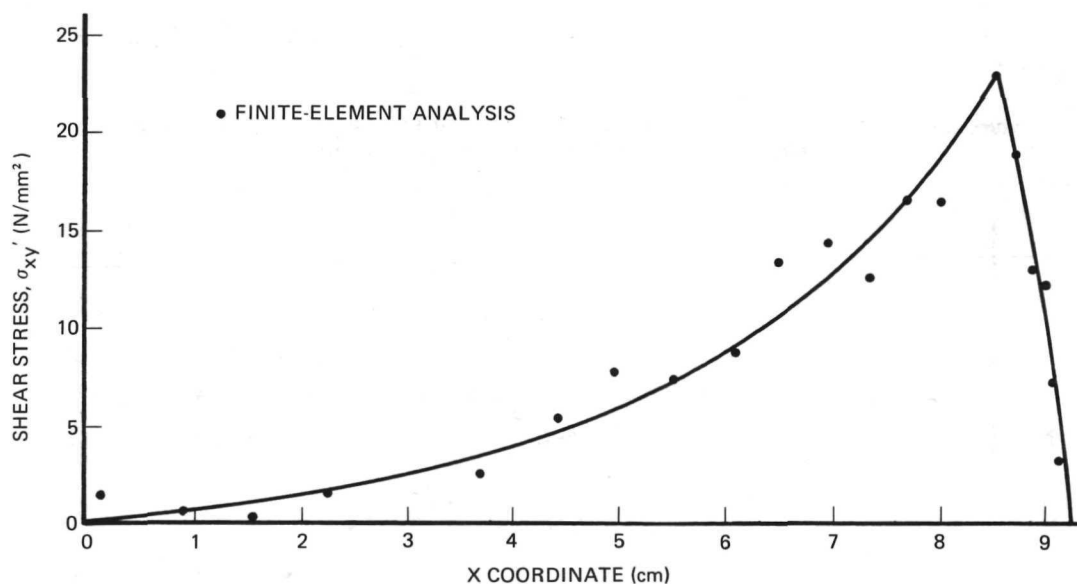


Figure 8.—In-plane shear stress along the leading edge: analytical results for torsion load of 8.85 N-m with blade at room temperature.

deflections measured experimentally against those computed analytically. Once the model had been verified in this manner, actual stresses and strains were taken to be those computed by the model. This approach is unique in the determination of actual

stresses and strains in holographic measurement programs. The other aspect concerns the performance of holography and holographic interferometry with the blade at elevated temperatures. Placement of the object when heated in a vacuum to eliminate turbu-

lent air fringes proved to be a practical and efficient method to overcome air convection problems in recording CW holograms.

VIBRATION MODE EXPERIMENTS

Holography was used to determine the number of the resonant vibration modes of the same turbine blade. For this experiment the blade was at room temperature and again clamped across its root. A small piezoelectric transducer was glued to the blade near the root and driven electronically. The purpose of the experiment was to determine the first 10 vibration modes of the turbine blade. Stored-beam holography was used first to identify the resonant frequencies of each mode. This was accomplished by recording a hologram of the blade, developing the hologram, and reinserting it in place after processing. Viewing through the hologram, the frequency of the driving signal was swept until a particular mode became visible through the hologram. This frequency was noted and then the frequency was again swept upward. After determining the frequencies of each resonant mode, time-average holograms were recorded of each mode by returning one at a time to each of the resonant frequencies.

Vibration amplitudes over the blade surfaces for each of the modes recorded were determined using the method of Powell and Stetson (ref. 5). For these experiments again only a single component of a three-dimensional vibration amplitude vector was recorded holographically. The same finite-element computer model was used to compute vibration modes in the turbine blade. The vibration amplitudes computed by the model were compared to the amplitudes measured holographically. In this case, the computer program not only calculated amplitudes of vibration over the blade surface, but also determined the frequency of each of the resonant modes. Table 1 compares the frequencies of the 10 modes recorded holographically and computed analytically. As can be seen, excellent agreement occurs for the lower modes, with the discrepancy increasing for the higher modes. It is felt that the stiffness of the finite-element model contributes to the analytical frequencies being higher than the experimentally determined frequencies. Figures 9 and 10 are samples of holograms recorded showing the second and sixth vibration modes. Figures 11 and 12 show the measured and calculated vibration amplitudes along the leading and trailing edges of the blade for these two modes. The

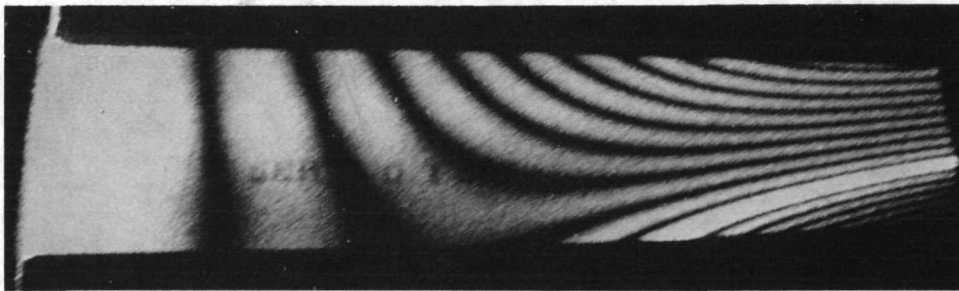


Figure 9.—Turbine blade vibration mode 2 ($f=1302$ Hz).

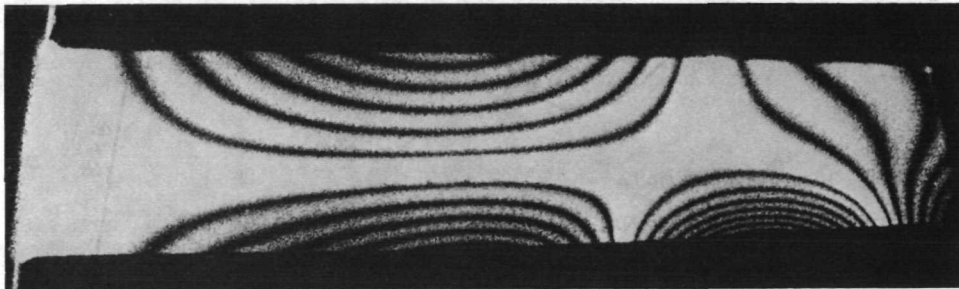


Figure 10.—Turbine blade vibration mode 6 ($f=5112$ Hz).

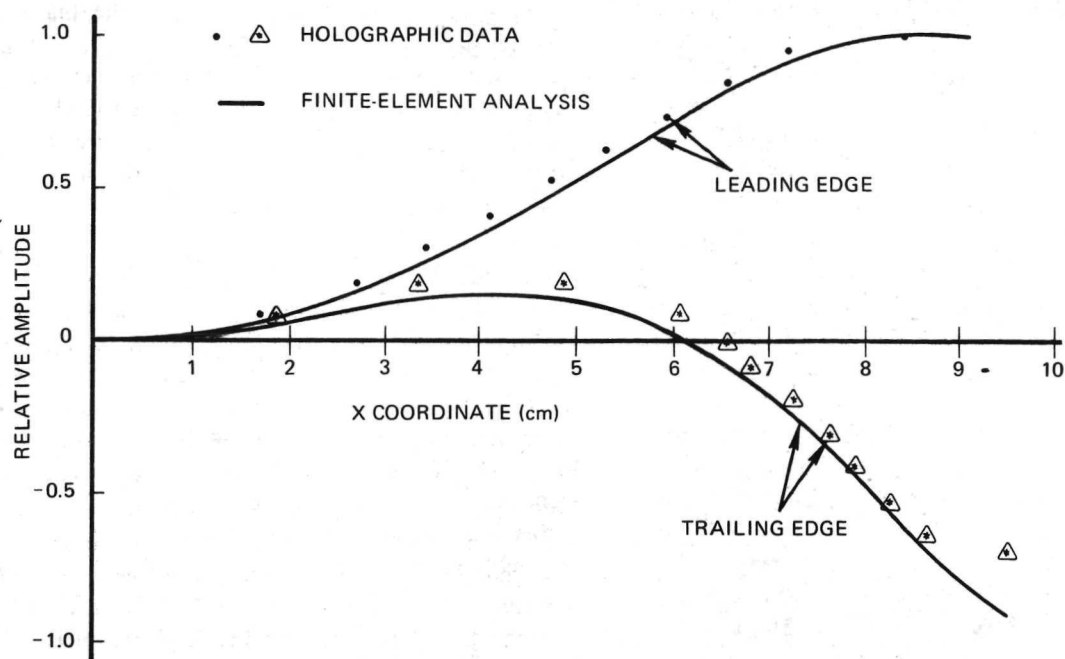


Figure 11.—Amplitude of vibration vs position along the span for mode 2.

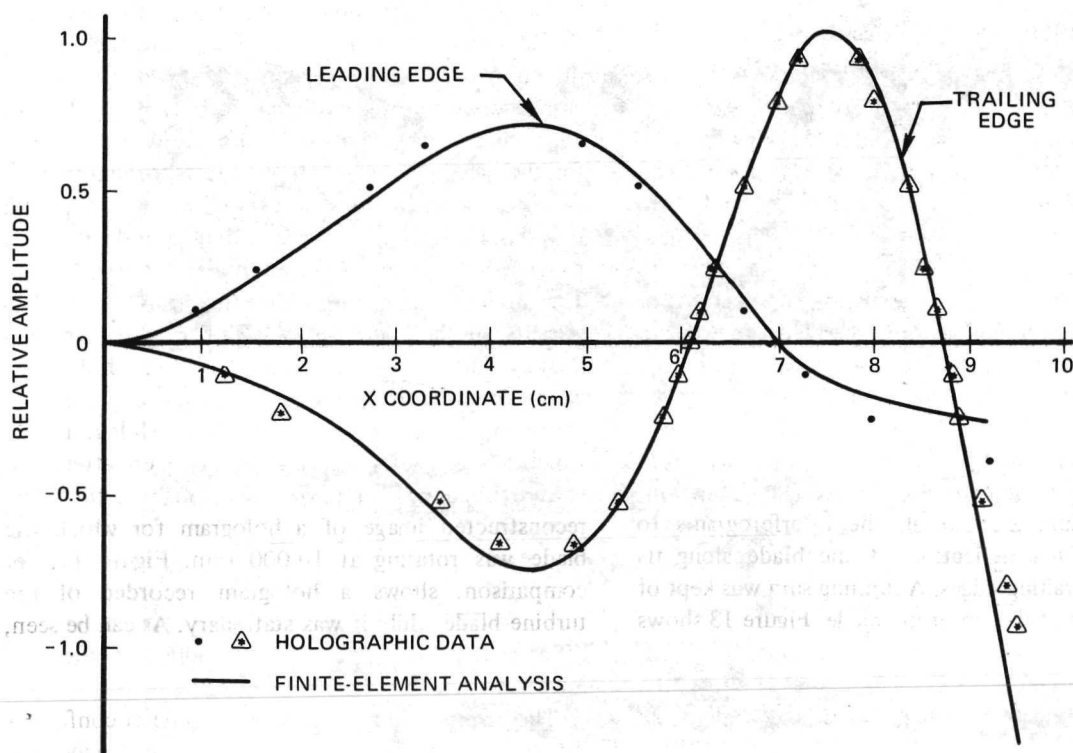


Figure 12.—Amplitude of vibration vs position along the span for mode 6.

Table 1.—Resonant Frequency vs Mode Number

Mode number	f_{expt} (Hz)	f_{calc} (Hz)	Variation
1	610	653	7%
2	1302	1396	7%
3	2126	2478	17%
4	2604	2916	12%
5	3686	4165	13%
6	5112	5742	12%
7	6063	7001	16%
8	6964	7827	12%
9	7840	9088	16%
10	8812	11432	30%

comparison was very good. Other modes showed reasonable concurrence, though not as good as these two modes. Since the agreement was good for these two modes, the stress plots and strain plots returned by the computer model could then be taken as the actual stresses and strains experienced by the blade.

Again, this experiment demonstrates the power of using a complete computer model of the blade which, when verified holographically, can be used to calculate directly the stresses and strains in a structure under inspection.

RESPONSE OF THE BLADE TO AN IMPOSED THERMAL GRADIENT

An experiment was performed to determine the response of the blade to an imposed thermal gradient. In this case the thermal gradient was that which existed as the blade was heated in steps from room temperature to approximately 760°C. Double-exposure holographic interferometry was used to measure the deflection of the blade that occurred for each step in the temperature of the blade. In order to prevent the fringe density from being excessive on the interferograms, 40 steps were made, each of approximately 20°C. Each of the 40 interferograms was analyzed to determine the deflection of the blade along its leading and trailing edges. The deflections were then summed for all the interferograms to obtain the final deflection of the blade along its leading and trailing edges. A running sum was kept of the deflection at the tip of the blade. Figure 13 shows the net position of the blade tip at the end of each increment in temperature, while figure 14 shows the final state of the turbine blade along the leading and trailing edges at the end of the heating sequence.

It was desired to compute analytically, using the

finite-element model, the response of the blade in heating it from room temperature to the final temperature of the experiment. However, preparation of the input for such computation was found to be beyond the scope of the program. Hence, stresses and strains were not computed for this experiment.

HOLOGRAPHY OF A ROTATING TURBINE BLADE

The first step toward using holography as a tool in testing turbine blades in an operating engine would be to determine whether holograms can be recorded of a turbine blade rotating at high velocity. The theory of the holographic recording process was therefore examined. The theory showed that for an object moving at high velocity the actual recording of a hologram becomes difficult, as a consequence of very stringent requirements for stability of the object during the holographic exposure. Fortunately the analysis showed that, for certain conditions, the requirements for object stability were reduced. These conditions included special arrangements of optical elements and short exposure times.

Figure 15 shows one arrangement used to record holograms of a spinning turbine blade. The angles of the illuminating beam on the blade and the viewing direction (θ_1 and θ_2 , respectively) through the hologram were selected so that $\cos \theta_1 + \cos \theta_2$ was approximately equal to 0. The analysis showed that for this geometry the holographic recording process was least sensitive to motion of the blade. A pulsed ruby laser operating in the Q-switched mode was used to record holograms of blades rotating at 10 000 rpm. The nominal laser pulse duration was 50 ns. The velocity of the blade tip at 10 000 rpm was approximately 850 meters per second. Successful holograms were recorded for cases in which the experimental geometry satisfied the criterion above. Holograms for which this geometry was not satisfied were attempted without success. Figure 16 shows a photograph of the reconstructed image of a hologram for which the blade was rotating at 10 000 rpm. Figure 17, for comparison, shows a hologram recorded of the turbine blade while it was stationary. As can be seen, little difference exists in the quality of the two images.

The results of the experiment in general confirmed the analysis, which showed that a special geometry was necessary before holograms could be recorded of

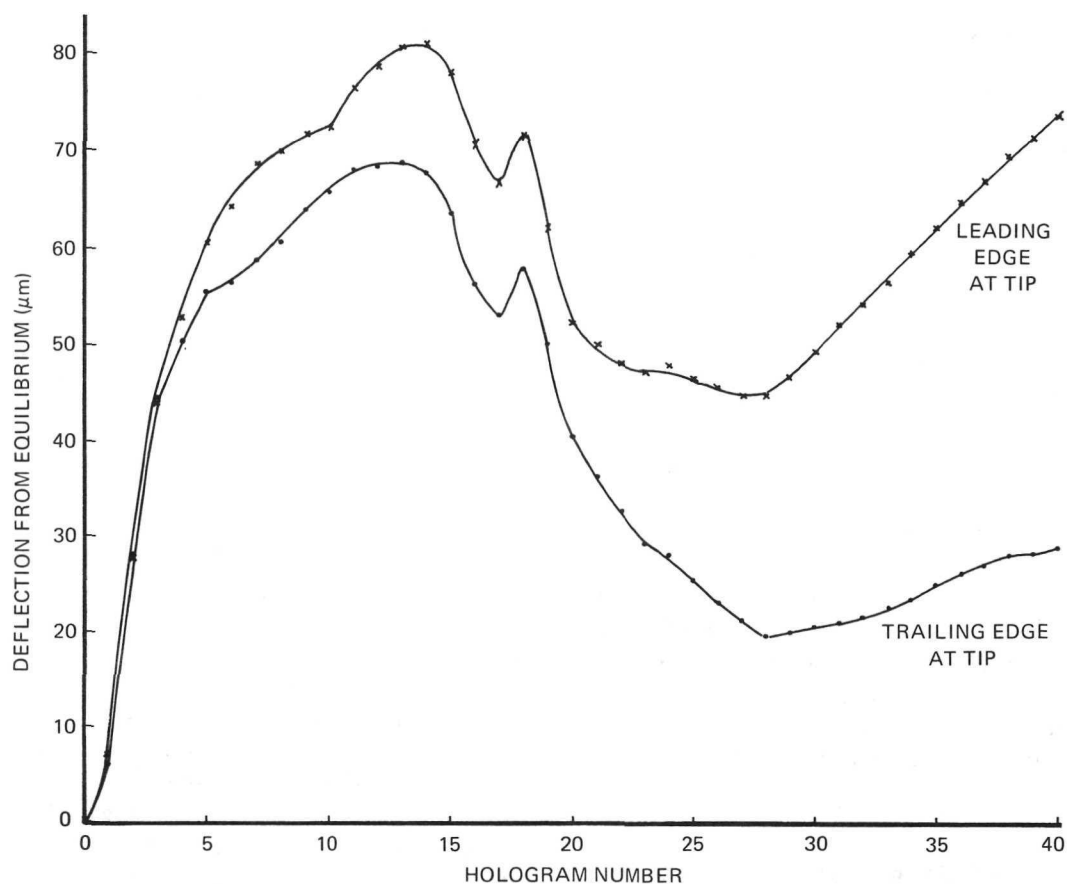


Figure 13.—Relative position of tip of blade vs hologram number for thermal gradient test.

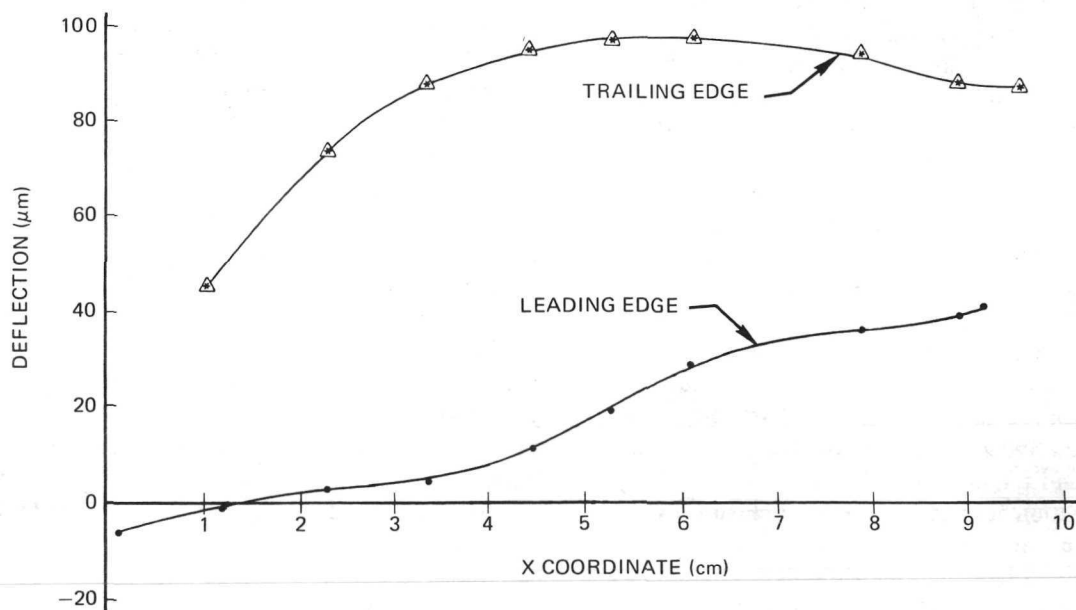


Figure 14.—Total deflection of the blade surface vs position along the span in heating the blade from room temperature to approximately 760 °C.

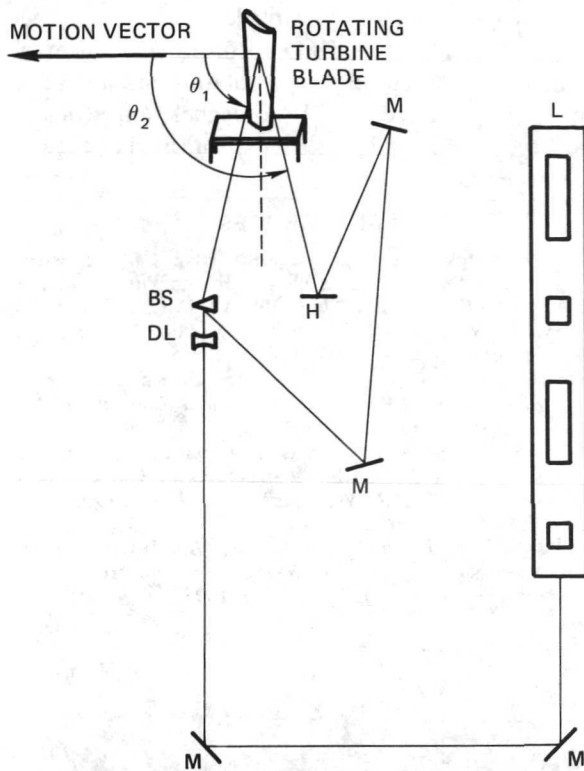


Figure 15.—Initial arrangement used to record holograms of a rotating turbine blade (L=pulsed ruby holographic laser with longitudinal and transverse mode selection; M=mirror; DL=diverging lens; BS=beamsplitter; H=hologram).

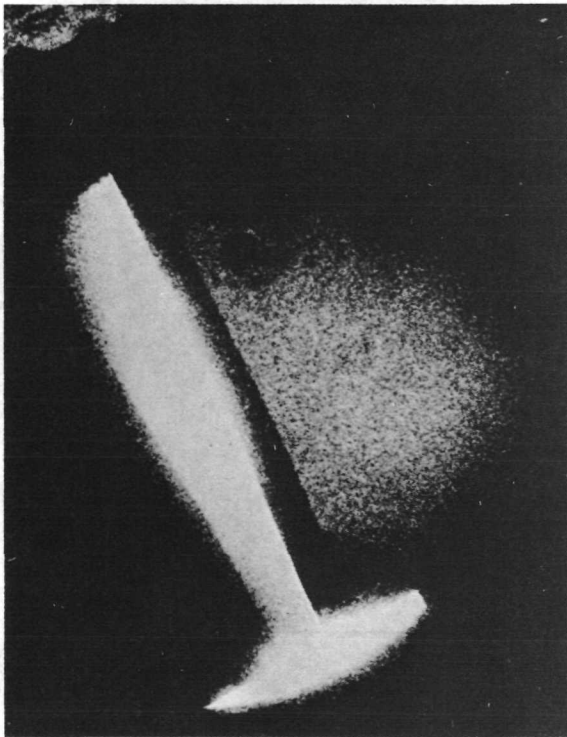


Figure 16.—Photograph of reconstructed holographic image of turbine blade spinning at 10 300 rpm.

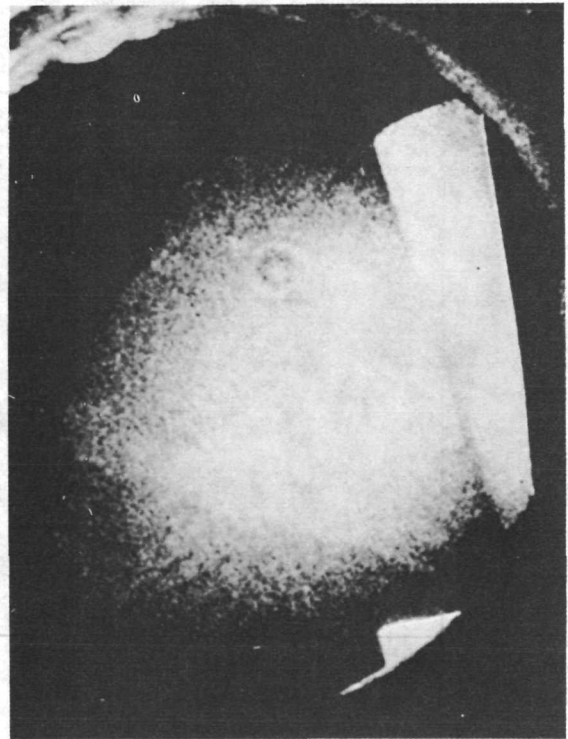


Figure 17.—Photograph of reconstructed holographic image of stationary turbine blade.

the rapidly moving blade. Using such geometries, however, the experiment showed that high rates of rotation were surmountable as obstacles to recording successful holograms.

CONCLUSIONS

As a result of the experiments conducted and the analyses performed during the course of the program, it was demonstrated that holographic interferometry can be used to measure accurately whole-surface deflections of turbine blades. Holography of turbine blades at high temperatures was also shown to be practical, provided convection current problems of gases over the blade are adequately handled. The analytical portions of the experiment demonstrated that a powerful and accurate computer model of the turbine blade could be formulated and verified against the holographic data. Once verified, this computer program could then be used to compute

stresses and strains in the blade itself with a high degree of confidence. The experiments also demonstrated that holography of a rotating turbine blade may be performed with little degradation in image quality, provided that certain experimental configurations are used.

REFERENCES

1. Aleksandrov, E. B.; and Bonch-Bruевич, A. M.: Investigation of Surface Strains by the Holographic Technique, *Soviet Phys.,-Tech. Phys.*, Vol. 12, 1967, p. 258.
2. Hurty, W. C.; and Rubinstein, M. F.: *Dynamics of Structures*, Prentice-Hall, 1964.
3. Zienkiewicz, O. C.; and Cheung, Y. K.: *The Finite-Element Method in Structural and Continuum Mechanics*, McGraw-Hill, 1967.
4. Ahmad, S.; Irons, B. M.; and Zienkiewicz, O. C.: Analysis of Thick and Thin Shell Structures by Curved Finite Elements, *Int. J. Numerical Methods in Engineering*, Vol. 2, 1970, pp. 419-451.
5. Powell, R. L.; and Stetson, K. A.: Interferometric Vibration Analysis by Wavefront Reconstruction, *J. Opt. Soc. Am.*, Vol. 55, 1965, p. 1593.

Applications of Holography to Wave Propagation in Shells and to Vibration at High Temperature

D. A. Evensen and R. Aprahamian

TRW Systems Group

Pulsed (double-exposure) holography was applied to measure (1) flexural waves propagating in circular cylindrical and conical shells and (2) vibration modes of a rectangular plate heated to 566 °C (1050 °F). The response of the shells appeared nearly axisymmetric at the wavefront, with asymmetric behavior evident well behind the wavefront. Propagation of waves past a circular cutout was also studied. A differential technique (involving two pulses of the laser in rapid succession) was used to record several transverse vibration modes of a heated stainless steel plate. This differential method can record vibrations despite the presence of thermal convection currents surrounding the heated plate. Such measurements (at high temperature and in the atmosphere) are not readily amenable to conventional continuous-wave holography.

This report presents recent results obtained on two NASA contracts* involving applied holography. One study involves pulsed holographic recording of wave propagation in circular cylindrical and conical shells, including both axisymmetric and asymmetric waves. This study was motivated by a need to provide experimental comparisons with computer analyses of wave propagation in shells. Wave propagation in shell structures is of engineering interest to NASA in that it relates to explosive shock and staging transients in launch vehicles.

The second study involves holographic measurement of vibration modes on high-temperature panels (540 to 1100 °C). Mode shapes have customarily been measured using time-average holography, but at high temperatures problems arise due to thermal convection currents and consequent changes in the index of refraction of the surrounding air. One solution to this problem is to use pulsed laser holography and make two exposures of the hologram

with a small time delay, Δt , between them. The convection currents do not change appreciably between exposures, and the resulting interferogram reveals only the structural deformation, e.g., the desired vibration mode. This approach has been used to record vibration modes of panels at 566 °C, and further work along these lines is in progress.

It is evident that the same approach may work equally well for holographic recording of flutter modes in a wind tunnel, where it will be necessary to operate through a turbulent boundary layer. Measurement of vibration modes of high-temperature panels is applicable to the NASA Space Shuttle vehicle, and flutter measurements are of general interest in the aerospace industry.

This paper is in the nature of an interim report and gives brief highlights of the results to date. A final report will be issued on each of the subject contracts in the near future.

WAVE PROPAGATION IN THIN SHELLS

The wave propagation problems which were examined are typified by the example shown in figure 1. A

*Contracts NAS1-9876 and NAS1-10169 with NASA/Langley Research Center

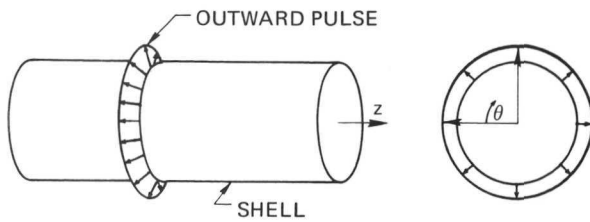


Figure 1.—Radial pulse loading on shell (r, θ, z are cylindrical coordinates).

thin-walled circular cylindrical shell is loaded by a radial dynamic pulse (at location $z=0$) which causes elastic waves to propagate along the shell. The loading is applied by an electromagnetic repelling-wire device, which makes use of the force acting between two parallel current-carrying conductors.

Ideally the impulsive radial load would be perfectly axisymmetric and concentrated in the plane $z=0$. Using a linear mathematical model of the shell, such a loading would excite only axisymmetric motions, involving the radial displacement (w) and the longitudinal displacement (u). Most computer

programs for wave propagation in shells are limited to axisymmetric response (refs. 1, 2, and 3). However, asymmetric wave propagation problems have recently been analyzed (ref. 4). It is anticipated that the experimental results of the present study will serve to confirm such analytical studies (both symmetric and asymmetric).

Experimental Setup and Preliminary Results

A standard holographic arrangement was used, and double-exposure holograms were made with a pulsed ruby laser. The holographic setup and electronic timing were similar to those used in previous studies (refs. 5 and 6). The first exposure of the hologram was made when the shell was stationary (undeformed), and the second exposure was made at a particular time t after initiation of the wave in the shell. The time t is measured from the start of the loading pulse, which has a $10\text{-}\mu\text{s}$ duration.

A typical interferogram obtained by this procedure is shown in figure 2. The shell extends from left to right in the photograph, and the black fiducial marks on the surface are 5 cm (2 in.) apart. The shell

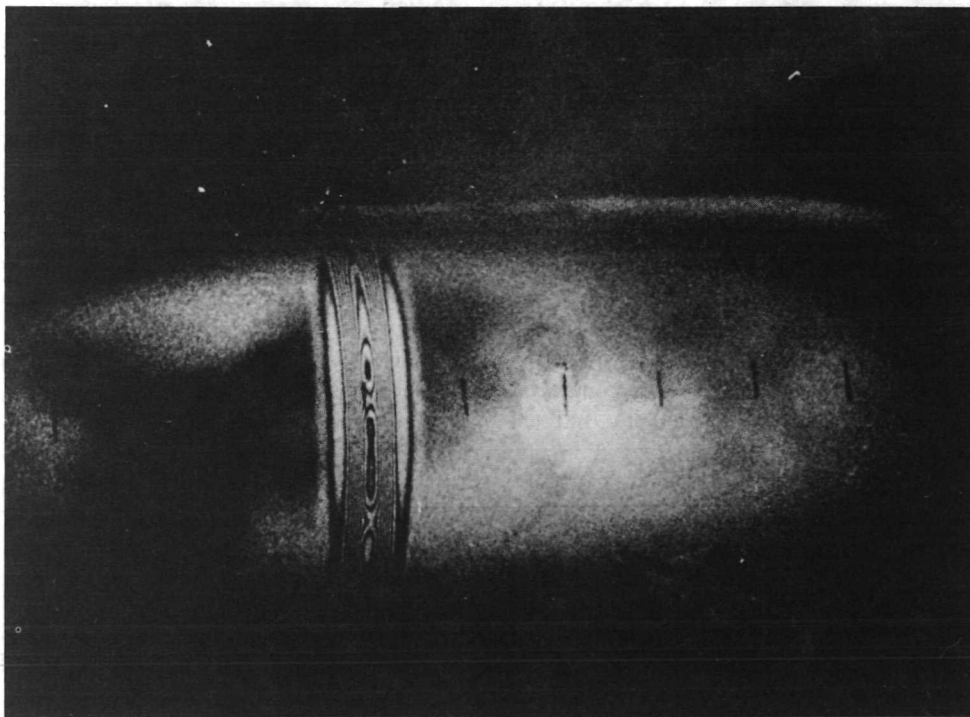


Figure 2.—Wave propagating in a cylindrical shell ($t=10\text{ }\mu\text{s}$).

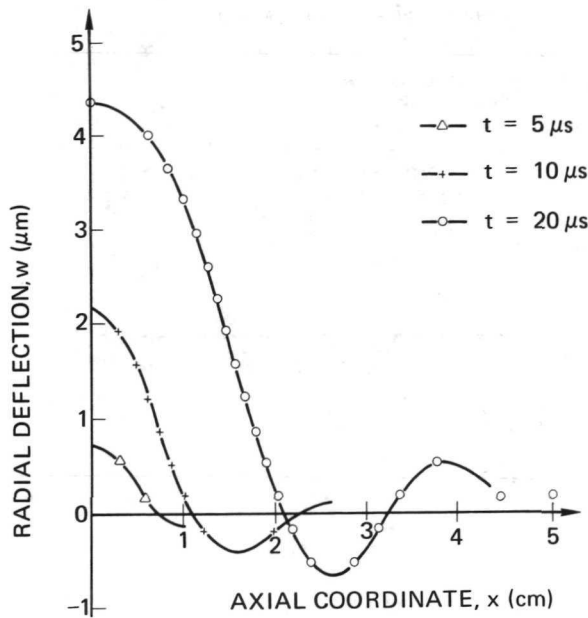


Figure 3.—Radial deflection along the shell.

is an aluminum tube approximately 61 cm long and 25 cm in diameter, with a wall thickness of 2.5 mm. The fringe pattern shown in figure 2 was recorded at $t=10\mu s$ and can be interpreted to yield the radial deflection of the shell. Such deflections are shown in figure 3 for three specific times.

Figure 4 is a hologram of the same shell at time $t=75\mu s$. At this later time, asymmetric deformations

are evident at the loading plane. The radial deformation of the shell can be closely approximated by

$$w \approx A_0 + A_k \cos k\theta \quad (1)$$

where θ is the circumferential coordinate, and the coefficients A_0 and A_k vary with the distance along the length of the shell. This variation is illustrated in figure 5, which presents data corresponding to the line $\theta=0$.

Wave Propagation Past Cutouts and in Conical Shells

The interferograms shown in figures 6 and 7 illustrate a wave approaching and propagating past a circular cutout in the shell. Figure 7 clearly shows that the cutout causes asymmetric responses and a "shadow zone" behind the hole. The effect of the cutout can be determined by comparing the left half of figure 7 (where the shell is continuous) with the right half (which contains the cutout).

Wave propagation in a thin-walled conical shell is illustrated by the interferogram of figure 8. The cone is aluminum, about 2.5 mm thick, and was loaded by the repelling-wire device.

Related Wave Propagation Studies

NASA/Langley is presently computing the response of a circular shell having geometry and loading that correspond to the experiments reported herein. Preliminary results (for times of 5, 10, and 20 μs) are

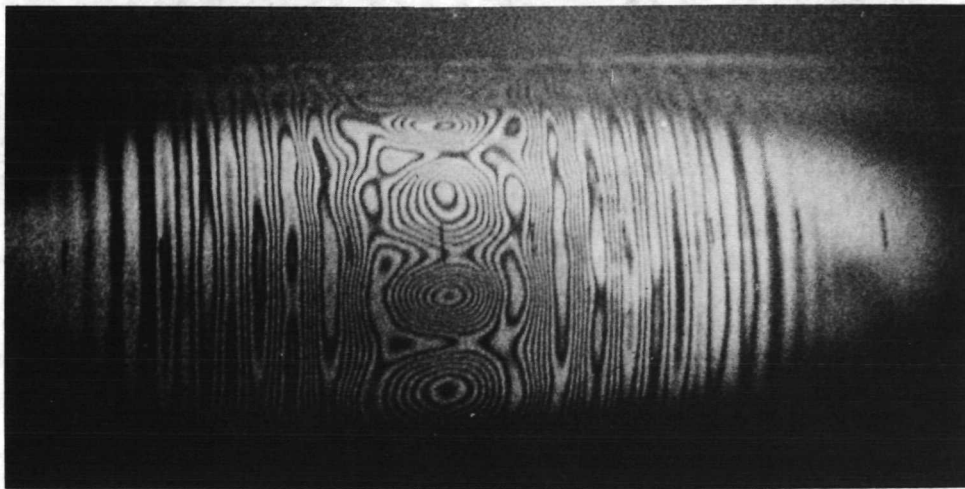


Figure 4.—Waves in a cylindrical shell ($t=75\mu s$).

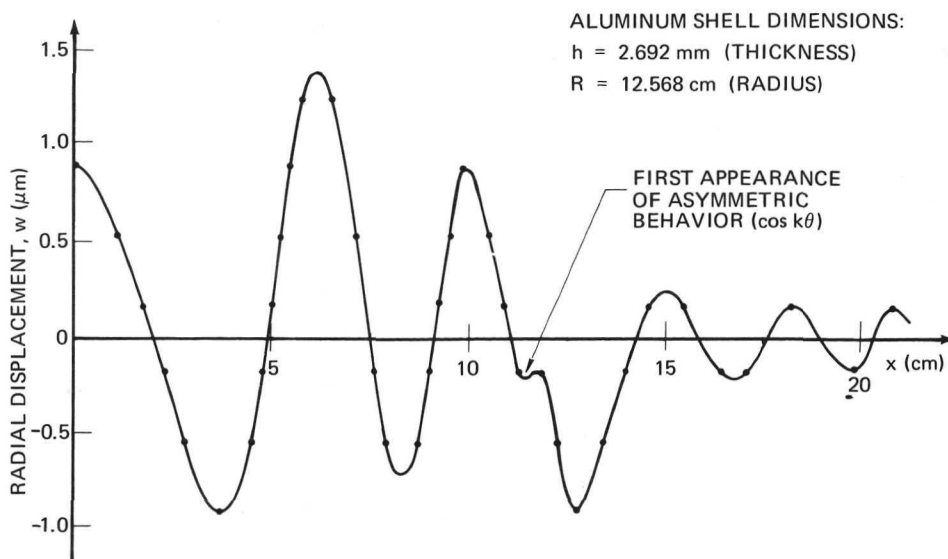


Figure 5.—Radial displacement, w , vs axial position, x ($t=75 \mu\text{s}$).

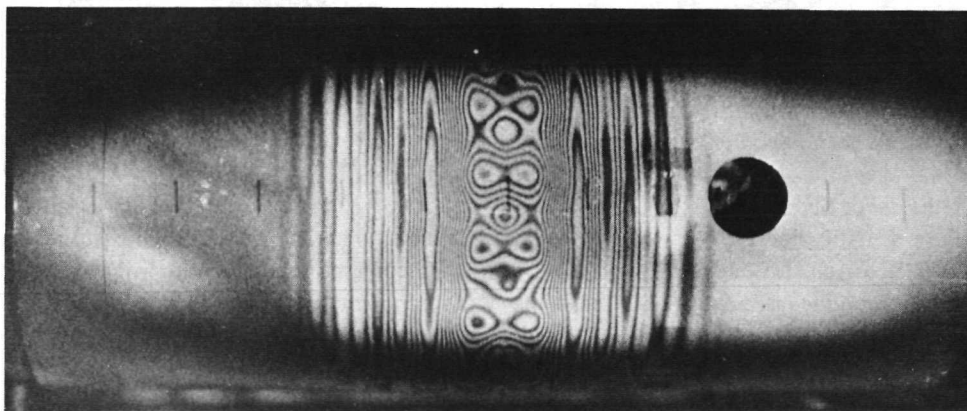


Figure 6.—Wave approaching a circular cutout ($t=48 \mu\text{s}$).

encouraging, with good to fair agreement between theory and experiment.

The asymmetric behavior at the later times may simply be the response of the shell to a slightly asymmetric loading. On the other hand, a stability analysis might show that the axisymmetric response is dynamically unstable and that asymmetric perturbations may increase with time.

Wave propagation past a rectangular cutout was also studied, using holography, for comparison with the analysis of reference 4. Preliminary comparisons appear encouraging for this study as well.

HIGH-TEMPERATURE VIBRATION MODE MEASUREMENTS

It was desired to record the vibration modes of a heated panel using holography. For simplicity, we began with a 20-by-25-cm flat rectangular plate of stainless steel. The plate was mounted vertically (for convenience) and was heated by quartz radiant lamps. The major experimental difficulty to be overcome involved thermal convection currents which cause optical pathlength changes and thus interfere with holographic measurements.

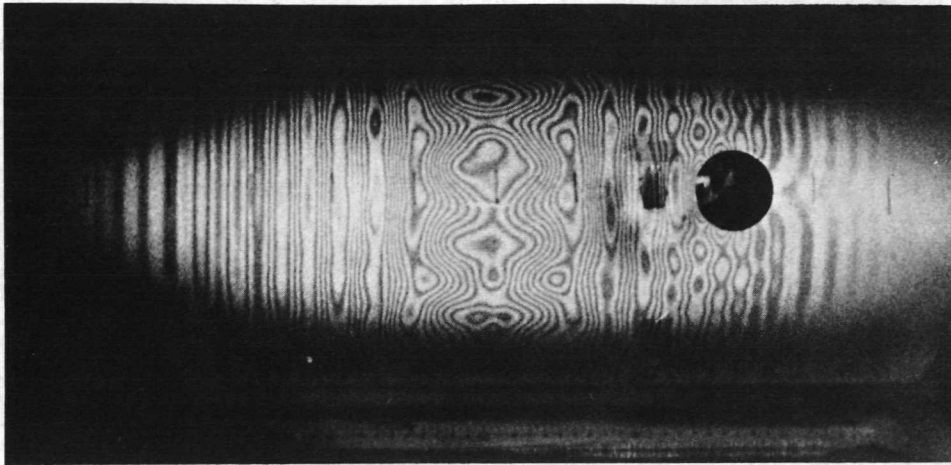


Figure 7.—Wave past a circular cutout ($t=92 \mu s$).

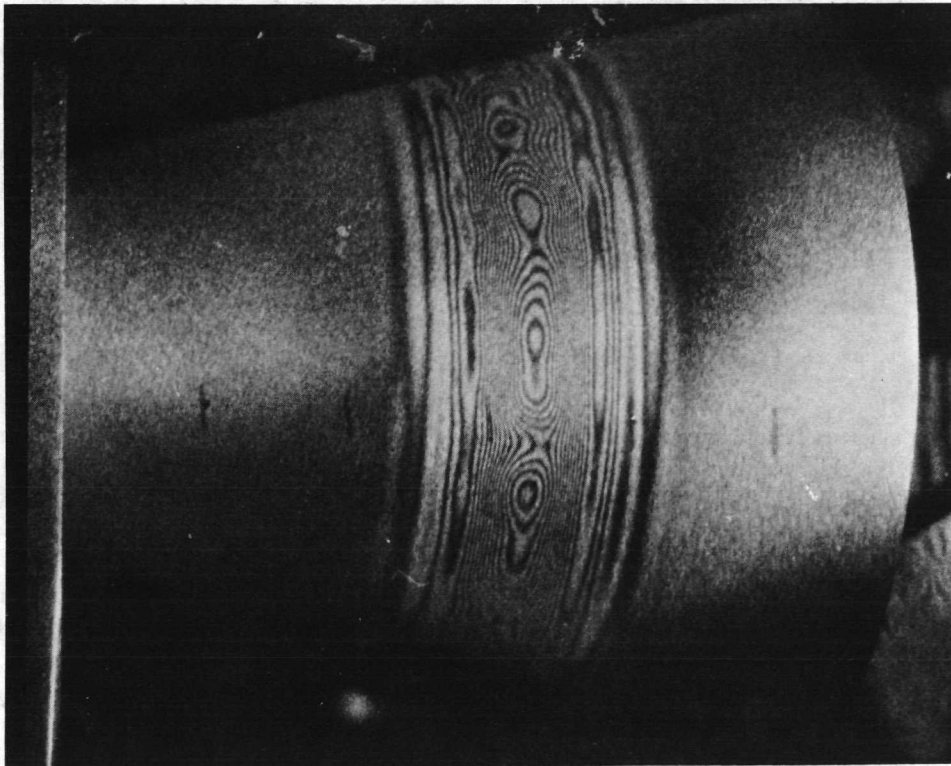


Figure 8.—Wave propagation in a conical shell ($t=20 \mu s$).

A schematic diagram of the experimental setup is shown in figure 9, and figure 10 is a photograph of the actual equipment. Originally it was planned to eliminate the thermal convection problem entirely by

mounting the heated plate within a vacuum enclosure and using conventional CW holography. The use of a vacuum chamber complicates the design, however, and the decision was made to concentrate on meas-

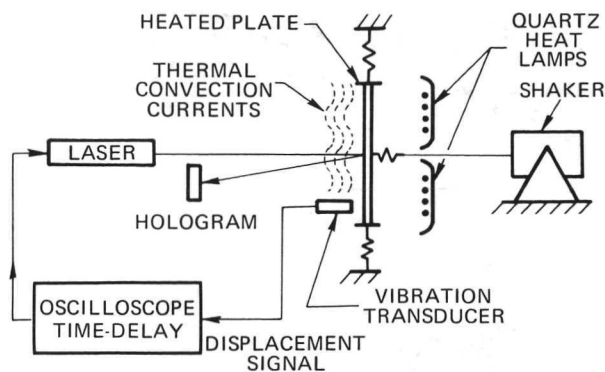


Figure 9.—Schematic of experimental setup for heated plate vibration test.

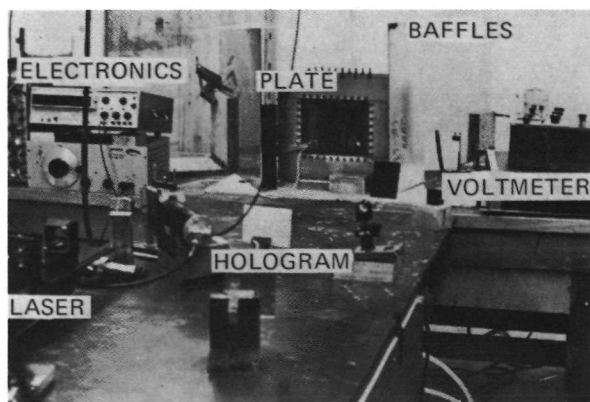


Figure 10.—Photograph of experimental setup.

urements (under ambient conditions) with the pulsed ruby laser. Such measurements were accomplished using a differential technique (ref. 7).

Pulsed Differential Holography

The technique of differential holography (applied to vibration problems) can be readily understood by referring to figure 11. When a normal mode is excited to resonance, a point on the plate surface vibrates sinusoidally with frequency ω and amplitude A . The output from the vibration transducer provides an electrical signal with the waveform shown in figure 11. This signal is used to fire the laser at times t_1 and t_2 , resulting in a double-exposed hologram. The fringes on such a hologram can be interpreted to yield the relative displacement, $w_2 - w_1$, between times t_2 and t_1 , where Δt is on the order of $50 \mu s$. In such a short time, the thermal convection currents around the panel do not change appreciably, whereas the

$$W(x, y, t) = A_0 \phi(x, y) \sin \omega t \quad (\text{DEFLECTION})$$

$$\phi_{mn} = \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b} \quad (\text{MODE SHAPE})$$

$$w = A \sin \omega t \quad (\text{ANY POINT ON PANEL})$$

$$w_2 = w_1 = A \sin(\omega t_2) = A \sin(\omega t_1)$$

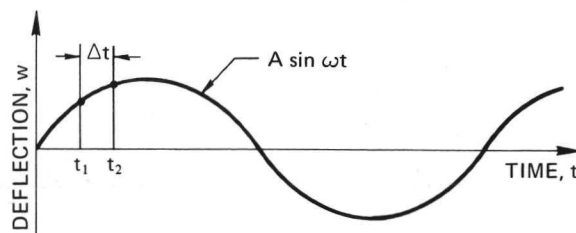


Figure 11.—Displacement-time history (t_1 and t_2 are laser pulse times).

vibrating panel undergoes a small displacement. Consequently, the change in optical pathlength recorded by the hologram results primarily from the structural deformation.

This technique can be used to record vibration modes of large-area structures (e.g., 3 by 3 m) in noisy environments and vibrating to large amplitudes (e.g., ± 12 mm). It appears promising for flutter measurements as well (see ref. 8).

Mode Shape Measurements at 566°C

Three examples of differential holograms (recorded in the fashion just described) are shown in figures 12, 13, and 14. The specimen was a 20-by-25-cm stainless steel plate, 12 mm thick. In all three cases the temperature of the plate was approximately 566°C , and a time delay of $\Delta t = 50 \mu s$ was used between pulses of the laser.

Figure 12 shows the fundamental mode, at a frequency of 200 Hz. Figures 13 and 14 show the 2X2 and 3X2 modes, respectively, with corresponding frequencies of 506 and 692 Hz. The temperature of the plate was measured at only one location, with a chrome-alumel thermocouple. The plate exhibited a dull red glow which was not quite uniform over the surface. Despite this evidence of nonuniformity in plate temperature, the vibration modes were relatively undistorted; i.e., they appeared very similar to the modes of an isotropic plate at room temperature. (It should be noted here that the plate was spring-supported at its boundaries to prevent large in-plane stresses that could cause buckling.)

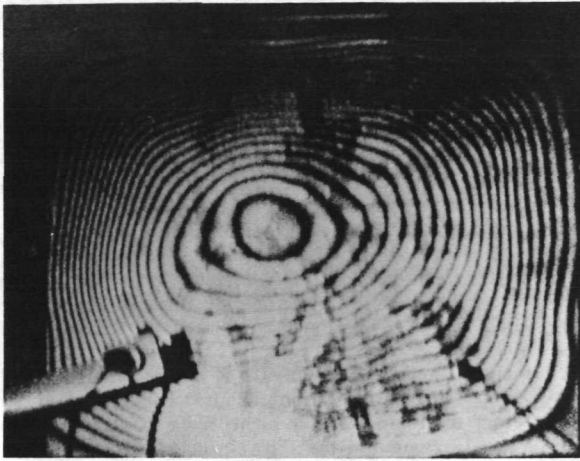


Figure 12.—Fundamental mode ($f=200$ Hz, $T=563^\circ\text{C}$, $\Delta t=50\ \mu\text{s}$).

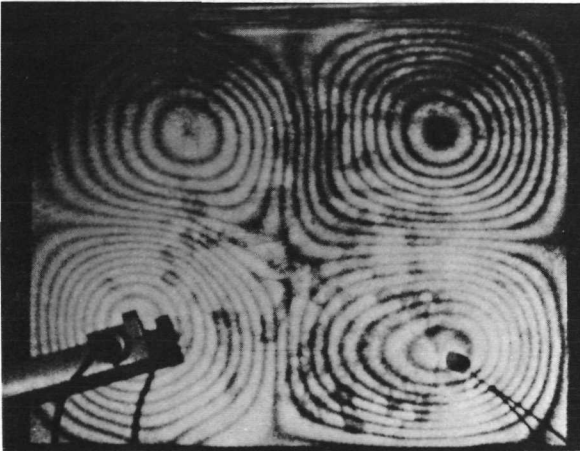


Figure 13.—The 2×2 mode ($f=506$ Hz, $T=560^\circ\text{C}$, $\Delta t=50\ \mu\text{s}$).

Related Plate Vibration Studies

We expect to extend these holographic measurements to panel temperatures of 1090 to 1200 $^\circ\text{C}$, and we plan to vary the time delay (Δt). It is a simple matter to calculate the vibration sensitivity of the differential pulsing technique, using the equation

$$\frac{(2n-1)\lambda}{4} = (2\pi f) A(\Delta t) \cos \omega t_1 \quad (2)$$

where λ is the laser wavelength (694.3 nm),

n is the fringe order,

$2\pi f = \omega$, the vibration frequency,

t_1 is the time of the initial pulse,

A is the vibration amplitude,

and Δt is the time delay between pulses.

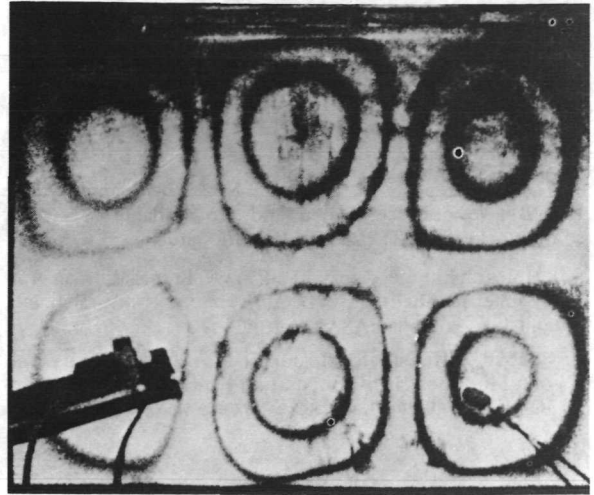


Figure 14.—The 3×3 mode ($f=692$ Hz, $T=566^\circ\text{C}$, $\Delta t=50\ \mu\text{s}$).

Equation 2 assumes:

- (a) normal viewing and illumination of the plate, and
- (b) $\Delta t \ll T/2\pi$

where T is the period of vibration.

From equation 2 it can be shown that the sensitivity of the differential pulsing technique increases as $1/\Delta t$. It is apparent that Δt cannot be increased indefinitely, since eventually it will be limited by effects of the thermal convection currents. That is, for large values of Δt , the convection currents will give rise to interference fringes and distort or "corrupt" the interferogram.

We hope to investigate problems of this type during the remainder of the study.

CONCLUSIONS

Pulsed double-exposure holography was applied to measure the deflection response due to elastic waves propagating in thin-walled shells. The resulting interferograms yield quantitative information regarding wave propagation in cylinders and cones, past ring stiffeners and cutouts, and wave reflection from various boundaries.

Pulsed differential holography was used to measure vibration modes of a stainless steel rectangular plate heated to 566 $^\circ\text{C}$. The holographic technique was successful in recording vibration modes despite the presence of thermal convection currents near the

plate. It is anticipated that the differential technique will allow holographic measurement of flutter deflections in wind-tunnel testing.

Note added in proof:

The final reports on contracts NAS1-9876 and NASA-10169 have been completed and are available as NASA contractor reports. Their respective titles are:

1. "Holographic Measurement of Wave Propagation in Axisymmetric Shells," by D. A. Evensen, R. Aprahamian, and J. L. Jacoby, NASA CR-2063.
2. "Pulsed Differential Holographic Measurements of Vibration Modes of High-Temperature Panels," by D. A. Evensen, R. Aprahamian, and K. R. Overoye, NASA CR-2028.

REFERENCES

1. Mortimer, Richard W.; and Hoburg, James F.: MCDIT 21—A Computer Code for One-Dimensional Elastic Wave Problems. NASA CR-1306, 1969.
2. Chou, Pei Chi, Analysis of Axisymmetric Motions of Cylindrical Shells by the Method of Characteristics. *AIAA Journal*, Vol. 6, 1968, pp. 1492-1497.
3. Raney, J. P.; and Howlett, J. T.: A Modal Solution for Wave Propagation in Finite Shells of Revolution. Presented at the AIAA/ASME 11th Structures, Structural Dynamics, and Materials Conference, NASA Langley Research Center.
4. Geers, T. L.; and Sobel, L. H.: Analysis of Transient, Linear Wave Propagation in Shells by the Finite Difference Method. Lockheed Palo Alto Research Laboratory, October 1970.
5. Aprahamian, R.; Evensen, D. A.; Mixson, J. S.; and Wright, J. E.: Application of Pulsed Holographic Interferometry to the Measurement of Transverse Waves in Beams. Presented at the SESA Spring Meeting, Salt Lake City, Utah, May 1971; to be published in *Experimental Mechanics*.
6. Aprahamian, R.; Evensen, D. A.; Mixson, J. S.; and Jacoby, J. L.: Application of Pulsed Holographic Interferometry to the Measurement of Transverse Waves in Plates. Presented at the SESA Spring Meeting, Salt Lake City, Utah, May 1971; to be published in *Experimental Mechanics*.
7. Aprahamian, R.; and Evensen, D. A.: Vibration Analysis by Differential Holographic Interferometry. *AIAA Journal*, Vol. 9, 1971, pp. 186-188.
8. Evensen, D. A.: On the Application of Holography to Panel Flutter. AM 70-13, TRW Systems Group, Redondo Beach, Calif., September 1970.

Application of Holographic Interferometry to Shell Structures*

J. C. Chen and R. Badin

Jet Propulsion Laboratory

A holographic interferometry technique was used to measure the prebuckling deformation of a thin-walled cylindrical shell under axial compression. Because of the noncontact mapping and highly sensitive deformation measurement capability of this technique, the extremely small deformations of the shell were developed in great detail.

Thin-walled shell structures are used as structural elements in virtually every missile, spacecraft, aircraft, or other structure in which light weight is an important consideration. Before the advent of the high-speed computer, our capability for analyzing the response of this important class of structures to realistic static and dynamic loading was minimal. Only very simple, highly idealized models of the shell could be analyzed. With the use of a high-speed digital computer, the solutions to complex shell problems become possible. Nevertheless, these solutions are still approximate. From time to time, an experimental study of the shell problem is required to establish confidence in our analysis.

Since most laboratory experiments have used very thin shells, the measurement of shell deformation must be made by noncontact means. Also, because the magnitude of the shell deformation is on the order of its thickness, highly sensitive instrumentation is required. Holographic interferometry is an ideal technique for this task. In addition to its noncontact, highly sensitive deformation measurement capability, it measures the deformation close to the boundary, which is not possible with conventional pickup measurement.

In the experiment reported here, a cylindrical shell under axial compression was used to demonstrate the advantages of holographic interferometry as applied to shell structures.

Reported experimental studies of buckling loads of thin-walled circular cylindrical shells under axial compression show that, when compared with the results predicted by the linearized small deflection theories, the experimental values are much lower and the data has a large scatter band. For the past 30 years, considerable effort has been made to find an explanation for the great discrepancy between theoretical and experimental results and for the large scatter of experimental results. In the past few years, the initial geometrical imperfections of the shell have come to be accepted as the main degrading factor. Investigations show that in some cases an imperfection of a mere 10 percent of the shell wall thickness would result in a 40-percent reduction of the load-carrying capacity of the shell. Therefore, the growth of the initial imperfections during the loading process, prior to buckling, provides the mechanism by which the initial geometric imperfections reduce the buckling load.

EXPERIMENTAL SETUP

The cylindrical shell used was made of Mylar sheet and had a 20.32-cm (8-in.) diameter, 25.4-cm (10-in.) length, and 0.1905-mm (0.0075-in.) thickness. It was

*This paper presents the work of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NAS7-100, sponsored by the National Aeronautics and Space Administration.

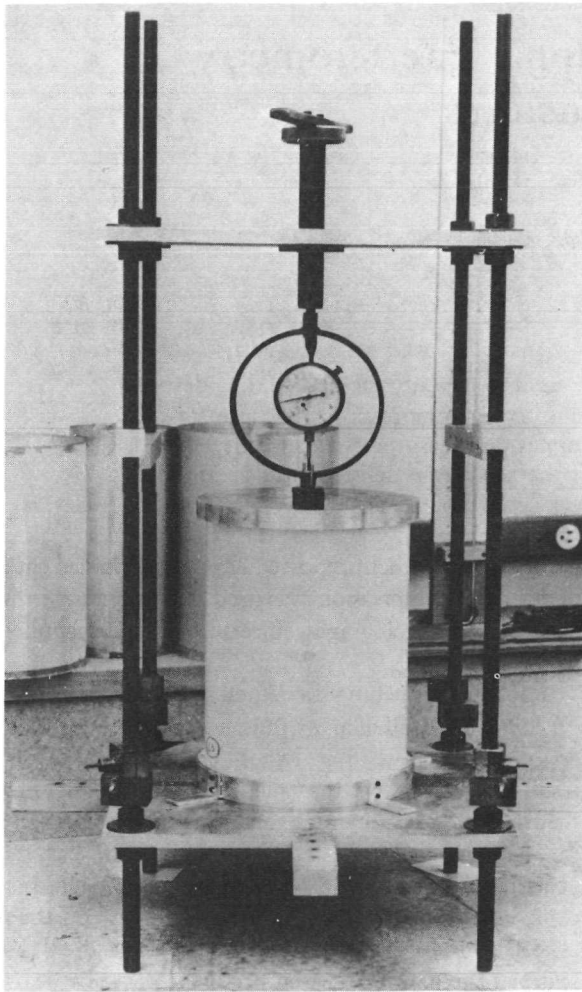


Figure 1.—Cylindrical shell mounted in controlled-load test fixture.

tested in the controlled-load testing machine shown in figure 1. The load was applied at a point on the top endplate by means of a loading screw, a calibrated load cell, and a ball bearing in a hemispherical cup.

Figure 2 is a diagram of the experimental arrangement. A 15-mW helium-neon laser was used. As shown in the figure, the beam from the CW laser is split after passing a beamsplitter. After reflecting off

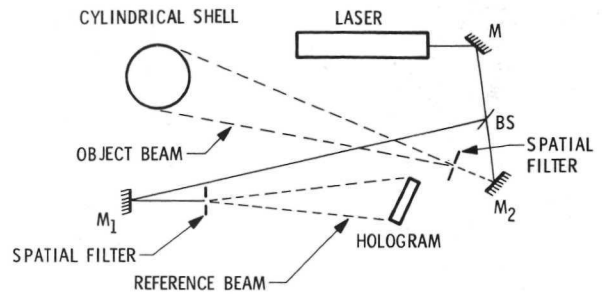


Figure 2.—Schematic of experimental arrangement.

mirror M1, the reference beam passes through a spatial filter and illuminates the hologram. The object beam also reflects off mirror M2 and through a spatial filter to illuminate the cylindrical shell.

The arrangement was vibration isolated on a 1.2-by-2.4-m (4-by-8-ft) optical table. Double-exposure holograms were recorded with a small incremental change in compression between exposures.

RESULTS AND CONCLUSION

The prebuckling imperfection growth of a thin-walled circular cylindrical shell under axial compression is shown in figure 3. Double-exposure holography was used with a small change in compression between exposures. The hologram thus reconstructs two different wavefronts of the cylindrical shell, and the fringe patterns represent the interference between the different wavefronts. It is of interest to notice the fine detail in the vicinity of the boundary, keeping in mind the extremely small deformations taking place. Although the initial imperfections are of a random nature throughout the shell, the prebuckling imperfection growth can be seen as a certain wave pattern.

The prebuckling imperfection growth patterns were obtained for the entire surface. The growth pattern indicates that the shell deforms in a certain fashion, depending upon the initial imperfections. These results contradict the linear shell theory, which states that the shell does not deform prior to buckling.

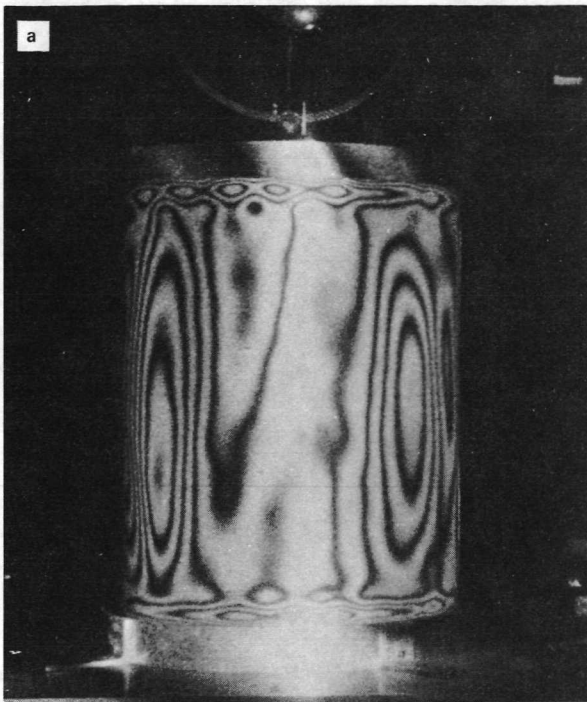
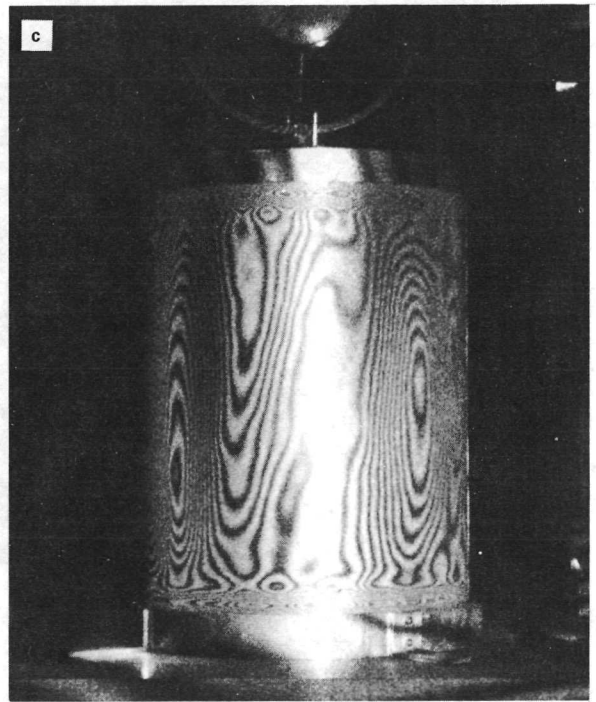
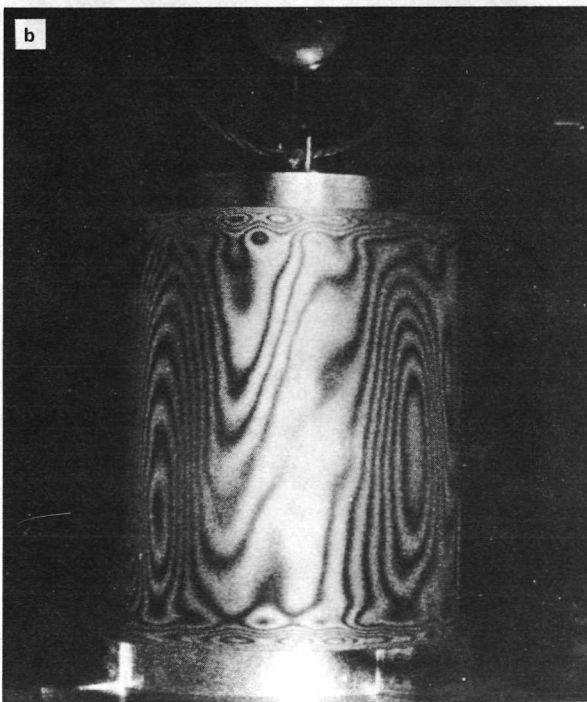


Figure 3.—Prebuckling imperfection growth at (a) 72% of buckling load with change of 0.5%, (b) 77% of buckling load with change of 6.5%, and (c) 83.5% of buckling load with change of 9.7%.



Page Intentionally Left Blank

Holographic Techniques Applied to the Solution of Aerospace Problems

Frederick C. Way

*Applied Optics Group
Pratt & Whitney Aircraft*

Holography is becoming more widely accepted throughout the aerospace industry as a nondestructive testing technique. This acceptance provides the basis for many advances in the state of the art and indicates an optimistic future for the use of optical measurement techniques in the industry.

This report describes the use of conventional holographic methods at Pratt & Whitney Aircraft's Florida Research and Development Center, including (1) routine time-average holographic vibration analysis for determining mode shapes and location of cracks and disbands, and (2) standard double-exposure holographic interferometry for measuring small displacements and locating flaws.

Advances in holographic applications and techniques, including real-time motion-picture vibration analysis, contour holography, bleaching to increase diffraction efficiency, and a method for determining holographic system performance, are also presented herein. The paper concludes with a description of anticipated future applications of holography at the Florida Research and Development Center, such as computer synthesis and redesign of engine components, pulsed ruby holography for flow visualization, and online quality assurance inspection techniques.

Holography is a laser-photographic process for rapid nondestructive testing of experimental and production hardware components and structures. A hologram is a photographic record of the amplitude and phase of light waves reflected from an object. Each area on the photographic plate contains the recorded interference of impinging wavefronts. Each point on the photographic plate receives light waves from the entire object, and thus each small section of the hologram is a recording of the entire field of view. Lenses are not used for imaging, but are used to expand the light beams that are recorded on the photographic plate. Therefore, objects cannot be recognized in the holographic plate because a conventional image is not formed.

Information from the hologram is obtained through reconstruction of the wave pattern reflected

from the subject by passing a beam of coherent light through the hologram. A record of a real image of the original object can be provided by placing a photographic plate at the position of the image. A three-dimensional virtual image is also produced when the image is viewed through the hologram. This three-dimensional image can be viewed and photographed at different angles to look at objects that are hidden in a normal view. Both images exhibit the same perspective, volume, and parallax properties as the original object.

Interferometric holograms are double-exposed or multiple-exposed holograms that reveal the physical displacement in opaque objects and the density changes in transparent volumes, which appear in the form of interference fringes. The reconstruction of an interferometric hologram produces an

image of the original subject superimposed with a pattern of black fringes spread over it, each representing the locus of points with equal displacement on the object surface.

Holographic techniques at Pratt & Whitney Aircraft's Florida Research and Development Center (FRDC) are applied on a routine basis for the determination of mode shapes of vibrating airfoils, combustors, plumbing, spraybars, and casings. Holographic nondestructive testing techniques have been used for determining the location of subsurface disbands in honeycomb material, measuring the effects of pressurization on cooled surfaces and plumbing, and the description of hardware with complex contours.

A hologram is a complex diffraction pattern formed on a photographic plate by the interference of two laser beams. The material to be tested is placed on one of the beams. The second light beam is a reference beam superimposed on the first beam at the photographic plate. When the processed plate is illuminated by a coherent beam resembling the reference beam, the rays that are diffracted duplicate the light rays from the material, and thus an image of the test object appears in the position it previously occupied. Within the viewing angle subtended by the photographic plate, the hologram provides a full-size, three-dimensional image of the test object with correct parallax and perspective. This image can be examined optically with devices such as schlieren, interferometers, telescopes, and microscopes, just as though it were the original object.

During the past three years many advances have been made in holographic nondestructive testing techniques at FRDC, arising from the desire to develop more precise and rapid methods. The intent of this report is to outline past accomplishments, describe present research and capabilities, and look at the future of holography applied as a measurement technique for the solution of aerospace design problems.

The Applied Optics and Flow Dynamics Group of Instrumentation Engineering are now studying several programs related to holography and optical measurements in general. These include holographic contour inspection of engine hardware, pulsed ruby holographic flow visualization, laser doppler velocimetry, determination of the performance of holographic systems, and real-time motion-picture holographic analysis.

ROUTINE HOLOGRAPHIC ANALYSIS

Time-Average Holography

Under certain conditions, mode shapes of vibrating objects and subsurface disbands in materials can be studied with time-average holography. Although the subject is not holographed in a steady state, a single exposure of the subject is made while it is vibrating at resonance. When the hologram is reconstructed, a series of decreasing-contrast interference fringes is superimposed on the object's image, representing the locus of points of equal vibrational amplitude.

Time-average holography is used at FRDC for the determination of mode shapes of engine hardware vibrating at resonance. It is an aid in the placement of strain gages to know the nodal pattern of an engine component. Furthermore, it is necessary to determine whether the object goes through high-stress-concentration vibrational modes in the critical operating range of the engine. Under certain conditions, defects and disbands in solids can be precisely located by means of time-average holography. Figure 1 is a block diagram of a typical optical system used in vibration analysis.

As previously stated, the reconstructed image of a vibrating object contains an interference pattern in which each fringe represents the locus of points on the object that vibrate with equal amplitude. The displacement represented by each dark fringe is

$$m = (\lambda/2\pi) (1/2\Phi_{0n})$$

where

m = displacement

λ = laser wavelength

Φ_{0n} = value of successive zeros of the Bessel function of the order J_0

n = fringe number

It is therefore possible to determine a displacement map over the surface of an object vibrating at resonance.

Figure 2 shows a series of photographs of the reconstructed images of an ST9 first-stage turbine blade. Results indicated that the object was experiencing a critical first bending mode near 8 kHz. The blade was subsequently redesigned to move the frequency of this mode out of the critical operating range of the engine, as shown in figure 3.

Holography is used on a routine basis to determine the mode shapes of various engine components. Figures 4 and 5 show photographs of the reconstructed image of a JT11 burner can. Nodal diameters

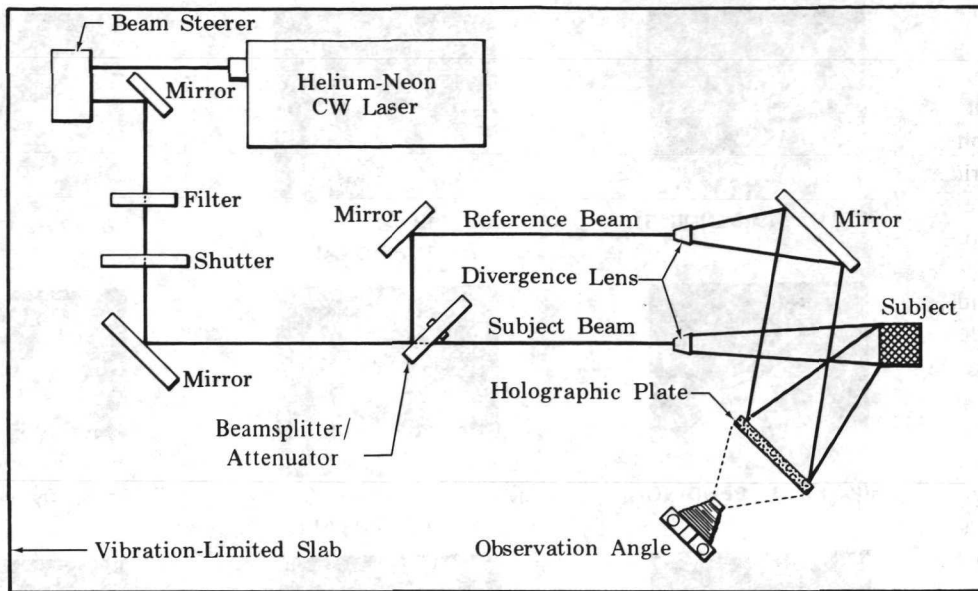
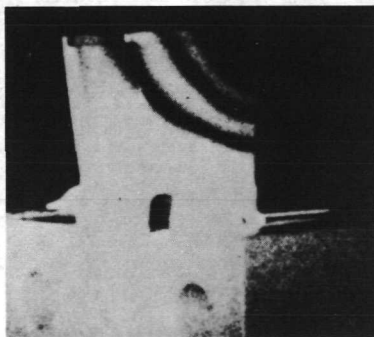
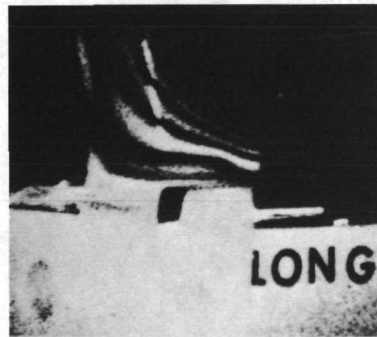


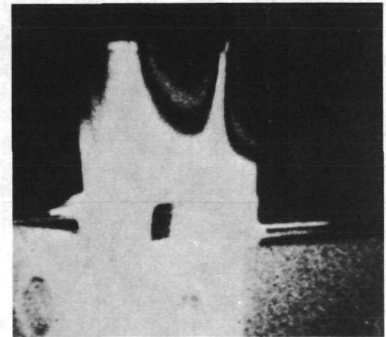
Figure 1.—Block diagram of optical system used for vibration analysis.



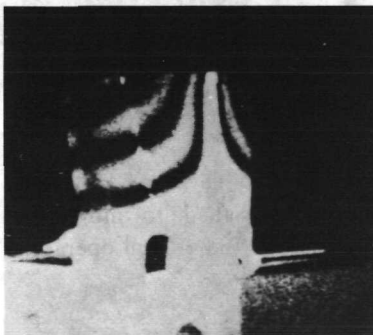
7986 Hz (FIRST BENDING)



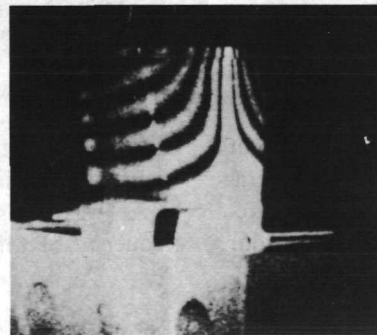
7319 Hz



18 226 Hz (COMPLEX)



13 744 Hz



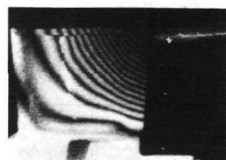
13 588 Hz (TORSIONAL)



11 855 Hz

Figure 2.—Mode shapes for ST9 first-stage turbine blade.

LONG CHORD



LONG
7319 Hz (1st BENDING)

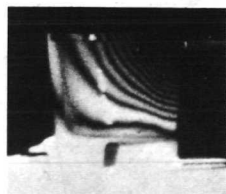


LONG
12 623 Hz
(1st TORSIONAL)

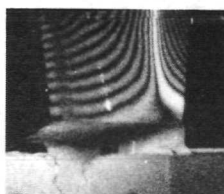


LONG
16 767 Hz (T-SHIRT)

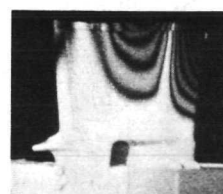
QUICK FIX



8048 Hz (1st BENDING)



13 220 Hz
(1st TORSIONAL)



17 357 Hz (T-SHIRT)

SHORT CHORD



SHORT
8465 Hz (1st BENDING)

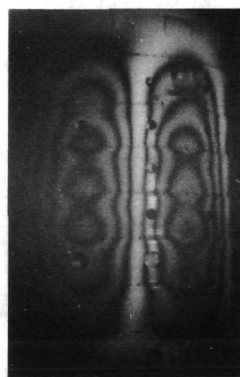


SHORT
12 069 Hz
(1st TORSIONAL)

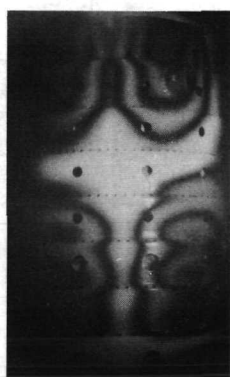


SHORT
16 767 Hz (T-SHIRT)

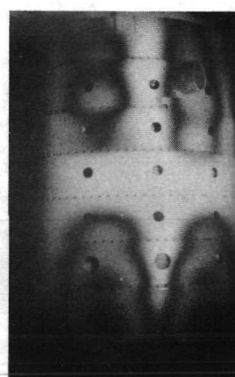
Figure 3.—Mode shapes for ST9 turbine blades of various configurations.



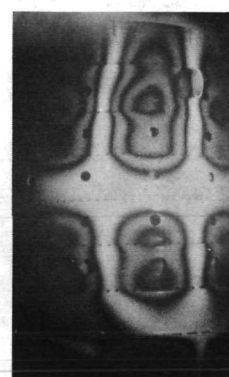
500 Hz



541 Hz



561 Hz



626 Hz

Figure 4.—Resonant mode shapes for JT11 claw burner can (light duty).

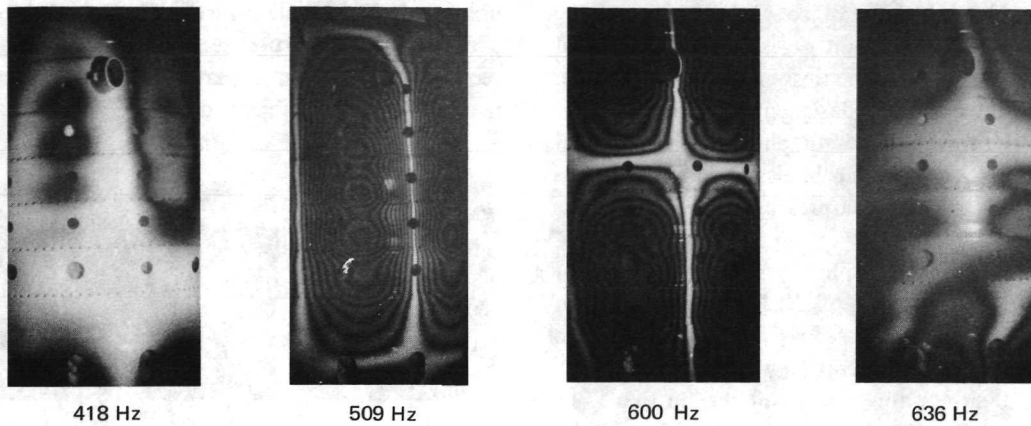


Figure 5.—Resonant mode shapes for JT11 six-claw burner can with machined 8th panel.

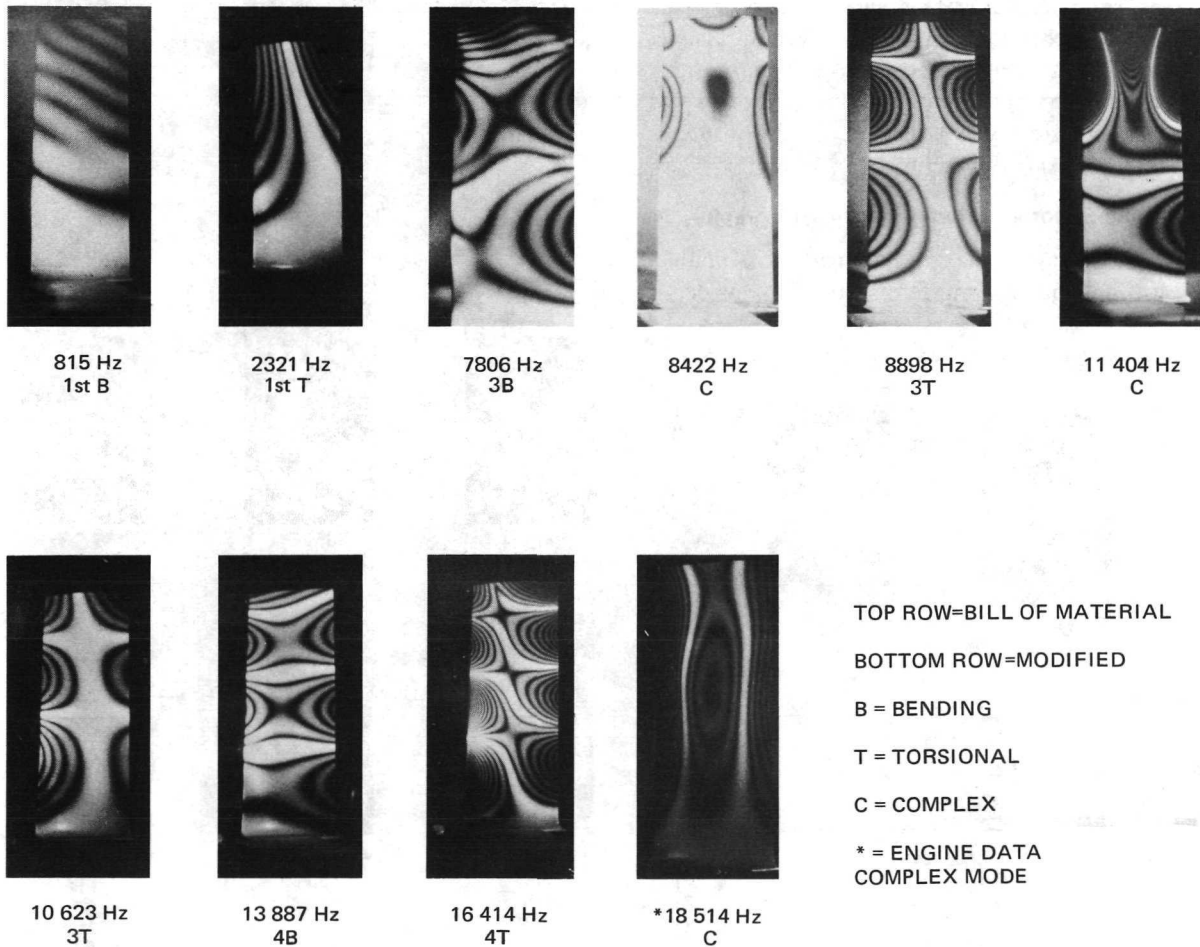


Figure 6.—Mode shapes for JTF22 sixth-stage compressor blade.

were determined for this object. It was noted, using both holography and strain gages, that a section of the can experienced a high stress concentration mode. As a result, the can was redesigned.

Figure 6 shows a series of photographs made of vibrating JTF22 compressor blades. As a result of this study, the sixth-stage compressor blade design was modified.

Figures 7, 8, and 9 display several photographs of reconstructed holograms of XLR129 spraybars of different configurations. From these data, an optimum spraybar configuration was determined.

Figure 10 shows how a crack at the tip of a JT11 first-stage compressor blade can be identified by the difference in mode shape at the blade tip.

Time-average holography has also been used to detect subsurface disbonds in honeycomb and thin-wall test samples. If the object is excited at frequencies above 50 kHz, disbonded areas are excited and act as small diaphragms. Figure 11 shows the detection of disbonded areas in a honeycomb sample. The sample was later dissected and a direct correlation between the hologram and disbonded areas was made. Approximately 80 percent of the disbonds were detected using this technique.

Double-Exposure Interferometric Holography

An investigation has been made of double-exposure holographic interferometry. The subject is

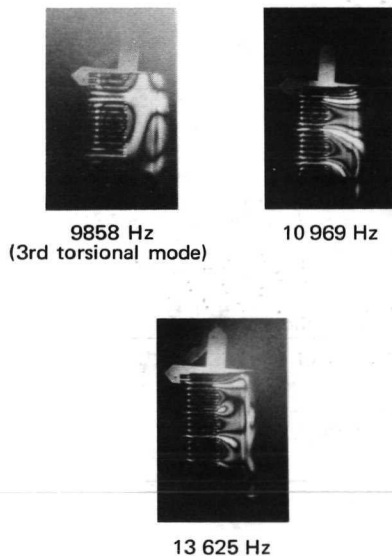


Figure 7.—Mode shapes for 250K short spraybar.

holographed in a steady state, but the plate is not processed after exposure. A second exposure is recorded on the same plate after some change has occurred in the subject due to heat, pressure, or

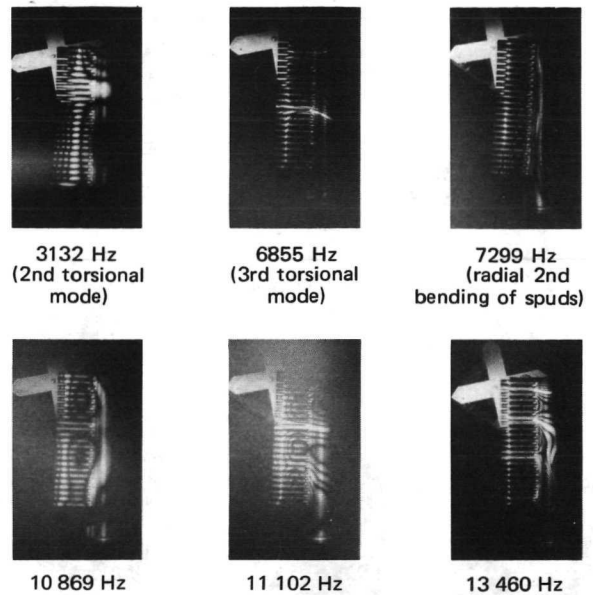


Figure 8.—Mode shapes for 250K medium spraybar.

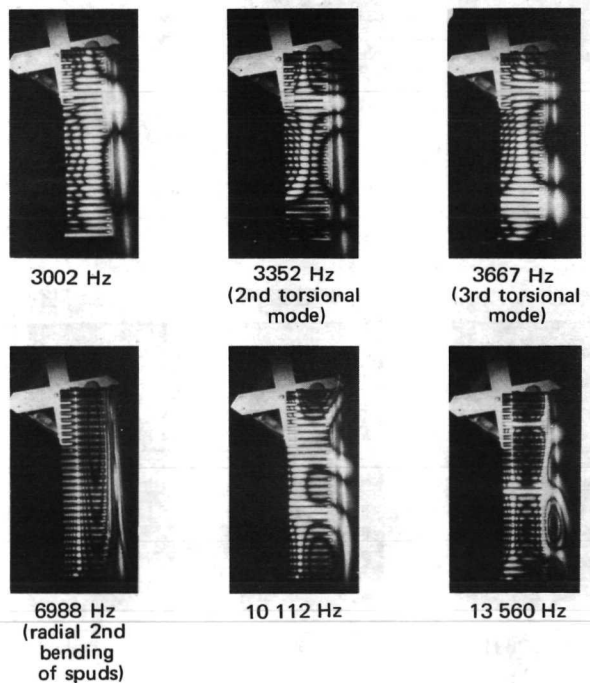


Figure 9.—Mode shapes for 250K long spraybar.

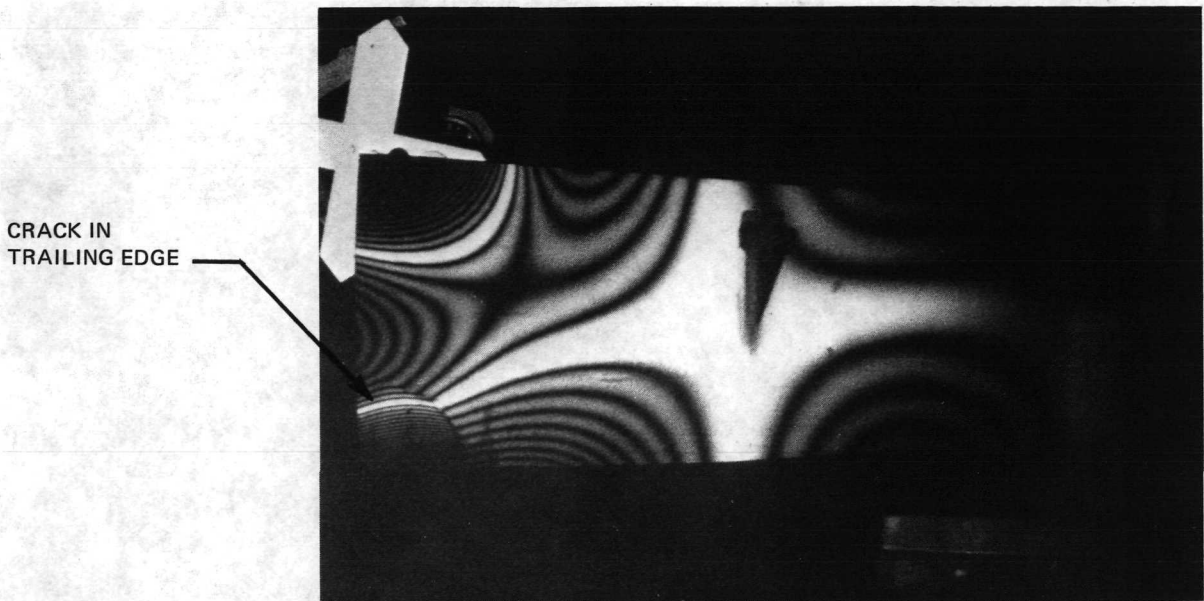


Figure 10.—Crack in trailing edge of JT11 first-stage compressor blade.



Figure 11.—Disbond detection in electron-beam-welded honeycomb sample.

mechanical stress. When the hologram plate is processed and viewed, both images of the subject will be reconstructed. For the stressed state of the object, if the length of the light path from the object to the recording plane is different by n wavelengths, the two images will interfere and produce $2n$ fringes. Using the 632.8-nm wavelength of a helium-neon laser, the displacement represented by each successive interference fringe is approximately $0.318 \mu\text{m}$. The results of such holograms can be quantitatively evaluated to determine the deformation of the object.

Double-exposure holography can also be used to determine the location of subsurface defects in materials. Figure 12 is a photograph of the reconstructed image of a variable-thickness honeycomb flap. A hologram was recorded and the flap was then uniformly heated approximately 5.5°C and a second hologram was recorded on the same plate. As can be seen, subsurface disbonds in the honeycomb structure appear as sources of fringes, or fringe discontinuities, caused by the different thermal conductivity in the disbonded area.

If it is possible to pressurize the object under test, disbonds can also be detected. Figure 13 is a photograph of a 3.81-by-7.62-cm diffusion-bonded panel, pressurized to 110 N/cm^2 (160 lb/in^2). Note the disbonded area at the top of the plate.

Figure 14 is a photograph of a high-pressure steel

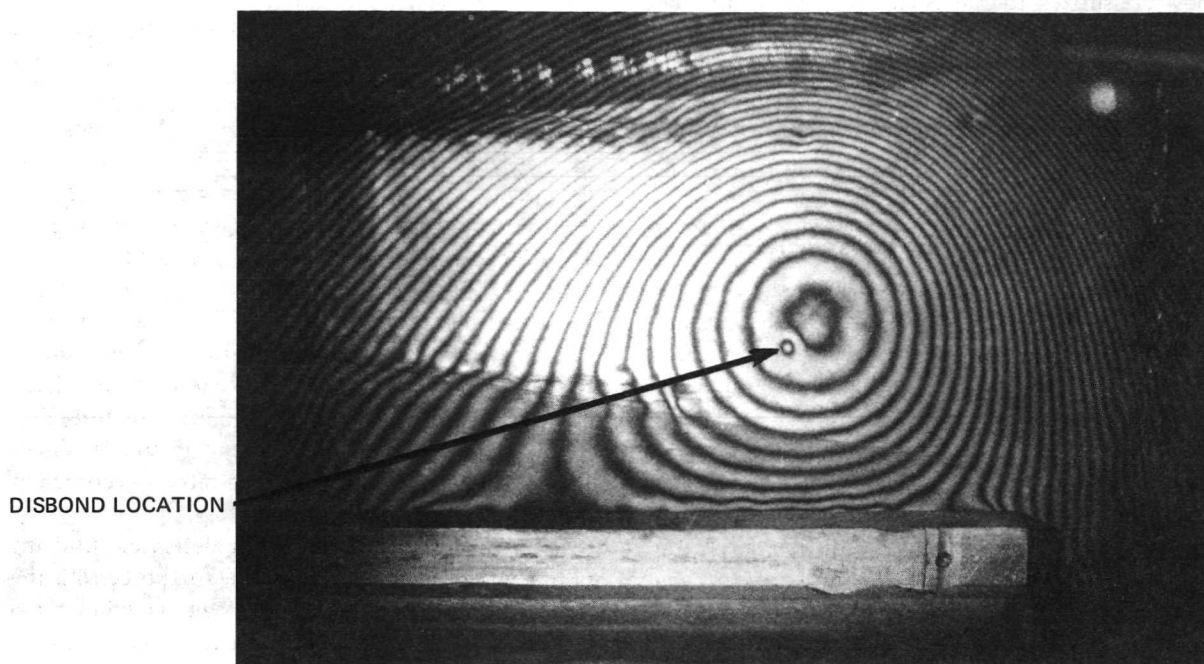


Figure 12.—Disbond detection in crushed honeycomb flap.

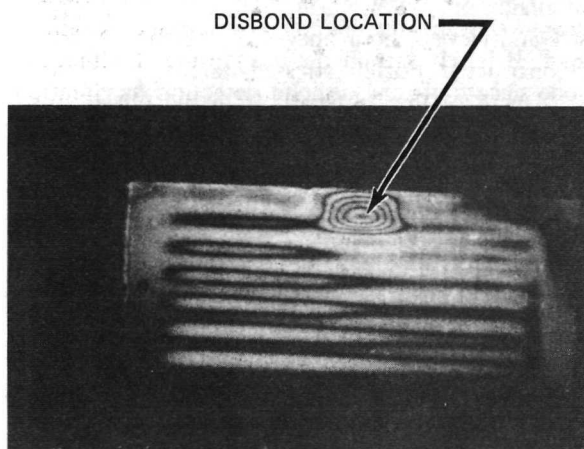


Figure 13.—Disbond detection in diffusion-bonded panel pressurized to 110 N/cm^2 .

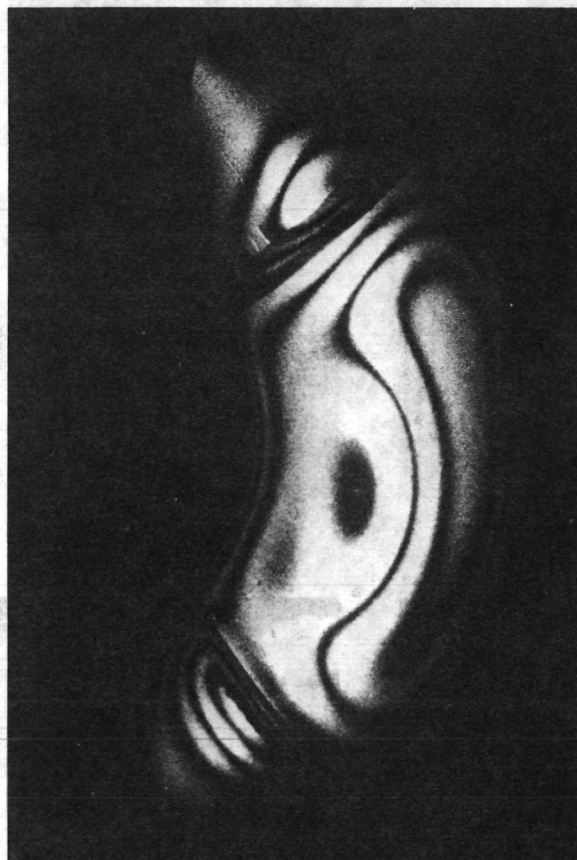


Figure 14.—Interferogram of steel elbow pressurized to 228 N/cm^2 .

elbow pressurized to 228 N/cm^2 (330 lb/in^2), showing fringes indicative of the object distortion. Braze joint defects, subsurface voids, and weak areas would be recognized in the photograph as a discontinuity in the fringes or a localized source of fringes.

CURRENT HOLOGRAPHIC RESEARCH AT FRDC

Real-Time Motion-Picture Vibration Analysis

A further extension of interferometric holography, known as real-time holography, records the continuous deformation of a variably stressed subject. The subject is recorded under steady-state conditions, and the plate is processed. This plate is then replaced in precisely its original position, so that the virtual image of the object and the actual object coincide. Stress applied to the object will cause a change in the optical pathlength between the object and plate, forming visible interference fringes. By photographing this image with a motion-picture camera, a continuous readout of the fringes can be obtained under all degrees of stress applied. This type of work has been performed during the past two years for recording the effects of pressure, temperature, or mechanical stress on engine hardware. An example is presented in figure 15, which shows an aluminum elbow being pressurized.

The technique of real-time holography has been extended to vibration analysis. A 90-percent decrease

in the time required to mode-signature an object is afforded by this technique. Because the object is vibrating, the fringe contrast is extremely low. Our present approach is to pulse the laser source in synchronism, but out of phase, with the vibrating object. This method allows high-contrast fringes to be recorded on motion-picture film as the object is excited throughout the frequency range of interest. The fringes recorded are very similar to double-exposed interference fringes, as opposed to time-average fringes which decrease in contrast with increasing fringe number. Furthermore, it is possible to code the frequency data from the input oscillator and print it on each frame of the motion-picture film, using a modified ADTROL system. Figure 16 shows several frames of a 16-mm motion picture recorded at 50 fps of a vibrating JTF22 inlet flap.

This system is presently being perfected, utilizing (1) a fluid-gate processing device for processing the holographic plate in place in less than one minute, (2) a low-voltage acousto-optic laser modulator for pulsing the beam at the same rate as the vibration frequency, and (3) a high-speed framing camera complete with ADTROL data coding system. Results indicate that the method is economical and extremely rapid. It is felt that in the near future all vibration-mode signaturing and disbond detection via vibration will be performed in this manner. Figure 17 is a block diagram of a typical real-time vibration analysis

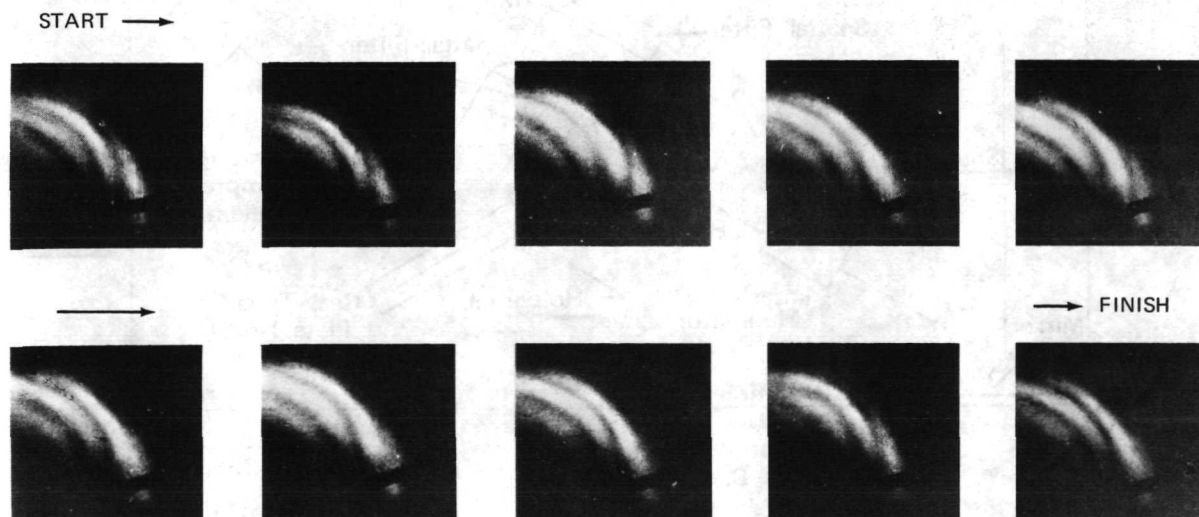


Figure 15.—Series of motion-picture frames of aluminum elbow with pressurization increasing from 14 to 55 N/cm^2 .

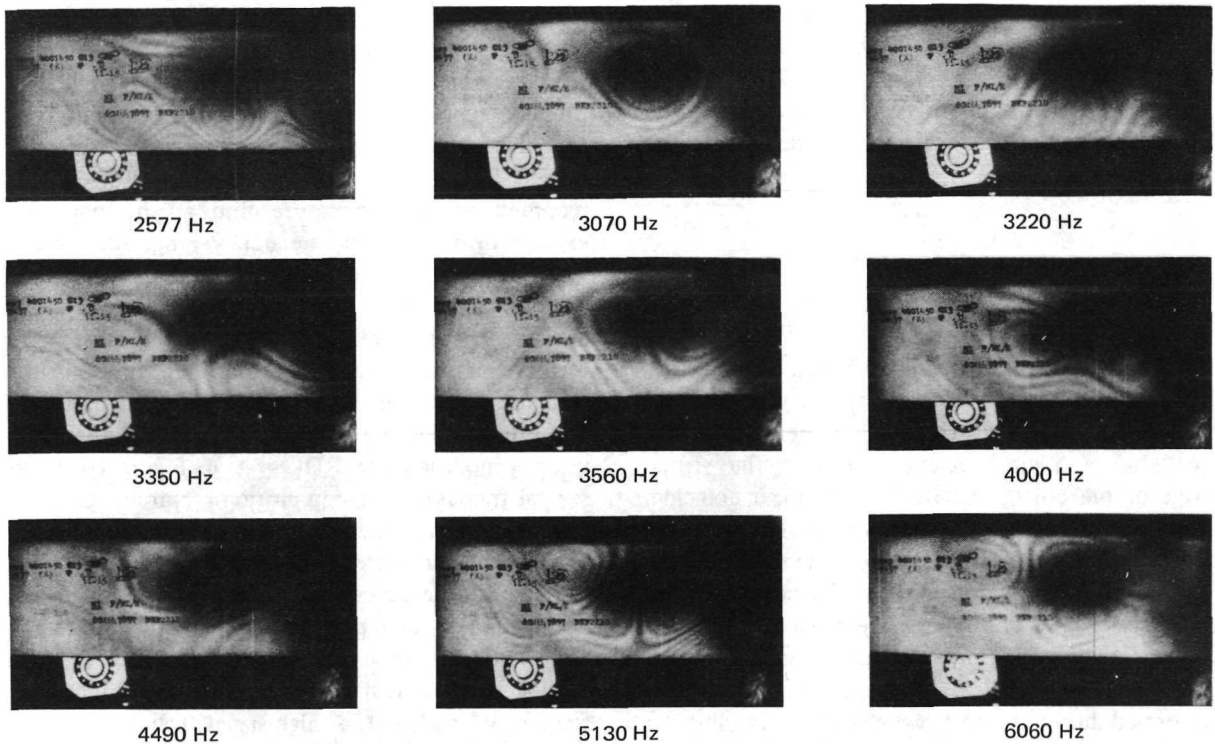


Figure 16.—Series of motion-picture frames of JTF22 inlet flap vibrating at increasing frequency.

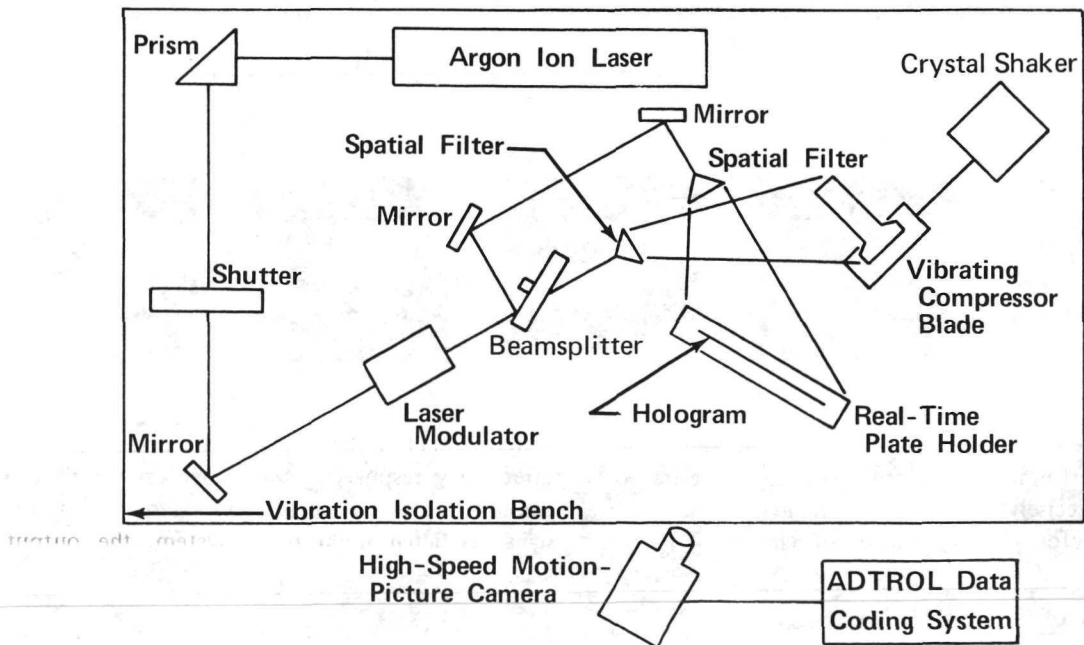


Figure 17.—Block diagram of real-time vibration analysis system.



Figure 18.—Real-time vibration analysis system in operation.

system. Figure 18 is a photograph of an actual system in use in our holography laboratory.

Determination of the Performance of Holographic Nondestructive Testing Systems

In utilizing the techniques of holographic nondestructive testing (HNDT), it has become apparent that present methods of describing system performance are inadequate. An estimate of hologram quality is usually based on an observer saying "good" or "bad". Some researchers have attempted to use resolving power or various quality coefficients to describe the system performance. Generally speaking, these techniques have proved to be unrepeatable. The measurement is subjective and incomplete because one single-point value is used to describe the performance.

The need for a different method of determining system performance has grown out of a desire to predict precisely the success of an experimental program before the expenditure of a large amount of money. Furthermore, it has become necessary to rapidly optimize the response of several holographic systems for varied uses.

Some examples of typical questions relating to system performance are:

1. How close can two adjacent interference bands in the reconstructed image of a double-exposure interferogram be, and still be seen above the noise level?
2. How well can two injector-spray liquid droplets be seen in the pulsed ruby hologram; i.e., how small can they be and how close can they get?
3. Is there a hologram exposure and processing combination that yields optimum system response?

Because an HNDT system is a communication system, it can be described using the mathematical procedures that have been developed for other communication systems. For the past several years, the modulation transfer function (MTF) has been used to describe the response of linear photo-optical systems. MTF is known to electronics engineers as "frequency response", "sine wave response", or the amount of attenuation at a given frequency. If a pure signal is acted upon by a system, the output is something different from the input. The ratio of output to input for several pure input signals is the frequency response of the system. Optical systems work in the same manner.

The use of the MTF for describing the perform-

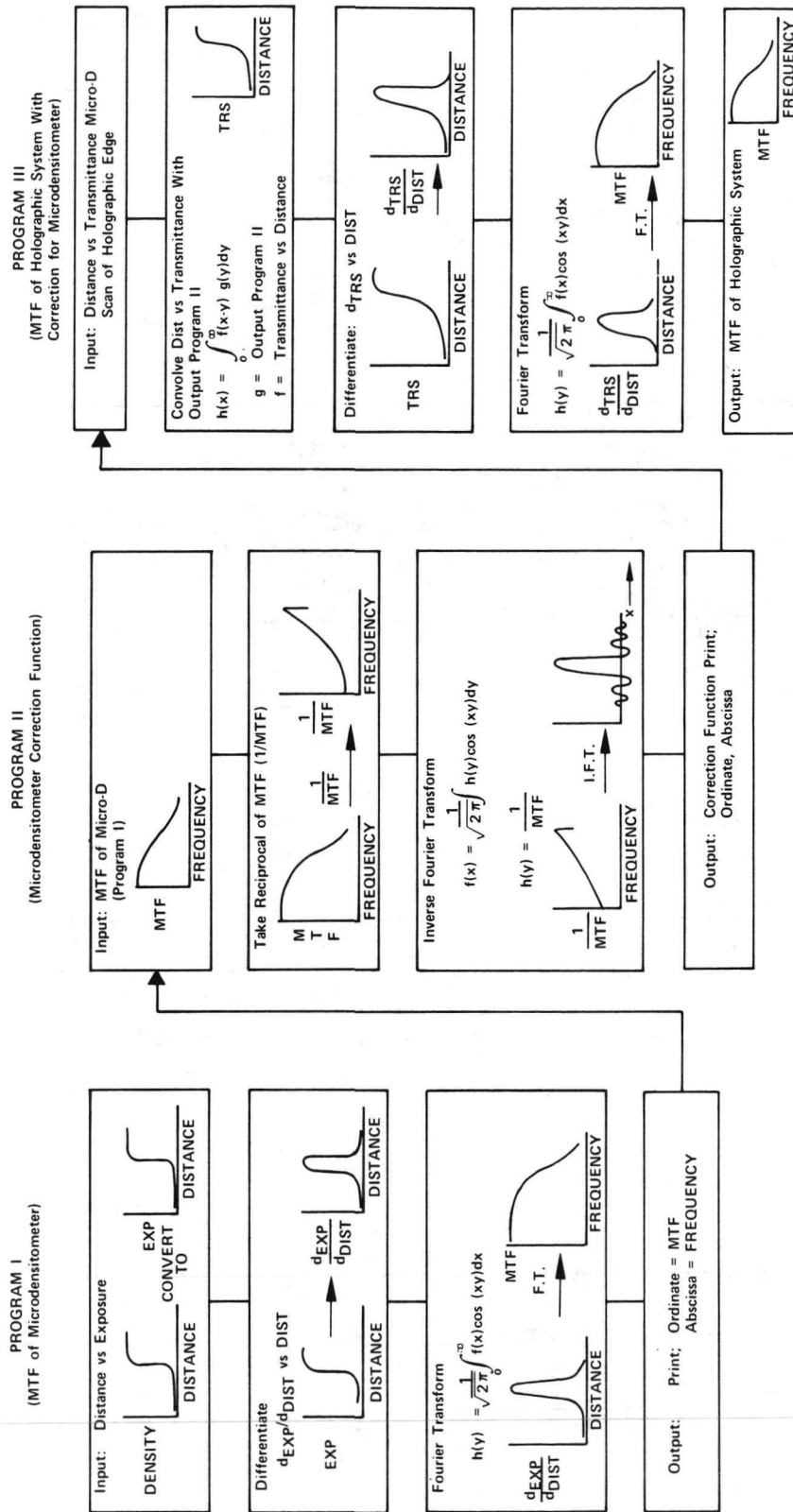


Figure 19. -MTF computer program.

ance of a holographic system is not altogether new, but past approaches have been slow, complicated, and expensive. We have combined and simplified existing techniques for MTF determinations. A computational procedure for determining the MTF of an optical system by photographic edge gradient analysis has been studied by such optical concerns as Itek and Perkin-Elmer, and a variation has been implemented at FRDC for determining the performance of a holographic system.

A typical experiment was performed, using this technique, in which conditions and precision of a holographic system were determined.

A computational procedure for determining the MTF of a holographic system has been set up as shown in figure 19.

A knife-edge distribution was produced by reducing a 1.2-m black plastic edge to 3.8 cm by standard photolithography. Adjacency effects around the edge were eliminated by careful processing chemistry and agitation. A duplicate of this edge was dry-mounted firmly to a 3-by-6-by-1¼-cm aluminum plate to be used as the target in a holographic system.

The characteristic H&D curves for the films used in making and reconstructing the holograms were determined by exposing a Kodak No. 2 stepped tablet in a laser sensitometer (see fig. 20). These data were put into the computer program to change transmittances measured by the microdensitometer to effective exposures.

The following tests were performed (sample size for each run is six):

Hologram	Light ratio	Pathlength difference (cm)	Exposure time (s)	Development time (s)
A	4:1	0	1.0	150
B	6:1	0	1.0	150
C	2:1	0	1.0	150
D	4:1	0	3.0	90
E	4:1	0	0.25	300
F	4:1	5.08	1.0	150
G	4:1	10.16	1.0	150
H	4:1	15.24	1.0	150

An example of a typical microdensitometer scan is shown in figure 21.

Graphs of the data obtained are shown in figures 22 and 23. As can be seen, the results indicated that a light ratio of 4:1, exposure time of 1.0 s, and

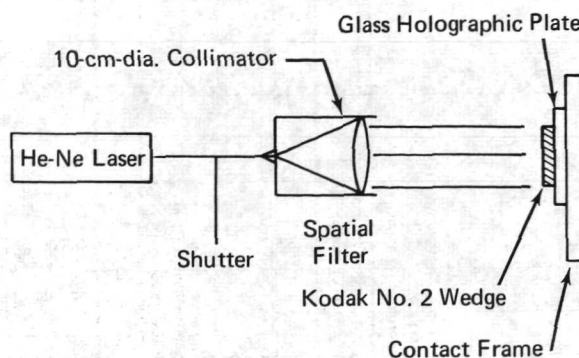


Figure 20.—Diagram of laser sensitometer.

development time of 150 s yielded maximum response for this particular system.

Although the results are not surprising or significant, they do show an important use for the MTF approach. This technique has been utilized for the analysis of several systems during the past 2 years. It is felt that the approach provides an advantage in studying systems because it is rapid and repeatable and yields quantitative results.

Contour Holography

One of the many optical measuring techniques which have evolved from research and development efforts in holography is holographic surface contouring.

Countour holography is accomplished by the superposition of two holographic recordings of the same object on a single photosensitive plate. Introducing a phase difference proportional to the distance from the photographic plate to the object surface between exposures causes the reconstructed image to have interference fringes superimposed on the surface.

The fringes represent constant phase difference between the two exposures. Because the phase difference is proportional to the distance from the holographic plate to the object surface, the fringes are a set of equal-range contours on the image. The phase difference between exposures can be introduced by (1) changing the wavelength of the laser source (multiple wavelength), (2) changing the index of refraction of the fluid medium surrounding the object between exposures (multiple index of refraction), or (3) changing the position of the illuminating source between exposures (multiple source). These three and

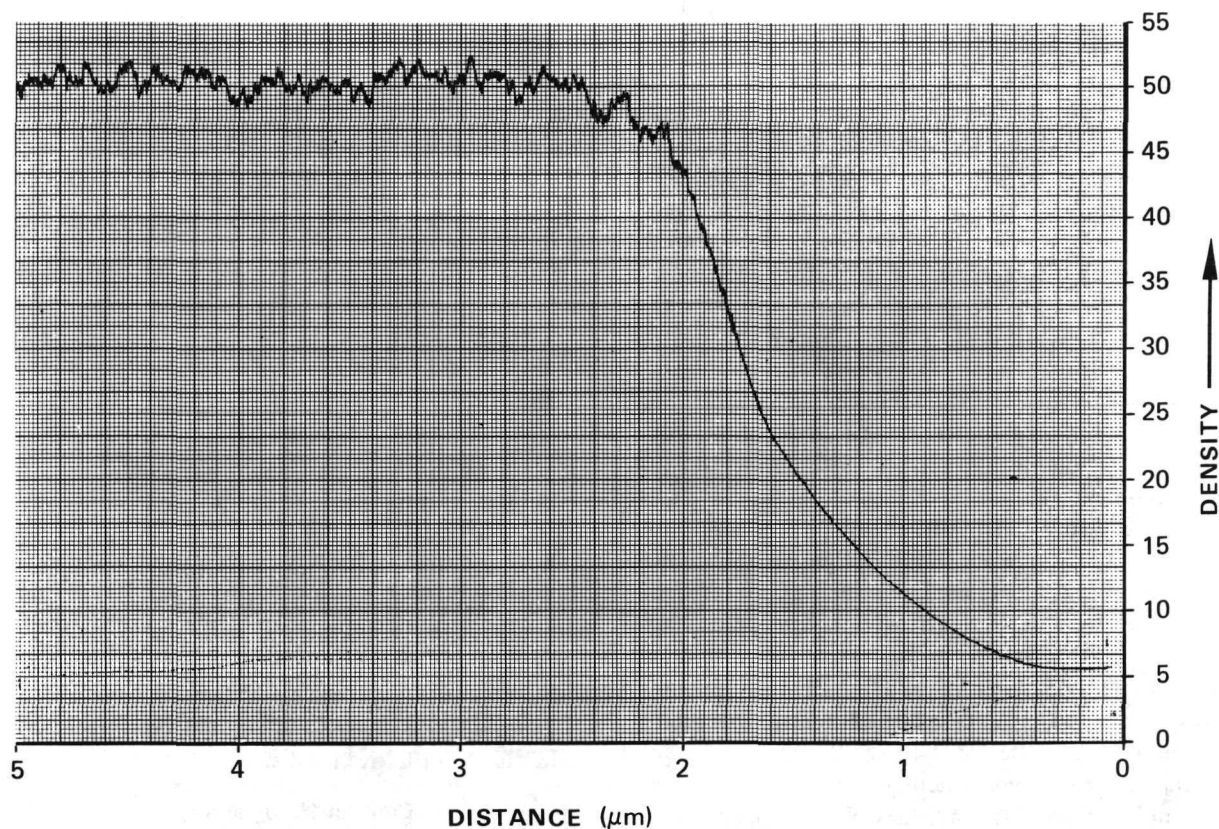


Figure 21.—Typical microdensitometer edge scan.

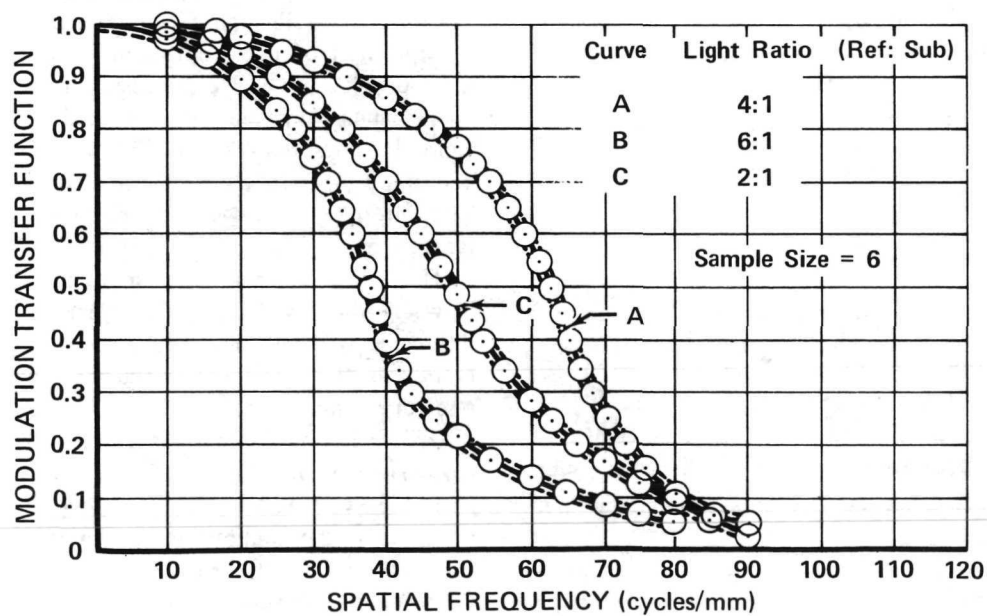


Figure 22.—Graph of data results for holograms A, B, and C.

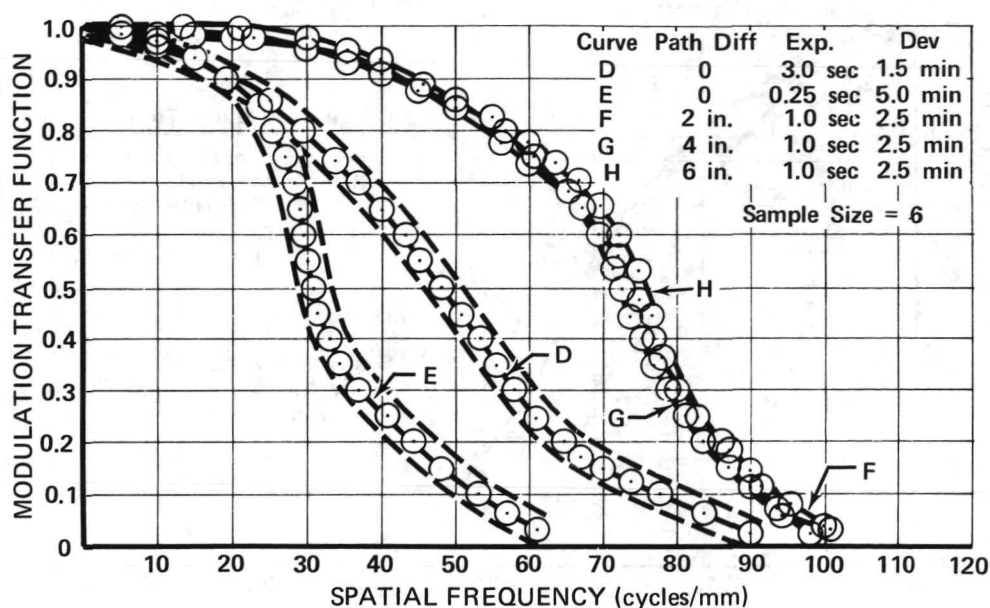


Figure 23.—Graph of data results for holograms D through H.

other methods of contouring were evaluated. Figure 24 shows two photographs of the reconstructed images of a contoured turbine blade, using a multiple-source technique and two contour spacings. The results of research to date indicate that contouring techniques may have applications in inspection and quality control of hardware.

Bleaching of Holograms to Increase Diffraction Efficiency

The intensity of reconstructed holographic images depends on the diffraction efficiency of the hologram. If the normal absorption-type hologram is bleached, the diffraction efficiency is increased by changing the hologram from an amplitude to a phase grating.

Bleaching (or reduction) consists of removing the silver particles, creating voids in their place. The voids change the index of refraction of the photographic emulsion wherever silver particles previously existed. Diffraction efficiencies of typical unbleached holograms are less than 1 percent. Efficiencies as high as 50 percent have been reported for bleached holograms produced with two plane-wavefront beams. In the only report on diffuse-wavefront object beam holography, efficiencies of 27 percent have been obtained.

Several bleaches and processing combinations have

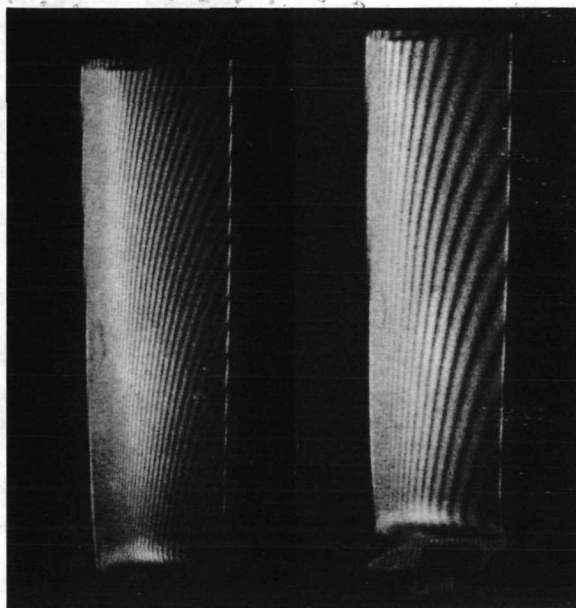


Figure 24.—Multiple-source contouring technique used to show different contour spacings on contoured turbine blade: left, 0.1 mm per fringe; right, 0.76 mm per fringe.

been tested in our laboratory. Results indicate that a diffraction efficiency in excess of 20 percent can be obtained with chromium intensifier or mercury chloride bleaches. MTF data representative of these are shown in figure 25. A modified R-10 bleaching

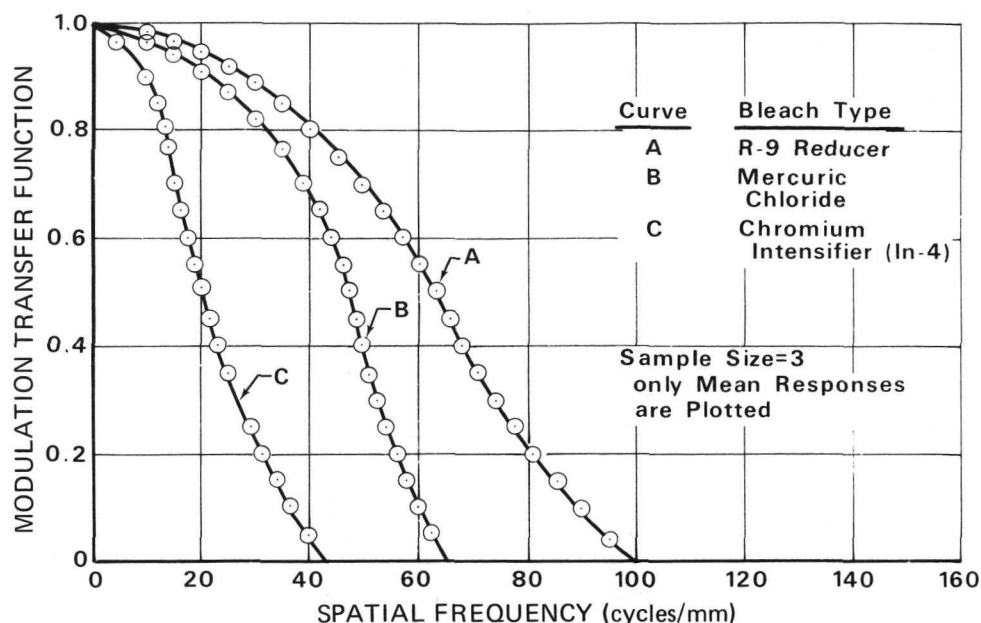


Figure 25.—Graph of MTF results for bleached hologram.

process, using stress relief and prehardening of the emulsion as described by Upatnieks, is presently being evaluated.

This study has resulted in a 75-percent decrease in the time required to photograph our hologram reconstructions and higher-intensity reconstructions for visual display.

ANTICIPATED APPLICATIONS OF HOLOGRAPHY

Pulsed Ruby Holography

Pulsed ruby holography has extensive applications in the aerospace industry. Transmission holograms of various flows allow a determination of variations in volumetric density due to thermal transfer, projectile wakes, and fluid dispersion analysis. With the development of pulsed holographic techniques, research has progressed toward developing mathematical techniques for obtaining a precise description of a flow field yielding a density mapping. The refractive index of a medium can be obtained from the fringe shift in a hologram, and the density can be obtained from flow-field models. Figure 26 is a photograph of the reconstructed image of a pulsed ruby hologram of a 12.7-mm free jet.

Without making any physical disturbance of, or

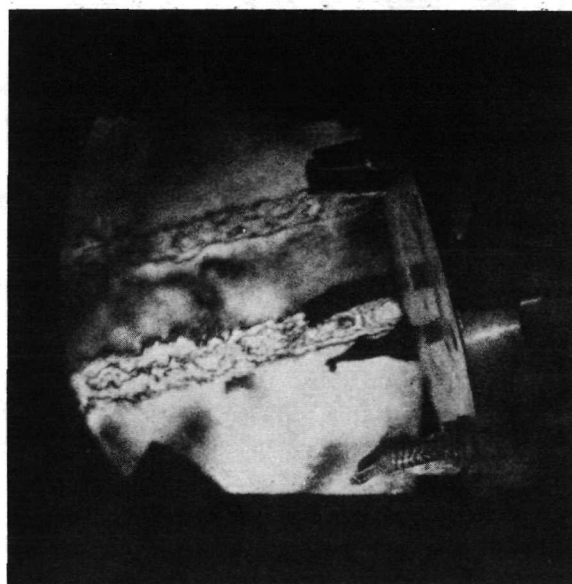


Figure 26.—Double-pulsed ruby laser interferometric hologram of 12.7-mm free jet.

projection into, the flow, a volume of fluid moving in a tube or from a nozzle can, at any instance, be permanently recorded for detailed studies at a later date. The recorded volume can be reconstructed optically at some future date, free of its hostile

environment; also, it can be examined with any optical device, as if it were the original subject. The hologram of a cold-flowing nozzle will show the impingement angles, the mass density distribution of atomized fuel, and the individual particles and droplets, which can be microscopically examined. A hologram of a hot-firing nozzle will illustrate the shock front propagation and three-dimensional location, the combustion front propagation, and the heat transfer rate. From a double-exposed hologram of a flow field such as an exhaust nozzle, it is possible to determine the density gradients and, by mathematical manipulation, the temperature-pressure gradients.

Techniques are presently being investigated to study the three-dimensional location of shock waves between blades in a rotating cascade rig. Other investigations include methods for determining boundary layer interaction, flow paths of turbulent blade wakes, particle size in an injector spray liquid droplet dispersion, and analysis of transmission pulsed holograms to obtain schlieren, shadowgraph, and interferometric data.

Pulsed ruby holography also can be used to study blades, vanes, engine casings, and plumbing in actual operation on the test stand. Double-pulsed reflection holograms can be used to determine heat transfer rates, vibrational modes, and the effects of pressure, just as conventional laboratory holography can. An investigation is being made to determine the utility of pulsed ruby holography for detecting disbands in hardware and for vibrational analysis.

Computer Synthesis of Holograms

From tests on a prototype turbine blade using time-average holography, data are produced which a computer can use to redesign the prototype. Fringes in the photographs could be analyzed by a microdensitometer for conversion of data to digital computer input. Equations of the mechanical design and required performance of the blade are input to the

computer. The computer contains the vibration requirements. By sorting through the variables, the computer makes the necessary changes in the blade and constructs a digital hologram of its new configuration. Figure 27 is a flow chart which illustrates this process.

The situation described above is still in the planning stages and may be realized in the not-too-distant future. Research at United Aircraft Research Laboratories indicates that computer synthesis of holograms is practical. A program to investigate the capabilities of digital synthesis systems was begun at FRDC approximately 2 years ago.

Holography as a Quality Assurance Technique

With improvements in holographic apparatus and techniques, it has become possible to move holography out of the laboratory onto the inspection floor. Some applications are described as follows:

1. Holographic nondestructive testing systems used for detecting disbands in honeycomb materials on a routine basis.
2. Holographic contouring techniques extended to determine the shape of hardware compared to a master object or a theoretical model.
3. Online tests of blading to determine vibrational characteristics compared to a master object.

CONCLUSION

The techniques of holography and many of its applications have been known and studied for several years. Only recently has holography become recognized as a testing technique for acquiring information which often cannot be obtained in any other manner.

Holographic techniques applied to aerospace design problems have an optimistic future. With continued industrial support and anticipated advances, many of the goals described will be realized.

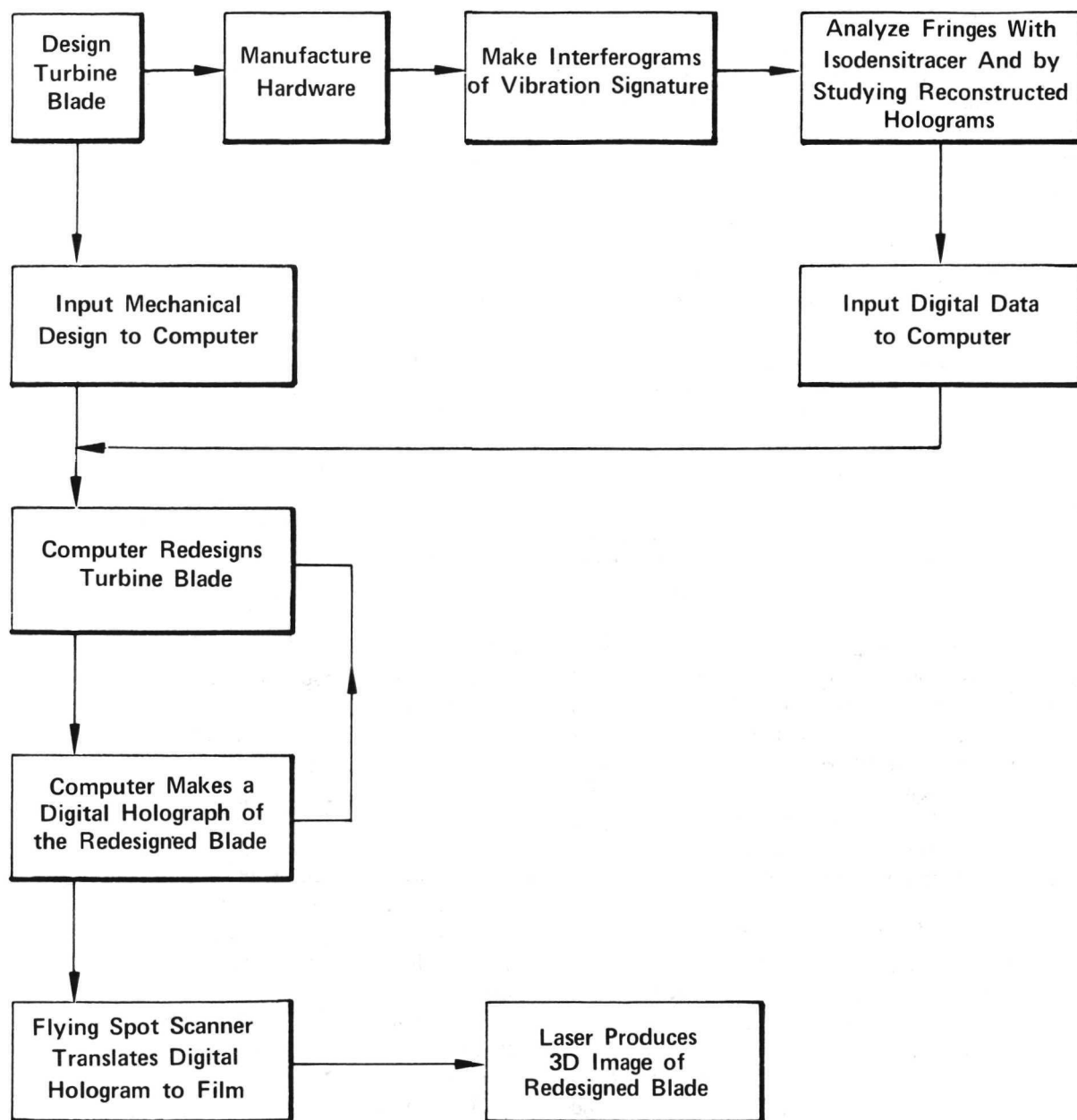


Figure 27.—Flow chart for computer redesign of a turbine blade.

BIBLIOGRAPHY

The following publications relating to holography and flow visualization were authored by United Aircraft personnel.

1. Alwang, W. G.; Cavanaugh, L.; and Cain, D.: The Observation of Three-Dimensional Shadowgraphlike Images in Holography of Phase Objects, *Applied Optics*, Vol. 8, 1969, p. 1256.
2. Alwang, W. G.; Cavanaugh, L.; Salent, R.; and Sammartino, E.: Visualization of Standing Acoustic Waves Using Time-Averaged Holographic Interferometry, *J. Acoust. Soc. Am.*, Vol. 44, 1968, p. 1732.
3. Alwang, W. G.; Cavanaugh, L.; and Burr, R.: Holographic Measurement of Compressor Blade, Turbine Blade, and Airframe Panel Vibration Distribution, SAE paper 690265, *Int. Auto. Eng. Congress*, Jan. 13-17, 1969.
4. Alwang, W. G.; Cavanaugh, L.; Burr, R.; and Sammartino, E.: Some Applications of Holographic Interferometry to Analysis of the Vibrational Response of Turbine Engine Components, Proceedings of the Electro-Optical Systems Design Conference, Sept. 1969.
5. Alwang, W. G.: Holographic Flow and Sound Visualization, Proceedings of the 16th International ISA Aerospace Instrumentation Symposium, May 1970.
6. Cain, D. A.: Holographic Flow and Sound Visualization, *Instrumentation in the Aerospace Industry*, Vol. 16, ISA, 1970.
7. Erf, R. K.; Waters, J. P.; and Aas, H. G.: Bond Inspection by Dynamic Time-Average Holography of Ultrasonically Excited Plates, *Journal of the Acoust. Soc. Am.*, Vol. 47, 1970, pp. 968-69.
8. Erf, R. K.: Holographic Investigation at the United Aircraft Research Laboratories, UARL Report H130555-2, Sept. 1969.
9. Michael, F.: A Rapid Check on the Stability of a Total Holographic System, *Applied Optics*, Vol. 9, 1970, p. 1481.
10. Waters, J. P.; Aas, H. G.; and Carriker, R. C.: Holographic Determination of Strain, Presented at Fall Meeting of Opt. Soc. Am., Oct. 1969.
11. Waters, J. P.: Continuous Lines and Planes Generated by Synthetic Holograms, Presented at Conference on Holography and the Computer, Dec. 1969.
12. Waters, J. P.; and Michael, F.: High-Resolution Images from CRT-Generated Synthetic Holograms, *Applied Optics*, Vol. 8, 1969, pp. 714-15.
13. Waters, J. P.: Three-Dimensional Fourier Transform Method for Synthesizing Binary Holograms, *J. Opt. Soc. Am.*, Vol. 58, 1968, pp. 1284-99.
14. Waters, J. P.: Holographic Image Synthesis Utilizing Theoretical Methods, *Applied Physics Letters*, Vol. 9, 1966, pp. 405-7.
15. Way, F. C.; and Herbert, L. P.: Holography at FRDC, Florida Report FR-3382, Jan. 1970.
16. Way, F. C.: Air Flow Studies—Measurements of Transient Velocity Gradients by High-Speed Schlieren Photography, *Image Technology*, Vol. 11, 1969, pp. 40-42.
17. Way, F. C.: Determination of the Performance of Holographic Nondestructive Testing Systems, Presented at Annual Conference of American Society for Nondestructive Testing, Oct. 1970, Published by P&WA as GP90-297, June 1970.

Page Intentionally Left Blank

A Novel Holographic Technique to Record Front-Surface Detail from a High-Velocity Target

Robert L. Kurtz

*Space Sciences Laboratory
NASA Marshall Space Flight Center*

It is known that any motion of the scene during the exposure of a hologram results in a spatial modulation of the recorded fringe contrast. On reconstruction this produces a spatial amplitude modulation of the reconstructed wavefront, which tends to blur out the image.

This paper discusses a novel holographic technique which uses an elliptical geometry for the holographic arrangement. It is shown that the degree of image degradation is not only a function of exposure time but also of the system used. The form of the functional system dependence is given, as well as the results of several systems tested, which verify this dependence. It is further demonstrated that the velocity of the target and the exposure time alone are inconsequential by themselves, and that the important parameter is the total motion of the target $\Delta x = v\tau$. Using the resolution of front-surface detail from a target with velocity of 175.46 m/s, we are able to predict an upper limit on target velocity for resolution of front-surface detail with a given system.

It is well known that any motion of the scene or optical components during the exposure of a hologram results in a spatial modulation of the recorded fringe contrast. On reconstruction, this produces a spatial amplitude modulation of the reconstructed wavefront which degrades the reconstructed image. It is generally felt, although not universally accepted, that a pathlength change of $\lambda/2$ in the illumination arm during the exposure will prohibit image reconstruction.

For motion holography it is necessary to find a geometrical arrangement which allows maximum scene travel with minimum change in pathlength of the illumination arm of the holographic system. This paper describes such a geometrical arrangement.

The new holographic technique described here offers promise for the holographic recording of front-surface detail from an object traveling in an essentially straight line with constant velocity of very

high magnitude. A simple analysis, given in the following section, shows that this technique is capable of recording front-surface detail from a moving scene traveling at very high velocities, depending upon the pulse duration of the laser source, its output power, and the tolerance of the optical path differences. According to the calculations shown, the technique described will allow resolution of front-surface detail from a moving scene having a velocity of 9×10^3 m/s using a ruby laser with a pulse duration of 25 ns. It is further shown that the amount of front-surface detail resolvable is a function of the configuration used, and the form of this specific function is given.

DESCRIPTION OF TECHNIQUE

Resolution of front-surface detail from targets moving with a velocity on the order of 9×10^3 m/s is obtainable if one uses a specific orientation of the

holographic system (ref. 1). With the specific orientation described below, the pathlength of the reflection arm is constrained to change by an amount equal to $\lambda/8$ and thus should allow front surface resolution heretofore unobtainable for moving targets. The choice of $\lambda/8$ was arbitrary and simply satisfied the need to be smaller than $\lambda/2$.

The specific orientation referred to above also involves the use of a hypothetical ellipse oriented with its major axis parallel to the line of motion defined by the moving scene (referred to in this section as a projectile which is to be considered as just one point of any arbitrary scene).^{*} This line of motion must be made tangent to the hypothetical ellipse at a certain point Q . One possible configuration of a holographic system with this preferred orientation inside the hypothetical ellipse is shown in figure 1. The specific orientation is defined by the following conditions: a thin-film beamsplitter centered at focus f_1 of the hypothetical ellipse; a film plane centered at focus f_2 ; and the major axis XX' of the ellipse parallel to tangent line PP' . This tangent line PP' may be identified as the line of motion of the high-speed projectile referred to above. Similarly, it may be defined as a tangent to the rim of a spinning wheel whose tangential velocity may be

very high. More generally, PP' may be defined as a line coincident with the linear velocity vector of the moving scene under investigation.

Again referring to figure 1, the system may be described as follows: Laser radiation is incident on the first thin-film beamsplitter, centered at focus f_1 . The transmitted beam from here is made incident on the projectile that is moving along the tangent line PP' and is momentarily at point Q on the perpendicular bisector of XX' . The beam is then reflected from the projectile and made incident on the film, centered at focus f_2 . The reflected beam from the beamsplitter at f_1 is made incident on a second beamsplitter, just slightly displaced from f_1 , where it is again split into two beams. The transmitted beam constitutes the reference beam for the system. After reflection from mirror M , this reference beam is made incident on the film at focus f_2 . The reflected beam from this last beamsplitter is used as a second signal beam that backlights the target via a diffuser plate. After being reflected from mirror M_2 , this signal beam passes through a diffuser plate in the region of the projectile, then is reflected by mirror M_3 to the film at focus f_2 .

By the use of the backlighting arm, a silhouette of the moving projectile is obtained. With this information one has more freedom to manipulate the orientation of the hypothetical ellipse until one obtains front-surface detail on the silhouetted projectile.

^{*}In this section we discuss a projectile target, while the actual target tested experimentally was a rotating disk. The concept of a projectile target facilitates the understanding of this section.

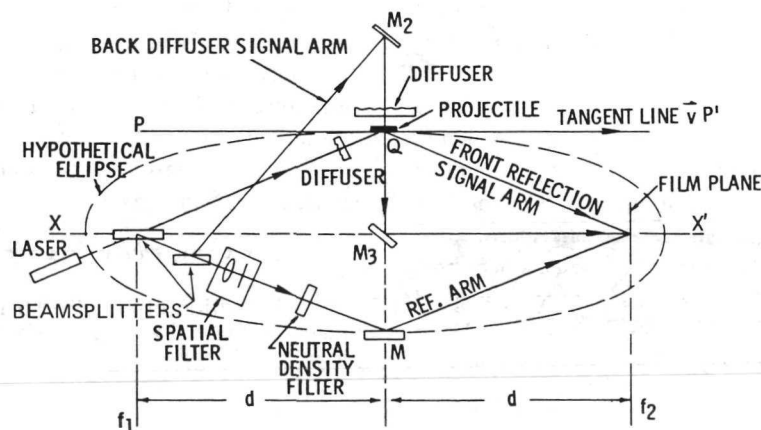


Figure 1.—Hybrid holography system with elliptical geometry.

Consider the ellipse shown in figure 2a. The general equation of such an ellipse is given by

$$b^2x^2 + a^2y^2 = a^2b^2 \quad (1)$$

The line segment PP' is considered to be tangent to this ellipse at point Q , which lies on the perpendicular bisector XX' . This line PP' is identical to the tangent line PP' of figure 1. It is parallel to the major axis XX' of the ellipse and may be considered perfectly straight. The projectile travels along PP' of figure 2 until it reaches point Q at some later time T_0 . At that time the radiation incident at point Q will be reflected to the film, which is positioned at focus f_2 . At this particular moment the hypothetical ellipse passes through point Q , with a beamsplitter at f_1 and

a film at f_2 , and we have the situation depicted in figure 1.

As the projectile moves some incremental distance Δx along PP' , past point Q , it moves off the initial ellipse, but it can be considered to move immediately onto another ellipse, just slightly larger than the initial one. If the elliptic constant of the initial ellipse was $2a$, the elliptic constant of this new ellipse will be $2(a+\Delta a)$. The radiation reflected from this moving projectile will then be incident on the film at f_2 and will interfere there with the reference beam as long as $2\Delta a$ is less than $\lambda/2$.

Figure 2b shows a family of such ellipses, each successive ellipse being intercepted by the line segment PP' at a point further to the right along PP' . We see that the separation of the foci remains constant and equal to $2d$ for the entire family of curves. Figure 2c is a convenient enlargement of the first quadrant of figure 2b. The points of interception of PP' with each successive member of the family of ellipses are given by P_1, P_2, P_3 , etc. We maintain that as PP' is traversed to the right, the original ellipse can be considered to grow successively to the next larger member of its family, while the focus separation distance $2d$ remains constant.

If we consider that the ellipse is to enlarge during the time τ , expanding to a larger ellipse, equation 1 becomes

$$b^2x\Delta x + b\Delta b x^2 + a^2y\Delta y + a\Delta a y^2 = a^2b\Delta b + b^2a\Delta a \quad (2)$$

From figure 2a we see that

$$a^2 - b^2 = d^2 \quad (3)$$

where d is a constant. Therefore

$$a\Delta a = b\Delta b \quad (4)$$

Further, since the direction of projectile motion is parallel to the x axis, $\Delta y = 0$ and equation 2 becomes

$$b^2x\Delta x = a\Delta a[a^2 + b^2 - (x^2 + y^2)] \quad (5)$$

From the basic equation for our ellipse (eq. 1) we may easily obtain

$$x^2 + y^2 = b^2 + x^2[1 - (b^2/a^2)] \quad (6)$$

By substitution of equation 6 into equation 5, we obtain

$$x\Delta x = \left(\frac{\Delta a}{ab^2}\right)(a^4 - d^2x^2) \quad (7)$$

For any ellipse $2a = L$, where L is a constant and at

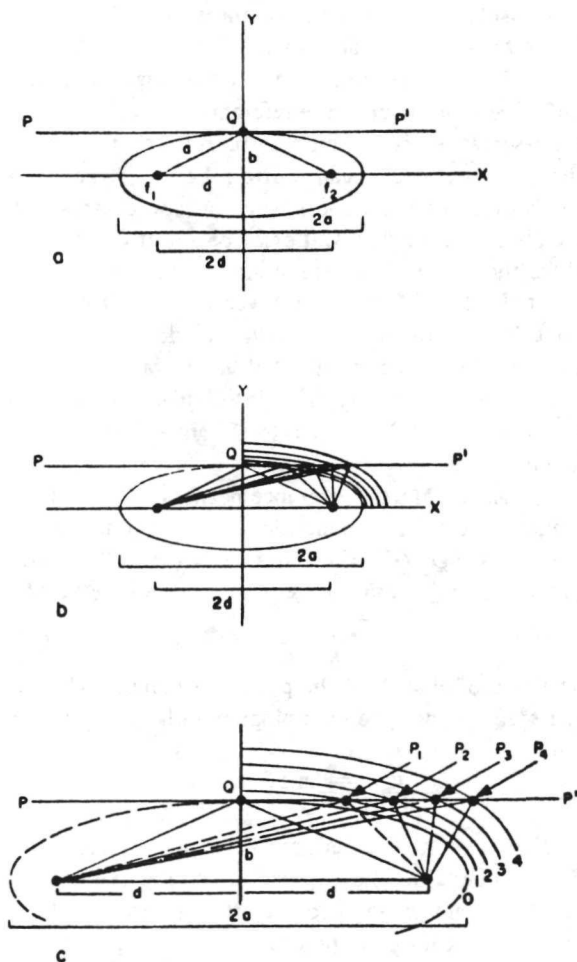


Figure 2.—Family of successive ellipses with constant separation of foci $2d$.

present is the optical pathlength of the front illumination signal arm. When the ellipse expands because of projectile travel along PP' , $2a=L$ changes by $2\Delta a=\Delta L$. Therefore, since $\Delta a=\Delta L/2$, equation 7 becomes

$$x\Delta x = \left(\frac{\Delta L}{2}\right) \left(\frac{1}{ab^2}\right) (a^4 - d^2 x^2) \quad (8)$$

Since we have taken point Q as the reference point for x (i.e., x is zero when the projectile is at point Q), therefore, as measurement of the projectile motion starts from point Q and traverses to some point P , $x=\Delta x$ and equation 8 becomes

$$(\Delta x)^2 = \frac{\Delta L a^3 / 2b^2}{1 + (L d^2 / 2ab^2)} \quad (9)$$

Making the assumptions that d^2 is not drastically different from b^2 and $\Delta L/2 \ll a$, we have that

$$\frac{\Delta L d^2}{2ab^2} \ll 1$$

and equation 9 becomes

$$(\Delta x)^2 \approx \left(\frac{\Delta L}{2}\right) \left(\frac{a^3}{b^2}\right) \quad (10)$$

where $\Delta L=2\Delta a$ is the variation in the original elliptic constant $2a$ caused by travel Δx of the projectile along PP' . At a given velocity v for a time τ ,

$$\Delta x = v\tau \quad (11)$$

where τ is the pulse duration of the laser and therefore the exposure time.

Equation 10 thus relates the distance Δx traveled by the projectile along PP' to the total change in elliptic constant, $\Delta L=2\Delta a$. That is, ΔL is the change in optical pathlength of the front surface illumination arm of the holographic system. Substituting equation 11 into equation 10 and solving for the projectile velocity, we have

$$v = \left(\frac{\Delta L}{2}\right)^{1/2} \frac{a^{3/2}}{b\tau} \quad (12)$$

We may use this relation to determine the permissible projectile velocities allowed by the specific configuration having a set of elliptic parameters and a specified tolerance ΔL . For illustration we arbitrarily set ΔL equal to $\lambda/8$ ($\lambda=694.3$ nm) and let the distance of separation between the center of the first beamsplitter, at f_1 , and the center of the photographic film, at f_2 , be a constant value $2d$. By varying the semimajor axis, a , which in turn varies the semiminor axis, b , we

may obtain a set of allowed distances of travel, $\Delta x=v\tau$. This set of Δx values is graphically shown in figure 3, where we have used the allowed Δx values as ordinate and the arbitrarily chosen values of the semimajor axis a as abscissa. Each separate curve corresponds to a specific value of d , and the elliptic parameters are related by $a^2=b^2+d^2$.

APPLICATION OF THEORY TO MOTION HOLOGRAPHY TECHNIQUE

References 2 and 3 provide the theory necessary to describe motion holography. We shall use the vector analysis approach from the above references, which is called the "scene-oriented coordinate" approach, since it allows more physical insight into the problem. Figure 4 represents a typical elliptical configuration such as that investigated earlier in this paper and subsequently tested experimentally.

Consider a single point of the scene, Q , having a linear velocity V parallel to the x axis. We shall take point R on the reference arm as our reference point. Let L be a point on some reference phase front from the laser which is common to both beams because of the presence of a beamsplitter. Let Q represent a single point of the scene having the coordinates $0, b$ (i.e., lying on the y axis). Let $\hat{a}_p$ be a unit vector lying along the line from the scene point Q to the hologram point P . Let $\hat{a}_k$ be a unit vector lying along the direction of propagation of the incident laser radiation at the scene point. Let $\hat{a}_v$ be a unit vector indicating the velocity of point Q . Then the angle γ between $\hat{a}_k$ and $\hat{a}_v$ is equal to the angle δ between $\hat{a}_p$ and $\hat{a}_v$.

We allow that the reference beam is constant in its length. The scene illumination beam is composed of two parts, $LQ+QP$. The rate of change of the partial pathlength LQ from the laser to the scene point Q is

$$\vec{V} \cdot \hat{a}_k = v \cos \gamma \quad (14)$$

The rate of change of the partial pathlength QP from the scene point Q to the hologram point P is given by

$$\vec{V} \cdot \hat{a}_p = v \cos \delta = v \cos \gamma \quad (15)$$

Following the procedure of Neumann (refs. 2 and 3), we may find the expression for the exposure of the hologram plate. Because of the motion of the scene, the exposure at point P is

$$\mathcal{E}(P) = m\tau \left\{ kc + E_r E_s \sin \left[\frac{kv\tau}{2} \hat{a}_v \cdot (\hat{a}_k - \hat{a}_p) \right] \cos \phi \right\} \quad (16)$$

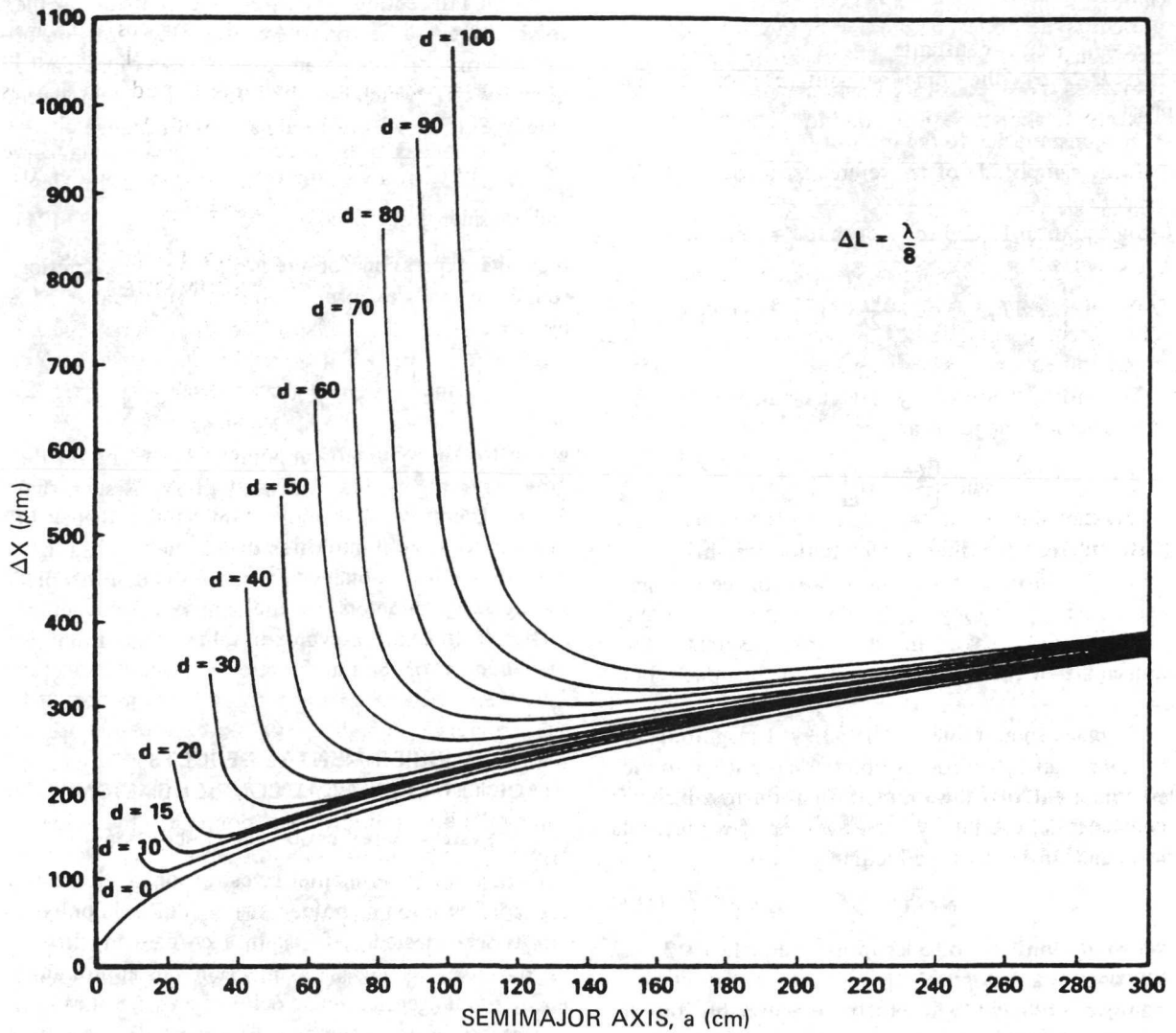


Figure 3.—Allowed travel, Δx , for various elliptical configurations.

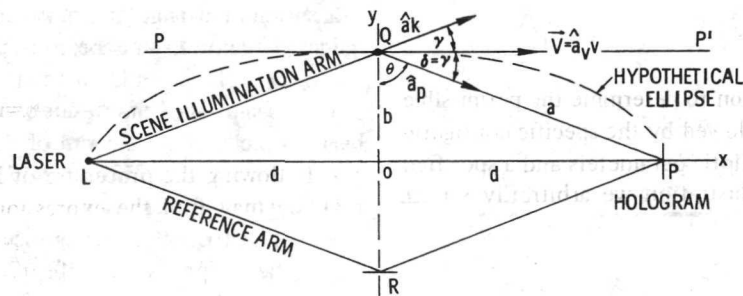


Figure 4.—Typical elliptical configurations.

where

$$kc = E_r^2 + E_s^2 = \text{constant}$$

$\phi = k(S_0 - r)$, the time-invariant portion of the phase

$m = \text{constant}$ due to the intensity

$E_r, E_s = \text{amplitude of the reference and scene fields, respectively}$

Using equation 15 and the fact that $\vec{V} = v \cdot \hat{a}_v$, equation 16 becomes

$$\mathcal{E}(P) = m\tau \left\{ kc + E_r E_s \operatorname{sinc} \left[\frac{kv\tau}{2} (\cos \gamma - \cos \gamma_i) \right] \cos \phi \right\} \quad (17)$$

Therefore, theoretically, the sinc function for the symmetrical scene point at Q is

$$\operatorname{sinc} \left[\frac{kv\tau}{2} (0) \right] = 1 \quad (18)$$

Then we see that the reconstruction of this scene point, Q , will be a maximum. It will still be a bright reconstruction as long as its travel along a_v is some small quantity $\Delta x \ll QP$; in other words, as long as the motion Δx of the scene point Q is small enough that $\delta \approx \gamma$.

To place some value on the allowed magnitude of Δx , such that $\delta_i \approx \gamma_i$ for all points of the scene to the left and right of Q , we direct attention to a plot of the sinc function, figure 5. We see that if we restrict the change in the total pathlength

$$S = LQ + QP \quad (19)$$

due to motion, Δx , to be less than or equal to $\lambda/2$, we will obtain a hologram. If we further restrict this change to $\lambda/8$, we will obtain a reasonably bright hologram.

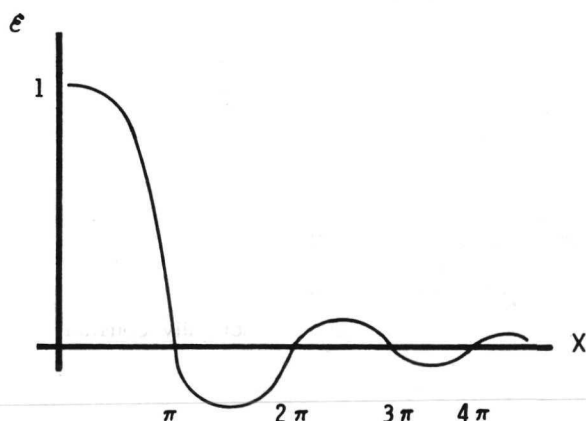


Figure 5.—Plot of $\operatorname{sinc} x = \sin x/x$.

In the last section we derived an expression for the total allowed scene travel, Δx , along the direction of $\hat{a}_v$ in terms of the parameters of an ellipse and a quantity ΔL , which was the total change in pathlength, S . If we set this total pathlength change

$$\Delta L = \lambda/8 \quad (20)$$

$$\text{and consider that } \Delta x = v\tau \quad (21)$$

then the expression for the modifying sinc function found in the exposure relation of equation 17 becomes

$$\operatorname{sinc} \left[\frac{k\lambda^{1/2} a^{3/2}}{8b} (\cos \gamma_i - \cos \delta_i) \right] \quad (22)$$

where for the symmetrical point Q , $\delta_i = \gamma_i$ and for the other extreme points, the value of Δx is such that $\delta_i \approx \gamma_i$. Therefore, the application of the theory of motion holography indicates that a reasonably bright hologram will be obtained from a moving scene, provided the parameters of the ellipse employed are sufficient to allow the proper value of Δx found in the argument of the sinc function.

EXPERIMENTAL RESULTS OF THE ELLIPTICAL CONFIGURATION

System Identification and Description

During the experimental investigation of the elliptical configuration technique, many elliptical configurations were tested (ref. 4). In each case the linear target velocity along the x direction was approximated by the tangential rim velocity of a wheel of radius r , centered at the symmetrical point $(0, b)$ of the respective elliptical configuration. The reason for this choice and the degree of approximation will be presented later.

Of the systems tested, five different configurations were selected. Figure 6 depicts a general configuration. Radiation from the ruby laser ($\lambda = 694.3$ nm) is made incident on the beamsplitter at focus f_1 by mirror M_1 . The beam is thus split into two beams, the object beam and the reference beam. The object beam is incident on the rim of the target wheel after passing through the diffuser. Radiation then scattered by the wheel's edge is made incident on the hologram, H , at focus f_2 . The diffuser in the path of the object beam provides uniform illumination of the target. The reference beam, reflected from the beamsplitter, passes through a single positive lens plus a

25- μm pinhole, which constitutes a spatial filter. This filter is necessary because of the inhomogeneity of the intensity of the normal-mode pulse from the laser. The spatial filter provides a uniformly intense divergent beam, which is directed onto the film plane at H by mirror M_2 .

Table 1, listing the parameters shown in figure 6, defines the six different system configurations investigated.

Table 1.—Parameters of Systems Investigated

System No.	r (cm)	θ	δ	a (cm)	b (cm)	d (cm)	$\Delta x\lambda/8$ (μm)	$\Delta x\lambda/2$ (μm)
1	20.32	36°	54°	25.4	20.5	15	128	257
2	20.32	70°	20°	53.3	18.5	50	438	875
3	20.32	36°	54°	50.81	41	30	182	364
4	20.32	70°	20°	50.79	17.9	47.5	415	830
5	10.16	36°	54°	50.81	41	30	182	364
6	10.16	36°	54°	50.81	41	30	182	364

r =radius of target wheel

θ =angle between b and a

δ =angle between a and a line perpendicular to y axis (i.e., parallel to x axis)

a =distance from target tangent point to focus f_2 (equal in magnitude to semimajor axis of ellipse)

b =semiminor axis of ellipse

d =distance from origin to either focus

$\Delta x\lambda/8$ =target travel distance for $\lambda/8$ pathlength change of front illumination arm from laser to hologram

$\Delta x\lambda/2$ =target travel distance for $\lambda/2$ pathlength change of front illumination arm from laser to hologram

NOTE: Systems 5 and 6 are identical except for perimeter of wheel (see text).

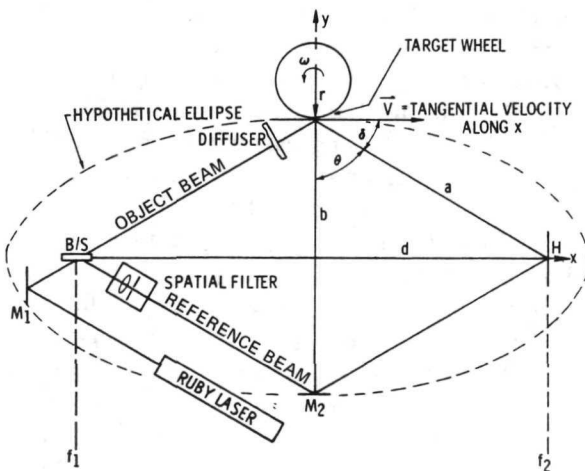


Figure 6.—General configuration of experimental system.

Figure 7 is a photograph of one of the configurations used, in which the location of the wheel is clearly visible.

Figure 8 is a photograph of the ruby laser showing the oscillator and amplifier cavity with the limiting aperture between them. This limiting aperture, when properly aligned, serves two purposes. It produces a marked increase in the coherence length of the radiation, at the expense of intensity, and it provides

a more uniformly intense source. However, the homogeneity of the intensity is still unacceptable without the use of the spatial filter described earlier. Two pulses of different durations were obtained from this source, using the two available mode selections, normal and Q-spoiled. Both of these pulses were detected and measured at the output of the spatial filter. The duration of the normal-mode pulse was 2.5×10^{-4} s, while that of the Q-spoiled pulse was four orders of magnitude shorter, 2.5×10^{-8} s. These values were monitored and stayed essentially constant for each shot. (This constancy was assured by the control of the water coolant temperature and the period of flash-tube firing.)

A photograph of the two different wheels used as the target for systems 1 through 6 is shown in figure

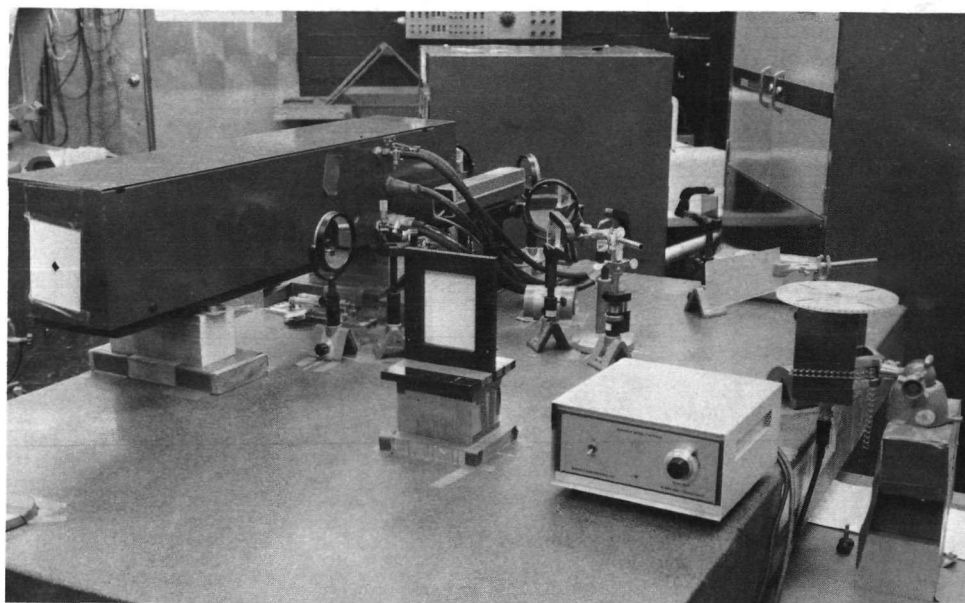


Figure 7.—Photograph of experimental setup.

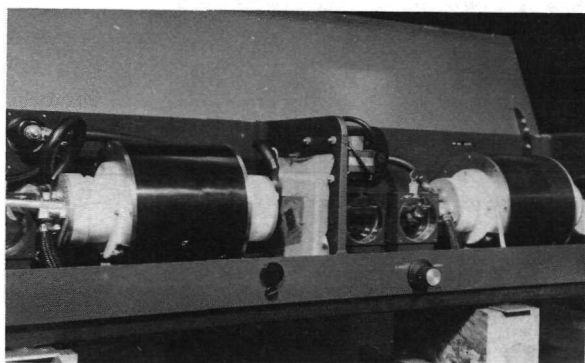


Figure 8.—Photograph of ruby laser system.

9. On the surface of the larger wheel ($r=20.32$ cm), it will be observed that a cross-hatched tape covers its entire periphery. This surface serves two purposes: (1) it provides some definite markings whose resolution can be determined, and (2) it provides a dielectric-type surface as a reflector or scatterer, instead of a metallic surface. A similar coating is found on the smaller wheel ($r=10.16$ cm), except that the white surface is a flat, diffuse white paint

with vertical lines hand-painted on it. This surface serves the same two purposes described above; the reason for the painted surface will be explained later.

Close inspection of figure 9 will show that the tape on the edge of the large wheel appears to have a slight curvature along its height. The height of this taped surface is greater than the thickness of the disk; consequently, the tape on either side of the edge tends to bend back toward the center of the disk. For the painted surface of the small wheel this curvature does not exist. To ascertain the influence of this surface curvature of the tape, refer to figure 10. The angle β is the total angle into which both wheels scatter the radiation originally incident at some point Q . (Actually, this will be a solid angle, not a plane angle, but for a hologram 10.2 by 12.7 cm it is sufficient to consider an angle β in the xy plane for this discussion.) Now the hologram in both cases intercepts an angle $\epsilon < \beta$. Thus, since the radiation is scattered over an angle β greater than the angle ϵ , the curvature of the surface is not important from this point of view. Of course, the magnitude of the angle ϵ will vary, depending on the magnitude of d or a , but ϵ is always less than β . The energy density at point P caused by radiation scattered from Q is probably less

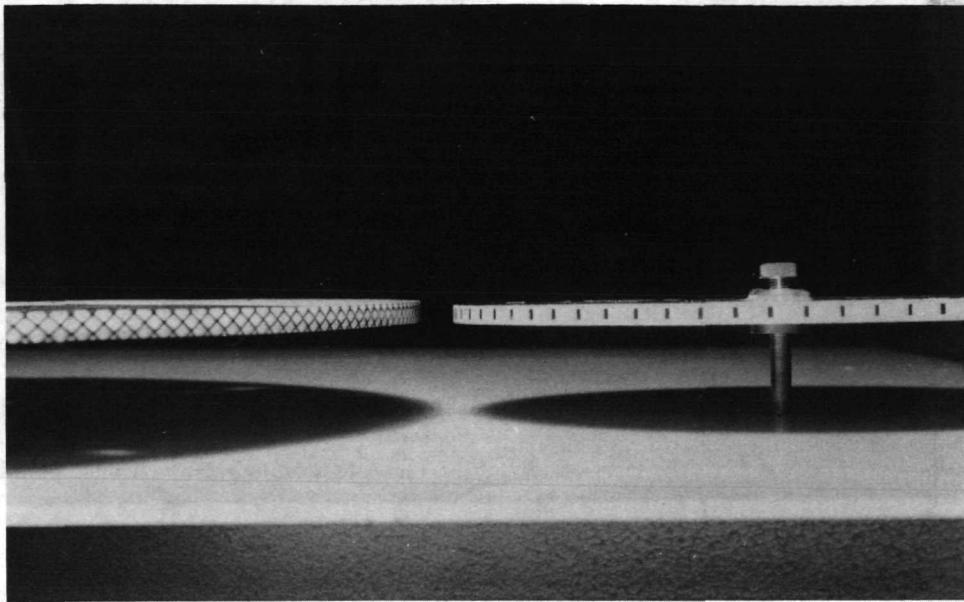


Figure 9.—Edge view of two different target wheels.

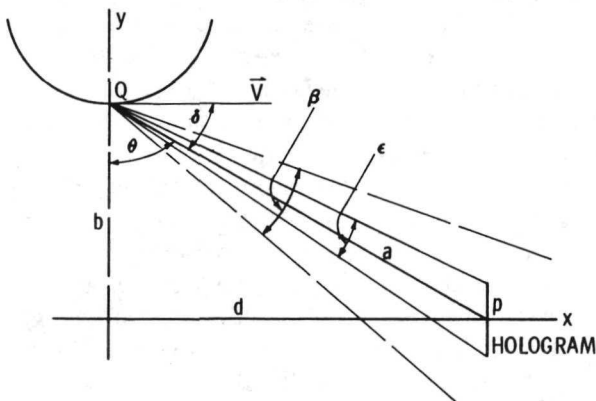


Figure 10.—Diagram of scattered radiation.

for the curved-surface disk, since β for this disk is slightly greater than β for the flat-edged disk. This, however, has little or no effect, since the ratio of the beams at point P is controlled through the use of neutral-density filters.

As mentioned earlier, it was decided for this project to use a continuous-type target to obviate the need for a synchronization circuit and to use a variety of slower velocities to investigate the physics of the elliptical configuration, i.e., the influence of such parameters as d , a , and θ (see table 1). To achieve

fairly high velocities as well as a continuous target, the decision was made to use a rotating disk. For the slower velocities a continuously variable-speed dc motor was used to rotate the target disk. For the highest velocity an ac motor, taken from a router tool, was used. The upper limit on the angular speed of this motor was approximately 417 revolutions per second. The maximum speed of the disk attached to the motor was somewhat lower because of air resistance.

The decision to use a rotating disk was further strengthened by the fact that the theory (as well as experimental evidence, described below) shows that the important parameter for motion holography is the total apparent distance Δx moved by the target during the exposure time, i.e., $\Delta x = v\tau$. Then the velocity *per se* is unimportant; its product with exposure time is the important parameter, other factors being constant.

Comparison of Experimental Results of Systems Studied

The systems numbered 1 through 6, identified in the preceding section, will be compared. Each system has the geometric parameters listed in table 1 and was tested in the following fashion.

To establish a reference for evaluation of the

resolution of a moving target, the first hologram taken for each system was of the stationary target. Ultimately, the measured value, S_i , for the length of resolved image from each hologram of a motion scene was divided by the respective value of S_i for the stationary target.

Equation 10 was used to calculate the value of Δx for each system sufficient to cause a pathlength shift of $\lambda/8$ in the front-surface illumination arm (table 1). From equation 11,

$$v = \frac{\Delta x}{\tau} \quad (23)$$

we were able to ascertain the velocity necessary to cause a $\lambda/8$ shift in this pathlength of each system. Then using

$$\frac{v}{r} = \omega \quad (24)$$

we were able to determine the rotational speed sufficient to allow the desired tangential velocity that was used to approximate a linear velocity. The same procedure was used to determine the proper rotational speed to cause a $\lambda/2$ pathlength shift in the front-surface illumination arm.

Two more holograms, therefore, were acquired in which the target moved the distances $\Delta x_{\lambda/8}$ and $\Delta x_{\lambda/2}$ during the exposure time of 2.5×10^{-4} s. This exposure time was constant for all shots of all systems tested, with two exceptions which will be explained later. From the value of ω determined above, the frequency of the rotating wheel was accurately set through the use of a stroboscopic tachometer calibrated to within 1 percent of the value being measured. This approach was followed systematically for all systems tested.

Thus, using a pulse duration or exposure time which was constant for all systems, we obtained the following three holograms of the target wheel for each system:

1. The stationary target wheel.
2. The target wheel while it moved a distance $\Delta x_{\lambda/8}$, sufficient to shift the pathlength by $\lambda/8$ for that system.
3. The target wheel while it moved a total distance $\Delta x_{\lambda/2}$ for that system.

Actually, holograms were taken with a Δx greater than $\Delta x_{\lambda/2}$ for each system, but we will compare only the holograms mentioned above for systems 1,

3, and 4, since these particular holograms have values of pathlength shift that are common to all of them. We will discuss a total of eight holograms for system 2 to demonstrate the effects of increasing target speed and reduced exposure time. Two holograms each of systems 5 and 6 will be discussed separately. In each case the detail was resolved best at the center of the image and became blurred toward the outer edges. (This effect can be explained by the fact that the geometry of the target satisfies the condition of the ellipse best at the point where the radius of the target wheel is aligned with the y axis of the ellipse. Therefore, any points displaced left and right of this point tend to blur out first, since as the velocity increases they allow greater change in the illuminating pathlength.)

After all of the holograms were developed in a carefully controlled manner, photographs were taken of the image produced by each hologram during reconstruction. (All images were placed in a one-to-one correspondence with their original target, and the target was the same for all systems.) The resultant negatives, whose development was also carefully controlled, were then used to measure the amount of front-surface detail resolved in each case. These measurements were made in the following way.

One of the negatives of the image of the target pattern was viewed and a point was subjectively chosen as the limit of resolved detail. A densitometer was then used to determine the density of this point and to locate the corresponding point of equal density on the opposite side of the image. At these precise positions on the negative, a fine line was etched with a sharp knife. This particular value of density was found on all the other negatives, and a fine line was etched at each such location. The background density of all the holograms and photographs was held as constant as possible so that the only influence on the density would be the reduction in brightness of the image due to the motion of the target during the exposure time.

Each negative was then aligned on the stage of a spectrum line comparator, where a visual display of the resolved pattern, magnified 10 times, was presented on a screen. The position of the fine line etched on the negative was electronically determined by a trace on the cathode-ray tube of the spectrum line comparator. A photograph of this line comparator is shown in figure 11. Using this instrument, the length of the image lying between the fine lines was

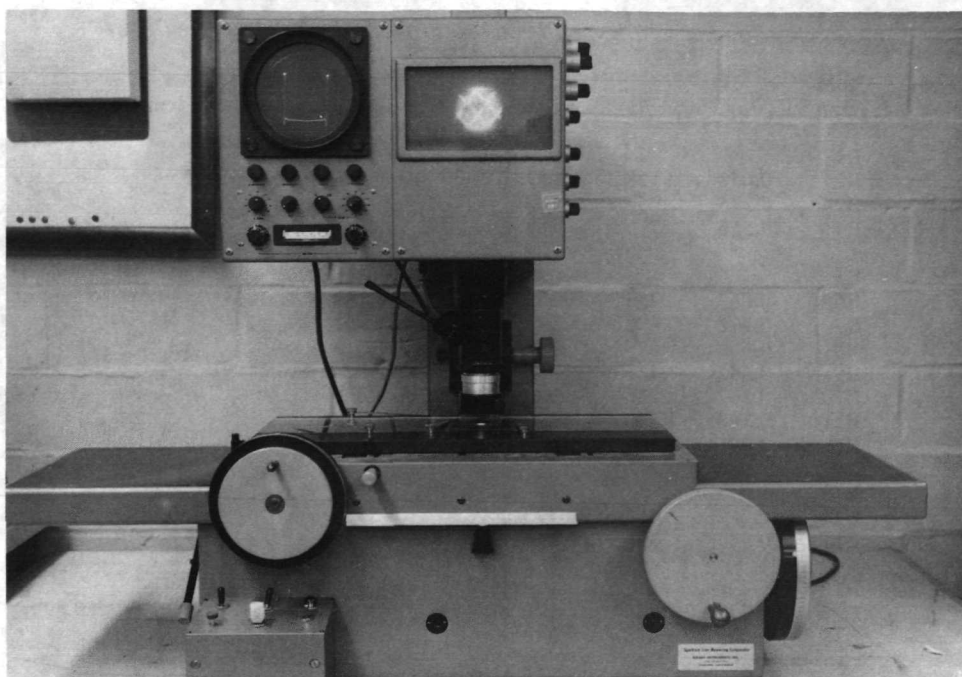


Figure 11.—Spectrum line comparator.

measured several times and an average value taken. We thereby obtained an average quantity, S_i , for the negative corresponding to each hologram of the specific system tested.

Since the stationary-target hologram of each system is the reference against which the motion holograms for that system are compared, we define another quantity, S_{oi} , for each hologram:

$$\bar{S}_{oi} = \frac{\bar{S}_i \text{ for motion case}}{\bar{S}_i \text{ for stationary case}} \quad (25)$$

This relationship is needed because the length of the image resolved is dependent on the length of the image illuminated, and this illuminated length was unavoidably different for each system tested. S_{oi} thus denotes the amount of the original stationary image resolved by each successive motion hologram of a given system. All of the values of S_{oi} are listed in table 2.

From the theory of the elliptical holographic system we know that the total allowable travel, Δx , is a function of the system parameters, a , b , θ , and d . That is, for a given specific value of Δx the effect of this motion in terms of the degradation of image

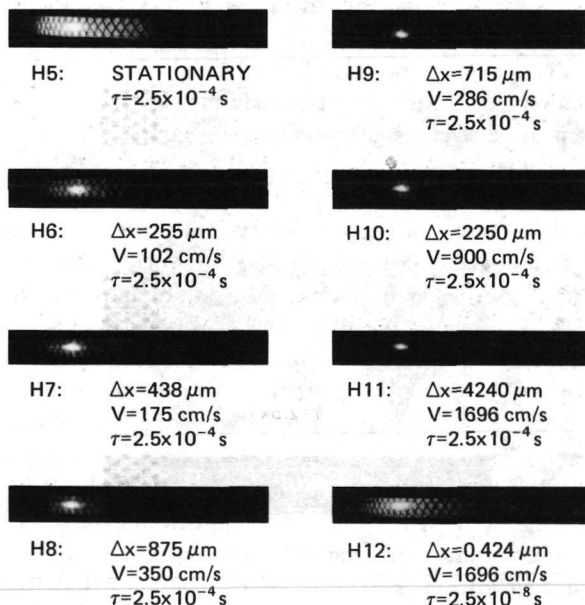
quality will be less for a large ellipse than for a small ellipse, other factors being constant. Shortly we will present experimental evidence to support this theoretical contention.

Figure 12 presents eight photographs showing the images resolved for eight successive holograms taken with system number 2. Photograph H5 is of the stationary target. Photographs H6 through H11 represent successively larger motions (i.e., values of Δx), all with the same exposure time (2.5×10^{-4} s). These photographs show a marked decrease in the target area resolved with increased motion. Photograph H12 is a Q-spoiled exposure ($\tau = 2.5 \times 10^{-8}$ s) made with the target moving at the same speed as for photograph H11. Because of the difference (4 orders of magnitude) in the exposure time, the resolved detail is strikingly greater. Therefore it is obvious that the area resolved is a function of exposure time, other factors being constant.

It is evident from the data in table 2 that the resolution is also a function of the elliptical system configuration. For example, the value of S_{oi} for photograph H6 is approximately 1.5 times that for H3. Since the only parameters that differ for these two cases are those defining the different systems, we

Table 2.—Summary of Experimental Results and Parameters (see fig. 6)

System No.	Photo-graph	S_{oi}	Δx (μm)	v (cm/s)	θ	δ	d (cm)	a (cm)	$a^{1/2}/\cos \theta$
1	H1	1			36°	54°	15	25.4	6.22
	H2	0.658	128	52					
	H3	0.595	257	102					
	H4	0.516	715	286					
2	H5	1			70°	20°	50	53.3	21.35
	H6	0.867	255	102					
	H7	0.776	438	175					
	H8	0.609	875	350					
	H9	0.652	715	286					
	H10	0.332	2250	900					
	H11	0.168	4240	1696					
3	H12	0.991	0.424	1696	36°	54°	30	50.81	8.81
	H13	1							
	H14	0.752	182	73					
4	H15	0.537	364	146	70°	20°	47.5	50.79	20.89
	H16	1							
	H17	0.776	438	174					
5	H18	0.609	875	348	36°	54°	30	50.81	8.81
	H19	1							
6	H20	0.667	4.4	17546	36°	54°	30	50.81	8.81
	H21	1							
6	H22	0.651	4.4	1.75	36°	54°	30	50.81	8.81
	H22	0.651	4.4	1.75					

Figure 12.—Photographic results for largest- d system (no. 2).

must conclude that the differences observed in the relative average length of the resolved image must be due to some function of the elliptical system itself, i.e., in the configuration of the holographic system used.

A second such comparison can be made between photographs H4 and H9. As shown in table 2, the total travel, Δx , is the same for both systems in spite of the difference in magnitude of the relative average value, S_{oi} , for each. We must again conclude that this observed difference is due solely to system dependence. Furthermore, it is apparent that the larger the system is, i.e., the larger the values of d , a , and θ , the larger the relative length, S_{oi} .

As further evidence of this last statement, consider the results for a constant pathlength shift for three successively larger ellipses. For H2, where $d=15$ cm, the magnitude of the relative average value of the resolved image is $S_{oi}=0.658$. For H14 ($d=30$ cm), $S_{oi}=0.752$. Finally, for H7 ($d=50$ cm), $S_{oi}=0.776$. We note from table 2 that, while the range of the values of d for these three systems is from 15 to 50 cm, the range of total travel Δx sufficient to shift

the optical pathlength in each system by a constant amount, $\lambda/8$, is from 128 to 438 μm . Thus, the larger ellipse allows the scene to travel farther during the exposure time before the total optical pathlength changes by $\lambda/8$. In spite of this increase in the total allowed travel, the ability of the larger system to resolve detail from the target, as indicated by the S_{oi} value, increases or at least stays approximately constant for the successively larger ellipses.

If we consider the results of a $\lambda/2$ pathlength change for these same systems, we see essentially the same result as noted above. The ability of the system to resolve detail from the moving scene, as indicated by the value of S_{oi} , increases or at least stays approximately constant for the successively larger ellipses. This occurs in spite of the fact that the total travel, $\Delta x_{\lambda/2}$, necessary to cause a $\lambda/2$ pathlength change is necessarily larger for the larger ellipses.

Having established that the area resolved is indeed a function of the system, we ask the question: What is the form of this function? To answer this question, we will compare two systems having identical values of the angle θ but different values of the length a . We will also compare two systems having approximately equal values of the length a but different values of the angle θ .

For the case of two different systems having the same value of the angle θ but different values of a , consider systems 1 and 3, where $\theta=36^\circ$. Comparing the values of Δx and S_{oi} for system 1 with those for system 3, we see that the increase in total travel, Δx , for a constant value of pathlength change is caused primarily by the difference in the values of the parameters d and a for the two systems.

Likewise, for two systems with $a \approx 50.8$ cm but different values of the angle θ , compare the values of Δx and S_{oi} for system 3 with those for system 4. Note that now the increase in Δx is due primarily to the difference in the value of the parameters d and θ for these systems. Therefore, the functional dependence must be of the form $f(d, a, \theta)$.

Recalling equation 10 for Δx , we have

$$\Delta x = \left(\frac{\Delta L}{2}\right)^{1/2} \frac{a^{3/2}}{b} \quad (26)$$

From the preceeding section we know that

$$\Delta L = 2\Delta a \quad (27)$$

and

$$\frac{a}{b} = \sec \theta = \frac{1}{\cos \theta} \quad (28)$$

Equation 26 may then be written as

$$\Delta x = (\Delta a)^{1/2} \frac{a^{1/2}}{\cos \theta} \quad (29)$$

or

$$\Delta x \propto \frac{a^{1/2}}{\cos \theta} \quad (30)$$

where θ is the angle between b and a of our ellipse. Thus we see that the analytical equation (eq. 10) derived for our hypothetical ellipse has the functional form that satisfies the results observed experimentally. The values of this function, shown in equation 30, are listed in table 2 for all systems tested. Note that the values of this function are larger for larger values of the parameter d . Figure 13 shows the photographs made with system number 1, which was the smallest system tested. Compare these results with those shown in figure 12 for system number 2, the largest system tested.

Figure 14 depicts the relationship of the parameters a and θ to the angle ϵ and illustrates another effect of the variation of the sinc function. From this figure we can write

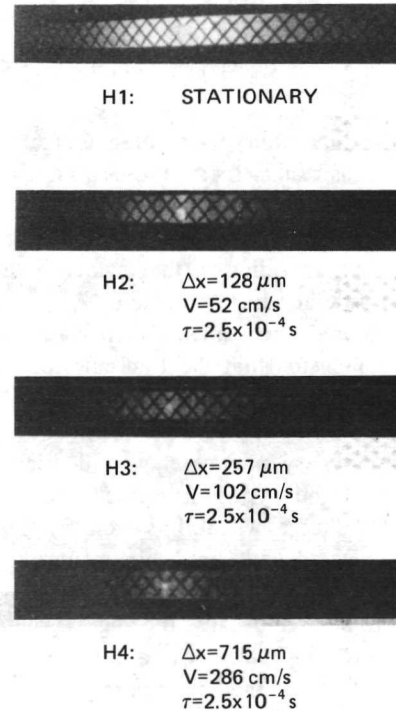
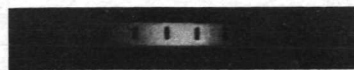


Figure 13.—Photographic results for smallest-d system (no. 1).



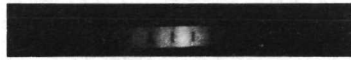
H19: STATIONARY



H20: $\Delta x = 4.4 \mu\text{m}$
 $V = 1.7546 \times 10^4 \text{ cm/s}$
 $\tau = 2.5 \times 10^{-8} \text{ s}$



H21: STATIONARY



H22: $\Delta x = 4.4 \mu\text{m}$
 $V = 1.76 \text{ cm/s}$
 $\tau = 2.5 \times 10^{-4} \text{ s}$

Figure 15.—Photographic results for systems 5 and 6.

Thus, even using a safety factor of one order of magnitude, our limiting upper velocity would be nearly 10^6 cm/s , or 10 km/s .

Therefore, with a system having parameters identical to those of system number 2 and using a Q-spoiled pulse of $2.5 \times 10^{-8} \text{ s}$ duration, a hologram could be made of a target moving at a velocity of 9 km/s , with results at least as good as the results shown by H10 of figure 11 and probably as good as H8, in view of the safety factor allowed above.

SUMMARY AND CONCLUSIONS

A holographic system of unique geometry has been developed that allows the resolution of front-surface detail from objects moving at high velocity. The highest velocity for which front-surface detail was experimentally resolved was 175.46 m/s . From

the results obtained, however, it has been calculated that front-surface detail could be resolved for scenes with very high velocities ($>9 \text{ km/s}$). Although these very-high-velocity cases have not yet been demonstrated, it is reasonable to expect that they could be if a sufficiently fast-moving continuous target were available. (Prior to this work, the highest object velocity from which front-surface detail was obtained was a few centimeters per second.)

For this experiment, the object velocity was the tangential velocity of the edge of a rotating disk. The degree to which this approximates linear velocity is indicated by the fact that for the largest total movement of the target ($\Delta x = 4240 \mu\text{m}$) the angle of rotation was only 1.2° .

From the experimental results of this investigation, we may conclude the following:

1. The total target motion during exposure, $\Delta x = v\tau$, the product of velocity and exposure time, is the most important parameter for motion holography.
2. The degradation of the cosine fringes due to scene motion during exposure causes the scene detail to blur out. This blurring or washout occurs symmetrically about that point of the target that is tangent to the surface of the hypothetical ellipse. (This was also shown theoretically in terms of the sinc function.)
3. The allowed motion or stopping ability of the system is a function of the elliptical geometry that defines the holographic system. The functional form of this system dependence is proportional to $a^{1/2}/\cos \theta$. (The value of this function was tabulated for all systems tested.)
4. The ability to allow larger total motion, Δx , for a given optical pathlength change during a constant exposure time increases with the size of the holographic system being used.

REFERENCES

1. Kurtz, R. L.; and Loh, H. Y.: A Holographic Technique for Recording a Hypervelocity Projectile with Front Surface Resolution, *J. Applied Optics*, Vol. 9, 1970.
2. Neumann, Don B.: Holography of Moving Scenes, *J. Opt. Soc. Am.*, Vol 58, 1968.
3. Neumann, Don B.: The Effect of Scene Motion on Holography, Ph.D. dissertation, Ohio State University, 1967.
4. Kurtz, R. L.: A Holographic System that Records Front Surface Detail of a Scene Moving at High Velocity, Ph.D. dissertation, Virginia Polytechnic Institute & State University, 1971.

Page Intentionally Left Blank

Light Scattering in Photographic Materials for Holography

Howard M. Smith

Research Laboratories

Eastman Kodak Company

A simple system for measuring the scattered flux from fine-grained photographic emulsions is described. With this system the Wiener spectrum of sample emulsions is measured for samples varying in grain size, thickness, silver-to-gel ratio, development time, and transmittance. It is shown that the measured results agree well with what is to be expected on theoretical grounds and that the functional form of the scattered light is well described by an overlapping circular grain model of the emulsion.

The measurement of light scattering from photographic materials dates back many years, primarily because it is a means for quantitatively characterizing the granularity of an emulsion (refs. 1 and 2). For photographic materials used in modern coherent optical systems, however, it is not the granularity itself that is of primary interest, but the light scattered by the developed silver grains. This is because in a coherent optical system the emulsion is generally not in an image plane but in the transform plane. Hence the signal-to-noise ratio in the image plane will be a function of the light scattered back at the transform plane. Recently, therefore, work has been done on the measurement of light scattered by a photographic film in a coherent optical system (refs. 3 through 11). In this paper I shall describe the measurement of the noise spectra of a few commercial silver halide photographic materials. In addition, the noise spectrum in the frequency range 200 to 1500 cycles/mm has been measured as a function of grain size, thickness, silver-to-gelatin ratio, and development time. Measurements for one of the emulsions are in excellent agreement with the results predicted by theory using an overlapping circular grain model for the emulsion, in contrast to the results of other workers (refs. 8 and 11), who have found close agreement with theory using the checkerboard model.

The scattered flux spectrum is normally measured by placing a detector at the focal plane of a lens placed adjacent to the illuminated sample. With this arrangement, the two-dimensional bandwidth of the measurement is determined by the aperture of the detector, and the spatial frequency by the off-axis position. In an extremely fine-grained material, very little flux is scattered into any reasonably small (two-dimensional) bandwidth. Noise tending to obscure the measurement comes mainly from stray light scattered from the optical components of the system. This scattered light adds directly to the light being measured, and therefore attempts to improve the signal-to-noise ratio of the measurement by increasing the spatial bandwidth of the detector are futile. Sensitive detection is then required because of the very low signal.

We have used a much simpler arrangement with good success. The setup is shown schematically in figure 1. The beam of collimated light from the laser *L* is expanded by the two telescopes *T* to a diameter of about 8 mm. The aperture *A* eliminates flare light but does not intercept the main beam. The inconel filters on the filter wheel *F* are used only for the measurement of the zero-order, specularly transmitted light. The sample is mounted at *S* and is illuminated normally from the base side. The lens *E*

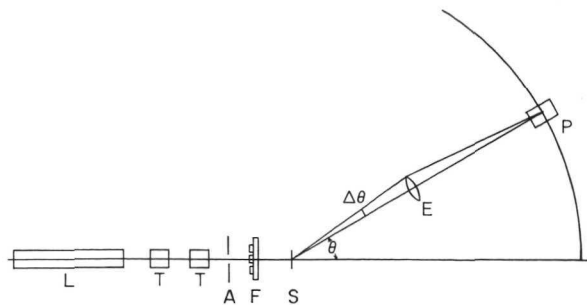


Figure 1.—Arrangement for measurement of scattered flux.

and photomultiplier P are mounted on an optical bench which pivots about the center of the illuminated area of the sample. The lens is located a distance $2f$ from the sample and the photomultiplier another $2f$ behind the lens, where f is the focal length of the lens E . In this way the illuminated spot on the sample is imaged 1:1 onto the photomultiplier tube (pmt). Any stray light in the system, scattered from any of the optical components, is generally *not* imaged by the lens onto the pmt. Hence this stray light irradiance at the pmt is very much lower than that of the signal light. Typically, sample-in to sample-out current ratios are on the order of 100:1 or 1000:1, without any elaborate precautions for reducing stray light. A simple ammeter records the signal.

The two-dimensional bandwidth of the system is determined by the size of the collecting lens, as indicated in figure 2. If the scattering angle θ is measured in a horizontal plane, the relationship between θ and the spatial frequency ν_h of the transmittance variations of the sample is simply

$$\nu_h = \sin \theta / \lambda \quad (1)$$

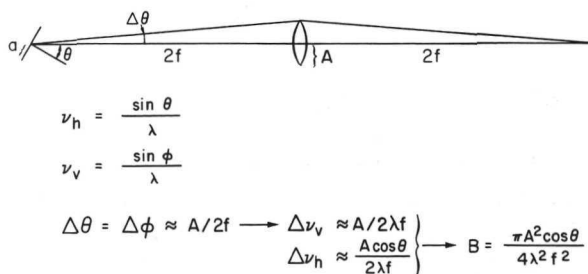


Figure 2.—Determination of system two-dimensional bandwidth.

For scattering into a vertical plane at an angle φ we have the corresponding relationship

$$\nu_v = \sin \varphi / \lambda \quad (2)$$

The lens of radius A collects light scattered horizontally into a range of angles $\theta \pm \Delta\theta$ and vertically into $\varphi \pm \Delta\varphi$, where

$$\Delta\theta \text{ or } \Delta\varphi \approx A/2f \quad (3)$$

In our experiment we measured the light scattered at a frequency $\nu = (\sin \theta)/\lambda$ at $\varphi=0$, i.e., in the horizontal plane. The two-dimensional bandwidth at the lens is thus in the shape of an ellipse with a semimajor axis

$$\Delta\nu_v = \frac{\sin(\Delta\varphi)}{\lambda} \approx \frac{A}{2\lambda f} \quad (4)$$

and a semiminor axis

$$\Delta\nu_h = \frac{\cos \theta \sin \Delta\theta}{\lambda} \approx \frac{A \cos \theta}{2\lambda f} \quad (5)$$

The area of the ellipse measured in frequency space $\pi\Delta\nu_v\Delta\nu_h$ is the two-dimensional bandwidth B :

$$B = \frac{\pi A^2 \cos \theta}{4\lambda^2 f^2} \quad (6)$$

Our lens has a radius of 9 mm and a focal length of 19 cm. The wavelength of the light is 632.8 nm, so that $B = 4.4 \times 10^3 \cos \theta$.

The data are presented in terms of the ratio of the scattered flux per unit two-dimensional bandwidth to the flux incident on the sample. The ratio is called the scattering ratio and is designated S . The units of S are $(\ell/\text{mm})^{-2}$. The materials are exposed through a step tablet by radiation passed through a Kodak® Safelight Filter, No. 1A. Measurements are made by placing the exposed and processed sample in the system and measuring the relative flux scattered into the bandwidth B as a function of the angle θ (frequency ν), the relative specularly transmitted flux, and the transmittance.

Figure 3 shows typical noise spectra for Kodak Spectroscopic Plate, Type 649F, processed for 5 minutes in Kodak HRP Developer. It can be seen from these curves that the scattering ratio S increases for increasing amplitude transmittance up to a value of $T_a \approx 0.6$, and then decreases with increasing transmittance. (Included for reference is a curve of S vs ν for a glass plate with no emulsion, showing that

except at very low frequencies the effect of the glass is negligible.) Figure 4 shows how S varies as a function of transmittance at 1000 ℓ/mm . The curves for other frequencies are the same shape and differ

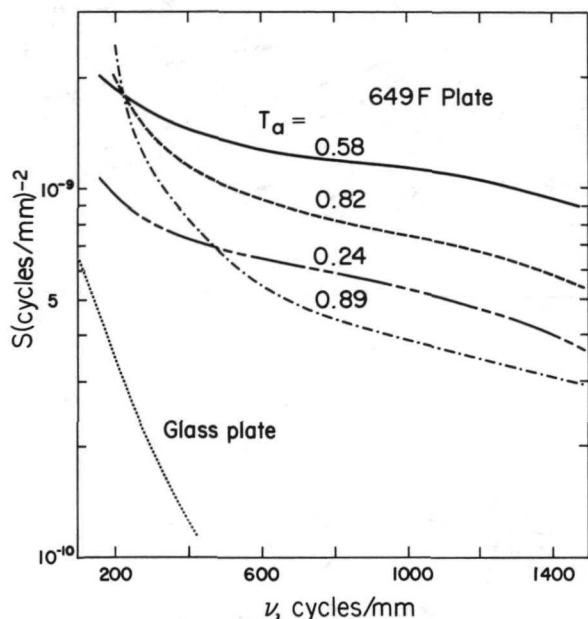


Figure 3.—Typical noise spectra for Kodak Spectroscopic Plate, Type 649F, at different values of amplitude transmittance.

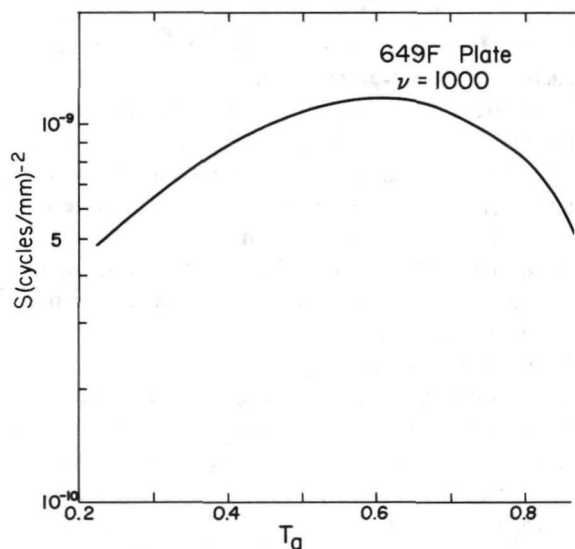


Figure 4.—Scattering ratio as a function of amplitude transmittance.

only in height. The maximum scattering occurs in the vicinity of $T_a=0.6$, and this has important implications for signal-to-noise ratio of hologram images. Figure 5 shows scattering as a function of spatial frequency for Kodak Spectroscopic Film, Type 649F, the 649F plate, and Kodak Extended Red Recording Film (Estar AH base), SO 382, all at the same value of amplitude transmittance, about 0.6. Note that the values for the films are considerably higher than those for the plates. This is not because of the emulsion characteristics, as we first thought, but because the film base material scatters significantly more than the glass plate. Figure 6 shows curves for scattering from acetate and polyester film base materials compared with glass. This difference, of more than an order of magnitude, made the interpretation of our thickness and silver-to-gel experiments rather difficult, and hence the results are not as clear-cut as we would have liked.

We were, however, able to obtain meaningful results of measurements for various development times for Kodak Spectroscopic Plates, Type 649F. These results are shown in figure 7 for development in Kodak HRP Developer 1:4, for 3, 5, 7, and 10 minutes, all exposed so that the average amplitude transmittance is 0.6. As expected, the amount of light scattering increases with increasing development time. The increase is fairly significant, being more than a factor of two between the 3-minute and 10-minute

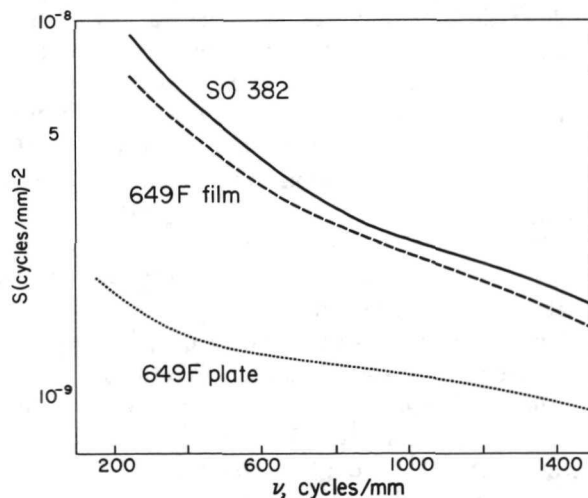


Figure 5.—Scattering ratio as a function of spatial frequency for $T_a \approx 0.6$.

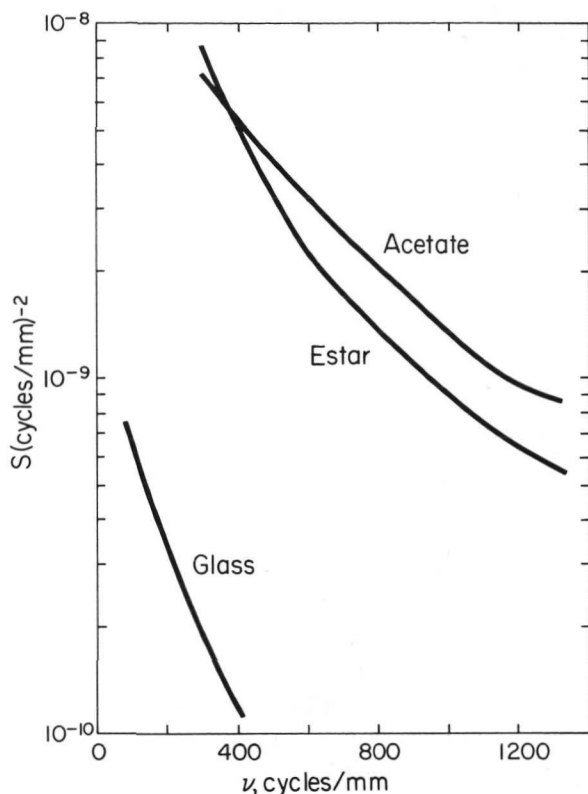


Figure 6.—Scattering from film materials compared with glass.

times. This spread was decreased slightly for higher values of amplitude transmittance and increased slightly for lower amplitude transmittance. Since increasing the development time increases the diffraction efficiency of holograms, as well as the scattered light, one has to be very careful when trying to optimize the signal-to-noise ratio of a holographic image.

For example, for this emulsion-developer combination, we have measured only a 25-percent increase in diffraction efficiency between 3-minute and 10-minute development times, so that the signal-to-noise ratio for these holograms will actually decrease with increasing development times (for constant amplitude transmittance). With development in Kodak Developer D-19, however, the increase of maximum reconstruction ratio with development time is much greater and optimum signal-to-noise ratio might occur at an extended development time. The best development time for optimum signal-to-

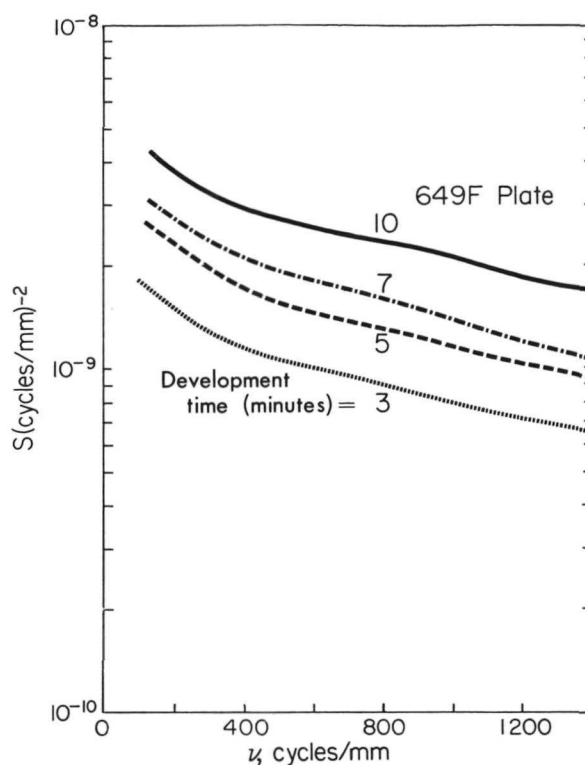


Figure 7.—Scattering for various development times.

noise ratio has to be determined experimentally for each emulsion-developer combination.

Figure 8 shows scattering for several experimental holographic emulsions of different grain size. The emulsions are coated on an acetate support material, and therefore a large proportion of the scattering is from the support. There is nevertheless an obvious increase in the amount of light scattered as the grain size increases. The curves are for amplitude transmittance $T_a=0.6$ and development for 5 minutes in Kodak Developer D-19.

Of potentially more interest are the curves shown in figures 9 and 10 for scattering as a function of thickness and silver-to-gelatin ratio of 50-nm-grain-size emulsions. The curves are all substantially the same, indicating no dependence of scattering or thickness or silver-to-gel. However, the following comments are in order. As mentioned earlier, most of the scattering by very fine-grained emulsions on a flexible support is due to the support material itself.

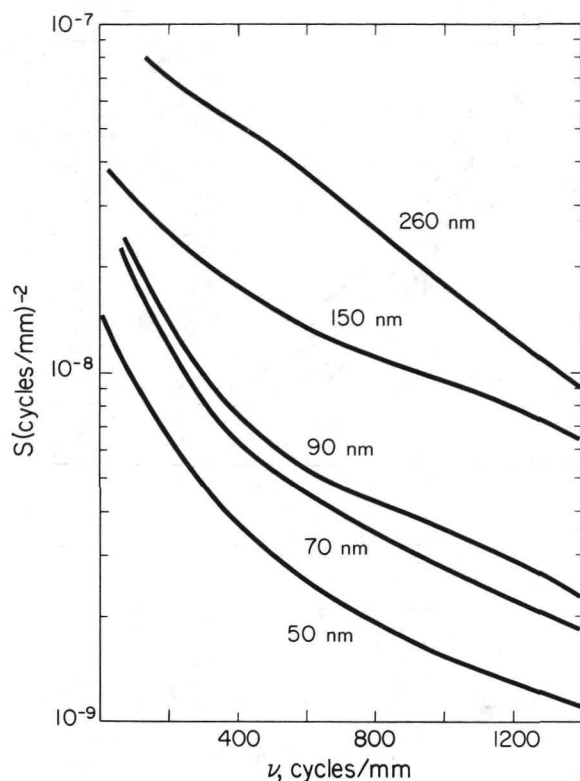


Figure 8.—Scattering for various raw emulsion grain sizes.

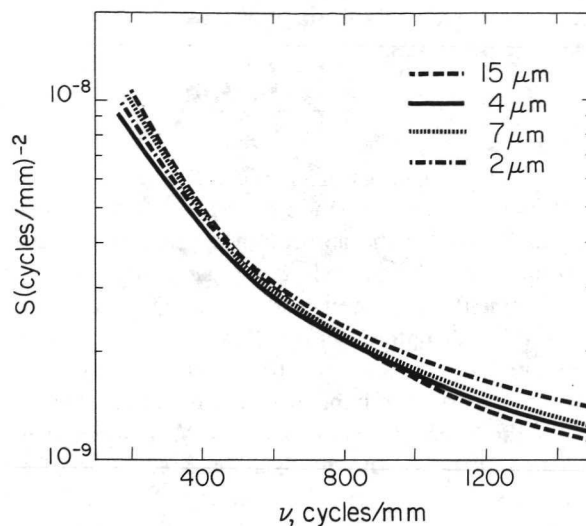


Figure 9.—Scattering for various emulsion thicknesses.

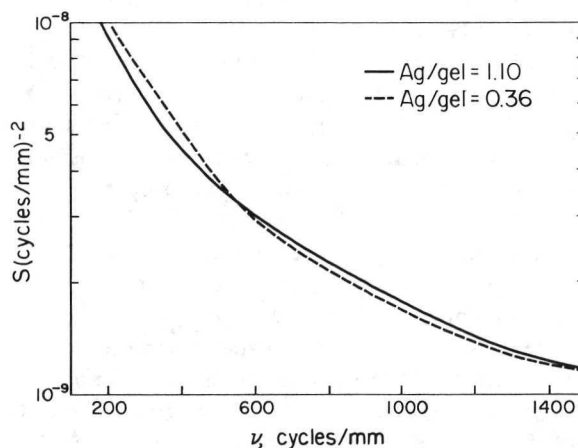


Figure 10.—Scattering for different silver-to-gel ratios.

In the vicinity of 1000 ℓ/mm the scattering ratio is approximately $1.7 \times 10^{-9} (\ell/\text{mm})^{-2}$, which is the same level as indicated in figures 9 and 10. Hence, virtually all of the scattered light in these figures is due to the support, and any dependence of scattering on thickness or silver-to-gel ratio is completely obscured. This conclusion is substantiated by the fact that curves of S vs T_a should look like that of figure 4 but instead are as shown in figure 11. Here the effect of decreasing transmittance is simply to decrease the amount of light scattered by the support. There is, however, a small contribution due to the silver grains, as indicated by the fact that the falloff of scattering with transmittance is not as fast as it should be according to a simple multiplication of a constant scattering ratio S by the transmittance.

Some conclusions can be drawn from these results, however. We can at least say that, if there is a dependence of S on thickness, it is very slight. Hartel (ref. 12) has derived an expression for $Q_k(x)$, the

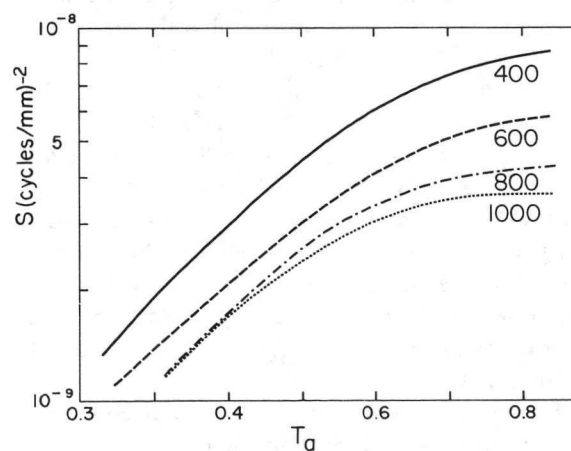


Figure 11.—Scattering for various values of spatial frequency.

quantity of light at a depth x of the emulsion due to k th-order scattering:

$$Q_k(x) \frac{(NFx + \mu x)^k}{k!} e^{-(NFx + \mu x)} \quad (7)$$

where N is the number of spherical silver particles per unit volume, F is the single-particle scattering cross section, and μ is the absorption coefficient for the concentration considered. Now, since all of our measurements have been made on samples with the same value of optical density D , we should have the total number of irradiated silver particles constant at each thickness. The number of irradiated particles is just N times the irradiated volume of NAx , where A is the area of the sample that is illuminated. Hence, for NAx to remain constant we must have $N \propto 1/x$. Since F is a constant independent of the thickness, the quantity NFx is independent of thickness.

A similar argument can be made for the μx term. The quantity μ is equal to Kc , where K is the computed absorption coefficient for silver and c is the volume of silver per unit volume of emulsion. Again, for constant density, the volume of silver within the irradiated volume must remain constant, while the irradiated volume is proportional to x . Hence $c \propto 1/x$ and $\mu x = Kcx$ is a constant. Therefore, according to the multiple scattering theory of Hartel, the light quantities $Q_k(x)$ are independent of thickness if the optical density is held constant.

The coating ratio of silver halide to gelatin should have no effect on scattering, since the total developed silver is what contributes to the scattering. There is one effect to be considered, however. For constant developed optical density, the amount of silver halide removed during fixing increases with increasing silver-to-gelatin ratio. There is evidence that the removal of the silver halide grains leaves holes in the gelatin, and these then contribute to the scattered light. This effect is shown in figure 12, where we have plotted scattering curves for four films of different thickness that have been developed and fixed but not exposed. Here we see a definite dependence on thickness, which we attribute to the voids left in the emulsion when the silver halide is fixed out. This effect may give rise to some dependence of scattering on silver-to-gelatin ratio, although we were unable to measure it as shown in figure 10.

Turning now to a theory for the observed scattering, we note that there are a number of models of the photographic emulsion from which a theoretical noise

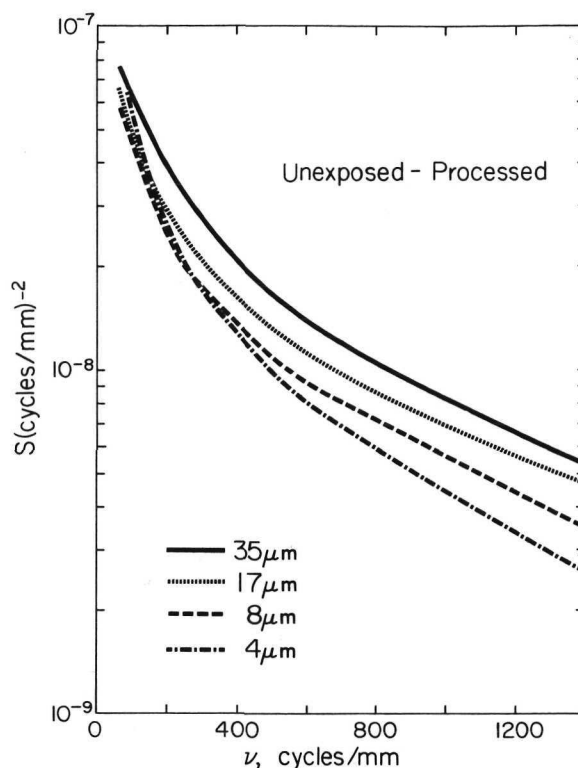


Figure 12.—Scattering for various film thicknesses (processed without being exposed).

power spectrum may be computed. One of the most common and simplest to use is the checkerboard model. Vilkomerson used this model, as did Goodman. The problem with this model is that it predicts a maximum in the scattering at a transmittance $T_a = 0.5$, which is not verified experimentally. We have found that very good agreement between experiment and theory can be achieved by using an overlapping circular grain model for the emulsion (refs. 13 and 14). In this model the grains are assumed opaque and circular with their centers randomly distributed over the transparency area. Goodman (ref. 6) has shown that the normalized average noise irradiance $G(T_a)$ is given by

$$G(T_a) = C \int_0^1 \left[T_a^{2-F(\xi)} - T_a^2 \right] \xi d\xi \quad (8)$$

where

$$F(\xi) = \frac{2}{\pi} \cos^{-1} \xi - \xi \sqrt{1 - \xi^2} \quad (9)$$

and C is a constant. Figure 13 shows a plot of this function along with points measured experimentally for Kodak Spectroscopic Plate, Type 649F, at an angle corresponding to a spatial frequency of 500 ℓ/mm . It is seen that the agreement is fairly good, especially with regard to the position of the peak at $T_a=0.6$. This is really a very fortuitous result in that the model in no way accounts for multiple scattering and emulsion thickness (the overlapping circular grain model is strictly two-dimensional). Goodman pointed out that this model is probably oversimplified since it does not take into consideration such basic factors as the variable size,

shape, and transmittance of the individual grains and the thickness of the emulsion. However, in spite of the simplicity of the model, our results show that it works exceedingly well, even for an emulsion as thick as Kodak Spectroscopic Plate, Type 649F (about 15 μm).

REFERENCES

1. Jones, R. Clark: New Method of Describing and Measuring the Granularity of Photographic Materials, *J. Opt. Soc. Am.*, Vol. 45, 1955, p. 799.
2. Thiry, H.: Power Spectrum of Granularity as Determined by Diffraction, *J. Phot. Sci.*, Vol. 11, 1963, p. 69.
3. Leith, E. N.: Photographic Film as an Element of a Coherent Optical System, *Phot. Sci. Eng.*, Vol. 6, 1962, p. 75.
4. Helstrom, C. W.: Image Luminance and Ray Tracing in Holography, *J. Opt. Soc. Am.*, Vol. 56, 1966, p. 433.
5. Burckhardt, C. B.: Storage Capacity of an Optically Formed Spatial Filter for Character Recognition, *Appl. Opt.*, Vol. 6, 1967, p. 1359.
6. Goodman, J. W.: Film Grain Noise in Wavefront Reconstruction Imaging, *J. Opt. Soc. Am.*, Vol. 57, 1967, p. 493.
7. Kozma, A.: Effects of Film Grain Noise in Holography, *J. Opt. Soc. Am.*, Vol. 58, 1968, p. 436.
8. Lee, W. H.; and Greer, M. A.: Noise Characteristics of Photographic Emulsions Used for Holography, *J. Opt. Soc. Am.*, Vol. 61, 1971, p. 402.
9. Brandt, G. B.: Coherent Optical Power Spectra of Photographic Materials, *Appl. Opt.*, Vol. 9, 1970, p. 1424.
10. Biedermann, K.: The Scattered Flux Spectrum of Photographic Materials for Holography, *Optik*, Vol. 31, 1970, p. 1.
11. Vilkomerson, D. H. R.: Measurements of the Noise Spectral Power Density of Photosensitive Materials at High Spatial Frequencies, *Appl. Opt.*, Vol. 9, 1970, p. 2080.
12. Hartel, W.: Zur Theorie der Lichtstreuung durch Trübe Schichten besonders Trübgelaser, *Licht*, Vol. 10, 1940, p. 141.
13. O'Neill, E., L.: *Introduction to Statistical Optics*, Addison-Wesley, Reading, Mass., 1963, p. 113.
14. Picinbono, B.: Modèle à Statistique Suggéré par la Distribution de Grains d'Argent dans les Films Photographiques, *Compt. Rend.*, Vol. 240, 1955, p. 2206.

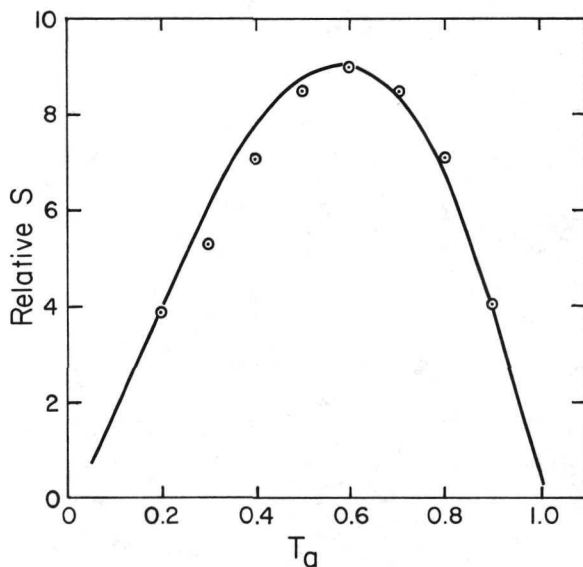


Figure 13.—Normalized average noise irradiance function compared with experimental points for Kodak Spectroscopic Plate, Type 649F.

Page Intentionally Left Blank

The Quantitative Measurement of Small Phase Differences in Holographically Reconstructed Optical Fields*

G. S. Ballard

*Department of Electronics and Instrumentation
University of Arkansas Graduate Institute of Technology*

The final design and performance of a technique for the measurement of small phase differences within holographically reconstructed optical fields are described.

The basis of the technique is a method of dual-exposure holographic interferometry which utilizes a separate reference beam for each of the two hologram exposures. This method, preliminarily described at the conference on Holographic Instrumental Applications at the Ames Research Center in January 1970, makes it possible to vary continuously the relative phase of the two beams reconstructed from the double-exposed hologram.

Two detectors, placed within the reconstructed field, produce periodic signals which are introduced into an electronic phasemeter, giving a measurement of the relative optical phase difference between the points at which the detectors are located. The precision and stability of the technique are demonstrated, the standard deviation of 60 phase measurements taken over a 30-minute period being 1.4° out of 360° per wavelength, using light with a wavelength of 632.8 nm.

With the addition of several components, a typical off-axis hologram arrangement can be modified into a three-beam system which can be used to study interference fields. The method can be described as "dual-exposure holographic interferometry with separate reference beams" (ref. 1). The resulting system combines many of the advantages of both the real-time and double-exposure methods, while eliminating many of their respective disadvantages. Transparent and diffuse subjects can be studied. Precise optical components are not required. Transient phenomena can be studied. Finite and infinite fringe interferograms are easily obtained from a single hologram, and the interference fringes can be adjusted to show the desired features of the test scene to the best advantage *after* the hologram has been

recorded. For transparent subjects, schlieren photographs and shadowgraphs can be obtained if desired, and the interference field can be observed in real time.

One disadvantage of all interferometric methods is that subfringe systems are difficult to interpret. A number of methods have been proposed to increase the sensitivity of interferometric measurements. Utilizing the separate-reference-beam technique, a method has been devised with which it is possible to measure the small phase variations within an optical field. It has been demonstrated that the relative phase of any point within the field can be measured with a standard deviation of approximately one degree, and this can be accomplished whether the field exists in real time or is holographically stored.

In this presentation the separate-reference-beam system will be briefly described and some of its capabilities will be discussed. The specific application of this technique to the measurement of subfringe

*This work was supported by Research Grant NGL 04-001-007 from the National Aeronautics and Space Administration.

systems will be described and the results of actual phase measurements will be presented.

A typical arrangement for recording a double-exposure hologram with separate reference beams is illustrated in figure 1. Essentially this is a normal off-axis hologram recording arrangement to which an extra beamsplitter has been added to provide three beams instead of two. With this arrangement, a hologram of R_{Obj} could be recorded using either R_1 or R_2 as the reference beam.

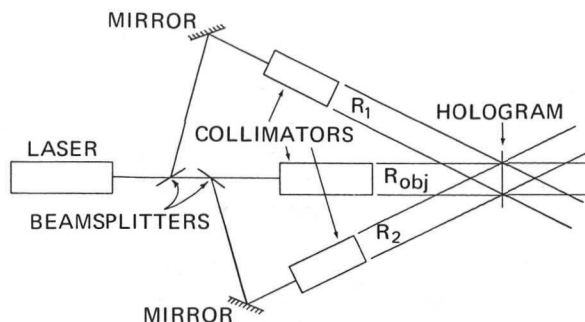


Figure 1.—Recording a double-exposure hologram with separate reference beams.

To record a double-exposure hologram, the test object of interest would be placed in the center beam, R_{Obj} . A hologram of this object is then recorded using beam R_1 as the reference beam. R_2 would be stopped and would not illuminate the hologram recording plate during this first exposure. The dual exposure would be completed by removing the test object from R_{Obj} and recording a hologram of this beam using R_2 as the reference. During the second exposure R_1 would be stopped and thus would not illuminate the hologram recording plate. The only difference in this technique from the well known double-exposure method is in the use of a different reference beam for each of the two exposures. This allows two distinct holograms of R_{Obj} to be formed on a single emulsion, one hologram with the test object present and one without.

After processing, the hologram can be replaced in its original position. If it is illuminated with R_1 alone, the original test scene will be reconstructed. This reconstruction can be used for obtaining shadowgrams, schlieren photographs, or any other purpose for which a hologram may be suitable. (It is pointed out that if the test object were still located in beam

R_{Obj} , illumination of the hologram with both R_1 and R_{Obj} would give the exact results as the real-time type of interferometer mentioned in the introduction of this report.) If the hologram is reconstructed using only beam R_2 , then R_{Obj} without the test subject will be reconstructed. Illumination by both R_1 and R_2 simultaneously will result in the reconstruction of R_{Obj} both with and without the test scene present. These reconstructions are coaxial, and the interference pattern of the test object will be observed.

A hologram was recorded using the above procedure, utilizing a microscope slide as the test object. Figure 2 shows the interference pattern of the object which is obtained when the hologram is reconstructed with both R_1 and R_2 simultaneously. This is the pattern that would have resulted from a conventional double-exposure hologram as described previously. One major difference, however, is that the two reconstructions are now independent of each other. If the resulting pattern does not show the desired information to the best advantage, the fringes can be shifted by any desired amount merely by altering the phase of either R_1 or R_2 . Figure 3 is the same reconstruction as shown in figure 2, except that the phase of R_2 has been shifted approximately 180° during the reconstruction. This resulted in a corresponding phase shift in the beam reconstructed by

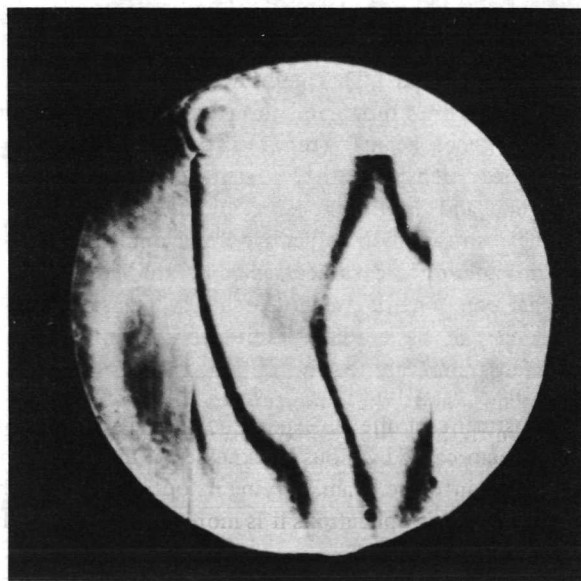


Figure 2.—Interferogram reconstructed from dual-reference-beam hologram.

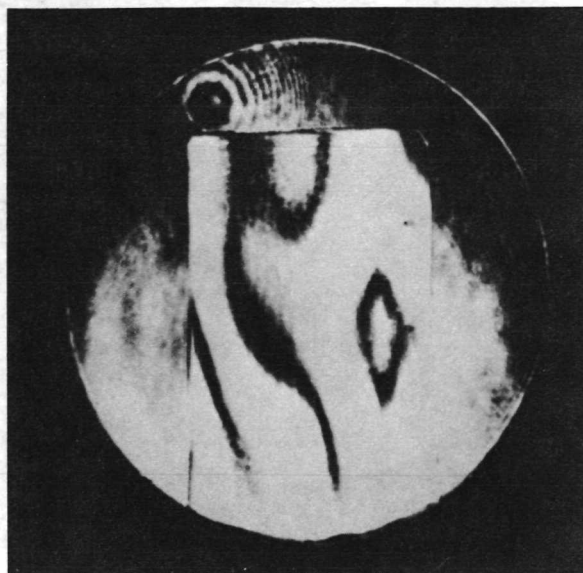


Figure 3.—Interferogram reconstructed with phase of comparison beam shifted 180° .

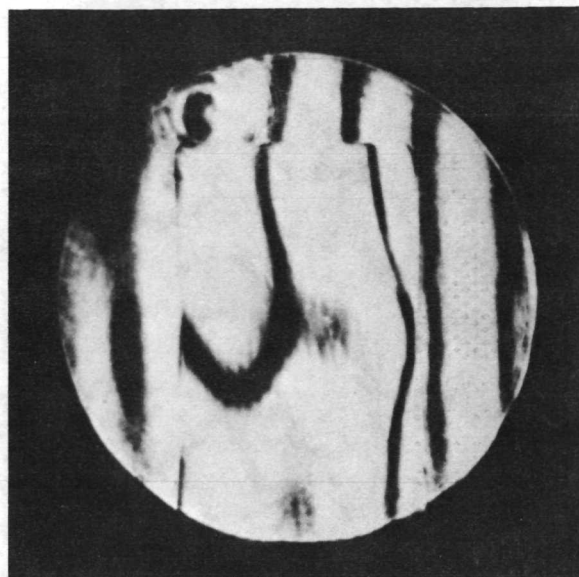


Figure 4.—Finite-fringe interferogram observed with horizontal change in reconstructing angle.

R_2 , but did not alter the phase of the beam reconstructed by R_1 . It can be seen that certain details of the interference pattern near the upper edge of the slide are more easily distinguished in this figure. Had the phase variation over the entire test object been less than one-half wavelength, a subfringe interferogram would have resulted which would be very difficult to interpret. By proper adjustment of the relative phases of R_1 and R_2 during reconstruction, the small phase variations could be displayed at maximum visibility.

Any convenient method can be used to adjust the phase of the reconstructing beam. This would include piezoelectric transducers, variable pressure chambers, and glass of varying thicknesses. For the preceding figures a very simple method was used. A glass microscope slide (actually the same slide which was used as the object of the hologram) was placed in one of the reconstructing beams prior to collimation. Adjustment of the slide perpendicular to the axis of the beam caused various thicknesses of the slide to be inserted into the beam, varying its optical pathlength.

For some applications it is more desirable to study a finite-fringe interferogram. This type of presentation can be obtained during reconstruction by altering the angle at which either R_1 or R_2 illuminates the hologram. The effect is the same as would

be obtained by slightly rotating one of the mirrors in a Michelson or other standard laboratory interferometer. Figure 4 illustrates the result of a slight horizontal change in the angle at which R_2 illuminates the hologram during reconstruction. The greater the angular change, the more closely spaced the fringe pattern will become. The effect of a small vertical change in R_2 is shown in figure 5. Combinations of adjustments both horizontally and vertically can produce any desired orientation and spacing of the finite fringes.

Figures 2 through 5, all reconstructed from the same hologram, are representative of the infinite variation of fringe presentation available to an observer during reconstruction, with no prior knowledge of the test scene or special procedures required during the hologram exposure. This capability would be a great asset in studying various transient phenomena, in which the flexibility of the reconstruction could be useful in assuring that the maximum amount of information would be derived from a single recording of the event.

Although the sample chosen for these figures is transparent, the method works equally well for diffuse objects. This fact has been ascertained in this laboratory and also has been independently described in the literature (ref. 2).

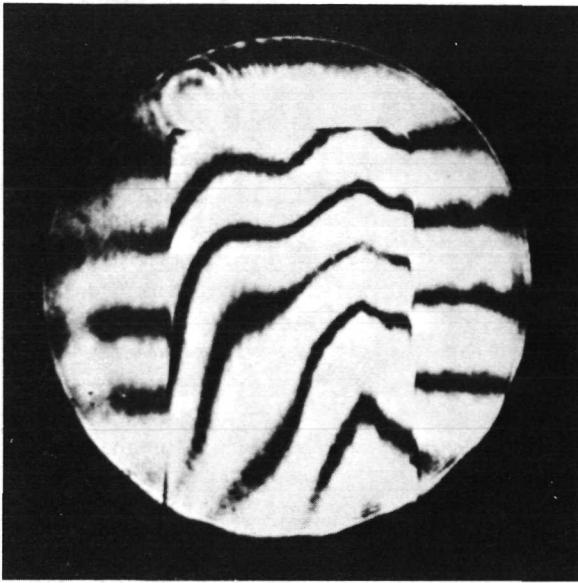


Figure 5.—Finite-fringe interferogram observed with vertical change in reconstructing angle.

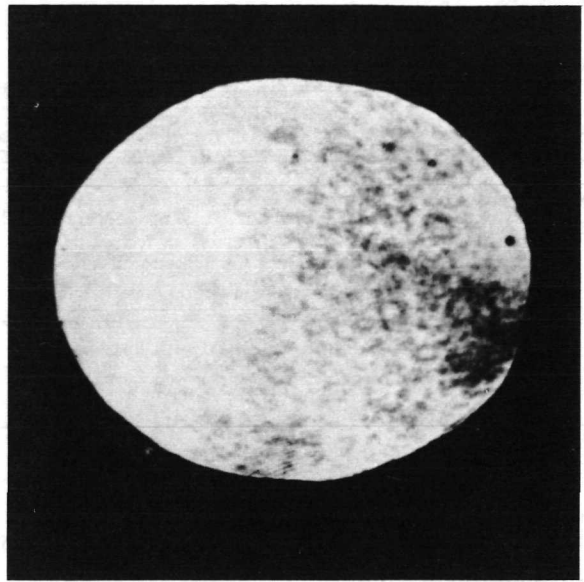


Figure 6.—Reconstruction of uniform field.

The separate-reference-beam technique has proved quite useful in the laboratory for the study of various transparent or reflective objects in real time. For real-time interferometry, a double-exposure hologram is recorded with separate reference beams in the same manner as described previously, except that no object is placed in R_{obj} for either of the two exposures. After processing and upon reconstruction of this hologram, a uniform optical field will be observed. Figure 6 shows the reconstruction of such a hologram. Since there was no difference in R_{obj} in the two exposures, no fringes would be expected. This will be true as long as the wavefronts used to reconstruct the hologram are identical to those wavefronts which originally formed R_1 and R_2 . If either of the two reconstructing beams is perturbed in any manner, the same perturbation will appear in the reconstruction. If, then, some object is placed in R_2 during reconstruction, any phase variations in this object will be present in the beam reconstructed by R_2 . Reconstruction of the hologram with the original R_1 and the perturbed R_2 will result in the interference pattern of the perturbing object appearing in the reconstruction.

Figure 7 is identical to figure 6 in every respect except that a transparent test object has been placed in beam R_2 during reconstruction. The test object was the same slide used in previous figures, and its

interference pattern can be observed in the reconstruction in real time. These real-time fringes can be shifted by the same means as described for the holographically stored image which was discussed previously, and finite-fringe interferograms can also be obtained.



Figure 7.—Real-time interferogram.

The double-exposure holographic interferometer with separate reference beams has proved to be a useful, versatile, and simple method of holographic interferometry for many applications, offering several unique capabilities. The hologram system is slightly more complicated than a conventional two-beam system due to the addition of a second reference beam, but even this small inconvenience arises only once, when the various components are originally arranged, and the resulting advantages make this effort negligible. The resulting technique, in common with other forms of holographic interferometry, does not require precise optical components. Diffuse as well as transparent subjects may be studied. As with the standard double-exposure technique, high-speed transient events can be recorded for study by using a pulsed laser. The method also possesses the flexibility of the real-time holographic technique and even that associated with nonholographic laboratory-type interferometers when used with static test objects. This flexibility enables even transient subfringe systems to be displayed to their maximum visibility and best advantage.

Double-exposure holographic interferometry using separate reference beams, with its unique properties and capabilities, is the basis for an instrument with which it is possible to measure very small phase variations within an optical field, whether the field exists in real time or is holographically stored. The resulting instrument combines simplicity with a reasonable degree of precision, relative phase measurements having been made with a standard deviation of 1° .

Figure 8 illustrates the reconstruction of a double-exposed hologram which has been recorded as shown in figure 1. Two right-angle prisms, one of which can be moved in the direction of the arrows, have been placed in reconstructing beam R_2 just prior to collimation. As the prism is moved, the pathlength of R_2 is changed. In this manner the relative phase of R_2 is continuously varied with respect to R_1 , and as a result the relative phase of the two beams reconstructed by R_1 and R_2 is also continuously varied. The phase variation is periodic in nature, one cycle being completed as the optical pathlength of R_2 is altered by a distance equal to one wavelength. The frequency of the phase variation is determined by the rate at which the prism is moved.

If a light detector is placed at some point in the reconstructed optical field (detector 1, fig. 8), it will produce an electrical signal which is proportional to the instantaneous light intensity at that point. As the prism is moved, the intensity measured by the detector will vary as alternate conditions of constructive and destructive interference occur. The output signal of the detector will be a sine wave, the frequency of which depends upon the rate at which the prism moves. A second detector placed at any other point in the reconstructed field will produce a similar signal. For purposes of illustration, let us assume that detector 1 of figure 8 happens to be placed on a dark fringe in the reconstruction and detector 2 is located on a bright fringe. These two points are optically 180° out of phase. As the prism is moved, both of these detectors will experience alternating conditions of constructive and destructive

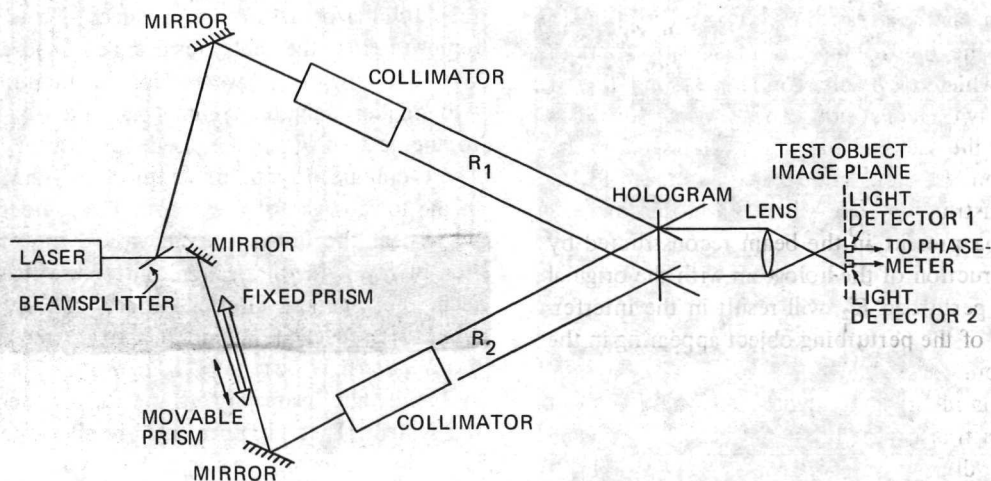


Figure 8.—Method of measuring small phase variations using a separate-reference-beam hologram.

interference and will produce an alternating electrical signal. These two electrical signals will not be in phase, however. Due to the location of the two detectors within the optical field, the levels of their signals at any one time will differ by an amount corresponding to the difference in optical phase between the two points at which the detectors are located.

A dual-reference-beam hologram was reconstructed as shown in figure 8, and an effort was made to locate the two detectors 100° apart in optical phase. As the prism was moved, the outputs of both detectors were displayed on a dual-beam oscilloscope, as shown in figure 9. It will be observed that the two signals are not exactly 180° out of phase; this is a result of an error in the positioning of the two detectors in the interference field. The relative phase of these two signals is a true measure of the actual optical phase difference between the two points at which the detectors were located.

If the two detector signals are fed into an electrical phasemeter, the relative phase of the two points can be read directly and recorded. A phase map of the entire optical field can be obtained by permitting one of the two detectors to remain stationary at some arbitrary reference point while the second detector is moved to all points of interest within the field. Any

low-frequency drift between the two paths which make up the two reconstructing beams will not have an adverse effect upon the phase measurement. This drift will affect the signal from both detectors equally; it will appear as a slight frequency modulation on both detector signals.

With the basic system that has been described, the relative phase of any two points within a reconstructed field has been determined with a 1° standard deviation. This figure is the overall precision for the entire system, including all components. It is important to point out that this precision is possible with an interference field using the separate-reference-beam technique, whether the field exists in real time or is stored in the hologram. This would make it possible to record high-speed projectiles in rarefied atmospheres using pulsed-laser separate-reference-beam holography and to study the resultant interference field in detail and with precision after the event has taken place. A discussion of the methods and equipment used to achieve these measurements follows.

The experimental arrangement which has been used for both recording and reconstructing double-exposure holograms with separate reference beams is shown in figure 10. This arrangement differs from those shown in figures 1 and 8 in that the two reference beams are not arranged symmetrically on either side of the object beam. This arrangement provides for a more efficient utilization of the available work area. The large-diameter collimator seen to the right in figure 10 forms the beam which is used for R_{Obj} . After the hologram has been recorded, this collimator is no longer needed and may be removed from the table, resulting in a more compact system than if R_{Obj} were placed in the middle. The two smaller-diameter collimators which can be seen to the left of R_{Obj} are used to form R_1 and R_2 . These collimators illuminate the hologram, which is in the lower right of the figure. Two detectors are in place near the hologram and within the reconstruction of R_{Obj} . In the background of the figure can be seen the Spectra Physics model 112 He-Ne laser which is used as the coherent light source. This laser has a rated CW output of 10 mW at 632.8 nm. Also visible are the beamsplitters and mirrors necessary to the system. These components are all mounted upon a 0.9-by-1.5-meter granite table. No provision has been made to isolate the table from room vibrations. The movable prism used to change the optical

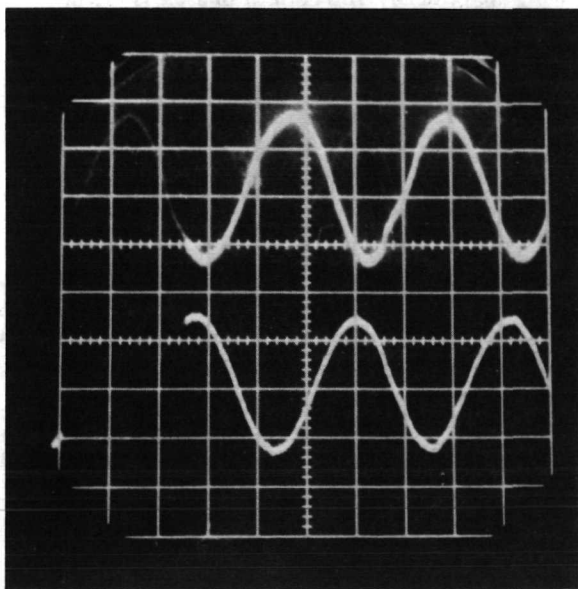


Figure 9.—Signals used in measuring phase shift.

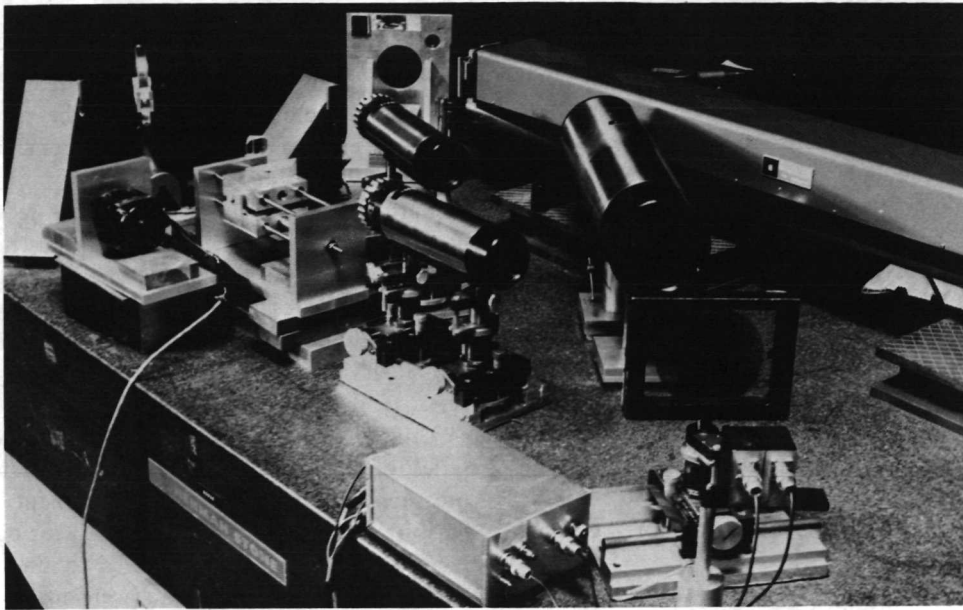


Figure 10.—Hologram recording and reconstructing arrangement.

pathlength of reconstructing beam R_2 is mounted on a mechanical drive unit which can be seen to the left of the collimators. The drive motor for this unit is mounted on rubber pads so that its vibration will not be transmitted to the optical table. This motor drives a lead screw by means of a flexible belt. As the lead screw is turned, it causes an aluminum block to be displaced. The motion of this block is guided by two cylindrical rods. Any eccentricity of the lead screw can be transmitted to the block in the form of a vertical displacement. To minimize this possibility, the aluminum block pushes a platform through an arrangement that allows vertical play between the two. The platform, whose motion is also guided by a pair of cylindrical rods, supports the right-angle prism. By this means it is intended that vibration from the drive motor and vertical movement caused by the lead screw will be avoided. The use of a right-angle prism is intended to eliminate any horizontal rotation of the laser beam. The effect of this rotation would be an alteration of the angle at which the hologram is reconstructed, resulting in errors in the phase measurement.

The light detectors in use are two identical LS-400-NPN silicon planar photo devices. The relative spectral response of these devices at 632.8 nm is

approximately 55 percent. The maximum sensitive area of these devices has a diameter of 0.8 mm, or essentially a point.

The output signals from the detectors are of such an amplitude that they cannot be introduced directly into the electronic phasemeter without amplification. Therefore two identical amplifiers, operated with a gain of approximately 10^4 , are used.

The phase difference between the two points at which the detectors are located is measured with an AN/URM-67 phase monitor. This instrument measures the phase angle between two periodic signals over the range of 20 to 20 000 Hz with an accuracy of $\pm 1^\circ$. The frequency of the input signals is determined by the rate at which the pathlength of the reconstructing beam is varied; it can be changed by altering the speed of the prism drive motor. This speed was selected so as to give a frequency of approximately 280 Hz at the detectors. The phase monitor also requires input signals with amplitudes of 4.0 to 60 V peak-to-peak. It was this requirement that necessitated the use of the matched amplifiers mentioned previously. The specific amplitude and frequency of the two signals applied to the phase monitor were approximately 10 V peak-to-peak at 280 Hz. These values are not critical as long as they

are within the specified operating range of the phase monitor.

With the equipment described, it was found that the phase measurements made with the system were noisy and difficult to interpret visually. Observation of these data did indicate that the recorded phase values were fluctuating about some mean value. With all parts of the system apparently functioning normally, it was necessary to find the cause of the erratic readings and, if possible, eliminate them.

The cause of the erratic phase measurements was determined to arise from incomplete damping of the prism drive motor vibration, vibration and irregular motion of the prism mount, building vibration, and other transient conditions within the interferometer. It was found that the effects of this noise could be eliminated by filtering the dc output of the phase monitor.

With a filtering circuit in use, two previously unnoticed sources of error became apparent. These were both associated with the mechanical drive unit used to move the prism, changing the optical pathlength of one reconstructing beam.

One source of error was the "sag" of the cylindrical rods which guide the prism platform. This sag causes the prism mount to travel up and down as it moves, and the result of this is a drift of the indicated phase angle. This has been overcome by experimentally locating a portion of the drive unit which did not exhibit this drift and assuring that all subsequent measurements were made with the prism moving over this same portion of the drive unit each time.

The second error showed up as a spike in the recorded phase information, which appeared to be caused by a sudden irregularity in the movement of the drive unit. It was found that a number of these spikes could be repeated by retracing the movement of the drive unit over a particular region. They were undoubtedly the result of some slight mechanical flaw in a portion of the drive unit itself. Other similar spikes were recorded which did not repeat, and these were attributed to a nonrecurring bind in the mechanism. Fortunately, the data recorded during these incidents is in obvious error and can immediately be discounted as having no significance with regard to the measured phase angle.

It was also found that the mechanical drive unit operated more smoothly in one direction than when it was reversed. In view of this, all measurements were recorded with the prism moving in the direction to

decrease the optical pathlength of the reconstructing beam. It would be desirable to record all phase angles with the prism moving in one specified direction in any case. If the carriage were to be reversed, the indicated phase angle would be the conjugate of that obtained when the drive unit was moving in the forward direction. This is due to the fact that one detector signal is taken by the phasemeter as a reference and the phase of the second signal is measured with respect to that reference. By changing the direction or travel of the movable prism, what was a phase lead will become a phase lag and vice versa, resulting in the conjugate angle being recorded.

Using the total system which has been described, a series of measurements was made to establish the precision and stability of the instrument. For these measurements the phase between two points in the reconstructed field was monitored continuously for 2 minutes. These measurements were made five times for a total elapsed time of over 30 minutes. It was desired to establish the precision of the instrument over each of the 2-minute periods and then compare the results to determine the long-term precision and stability.

The minimum time interval from the termination of one run to the beginning of the next was 2 minutes. This interval was necessary to return the prism drive unit to its original position.

The minimum short-term standard deviation for a 2-minute period was $\pm 1.0^\circ$, with a maximum deviation from the mean of $+2.5^\circ$ and -0.7° . The long-term standard deviation for the entire 30-minute period was $\pm 1.4^\circ$, with a maximum deviation from the mean of $+3.2^\circ$ and -2.2° .

A recording of the measured phase angle is shown in figure 11. This curve represents the entire 2-minute period during which a phase measurement was being taken. For purposes of analysis, the phase angle indicated by the recording was read at 7.5-second intervals. The angles read and the accompanying analysis for a typical 2-minute period are shown in table 1. Some of the 7.5-second time periods have been omitted from the table because the measurements at those particular points were in obvious error. These were points at which spikes mentioned earlier had occurred.

Readings for the first of the 2-minute periods are listed in table 2. These measurements were made immediately after a small adjustment was made in the optical system of the interferometer. The slight

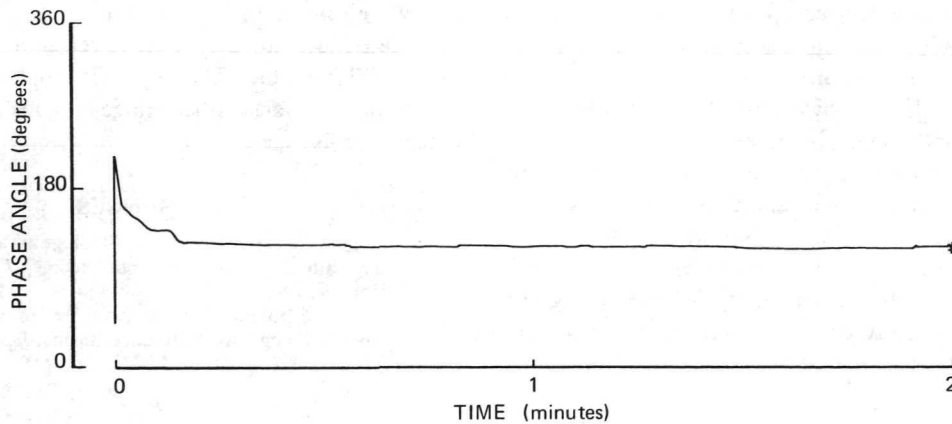


Figure 11.—Recording of averaged phasemeter output signal.

Table 1.—Phase Angles as Measured from Recorded Average Phasemeter Output (Typical Run)

Time (s)	Phase angle (°)	Deviation from mean $X - \bar{X}$ (°)	$(X - \bar{X})^2$
22.5	119.2	2.5	6.1
30.0	117.4	0.7	0.4
37.5	117.9	1.1	1.3
45.0	117.0	0.1	0.0
52.5	117.0	0.1	0.0
60.0	116.1	-0.7	0.5
67.5	116.1	-0.7	0.5
75.0	116.1	-0.7	0.5
82.5	116.1	-0.7	0.5
90.0	116.1	-0.7	0.5
97.5	116.1	-0.7	0.5
112.5	116.1	-0.7	0.5

$$\bar{X} = 116.8^\circ \quad \Sigma(X - \bar{X})^2 = 11.1 \quad \sigma = \Sigma(X - \bar{X})^2 / N = 1.0^\circ$$

Table 2.—Phase Angles as Measured from Recorded Average Phasemeter Output (First Run)

Time (s)	Phase angle (°)	Deviation from mean $X - \bar{X}$ (°)	$(X - \bar{X})^2$
30.0	132.8	6.6	44.1
37.5	130.5	4.4	19.3
45.0	130.5	4.4	19.3
52.5	134.1	8.0	63.8
60.0	126.9	0.8	0.6
67.5	128.2	2.1	4.6
75.0	123.8	-2.4	5.6
82.5	121.5	-4.6	21.3
90.0	121.5	-4.6	21.3
97.5	120.6	-5.5	30.4
105.0	121.5	-4.6	21.3
120.0	121.5	-4.6	21.3

$$\bar{X} = 126.1^\circ \quad \Sigma(X - \bar{X})^2 = 272.6 \quad \sigma = \Sigma(X - \bar{X})^2 / N = 4.8^\circ$$

Note: System was reaching equilibrium while measurements were being recorded.

change in measured phase angle as the interferometer attained equilibrium during this time has been measured. This recording was a fortunate accident, brought about by overeagerness to obtain data, but it dramatically points out the sensitivity of the method and the system.

The extreme stability of the system has been attained with no measures taken other than those normally associated with any holographic recording system. The granite table upon which the instrument is located is not isolated from building vibrations. This fact, coupled with the facts that the laser laboratory of the Graduate Institute of Technology is located on the fourth floor of the GIT building and

that this building is immediately adjacent to an Interstate highway with heavy truck traffic, makes the performance of the system quite remarkable. It was found necessary to cover the system during phase measurements to prevent air currents from affecting the results.

The dual-exposure hologram with separate reference beams has been demonstrated to be a flexible, versatile, and simple method of holographic interferometry. The unique combination of advantages possessed by this method makes it ideally suited for a number of applications, such as the real-time

comparison of optical components and the study of holographically recorded transient systems resulting in subfringe interferograms.

It has also been shown that the double-exposure technique with separate reference beams can be utilized as the basis for an instrument that is capable of measuring small phase variations within an optical field, whether that field exists in real time or is holographically stored. The instrument, as conceived, has the demonstrated capability of measuring the relative phase between two points with a standard deviation approaching $\pm 1.0^\circ$. This precision would

allow entire subfringe interference fields to be mapped and studied in detail, even though no fringes were visible to the naked eye. The application of this technique to transient subfringe systems is but one of many possible uses.

REFERENCES

1. Ballard, G. S.: Double-Exposure Holographic Interferometry with Separate Reference Beams, *J. Appl. Phys.*, Vol. 39, 1968, p. 4846.
2. Tsuruta, T.; Shiotake, N.; and Itoh, Y.: Hologram Interferometry Using Two Reference Beams, *Japanese J. Appl. Phys.*, Vol. 7, 1968, p. 1092.

Quantitative Measurement Using Holographic Interferometry

Edwin B. Champagne

GCO, Inc.

The fringes superimposed on the reconstructed image of an object in holographic interferometry represent loci of equal optical pathlength change between the two holographic states. This fringe system can be analyzed on a point-by-point basis and a quantitative measure of the object displacement and deformation obtained. However, the process of data reduction is long and tedious and becomes impossible when the order of the fringe system becomes such that it cannot be resolved. This paper discusses optical techniques which will be useful for the rapid reduction of the data obtained in holographic interferograms.

Page Intentionally Left Blank

Nondestructive Testing and Flow Visualization — Two Aerospace Applications of Holography*

R. K. Erf, R. M. Gagosz, and J. P. Waters

United Aircraft Research Laboratories

The application of holography to both nondestructive testing (NDT) and flow visualization has been extensively studied at United Aircraft Research Laboratories (UARL). This work is presented in two sections representing these two major areas of continuing investigation.

In the NDT area, particular attention has been given to determining the most suitable stress systems for recognizing potential defects within aerospace materials and components when subjected to interferometric holographic examination. It has been found, for instance, that pressure cycling is most appropriate for studying honeycomb structures, diffusion bonds, electron beam and resistance welds, rubber laminates, and solid-propellant-to-liner disbonds; acoustic excitation procedures are preferred for composite bond studies, material thickness measurement, and vibration analysis; and thermal shocking shows promise for the inspection of some composite components. Representative results from these investigations are summarized with the intent of describing the several tools which have been developed and are now available for studying the various problems confronting the aerospace industry.

For flow visualization work, a pulsed laser holographic system was developed at UARL and employed at several wind tunnel test facilities, offering evidence of the portability and on-site testing capability of such systems in somewhat hostile environments. Both diffused and direct undiffused laser source techniques have been studied, with the latter method permitting the versatility of reconstructing shadowgraph, schlieren, and interferometric flow records from the same single-pulse hologram. In addition, double-source techniques have been incorporated which permit full utilization of the three-dimensional characteristics of holography in direct undiffused, single-pulse laser studies of flow fields. Results of this work, including some discussion as to the advantages and disadvantages of the various techniques, are presented.

HOLOGRAPHIC NONDESTRUCTIVE TESTING

The ever-increasing complexity and sophistication of aerospace structures and components, together with the demand for lighter, stronger, and more reliable materials, inherently requires a more detailed knowledge of any deficiencies or flaws which may be present. New manufacturing processes and fabrication techniques to realize such structures pose two poten-

tially dangerous problems: (1) The nature of the flaws which might be encountered in production or develop in service are not as well understood, and (2) their identification is more difficult. Consequently, application of conventional NDT methods to these problems must be reexamined to determine their suitability, and new tests and tools must be developed and demonstrated. Holography is one such tool that has recently become available and well established. Therefore, it is important to explore the feasibility of using this technique, along with other, longer established, more widely used techniques, when seeking

*A portion of this work was supported by NASA Contract NAS1-9926.

solutions to the inspection of advanced aircraft and aerospace hardware.

At the same time, the importance of properly interpreting holographic nondestructive testing (HNDT) results cannot be overemphasized. A hologram showing many meaningless anomalies is of little value in establishing product integrity. Therefore the HNDT results must satisfy several criteria. These include:

1. Reproducibility of results with repeated tests on the same defect. This requires that effects of such factors as equipment operating instability, environmental severity, and operator variability will not affect the results obtained.
2. Explicit interpretation of results. The inspection results must clearly indicate whether or not a component is acceptable, and must be easily and repeatably interpreted by manufacturing and maintenance personnel.
3. Correlation of HNDT results to known standards and destructive test information. The results must clearly distinguish such items as flaw size and location. This is particularly important in hardware involving composite materials where a considerable number of plies and ply orientations may exist. It is equally important in structures involving a combination of materials and fabrication techniques, such as honeycomb, metal stringers, weldments, and adhesive or braze bonds.

Simply stated, holography is a process which allows the photographic recording of an object and reconstruction of its image in such a way that it is indistinguishable, except in color, from the original. The availability of such a viable technique suggests several possible variations for storing a great deal of information about an object or event for subsequent analysis. The use of pulsed systems (ref. 1) permits the recording of dynamic subjects in three dimensions and, more importantly, eliminates the effects of environmental vibration and the associated need for massive vibration-isolated tables, a problem often felt to limit the practical application of holography. It is this pulsed laser approach that gives holography maximum potential for successful application to NDT of large structures. Without this capability it would not be practical to consider the use of holography for the inspection of large aircraft hardware in a manufacturing or maintenance environment.

The storage feature of holography allows the use

of interferometric processes (refs. 2 and 3) for the measurement of extremely small optical pathlength differences and thus surface deformation, unencumbered by the restrictions of classical interferometry, which demands flat, optically polished surfaces. In addition, holographic contouring and moiré interferometric techniques (refs. 4 and 5) have been developed and are available when required for extending the extremely sensitive interferometric process to large structures and/or large stress deformations. They also offer a potentially attractive method, because of the three-dimensional capability, for inspecting production line components by visual comparison with a contour map of a reference piece. Finally, holographic autocorrelation (ref. 6), a unique process based upon reconstructing a reference-beam point source using light from the object only rather than reconstructing the object with a reference beam as in standard holography, permits an extremely sensitive comparison of a surface with itself at a later point in time. Thus it has potential application to the monitoring of surface corrosion, absorption, depositions and chemical reactions, as well as fatigue cracking.

At UARL, interferometric holography and its several variations, in combination with various stress mechanisms, have been applied to a diversity of NDT problems. Several of these are briefly reviewed in this section. The accompanying table indicates which of the potential combinations of holographic technique and stress mechanism have been applied to specific problems.

This paper does not attempt to describe all the studies, but provides a representative sampling to indicate the more favorable approaches, as determined to date, for the various problems. The discussion has been organized to cover the NDT problem areas as listed in table 1.

Composites

Among the most rapidly developing types of structural components are composites fabricated by molding layers of high-strength fiber tape, such as boron or carbon, either by themselves or bonded to a substrate. While these structures are stronger than conventional homogeneous materials of comparable weight, bond defects can occur either between individual fiber plies or between the plies and the substrate. Detailed knowledge of these flaws is required before the reliability of a structure can be

Table 1.—Applications of Holographic Techniques and Stress Mechanisms (A, Acoustic Excitation; M, Mechanical Stressing; P, Pressure Stressing; T, Thermal Shock)

	CW laser, double-exposure	CW laser, time-average	CW laser, real-time	Pulsed laser, double-exposure
Composites	T, M	A	A, T, M	A
Honeycomb panels:				
Adhesively bonded	P, T	A	P, T	
Braze bonded	P, T	A	P	
Diffusion bonded	P, T	A	T	
Welds:				
Electron beam	P			
Resistance	P, T	A	P, T	
Rubber delamination and solid propellant liner bonds	P		P	
Turbine blades:				
Vibration analysis		A	A	A, M
Cooling passage alignment		A		A
Internal flaw detection	P	A	P, T	A
Stress and strain measurement	M	A	M	A, T

evaluated. An important facet in determining the effects of various flaws is the detection of their existence.

Ultrasonic plate vibration, with interferometric holographic readout, may be one of the most inclusive testing methods for the detection and characterization of bond defects in composite material structures. More important, it may provide a technique for determining bond quality. Disbonds and voids are readily made to vibrate, thereby producing an easily distinguishable change in the mode pattern. Frequencies below 100 kHz can be used to measure accurately the composite elastic properties. At higher frequencies the absorption and complex modulus of adhesive materials cause phase and propagation changes in the deformation of composite surfaces which potentially can be used to describe the properties of the resultant structure. For example, less than maximum adhesion will cause an apparent decrease in the adhesive modulus and, for the same amplitude of vibration, the acoustic attenuation will be greater. The application of HNLT to bond and weld inspection has been the subject of extensive investigations at UARL (refs. 7 and 8). Studies have been made using acoustic, thermal, and pressure stressing methods in combination with time-average, double-exposure, and real-time holographic

techniques. The investigations described below were primarily empirical approaches to establish the requirements for identifying the location and size of definable unbonded areas in several important types of composite structures. These structures included boron and carbon-epoxy prepreg bonded to a metal substrate, boron-polyimide airfoils, and Borsic® aluminum fan blades.

BORON AND CARBON-EPOXY PREPREG BONDED TO A METAL SUBSTRATE

The identification of disbonds in composite test samples fabricated by bonding boron and carbon-epoxy prepreg to a metal substrate was the subject of a study carried out under NASA Contract NAS1-9926 (ref. 9). During the course of this study it was experimentally demonstrated that HNLT with ultrasonic stressing is an effective method for detecting bond flaws as small as 5 by 5 mm in both the boron and carbon-epoxy composites. Successful tests were run with both titanium and aluminum substrates as thick as 1.6 mm (the thickest substrate evaluated). Flaws were detected under as many as 10 plies or 1.25 mm (the largest thickness tested) of prepreg material. In addition it was shown that the technique is unaffected by either fiber orientation of the flaw position (i.e., whether it is between the substrate and

the prepreg material or between the plies of the prepreg material itself).

The majority of the testing of these materials was performed with ultrasonic excitation of the test piece and time-average holographic recording. In applying this technique, the excitation of the test piece was, in most cases, accomplished by electrically driving a piezoelectric transducer which had been bonded to the surface of the test piece. The electrically induced transducer deformations caused flexural displacements due to the restraining force of the bond, and in this way a resonant-plate mode could be established in the sample with the proper choice of driving frequency. This method of excitation has the advantage of having a nearly unlimited range of frequencies.

In a few cases, where larger-amplitude vibrations appeared to be required, a transducer was mechanically coupled to the test piece through a solid exponential horn (acoustic transformer). The horn consisted of an aluminum rod with a piezoelectric transducer mounted on one end and its diameter decreasing exponentially toward the other end, which was pressed against the test piece. When the transducer was driven at its axial resonance (approximately 50 kHz), a large amount of acoustic energy could be transmitted into the sample. Using this type of drive a peak displacement of approximately 10 μm could be obtained at the horn output. Of additional interest is the fact that horn coupling excitation facilitates the experimental procedure by eliminating the bonding process, thus suggesting a practical method for implementing this type of HNMT.

A description of the experimental results obtained is presented below, following a brief analytical treatment of the flaw size limitations inherent in the technique.

Analytical Considerations

Since, at the fundamental resonance mode, an unbonded area can be considered a clamped circular plate, its fundamental resonance in Hz is given (ref. 10) by

$$f_0 = 0.9342 \frac{h}{a^2} \left[\frac{Y}{\rho(1-\sigma^2)} \right]^{1/2}$$

where h is one-half the plate thickness, a is the plate radius, Y is Young's modulus, ρ is the density, and σ is Poisson's contraction.

If the material characteristics and thicknesses were such that the resonant frequency of the substrate, the fiber matrix, and the bonded composite were equal for the same radius, it would not be possible to detect any mode change. Identifying the composite parameters by the subscript 3, the fiber matrix by the subscript 1, and the substrate by the subscript 2, Young's modulus and the density of the composite may be defined as

$$Y_3 = \frac{h_1 Y_1 + h_2 Y_2}{h_1 + h_2}$$

and

$$\rho_3 = \frac{h_1 \rho_1 + h_2 \rho_2}{h_1 + h_2}$$

Consequently, the ratio of Y_3/ρ_3 must always lie between Y_1/ρ_1 and Y_2/ρ_2 or be equal to one of them. Since h_3 is the sum of h_1 and h_2 , then f_{03} must always be different from f_{01} and/or f_{02} , and the mode pattern of at least one of the individual components will always be different from the composite at f_{01} and f_{02} . Furthermore, since the plate wave velocity, as defined below, is proportional to $\sqrt{\omega}$ and $\sqrt{h}$, where ω is the frequency in radians per second, the differences in the mode pattern will increase as higher-order modes are excited.

Of particular importance is the minimum size flaw that can be detected. The velocity of propagation of a plate wave v_p is given (ref. 11) by

$$v_p = \sqrt{\frac{2h\omega}{\sqrt{12}}} \sqrt{C_{ext}}$$

where C_{ext} is the extensional velocity of sound. When $2h\omega/\sqrt{12} = C_{ext}$, the plate velocity approaches the extensional velocity of sound and it would be unlikely that a plate vibration could be excited. Since $\omega = 2\pi f$ and since $\sqrt{12}$ is nearly equal to π , the plate and extensional velocities will be equal at the frequency for which the extensional wavelength is approximately equal to twice the plate thickness. Consequently, the minimum dimension of a detectable flaw will be a few times the plate thickness.

Experimental Results

Typical examples of flaw detection in boron-epoxy prepreg composites are shown in figure 1. The particular flaws being studied consist of seam-welded, airtight stainless steel bags made up of two sheets of

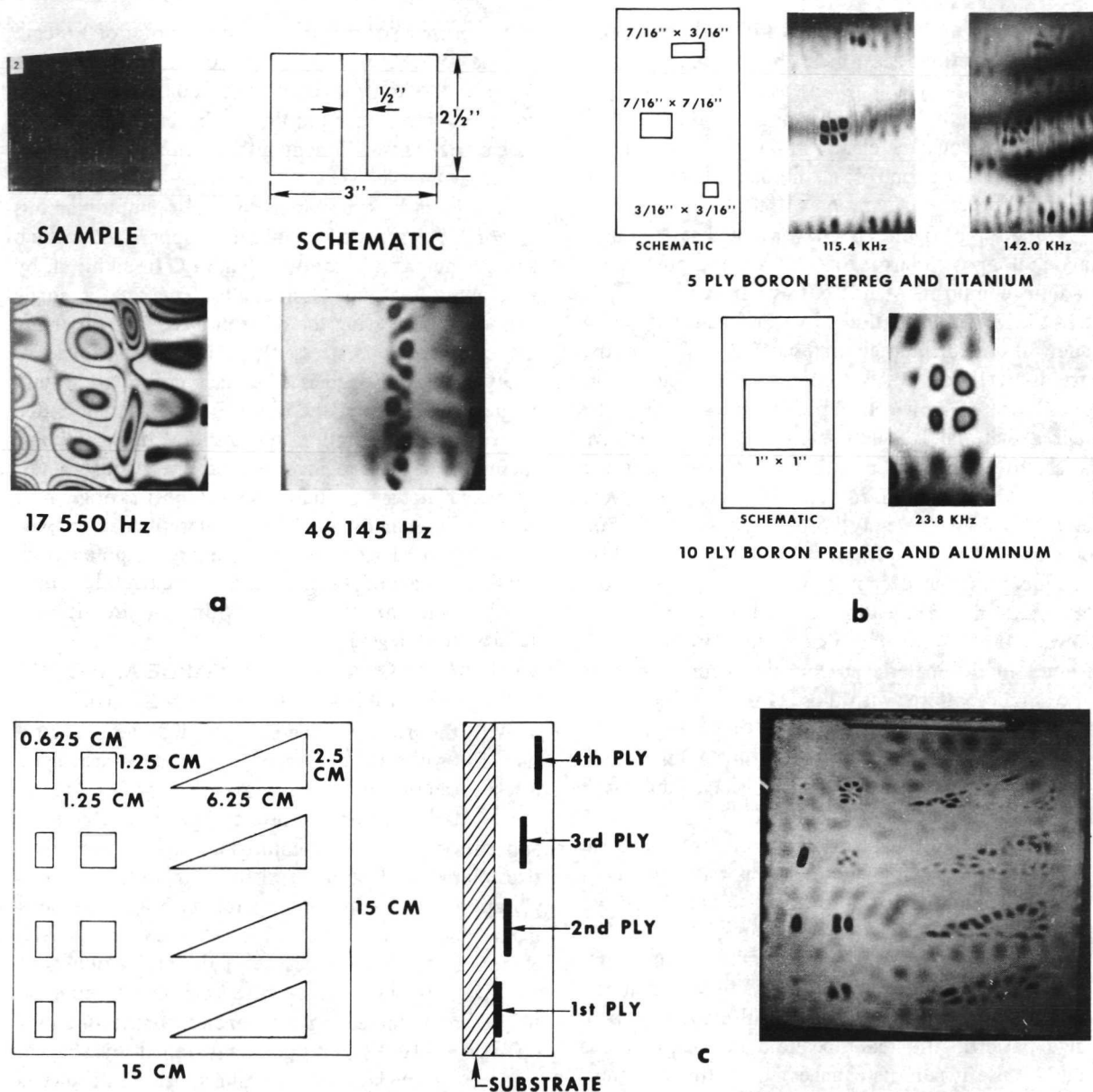


Figure 1.—Holographic reconstructions illustrating the inspection of boron-epoxy prepreg bonded to a metal substrate, using the time-average exposure technique with ultrasonic stressing. Shown are the capabilities of HNDT to characterize the size, shape, and depth of disbonds at the substrate-prepreg interface (a and b); within the prepreg material itself (c); as small as 4.7 mm square (b); and under 10 plies of prepreg (b).

2-mil stock, placed in the prepreg ply adjacent to the substrate. This procedure guarantees that voids are left in the prepreg-to-substrate bond at the programmed locations. Equally successful results have been obtained by creating the air pocket with Mylar and Teflon materials. Also, the use of fluorocarbon release agents to weaken a bond has indicated that it

might be possible to measure bond strength. A four-ply boron-epoxy and aluminum composite with a strip across the entire sample left unbonded is illustrated in figure 1a. A photograph of the sample and a diagram indicating the flaw position are included along with two reconstructions of time-average holograms made while the piece was ultrason-

ically excited at 17 550 and 46 145 Hz. The lower-frequency picture illustrates the breakup of the normal plate mode pattern as a result of the discontinuity (void) in the composite material, while the higher frequency clearly shows the area of the defect by excitation of membrane modes in the unbonded boron-epoxy prepreg itself.

At the top of figure 1b a flaw as small as 3/16 inch square, along with larger flaws, in a boron prepreg-to-titanium composite stands out as a membrane mode at 142 kHz. The detection of a 1-inch-square disbond under 50 mils of prepreg material is illustrated at the bottom of figure 1b. Holographic detection of disbonds located between different plies within the prepreg material is illustrated in figure 1c. Twelve flaws, three each in the first (counting from the substrate), second, third, and fourth plies, were incorporated in a five-ply boron-epoxy and titanium composite. The sample was driven with a 52-kHz transducer and horn coupler near the center of the plate, and the delineation of the flaws is clearly shown. As seen in the figure, the depth of the disbond in the material affects the membrane resonance mode pattern, with those closest to the surface (top of the reconstruction) exhibiting a higher frequency response. Thus, in addition to the simple identification of a disbond, its size, shape, and depth characteristics are readily established.

In addition to the ultrasonic work, another form of low-level stressing—thermal—was studied as a potential technique for detecting disbonds in boron-epoxy prepreg bonded to an aluminum substrate. The technique involves establishing a mild thermal gradient ($\Delta T = 5^\circ \text{C}$) in a test piece of composite material and observing in real time the resulting holographic fringe pattern. The real-time holographic process is used because it permits changes in the fringe pattern to be observed as a function of time and thus facilitates detection of any surface variations. The technique was found suitable for detection of disbonds, with its main advantage being the extreme ease of application. A disadvantage is that the thermal stressing does not delineate the flawed region as sharply as acoustic stressing, and it does not indicate the depth of the flawed area.

A further advantage of the ultrasonic inspection procedure is the fact that much lower frequencies can be employed than would be possible by applying conventional ultrasonic test procedures to similar structural problems. For the type of defect examined

in the current work, an area on the order of 1.6 cm^2 can be located with an excitation frequency on the order of 20 to 40 kHz, whereas conventional ultrasonic test techniques would require excitation in the megahertz range. Consequently, it should be possible to inspect larger areas at one time, thus easing the material handling problems, and also employing less elaborate transducer coupling apparatus, which should increase detection reliability. In addition, by employing real-time holography (making a single exposure, processing the plate in place, and observing the object as it is stressed), it is possible to observe many types and degrees of surface deformation on a single plate. Finally, the results of using a nonbonded transducer configuration indicate that it is a practical method for introducing acoustic energy into a test specimen at considerable time and cost savings. As a result of the encouraging results described above, the work has been extended to examine its potential as applied to actual engine hardware currently under development at Pratt and Whitney Aircraft; the results are reviewed below.

BORON- OR GRAPHITE-POLYIMIDE AIRFOILS AND BORSIC-ALUMINUM FAN BLADES

With the need for high-strength, lightweight materials for gas turbine engines, composites are being investigated as potential materials for fabricating some of the low-temperature components. One such application is in the compressor stages, where relatively large, high-strength airfoils are utilized. Some vibrational problems encountered with homogeneous metal airfoils are reduced by the use of Borsic-aluminum fan blades because of the high modulus of the reinforcement. Part-span shrouds can be eliminated, thereby increasing efficiencies on the order of one percent (ref. 12), a significant step at this stage in compressor development. Of additional significance is the 40-percent weight saving over titanium blades. However, in this type of application the airfoil undergoes tremendous stress loads, and if manufacturing defects are present, complete failure of a compressor stage is possible. It is therefore of paramount importance that an effective nondestructive testing procedure be developed for the inspection of these airfoils.

In general, these structures are usually fabricated entirely of fiber-reinforced resin material (boron- or graphite-polyimide) or metal bonded fibers (Borsic-aluminum) and contain only a small amount of noncomposite material. (Usually some metal is pres-

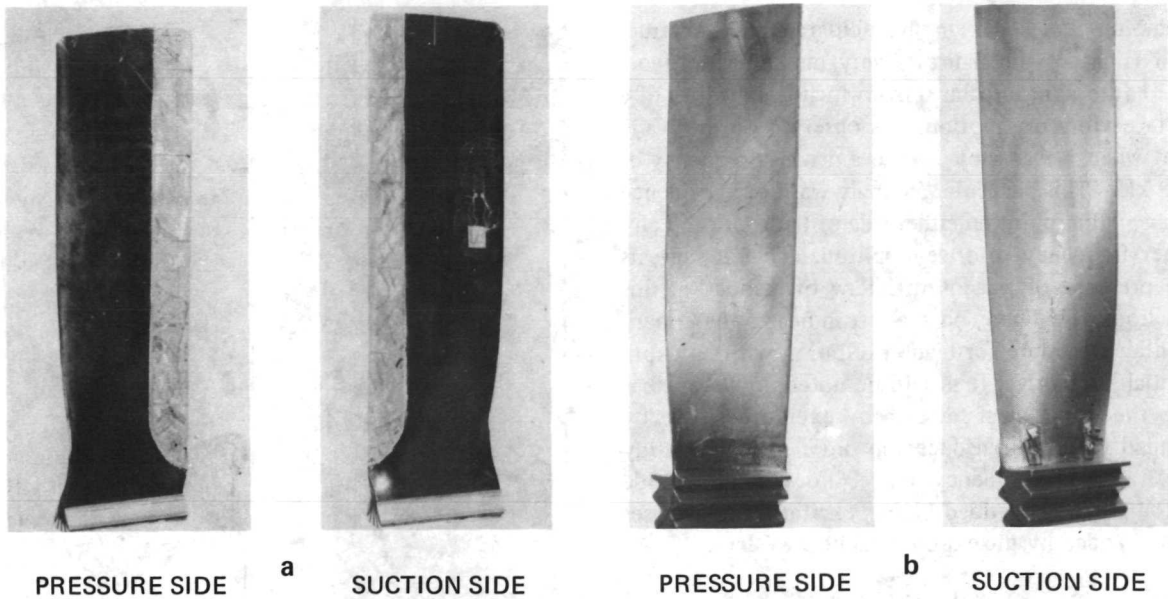


Figure 2.—Typical composite airfoils: (a) boron-polyimide; (b) Borsic®-aluminum.

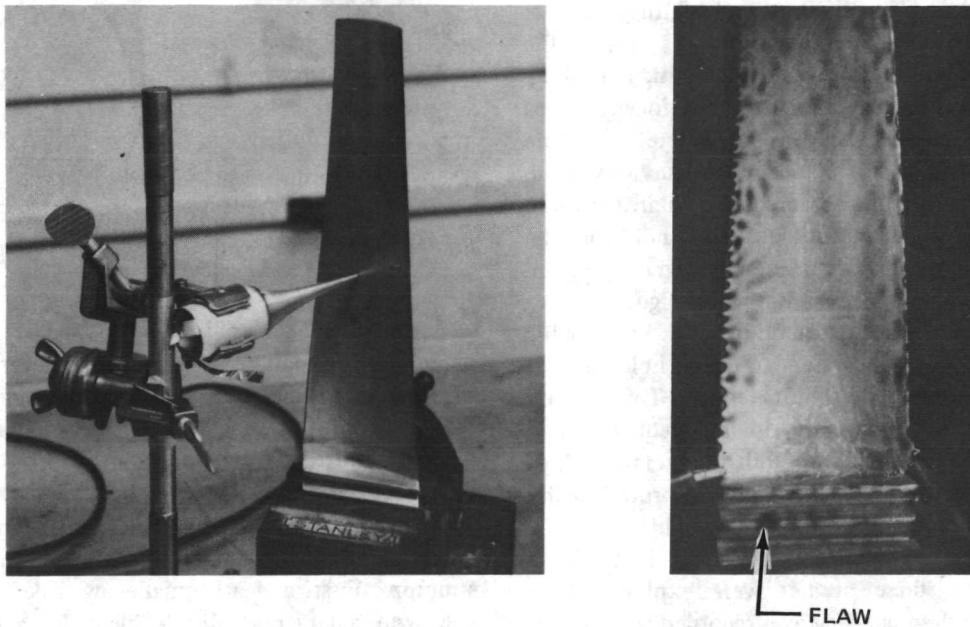


Figure 3.—Exponential-horn ultrasonic drive system used to inspect the root of a Borsic-aluminum fan blade (right).

ent at the base of the foil.) Typical examples are presented in figure 2, which shows both a boron-polyimide airfoil and a Borsic-aluminum fan blade. Except for the composite material used, the construction of the foils is similar: vertical unilateral fibers forming a core, with 45° fiber cross-piles bonded to it to form the outer shell. The root material is usually added to the foil after fabrication. The usual types of flaws encountered in manufacturing are disbands

between successive cross-piles, between the core and the 45° plies, and between the fibers and the root material, the latter being the most difficult to detect because of the thickness and complexity of the fir-tree type of root.

Borsic-Aluminum Blades

An example of the last mentioned type of flaw (root area) is illustrated in figure 3 for a Borsic-

aluminum fan blade. In the holographic reconstruction (right of the figure) a very distinct vibrational point (the dark circular spot), which is indicative of a surface vibratory motion, was observed on the blade root when it was subjected to a driving frequency of 273 kHz. This particular anomaly was not in evidence at any other point on either side of the root or at any other frequency or drive amplitude. Thus it suggests the presence of an internal flaw or disbond at this location. The figure on the left indicates the experimental procedure for blade excitation with an exponential horn drive. It should be noted, however, that for the result just described, excitation was by bonded flexural transducers in order to permit study over a wide frequency range. For the polyimide airfoil studies described below, excitation in all cases was provided by the exponential horn system.

Boron- or Graphite-Polyimide Airfoils

Several boron-polyimide and graphite-polyimide airfoils, fabricated by the Pratt and Whitney Aircraft Division, have been examined for flaws both in the as-manufactured condition and after fatigue cycling. It is of interest to note that, for the airfoils tested to date, only in one instance was a flaw detected before fatigue cycling. Holographic reconstructions from two blades in which flaws were detected are shown in figures 4 and 5, along with diagrams indicating the areas in question. For comparison, holographic reconstructions of a good blade are shown in figure 6.

For proper interpretation of the holographic reconstructions, it is necessary to record holograms of both sides of the blade simultaneously. This method assures that the ultrasonic driving frequency and amplitude are identical for both holograms and, in addition, expedites the experimental procedure by shortening the test time. Two holographic plates are employed, one for viewing each side of the blade. In general, since these studies were exploratory in nature, more than one view was recorded of each side to assure complete coverage of the airfoil surface. When this procedure was used, as observed in figures 5 and 6, the lower reconstruction covered all or almost all of the blade surface. Also provided is a closeup of the tip area, which is sometimes obscured by the transducer in the lower picture. (Holograms were also recorded of the root area, but since they do not contribute information of significance to the present discussion, they have been omitted.) While the driving frequency, and thus the resonant plate

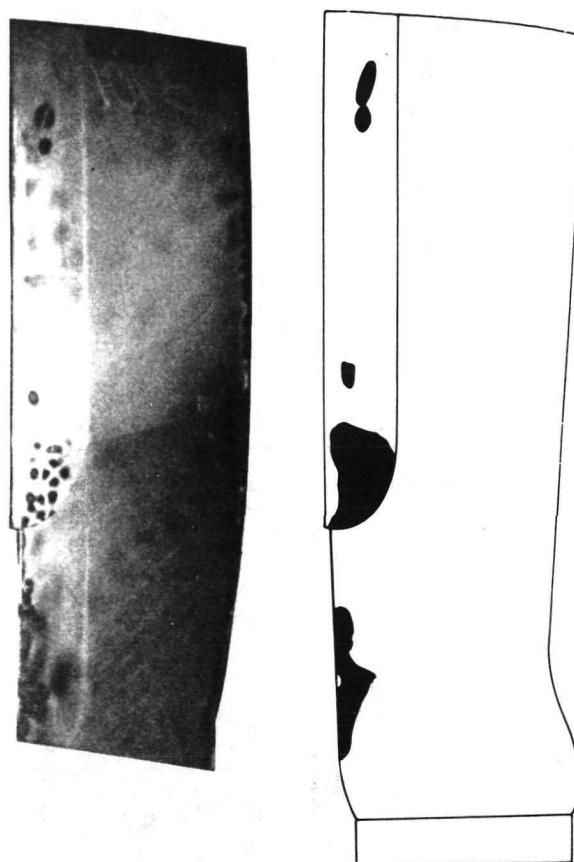


Figure 4.—Disbands revealed under the FOD shield on a boron-polyimide airfoil.

mode pattern, may be slightly different for each pair of reconstructions, the important consideration is that both sides in each pair are recorded simultaneously, permitting a comparison by which pattern differences, and thus flaws, can be detected.

Two vibrational characteristics, as recorded holographically, indicate lamination defects in this type of structure. First, a clearly smaller, well defined mode size with a larger amplitude identifies a definitely more compliant region, and thus an unbonded area. Further, the nonexistence of this mode on the other side of the blade shows that the unbonded area is closer to the surface on which the mode is visible. This type of flaw is visible in the reconstructions (figs. 4 and 5) of both defective blades. Because the blade depicted in figure 4 was studied before the double holographic plate procedure was employed, only one side, exhibiting disbonding between the foreign object damage (FOD) shield and the airfoil

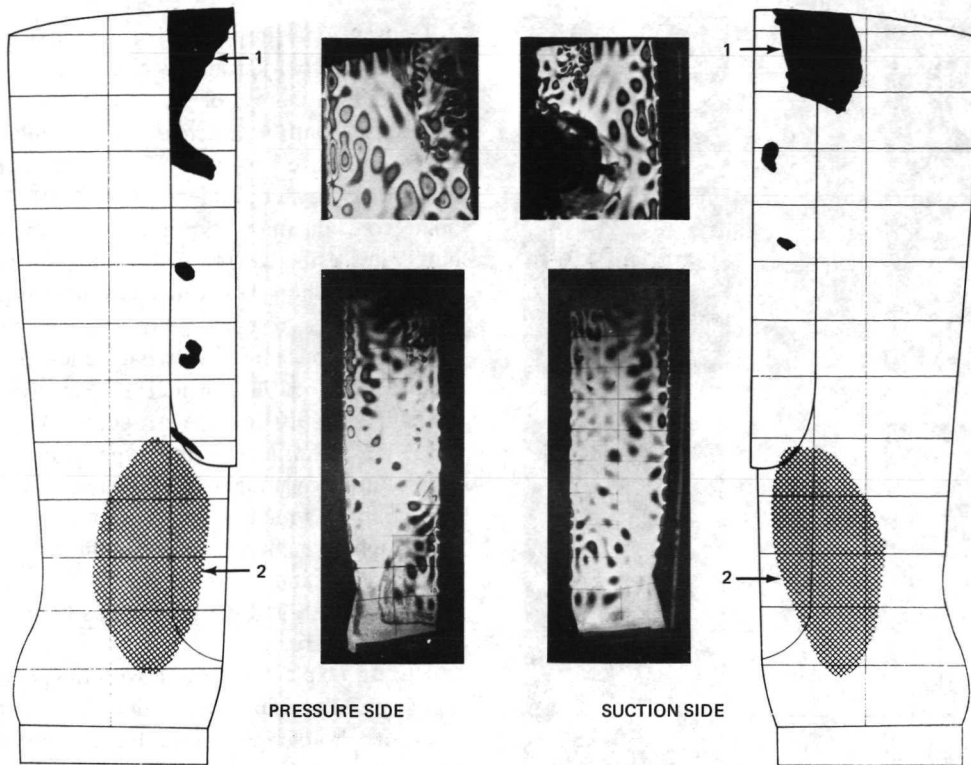


Figure 5.—Two vibrational characteristics which identify lamination defects in a boron-polyimide composite airfoil: (1) a small, well defined, large-amplitude mode pattern locating a disbond near the side on which the pattern appears; and (2) areas where the mode pattern is different on the two sides of the blade, indicating a deterioration of the adhesive within the blade without a complete disbond

surface, is shown. The flawed area indicated below the FOD shield was probably caused by the removal of an earlier, longer protective strip.

The second type of vibrational characteristic indicating a structural anomaly is seen in figure 5 between grid lines 7 and 10 (the lighter cross-hatched area in the schematic of figure 5 denotes the location). In this instance, the mode pattern size and amplitude are not distinctively different from the adjacent areas, but the mode pattern itself is different for the two sides of the blade, indicating a deterioration of the adhesive within the blade without a complete disbond. Also observed at the tip of this blade, both under and overlapping the FOD shield, is the smaller-mode, higher-amplitude type of flaw denoting vibrational characteristic. In this particular instance, the delaminations observed were the result of impact damage during blade testing. In the holographic reconstructions of the good blade (fig. 6), the striking feature is the exact correspondence of the mode patterns for both sides of the blade,

verifying that it is vibrating as a structural entity and that no flaws are present.

In cases where comparison studies have been made of the above results with other NDT techniques, such as acoustic C-scan and X-ray, good agreement has been observed. In general, it appears that the holographic technique has a greater potential to define the area of delamination, determine which surface it is nearer to, and indicate whether it is a partial or total disbond. Holography thus offers a valid technique for the detection of composite bond flaws, with the added advantage of its ease of application.

Honeycomb Panels

Another lightweight, high-strength structural material which receives a great deal of interest for aerospace applications is honeycomb. It usually consists of an internal cell structure with any of various types of face sheets bonded to each side. Various methods are employed to attach the face sheets, including crush bonding with an organic film adhe-



Figure 6.—Holographic reconstructions of a good airfoil. Note the exact correspondence of the mode patterns over the entire surface of both sides, verifying that it is vibrating as a structural entity.

sive, braze bonding with heat, and diffusion bonding with heat and pressure. In all cases the bond between the face sheet and the core material is critical to the structural integrity of the finished component. A defective bond in this area can cause a reduction in the overall strength or create thermal hot spots in the face sheets.

Conventional inspection of honeycomb structures is usually accomplished by either acoustic transmission methods, X-ray, or pressure stressing techniques. (The latter method is often used in combination with stress-responsive coatings.) The acoustic transmission method is very convenient and effective in locating bond voids in many types of honeycomb materials but is less effective for delineating the void regions and distinguishing between voids on opposite sides of the core. Stress-responsive coatings do not have these deficiencies but are somewhat time-consuming and require heat curing, which makes this technique difficult to apply to large structures. The application of HNDT techniques to this type of material affords the definite advantages of being relatively easy to use and requiring a relatively short time to conduct a test. Holographic techniques are not limited as to structural size or shape, can delineate the flawed region extremely well, and can distinguish between opposite sides of the core.

Ultrasonic plate vibrations with time-average holography and pressure stressing with static double-exposure holography have both been successfully employed to identify unbonded areas in honeycomb panels. Examples of these techniques are shown in figure 7. The honeycomb structure illustrated in figure 7a is a standard panel (supplied by Wright-Patterson AFB) with 1/16-inch-diameter core cells and a 30-mil-thick face sheet, while that shown in figure 7c is a fuel-cooled panel (supplied by NASA-Langley) with a complex core cell structure and a 12-mil-thick face sheet.

Results of the acoustic and pressure stressing tests on the standard panel are shown in figures 7a and 7b, respectively. As seen in the holographic reconstruction of figure 7a, the vibrational response of the panel, when subjected to ultrasonic excitation, indicates that a disbond (a circular area approximately 5 cm in diameter created by cutting that area out of a piece of sheet adhesive used to bond the face sheet to the core) is definitely present but slightly displaced from the marked location. In order to establish positively that the flaw was indeed offset, the tests were repeated with different transducer locations, and it was found that the vibrational mode pattern remained unchanged. As noted in the figure, the excitation frequency was 56.8 kHz. Of additional interest is the fact that at sufficiently high frequencies (approximately 200 kHz) the individual honeycomb cells in the vicinity of the transducer could be

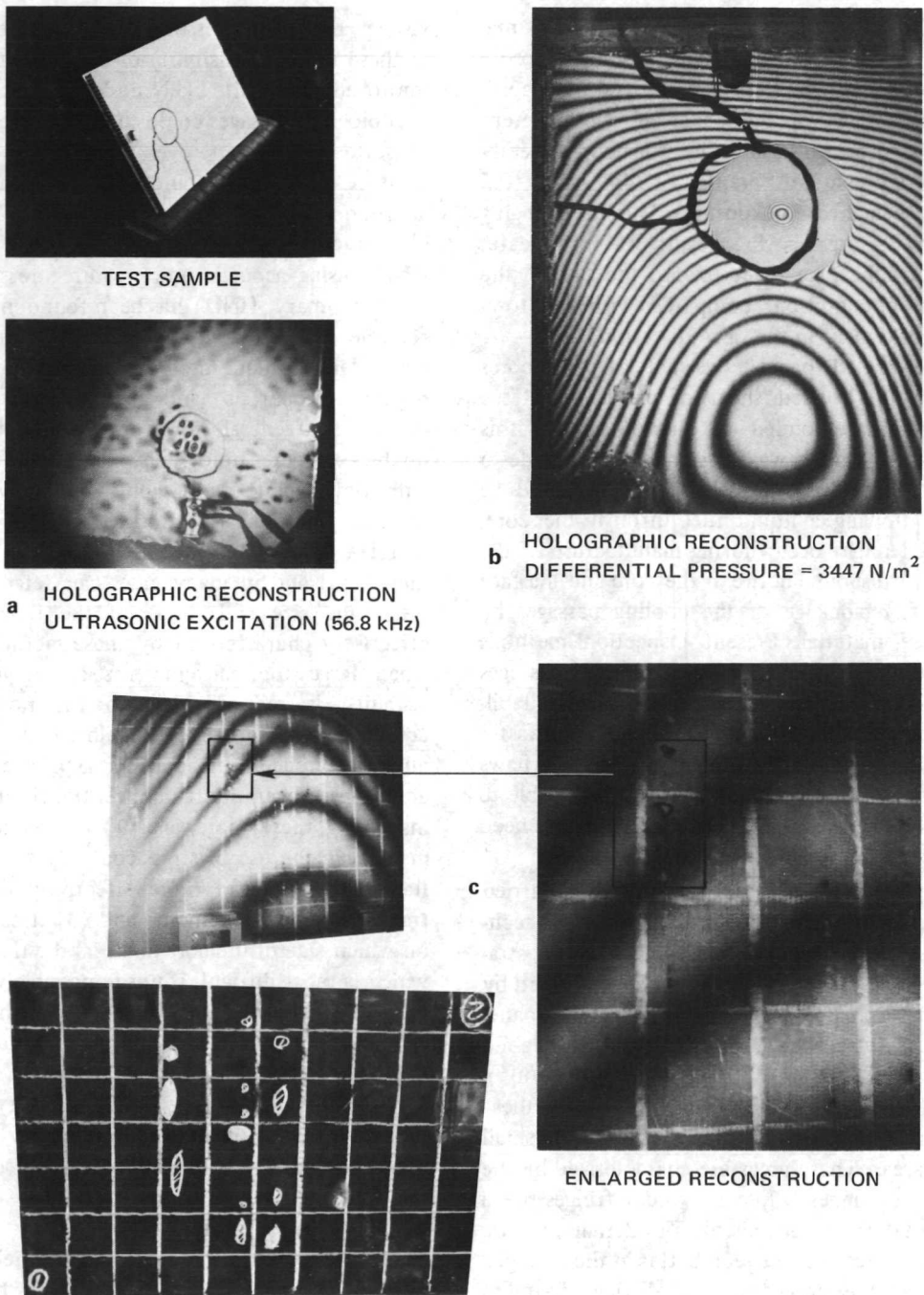


Figure 7.—Holographic reconstructions illustrating the inspection of faceplate bonding on adhesively crush-bonded (a and b) and braze-bonded, fuel-cooled (c) honeycomb panels using both acoustic (a) and pressure (b and c) stressing systems.

identified in the reconstruction. Further study of the honeycomb panel with pressure stressing also showed that the flaw was displaced from its marked location,

placing it at the same spot identified by the ultrasonic tests. The pressure tests were performed by evacuating a small volume between the face sheet and a

piece of plate glass (1 cm thick) spaced approximately 3 mm in front of the panel. Double-exposure interferometric holography was employed by recording two holograms of the panel at two different pressures. As shown in figure 7b, a disbond is clearly visible with a pressure differential of 3447 N/m^2 (0.5 lb/in^2) between the two exposures. The finer fringing in the flawed area is the result of the greater movement of the face sheet toward the glass at the lower-pressure condition, compared with the total structural movement in the same direction.

The fuel-cooled panel consisted of two cores separated by a bonded sheet of metal. Two face sheets were braze-bonded to the outside of this structure. The panel was designed to provide a lightweight, high-strength material which could be cooled by flowing a liquid fuel through the core. Flaws which might occur during manufacture of the panel are (1) disbonds between the core and the face sheet and (2) blockage of the cooling passages by excess braze material. Present inspection methods include the use of X-rays to detect blocked passages and stress coat to find the bond flaws. The availability of holographic techniques provides a faster method than stress coat for detecting the bond flaws and potentially has the added benefit of being able to detect the blocked passages, thus eliminating the need for two inspection procedures.

Holographic inspection of the panel was carried out using pressure, heat, and acoustic stressing techniques. The results from the first method are illustrated in figure 7c. The pressure tests were performed by making one holographic exposure with the panel unpressurized (atmospheric pressure) and the second with an internal pressure of 20.7 N/cm^2 (30 lb/in^2), using the fuel in-and-out fixturing. Results of these tests clearly show the presence of many small unbonded areas. These areas are characterized by the narrow closed fringes, while the wider fringes are a result of total panel movement. The detailed nature of the flawed areas can be seen better in the enlarged photograph of the reconstruction. All flaws found in this manner were marked in chalk on the panel and are shown in the direct photograph of the panel (lower left). The solid chalk areas are flaws which were detected by a relatively large surface movement of the panel, while the striped areas are flaws which had little surface movement. Indications of blocked passages were not found in these tests. However, the internal structure of the core nearest the surface is

visible, and if the pressure differential were increased in these tests, the visibility of the structure should be improved. It is quite likely under these circumstances that blocked passages could then be detected as a lack of surface movement over the blocked cell, since a pressure differential would not exist in these areas. In addition to the above, diffusion-bonded honeycomb-like structures have been successfully inspected with HNDDT using acoustic and pressure-stressing systems.

In summary, HNDDT has been found most effective for the inspection of honeycomb structures. The particular technique used depends on the material, its physical properties, and the type of flaw to be detected. In general, however, pressure stressing with double-exposure holography and acoustic stressing with time-average holography seem to be the most suitable techniques. Although thermal stressing and double-exposure or real-time holography are easier to implement and in many cases can detect the flawed areas, the size and shape of the flaw are not as effectively characterized by these methods. Further, when large thermal gradients are required, fringe visibility is reduced due to the nonsteady-state conditions characteristic of maintaining large temperature differences. In addition, HNDDT offers certain advantages over more conventional methods for inspecting these materials: (1) it is easier to implement than the use of stress coat; (2) it can determine flaw size and shape more effectively than acoustic transmission measurement; and (3) it can determine on which side of the core material the flaw is located, which is most difficult if not impossible with conventional acoustic methods. In addition, the individual cell structure can be examined, which has previously required the use of X-ray techniques. Finally, and perhaps most important, HNDDT has the potential to provide information that had previously required the use of two or more separate testing procedures.

Welds

One final area in the metal joining field which has received considerable attention by holographers active in NDT is that of weld inspection. At UARL, conventional interferometric holography with pressure stressing has been found quite satisfactory for the study of both electron-beam and resistance welds. Rather than review that work here, we will describe the use of moiré interferometry as applied to the HNDDT of welds, since it illustrates one way in which holographic interferometry can be desensitized so

that the fringe shape is more clearly apparent while still maintaining flaw detection sensitivity. This technique has particular application to welded structures, which often require somewhat extreme pressures for flaw detection and consequently suffer considerable surface deformation unrelated to the weakened weld being sought. Thus, any anomalies indicative of a flaw are more difficult to observe in the resultant high-density fringe pattern. The component used to illustrate the moiré technique is a JT9D deicing vane especially fabricated with intentional flaws for these holographic tests.

The deicing vane consists of two thin titanium skins resistance-welded together at the leading and trailing edges. Two weld seams are used to secure the trailing edge, while only one is used on the leading edge. On the inside of this structure, cooling chambers are inserted by an electron-beam welding process, and two thick titanium shrouds are welded on either end. In normal operation, bypass air from the engine is injected into the vane through a hole in one of the shrouds and is exhausted through small holes located on the high-pressure side near the trailing edge of the vane. The vane is approximately 20 cm in length and 7.5 cm in width. The defective component used for testing was prepared by lowering the current at various locations along the seam as the leading edge was being resistance-welded, thereby producing a cold weld in these areas. The results of the holographic tests are shown in figure 8a. The holograms which produced the reconstructions pictured were made by using three separate exposures on the hologram. One exposure was made at atmospheric pressure, the second at a pressure of 44.6 N/cm^2 (64.7 lb/in^2), and the third at a pressure of 51.5 N/cm^2 (74.7 lb/in^2). Each reconstruction presented in the figure is an incoherent interference between the two coherent interferometric fringe patterns formed when the vane was at atmospheric pressure and at one of the higher pressures. As seen in the figure, there are two distinct areas of difference (indicated by arrows) in the fringe patterns, as recorded for the good and bad vanes, along the leading edge. As observed in the reconstruction of the bad vane, the two anomalies are situated on either side of an elliptically shaped set of fringes (a pattern existing on all such vanes when interferometrically holographed under pressure, due to the overall physical configuration of the vane and its surface deformation when subjected to internal pressurization). The anomaly to the right of that elliptical set

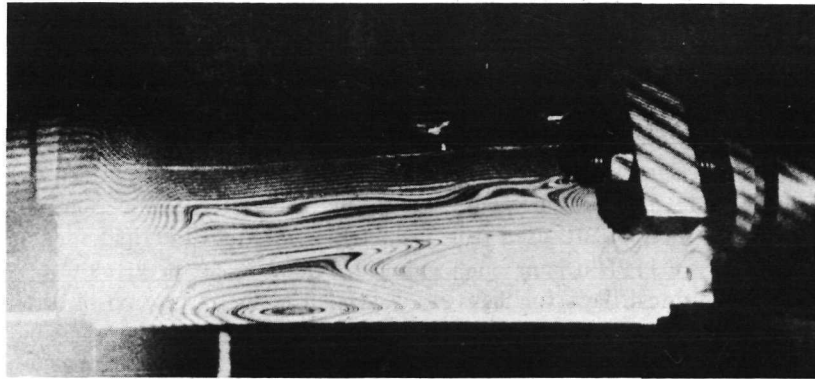
of fringes appears as a "closed" fringe itself, whereas the other, immediately to the left of the common set of elliptical fringes, manifests itself as a slight distortion in the fringe shape.

Rubber Delaminations and Solid-Propellant-to-Liner Disbonds

The successful application of HNDT to both metallic structures and rigid, metallic-like composites, as described in the previous three sections, has been extended to the inspection of softer, more compliant materials including rubber and solid propellants. The work with rubber laminates was undertaken in preparation for the inspection of a solid-fuel propellant grain manufactured by the United Technology Center. The rubber laminate sample consisted of black neoprene sheets 3 mm thick, 5 cm wide, and 10 cm long, bonded together with Weldwood contact cement. The bond flaw was incorporated into the sample at various depths by the omission of cement in an area between two laminae. The laminated sample was placed in a sealed chamber, to permit evacuation of the space surrounding it, and tested using static double-exposure holography. Two pressure stressing methods were employed: (1) making both holographic exposures at the same absolute pressure but waiting a relatively long period of time ($\approx 5 \text{ min}$) between exposures; and (2) making two holographic exposures at different absolute pressures.

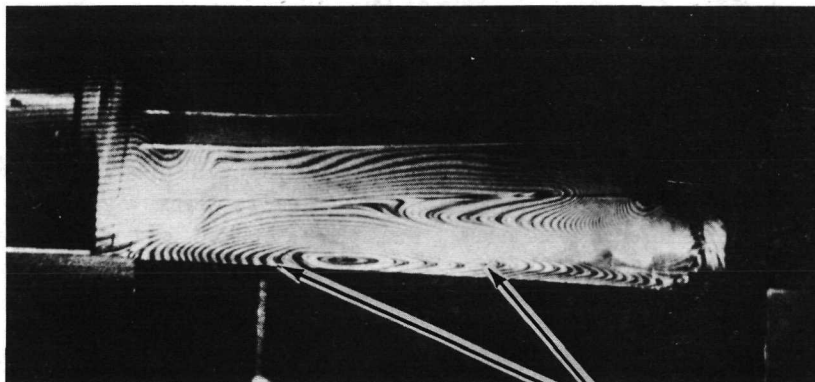
The detection of subsurface flaws using the first method relies upon the slow relaxation rate of rubber after a distorting force has been applied and the fact that the relaxation is dependent upon bonds between laminae, while the second method relies on the fact that a small amount of gas is entrapped at the flawed region during the fabrication process. When the surface pressure on the material is lowered, the subsurface gas pressure will cause a surface movement in the flawed region and, under holographic examination, a discontinuity in the fringe pattern at this point will be detected.

The results are shown in figure 8b, along with a photograph of the sample taken after the tests and subsequent delamination (the other observed cement voids are a result of delamination and did not exist when the sample was tested). Although the flawed area can be detected using either of the two techniques, the results tend to indicate that as the number of plies is increased, the method relying on the relaxation of the rubber is not as effective as the



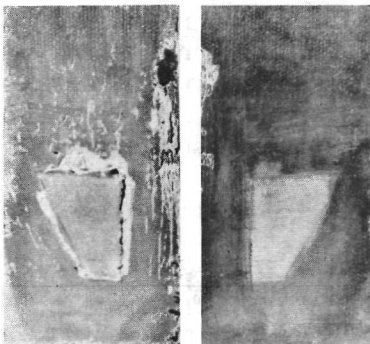
a

GOOD VANE



COLD WELDS IN VANE

PHOTOGRAPH OF DEBONDED
AREA AFTER DELAMINATION



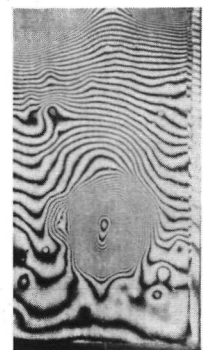
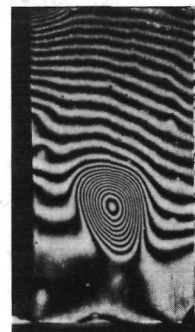
PRESSURE
RELAXATION



b

FLAW UNDER 1 PLY

PRESSURE DIFFERENTIAL $\approx 6895 \text{ N/m}^2$



UNDER 4 PLIES

Figure 8.—HNDT with pressure stressing as applied to a resistance-welded rigid metallic structure (a, deicing vane) and an adhesively bonded compliant material (b, rubber plies). The former illustrates the use of the moiré technique to desensitize holographic interferometry so that the fringe shape is more clearly apparent, while flaw detection sensitivity is maintained. The latter illustrates the use of both the pressure relaxation and pressure differential methods.

two-pressure technique. However, for the detection of flaws in relatively thin samples, the relaxation method is superior in that a more detailed delineation of the flawed area is shown.

These conclusions are supported in the holographic reconstructions of figure 8b. The pressure relaxation test was made at 5.5 N/cm^2 (8 lb/in^2) absolute, while the pressure differential studies were made by taking the first exposure at 5.5 N/cm^2 absolute and the second at 6.2 N/cm^2 (9 lb/in^2) absolute. Only with the flaw under one ply did the pressure relaxation technique provide a clear delineation of the disbonded area (reconstruction on the left), whereas, with 0.7 N/cm^2 (1 lb/in^2) pressure differential, indication of the disbond is clearly evident under four plies, as well as under one ply, as seen on the right.

SOLID-PROPELLANT-TO-LINER DISBONDS

The test sample, an inert solid-fuel propellant

grain, employed in these studies is shown in figure 9 set up in the holographic inspection system in operation at United Aircraft Research Laboratories. The system shown is a typical setup for an HNDT investigation and is characteristic of the optical component configuration employed for most of the tests described in this paper. The sample was approximately 38 cm long by 10 cm in diameter and consisted of the following materials: a 0.5-mm fiberglass outer case; a 0.8-mm polymer liner; and a propellant web (a rubber-like mixture consisting of 14% polymer and 86% solids) approximately 3.8 cm thick. The center of the grain was a hollow cylinder approximately 2.5 cm in diameter. Five programmed disbonded areas, ranging in size from a few square millimeters to a few square centimeters, were incorporated in the sample by placing Teflon at the desired locations between the liner and propellant during the casting of the grain. Detection of this type of disbond is quite important in insuring reliable performance of solid-fuel rocket motors. Disbonds in this region can occur

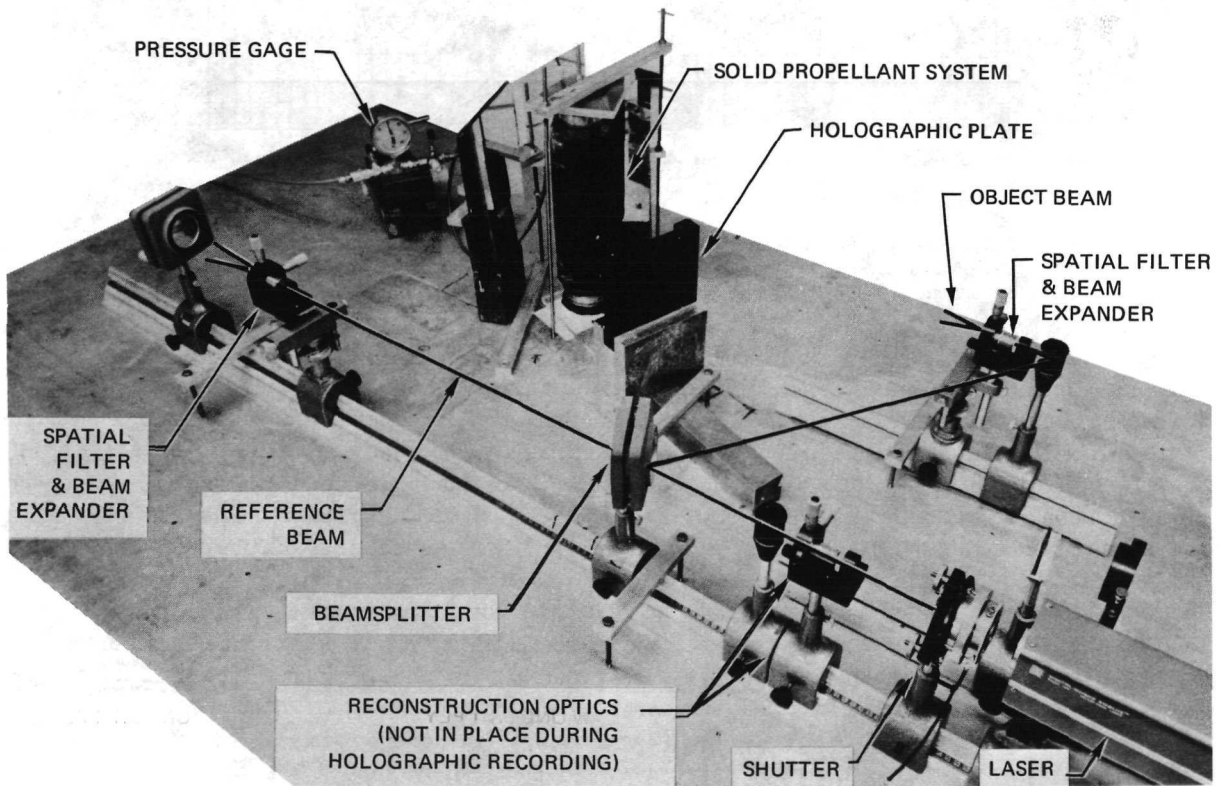


Figure 9.—A typical holographic inspection system, shown as set up for the examination of a solid-fuel propellant grain.

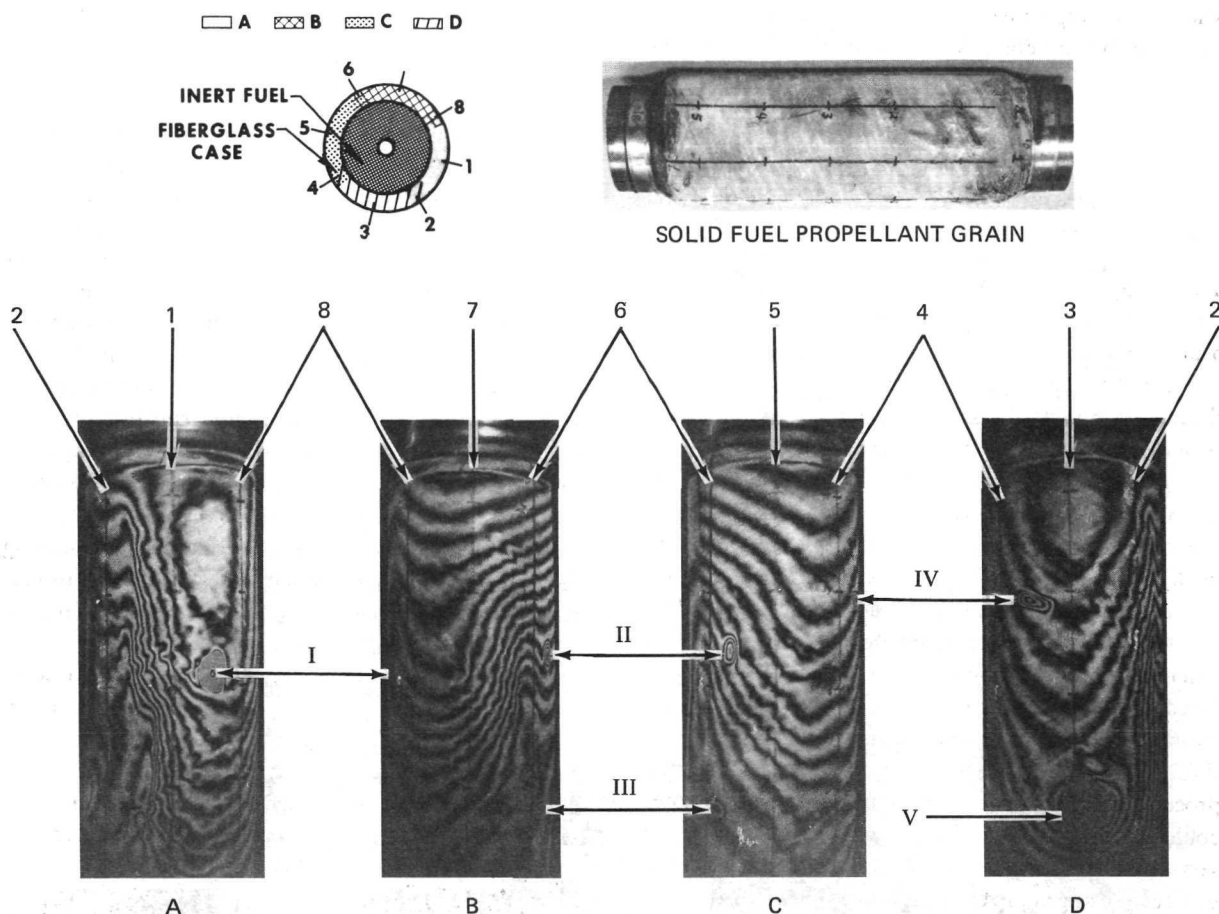


Figure 10.—Reconstructions illustrating the successful application of HNDT to the identification of five intentionally placed disbonds between a solid-fuel propellant and its polymer liner. Areas of disbond (produced by Teflon inserts) are denoted by Roman numerals.

any time after casting of the propellant grain due to residual stresses associated with the curing process. If left undetected, this type of disbond could propagate during motor ignition and cause a ballistic malfunction which could abort the flight.

The HNDT procedure involved reducing the internal pressure by 3447 N/cm^2 and using the double-exposure (before and after the pressure change) interferometric holographic technique to record the accompanying surface deformation of the fiberglass case. The results are shown in figure 10. The five areas of disbond are clearly visible in the four holographic reconstructions covering the entire surface of the sample; they correlated exactly with the programed disbonds, both in location and size. In addition to the above procedure, real-time holographic interferometry was employed and other

stressing techniques evaluated. The results showed that using an internal pressure higher than atmospheric yielded the same results as above. The significance of this result is that, alternatively, the pressure on the outside of the case could have been lowered to produce the same stress distribution for inspection. This suggests an extremely valuable procedure for the inspection of large cases where it may not be convenient to reduce or raise the internal pressure. In addition to the programed disbonds, two cracks developed on the inside surface of the propellant wall during the curing process. Interferometric holographic observation of the fiberglass case with a 2.8-N/cm^2 (4-lb/in^2) differential between exposures revealed the presence of these cracks. The potential of detecting internal propellant cracks from the outside of the case may be of particular significance

when inspecting some of the more sophisticated grain structures having complicated hollow core configurations.

Turbine Blades

Holographic techniques have been extensively employed to study various turbine blade characteristics. The successful application of interferometric holography to stress and strain measurement, vibration analysis, and elevated temperature studies has been demonstrated and reported earlier (refs. 13 and 14). Building upon these results, additional work has shown its potential use for evaluating the internal structural characteristics of hollow turbine blades. This becomes important when one considers that recent progress in improving gas turbine efficiencies is the result of higher turbine inlet temperatures, a step made possible through improved materials and cooling techniques. These latter advancements are a result of sophisticated internal turbine blade cooling schemes which call for elaborate cooling passages, bleed holes, and precisely controlled thin-walled structures. Current manufacturing techniques for these blades incorporate ceramic cores in the casting process, and a slippage or misalignment of these cores could result in too thin a wall, thus impairing serviceability. Inspection for this type of defect is difficult using conventional X-ray and ultrasonic techniques, since (1) the lack of change in the total amount of material makes X-ray techniques ineffective, and (2) the thinness of the wall lowers the sensitivity of acoustic pulse echo techniques.

For example, ultrasonic inspection of thin materials requires frequencies in the megahertz range; however, interpretation of these frequencies is extremely difficult, if not impossible, considering the roughness and complexity of the supporting structure on the inaccessible side of hollow structural components such as jet engine turbine blades. The use of ultrasonic plate vibrations for nondestructive inspection is relatively unexplored to date because the complexity of the acoustic propagation makes interpretation of the signal as received at a point very difficult and also because the inability to define boundary conditions with reasonable accuracy prevents the analytical prediction of the vibrational modes. However, by combining holography with ultrasonic plate wave excitation, turbine blade wall thickness differences between the pressure and suction sides have been exhibited and pulsed holography,

in combination with acoustic traveling waves, has been used to observe material thickness variations.

ULTRASONIC PLATE WAVES

A representative result from investigations to determine the applicability of ultrasonic plate wave stressing to cooling passage alignment inspection in hollow turbine blades is illustrated in figure 11. Reconstructions of holograms recorded of both sides of a blade are shown for a resonant frequency of 18 900 Hz. At the middle of the blade near the root, the pressure wall is approximately 20 percent thinner than its suction wall. The ultrasonic driving amplitude was approximately the same when the hologram of each side was made. This can be seen by comparing the corresponding fringe patterns at the leading and/or trailing edges (solid regions) for both sides of the blade; they are essentially identical, representing equal driving amplitudes. However, those modes which occur on the pressure side over the hollow portion of the blade have a noticeably larger amplitude than the same modes on the suction side, due to the thinner wall. Furthermore, the vibration amplitude increases on both sides of the blade as the wall thickness decreases from the root to the tip.

While the results described above are qualitative in nature, they demonstrate the potential of interfero-

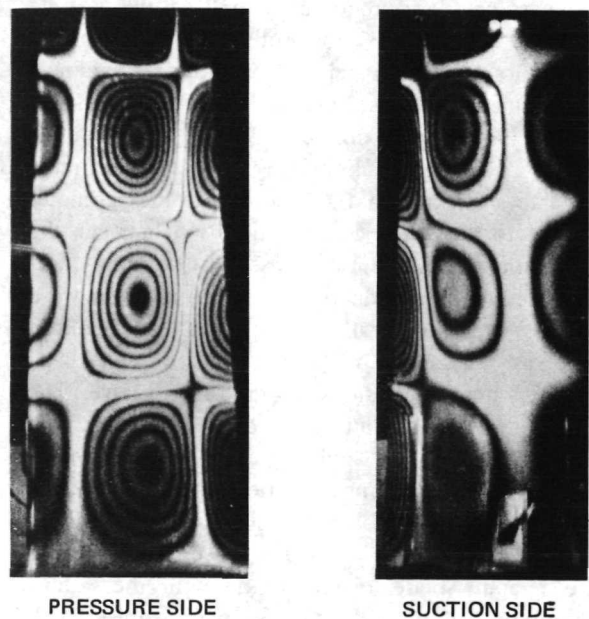


Figure 11.—An example illustrating the potential of CW interferometric holography and ultrasonic plate waves to determine thickness profiles.

metric holography to map a surface instantaneously and thereby determine the thickness profile of components with an inaccessible side. Also of importance is the relatively low frequency range which this combination of ultrasonics and holography affords, since it permits one to neglect the effects of grain scattering and attenuation in metals. These are factors that would tend to limit resolution in the more conventional pulse echo and transmission types of ultrasonic testing, which require frequencies of 5 MHz and higher to detect a 20-percent change in thickness. In addition, diffraction effects from substrates and/or abrupt geometry and thickness changes would further limit the portion of a particular component that could be accurately measured at megahertz frequencies.

In addition to the use of ultrasonic plate wave excitation with time-average holography, studies of acoustic traveling waves with pulsed holographic techniques for wall thickness measurement have been initiated. A brief review of this work is presented below.

Acoustic Traveling Waves

By employing pulsed interferometric holography to map a surface excited with acoustic traveling waves, it has been shown possible to determine the thickness profile of components with an inaccessible side. An example of this potential application of ultrasonics and holography to material thickness measurement is illustrated in figure 12. A small circular area (approximately 2.5 cm in diameter) within a 1.27-mm-thick aluminum plate was thinned down to a thickness of 0.635 mm, with the perimeter beveled to provide a gradual transition between the two thicknesses. Pulsed laser holography was employed with a simulated traveling acoustic wave type of excitation, rather than a standing acoustic wave as was done with the turbine blade wall thickness measurement work described above. The traveling wave was simulated by driving the plate with a CW oscillator and applying edge damping on all sides of the plate to prevent reflection of the acoustic energy. Each interferometric hologram was constructed by making two pulsed laser exposures on a photographic plate, one exposure with the sample stationary and the other while it was subjected to acoustic excitation. The holographic reconstructions shown are typical of the results obtained. They show the effect of "catching" the plate at different points

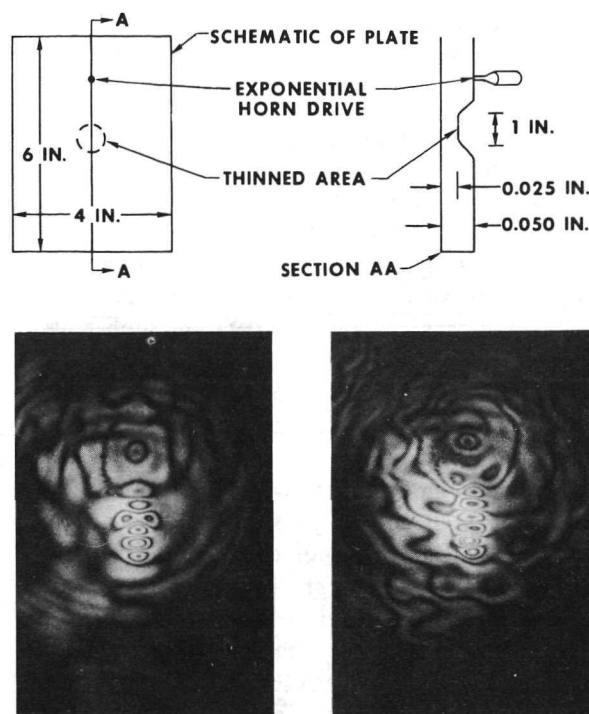


Figure 12.—An example of the use of pulsed holography and acoustic traveling waves for the measurement of material wall thickness.

in its vibration cycle. An ultrasonic driving frequency in the 50-to-60-kHz range was employed, and the timing of the second, short-duration (20-ns) exposure determined at what point the traveling acoustic wave with its resultant effect on surface deformation was recorded. As evident in the photographs, the trapped energy in the thinned area appears as a discrete mode, well defined and easily identified.

HOLOGRAPHIC FLOW VISUALIZATION

Shadowgraph, schlieren, and interferometric techniques have long served the aerodynamicist as an invaluable tool in gas dynamic studies, providing a means for visualizing flow patterns and determining density gradients. It is not surprising, therefore, that considerable effort has been expended on integrating these highly sensitive flow visualization systems with the high-speed, three-dimensional recording and storage capabilities of pulsed holography. Many techniques have been investigated at UARL and elsewhere (refs. 15, 16, and 17), each including some combination of the following: diffuse or direct source illumination; single or double-pulse exposure; and one or two holographic plates.

We will describe a method incorporating a single-pulse exposure with direct, undiffused source illumination requiring one holographic plate. Use of a singly exposed hologram does not sacrifice the potential of interferometric analysis because the hologram stores all of the information regarding the object flow field, and it can be extracted in several ways. The hologram in this case is a shadowgraph modulated by the superposition of the reference wavefront. The shadowgraph information can be extracted by simply photographing the recorded image using noncoherent light. Using holographic reconstruction techniques, the stored information can be extracted using either schlieren or interferometric techniques. To obtain the schlieren information, a lens is inserted into the reconstructed beam, a knife edge is inserted into the focal point, and the schlieren information is extracted at the image plane of the lens. This technique has a further advantage in that the knife edge can assume various directions with the guarantee that the acquired data can be properly correlated, since all the data were obtained under the same test conditions. In the interferometric case, a portion of the wave used to illuminate the hologram is redirected around the hologram and then recombined with the reconstructed beam to form the interferogram, so that the desired quantitative information regarding the density can be obtained. This method has the advantage that the interferometric apparatus can be set up and the interferograms constructed using the hologram in a controlled environment, away from the test stand, so that a detailed analysis can be accomplished. All the techniques of classical interferometry related to either finite- or infinite-fringe interferometry can be utilized in the reconstruction process to provide analysis in various ways so that accurate fringe counting can be achieved.

The use of undiffused source illumination has the advantage of a lower pulse energy requirement, while the single-exposure feature, with interferometric analysis introduced during reconstruction as described above, eliminates the problem of vibration which is inherent in the double-exposure technique using either diffused or undiffused illumination. For example, in gaseous systems, the two exposures are often made under flow and no-flow conditions. However, in hostile environments containing considerable vibration, precautions must be taken to prevent any components in the optical system from changing their

position between the two exposures, in order to preclude the introduction of a second set of interference fringes which may mask completely the effects in the object field. This vibration problem can be avoided by utilizing a very rapid double-pulse exposure. However, successful application of this technique relies on rapid changes in density within the flow field itself to produce the interference upon reconstruction. Thus, in steady-state flow situations, or in those cases where the flow conditions vary too slowly to effect a sufficient density change between pulses, the technique would be unsatisfactory.

A distinct disadvantage of the direct, undiffused-source technique, relative to the diffuse method, is the loss of the three-dimensional characteristic associated with holography. This disadvantage has been overcome by a further development which utilizes two object beams to provide the sharp-focusing capability associated with the multiple-source schlieren method. Use of this more conventional, well established technique does not mean that the holographic advantage has been denied, and therefore that holography serves no useful purpose. Indeed, the three-dimensional storage characteristic now permits all planes within the flow field to be examined with a single hologram, rather than requiring a multiplicity of schlieren photographs, one for each flow plane of interest, while maintaining constant tunnel flow conditions, as in conventional multiple-source schlieren systems.

Pulsed Laser Holographic System

A schematic diagram of the single-mode, Q-switched ruby laser system is shown in figure 13 along with a photograph of the system. In addition to the ruby rod and cavity end mirrors, there are the following: (a) a bleachable dye cell (cryptocyanine in methanol) for passive Q-switching, (b) an aperture to control the transverse mode structure by reducing the number of off-axis modes, and (c) a Glan-Laser polarizer which serves as a Fabry-Perot (F-P) etalon to select a single axial mode. With this system, the two prime requirements for good holograms are met: (1) uniformity of phase in the direction of wavefront propagation, which provides the good temporal coherence needed for large depth of field; and (2) uniformity of phase in the direction transverse to wavefront propagation, which provides the good spatial coherence needed for wavefront matching in the reconstruction process. The pulsed ruby laser

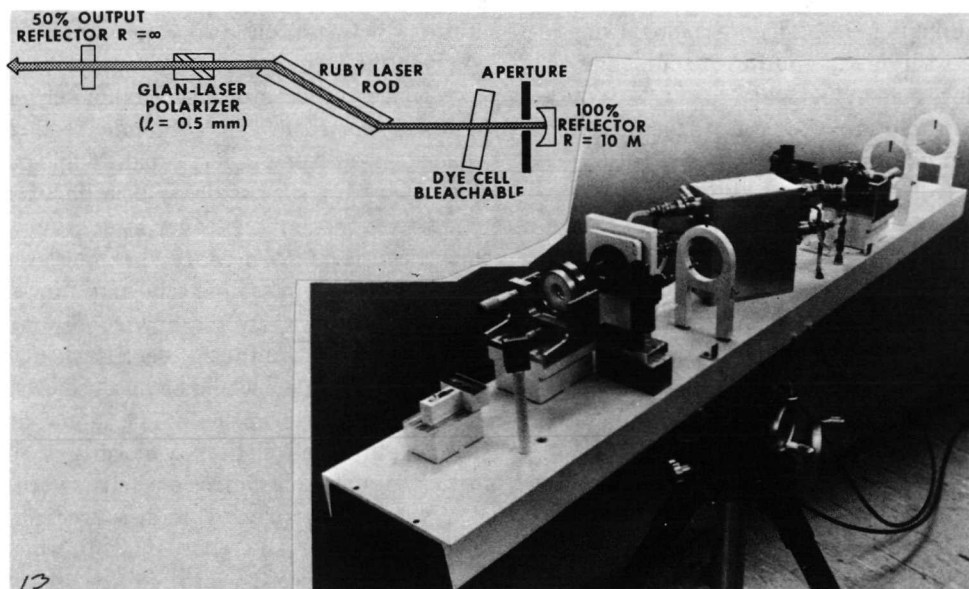


Figure 13.—The single-mode 20-ns pulsed ruby laser system developed at UARL for flow visualization studies.

holographic system has a coherence length of 1.5 m (sufficient for a 3-m depth of field, or a comparable size mismatch in the reference and test beam path-lengths), a pulse duration of 20 ns, and an output energy of approximately 40 mJ.

Divergent-Convergent Single-Beam System

An optical schematic illustrating a typical holographic schlieren recording system of the divergent-convergent beam type is shown in figure 14. Except for the use of a parabolic rather than a flat mirror at a position just to the right of the test area, it is a conventional system for constructing holograms in transmitted light. (The solid lines represent a conventional schlieren system, with the additional beam required for holography and the photographic plate shown dashed.) When used as a holographic schlieren system, the test beam wavefront will be converging as it is incident on the photographic plate. After construction and photographic processing of the hologram, its illumination with a CW laser beam reconstructs the converging object beam, which comes to focus at the focal plane of the reconstructed mirror. It is this reconstructed object beam which possesses the characteristics of a schlieren system; that is, a knife edge can be inserted into the focal point so that density variations, which may have been present in the object field during construction of the

hologram, can be observed. Referring to the figure, the test beam, after traversing a beamsplitter (M-2) and negative lens (L-1, to provide beam expansion), is directed through the test area by mirror M-1 to the parabolic mirror (30.5 cm diameter; 2.44 m focal length), which provides the required wavefront convergence and directs the test beam to the photographic plate. No modifications, other than beam expansion provided by lens L-2, are required on the reference beam. A narrow-band interference filter, tuned to the 694.3-nm ruby laser wavelength, was installed immediately ahead of the photographic plate so that the system could be operated in ambient light. The holograms were constructed on Agfa 10E75 photographic plates.

Figure 15 shows the test setup for conducting a pulsed holographic schlieren investigation at the UARL Model Rotor Hover Test Facility. The object beam path from the laser to the photographic plate is indicated in the figure; the reference beam (not shown) traverses a comparable distance, within the coherence length of the laser, to the photographic plate. This example clearly demonstrates the adaptability of pulsed laser holographic techniques to a hostile environment. All of the optical components, including two massive 46-cm-diameter folding mirrors, were mounted in a temporary fashion using lightweight structures and scaffolding. Total optical

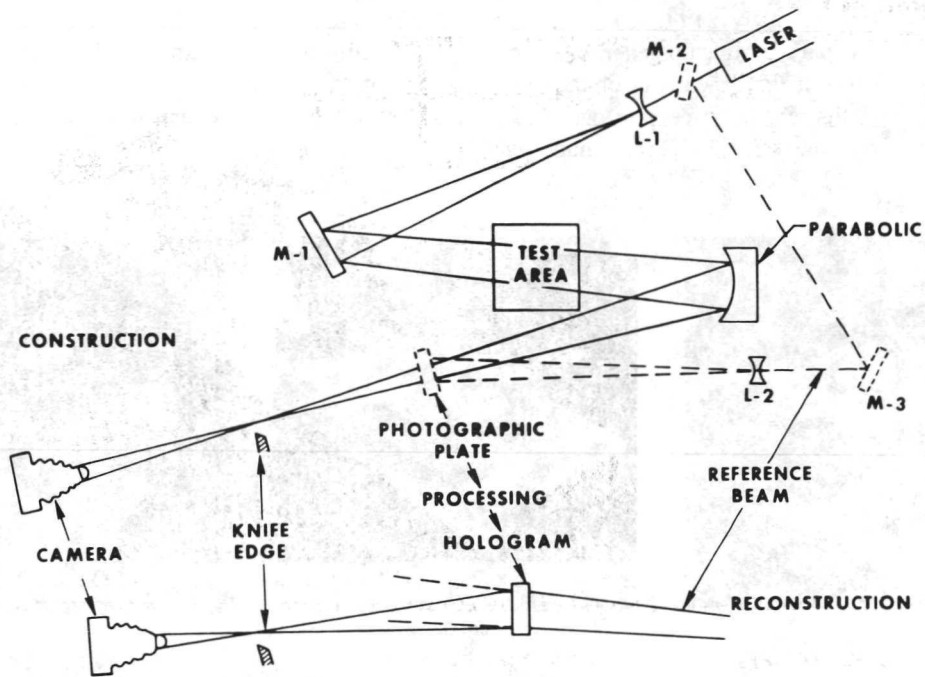


Figure 14.—The divergent-convergent holographic schlieren technique.

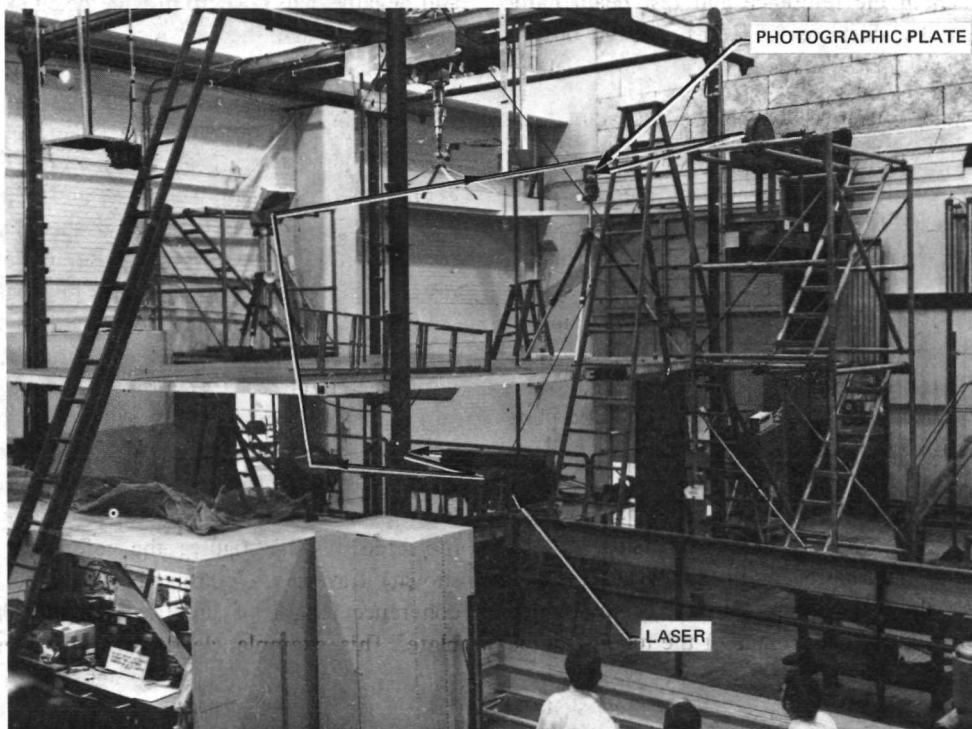


Figure 15.—The holographic schlieren system installed at the UARL Model Rotor Hover Test Facility showing the object beam path from the pulsed laser to the photographic plate. The reference beam traverses a comparable 21-meter pathlength to the photographic plate.

pathlength was approximately 21 m. A typical result showing the helical path of the tip-generated vortex core as it propagates in the downwash of the model rotor is shown in figure 16. Three photographs, all reconstructed from the same hologram, have been

included to indicate the versatility afforded in both the knife-edge orientation and degree of cutoff. Two orientations (from above and from below) are shown, along with one reconstruction exhibiting no cutoff (shadowgraph).

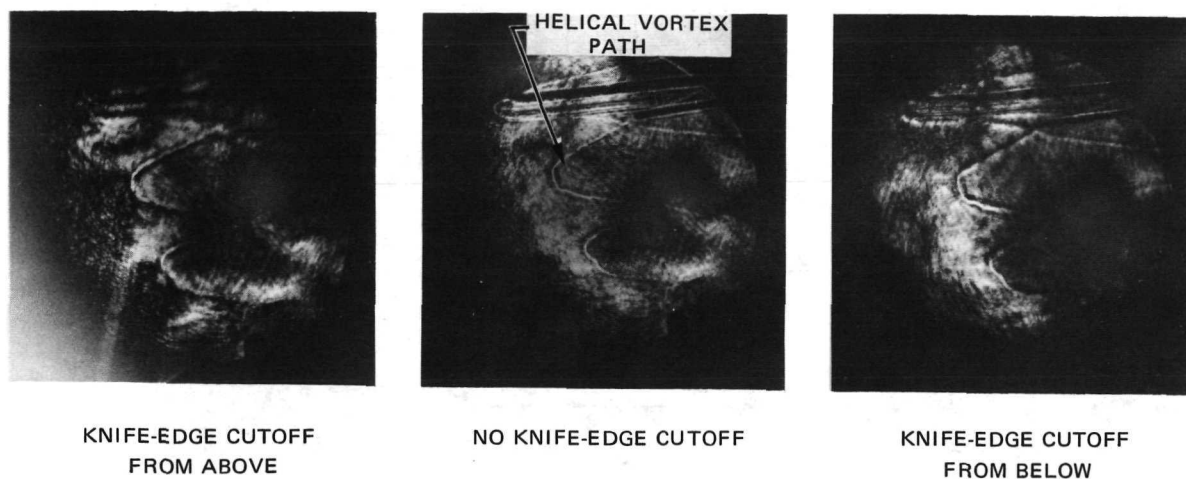


Figure 16.—Typical results, all reconstructed from the same hologram recorded with the holographic schlieren system illustrated in figure 15, indicating the versatility afforded in both knife-edge orientation and degree of cutoff in studying the helical path of a tip-generated vortex core.

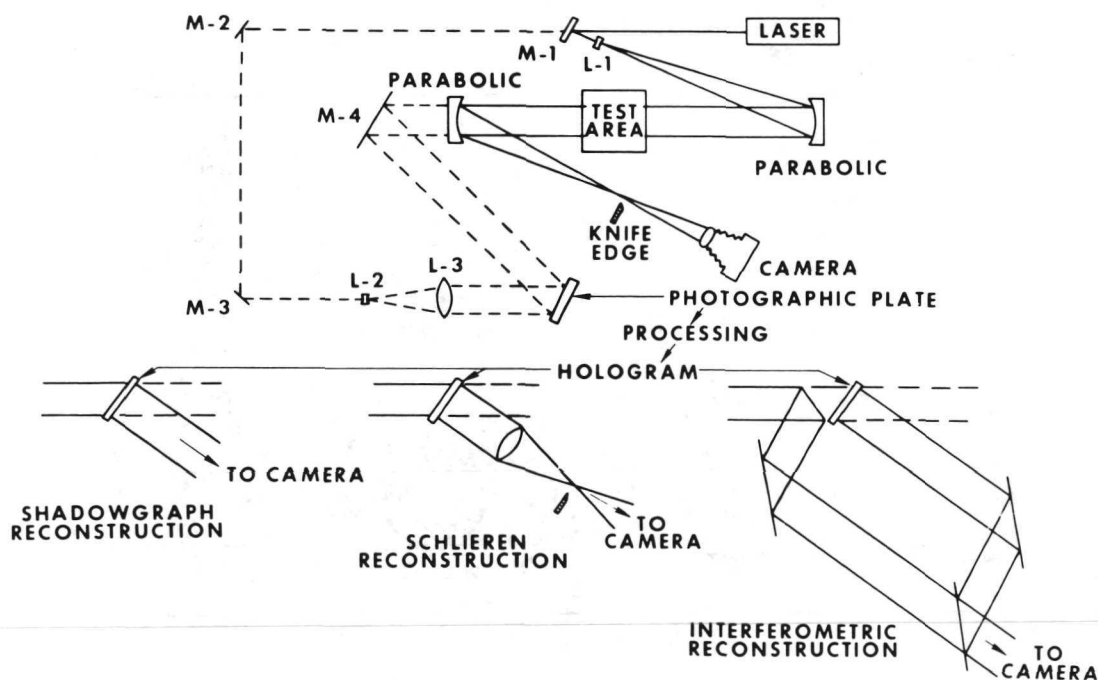


Figure 17.—The three types of analysis possible in the reconstruction process with one singly exposed hologram.

Collimated-Beam System

Conversion of the above system to a collimated-beam configuration can be accomplished with the simple addition of a parabolic mirror in the object beam path before it traverses the test area. Such a setup is diagrammed in figure 17, where the solid lines represent a conventional schlieren system which can be converted for holography by the addition of a reference beam path and photographic plate as shown with the dashed lines. In addition to the advantage of low energy requirements on the laser source for this transmission type of holography, the use of a collimated beam permits interferometric as well as shadowgraph and schlieren analysis of the singly exposed hologram in the reconstruction process.

Typical setups for performing these three types of analysis are shown in figure 17.

The results obtained from applying this type of system to the study of a supersonic wind tunnel flow field are shown in figure 18. As in the previous example, all of the reconstructions were recorded from one singly exposed hologram. In addition to the shadowgraph and two schlieren pictures, an interferogram has been included. The shock wave generated at a step in the tunnel sidewall is clearly visible in all of the reconstructions. Furthermore, a qualitative indication of the weakness of the shock is immediately apparent by the slight fringe exhibited in the interferogram; calculation would permit a quantitative measure of the density variation across the shock. As noted in the figure, one of the schlieren reconstruc-

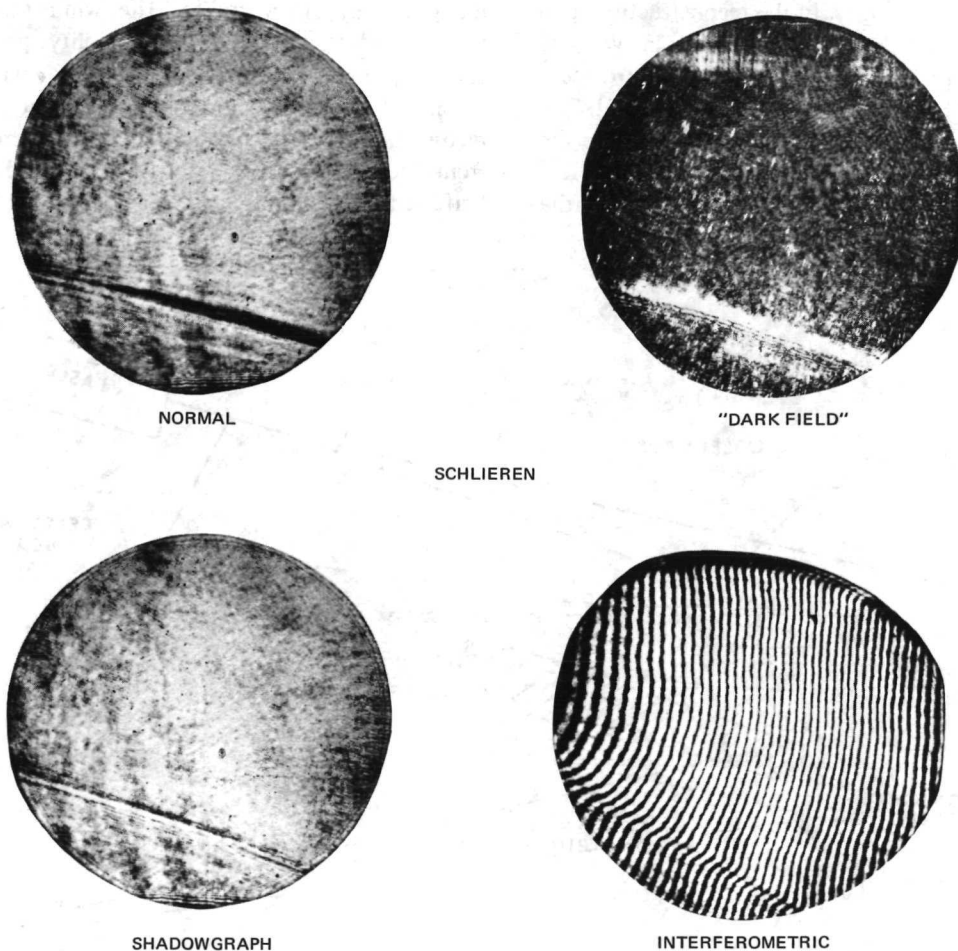


Figure 18.—Schlieren, shadowgraph, and interferometric reconstructions from a singly exposed hologram recording of the shock wave generated in a supersonic wind tunnel flow facility.

tions resembles a dark-field system wherein the entire schlieren source image has been blocked, allowing only the refracted, or disturbed, portion of the beam to pass.

Divergent-Convergent Dual-Beam System

Since the schlieren technique (conventional or holographic) usually incorporates small-cone-angle optical components (large f -number) to increase the sensitivity, the reconstructed image when using holography will have a large depth of field. To take advantage of the three-dimensional aspect of holography, the divergent-convergent single-beam system described previously can be modified, as in the conventional multiple-source schlieren, to provide a sharp-focusing capability.

As shown in figure 19, two object beams can be derived from the same source to traverse the test area at slightly different angles. In the reconstruction, two knife edges are used to cut off the source images, and a lens is used to image the two beams to provide a short depth of focus within the schlieren field. The depth of focus will be inversely proportional to the angular divergence between the two beams.

Experimental tests were conducted using the

above optical configuration to demonstrate its effectiveness in extracting three-dimensional information on a UARL supersonic cascade wind tunnel. Typical results from these tests are presented in figure 20, which shows two photographs of holographic-schlieren reconstructions recorded from the same hologram. The two photographs represent two different focal positions within the object field, illustrating the sharp-focusing capability and therefore the ability to examine the flow field in detail during the reconstruction process. One reconstruction is in focus near the far tunnel wall (note the sharpness of the pressure taps mounted in the wall), while the other is in focus near the tunnel midspan.

In summary, holographic flow visualization, successfully integrating the sensitive analytical schlieren and interferometric processes with three-dimensional holography, provides a unique tool for application to many gas dynamic studies. The wind tunnel and hover stand tests indicate the versatility, portability, and adaptability of the system to an environment outside the optical laboratory. Furthermore, in the reconstruction process, which can be performed away from the test facility, both schlieren, with various knife edge positions, and interferometric analysis

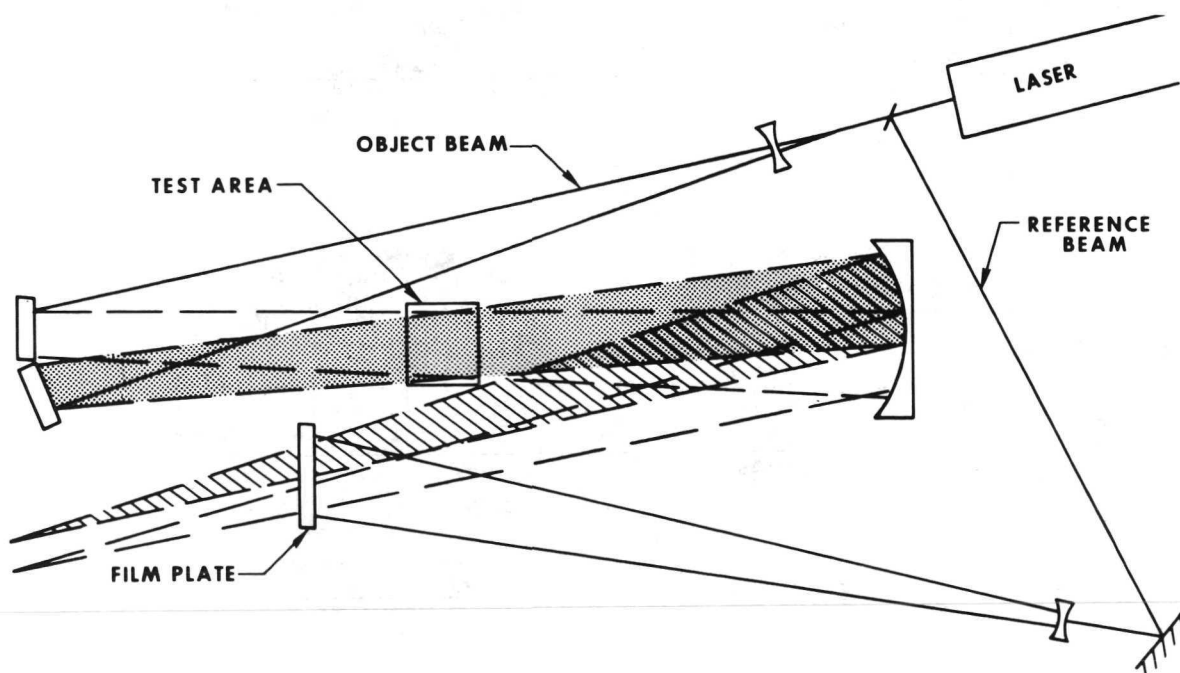


Figure 19.—Diagram of dual-beam holographic schlieren technique.

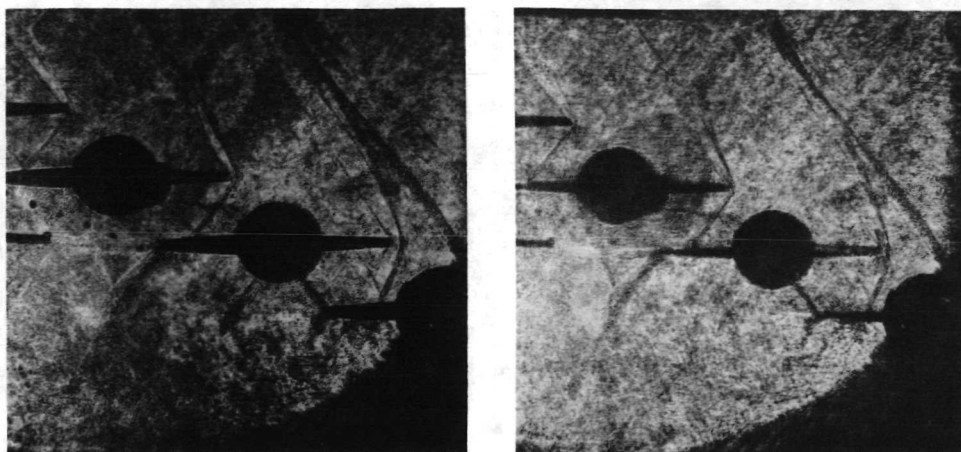


Figure 20.—Two reconstructions, recorded from the same hologram of a supersonic cascade wind tunnel, showing the capability to focus on different planes in the flow field. The left photo is in focus near the far wall of the tunnel, and the reconstruction at right is focused near the tunnel midspan. The hologram was made by the technique shown in figure 19.

systems can be used to examine the flow field at various image planes in detail, without the need for repeated test runs.

CONCLUSIONS

Two specific areas of application for the holographic process have been described, and illustrative examples, typical of the many potential uses in these two areas, have been presented. First, it was amply demonstrated that interferometric holographic techniques taken in combination with various stress mechanisms offer considerable promise in the area of nondestructive testing. Indeed, the approach offers a powerful technique with which to explore many areas that have been previously inaccessible, or have had restricted access, by other more conventional NDT techniques. Specific examples included composites, metallic and rubber bonding processes, and cooling passage alignment in hollow turbine blades.

In the second area, it was shown that pulsed holography coupled with the schlieren and interferometric methods offers a viable technique for three-dimensional flow visualization studies, and further, that pulsed holography itself offers a satisfactory

answer to the question of whether the somewhat delicate holographic process is amenable to the more hostile environment of an operating test facility or the production floor. In summary, holography offers significant advantages in many areas of concern to the aerospace industry. Which particular experimental configuration or process is employed will depend upon the particular situation. However, this new tool, holography, is now available and well established; therefore, it must be considered along with other, longer established, more widely used techniques when seeking solutions to specific engineering problems.

ACKNOWLEDGEMENTS

The extensive contributions to the work described herein by H. Aas, R. Leighton, F. Michael, and G. Whitney, all of the UARL staff, are gratefully acknowledged. Thanks are also due to the Langley Research Center of NASA, who supplied two of the composite samples and one of the honeycomb panels tested; the Materials Laboratory at Wright Patterson Air Force Base for one of the honeycomb panels; Pratt and Whitney Aircraft for the composite fan blades; and United Technology Center for the solid propellant grain.

REFERENCES

1. Foster, M.: Pulsed Laser Holography Applications, *J. Opt. Soc. Am.*, Vol. 59, 1969, p. 1540.
2. Powell, R.; and Stetson, K.: Interferometric Vibration Analysis by Wavefront Reconstruction, *J. Opt. Soc. Am.*, Vol. 55, 1965, p. 1593.
3. Waters, J., Aas, H.; and Carriker, R.: Holographic Determination of Strain, *J. Opt. Soc. Am.*, Vol. 59, 1969, p. 1540.
4. Hildebrand, B.; and Haines, K.: Multiple-Wavelength and Multiple-Source Holography Applied to Contour Generation, *J. Opt. Soc. Am.*, Vol. 57, 1967, p. 155.
5. Takasaki, H.: Moiré Topography, *Applied Optics*, Vol. 9, 1970, p. 1467.
6. Marom, E.: Real-Time Strain Measurements by Optical Correlations, *Applied Optics*, Vol. 9, 1970, p. 1385.
7. Erf, R. K.; Waters, J.; and Aas, H.: Bond Inspection by Dynamic Time-Average Interferometric Holography of Ultrasonically Excited Plates, *J. Acoust. Soc. Am.*, Vol. 47, 1970, p. 968.
8. Erf, R. K.; and Waters, J. P.: Holographic Characterization of Aerospace Components, ASME Publication 71-GT-74, Mar. 1971.
9. Aas, H. G.; Erf, R. K.; and Waters, J. P.: Investigation to Determine the Feasibility of Employing Laser Beam Holography for the Detection and Characterization of Bond Defects in Composite Material Structures, Contract NAS1-9926. NASA CR-111836. Feb. 1971.
10. Morse, Philip M.: *Vibration and Sound*, 2nd Edition, McGraw-Hill Book Co., Inc., New York, 1948, p. 210.
11. Skudrzyk, Eugene: *Simple and Complex Vibratory Systems*, Penn. State University Press, University Park, 1968, p. 249.
12. Schulz, W. J.; Mangiapane, J. A.; and Stargardt, H.: Development of Borsic®-Aluminum Composite Fan Blades for Supersonic Turbofan Engines, ASME Publication 71-GT-90, Mar. 1971.
13. Waters, J. P.; and Aas, H. G.: Holographic Analysis of Turbine Blades, ASME Publication 71-GT-84, Mar. 1971.
14. Waters, J. P.; Aas, H.; and Erf, R. K.: Investigation of Applying Interferometric Holography to Turbine Blade Stress Analysis, Contract N00019-69-C-0271, UARL-J990798-13, Feb. 1970; AD 702 420.
15. Chow, H. H. M.; and Mullaney, G. J.: An Example of the Application of Pulsed Light Holography to Aerodynamics, *Applied Optics*, Vol. 6, 1967, p. 981.
16. Reinheimer, C. J.; Wiswall, C. E.; Schmiede, R. A.; Harris, R. J.; and Decker, J. E.: Holographic Subsonic Flow Visualization, *Applied Optics*, Vol. 9, 1970, p. 2059.
17. Havener, A. G.: Holographic Applications in Shadowgraph, Schlieren and Interferometry Analyses of Heat Transfer and Fluid Flow Test Subjects, Aerospace Research Laboratories Report 70-0270, Nov. 1970.

Review of Holographic Instrumentation at Arnold Engineering Development Center

J. D. Trolinger

Arnold Research Organization, Inc.

During the past four years holographic instrumentation systems have been employed in 12 different test facilities at the Arnold Engineering Development Center (AEDC). In addition, a large number of applications have been researched to improve the systems which are presently in use and to determine the feasibility of new applications. Operational systems and research include the application of holography to particle sizing, three-dimensional visualization, flow visualization, nondestructive testing, and optical data processing. This paper is a summary of the systems and research. New techniques which have evolved in the development of these systems are discussed. Emphasis is placed on those systems in which holography has provided a data capability which was not obtainable by other methods.

Investigations into the application of holography and other laser instrumentation in the AEDC instrumentation program were begun in early 1967 by the Managing Director's Technical Staff, Experimental Research Branch (TS/ER). In the intervening years TS/ER, working jointly with the three test facilities, von Karman Facility (VKF), Engine Test Facility (ETF), and Propulsion Wind Tunnel Facility (PWT), has developed operational holographic systems which have been applied in many AEDC test programs and have become an integral part of the AEDC instrumentation capability. To date, seven operational holographic systems, all but one of which are portable, have been applied to testing in 12 different wind tunnels and test chambers, performing many tests to provide data which had not been obtainable previously. Each test facility now maintains a working group trained in the applications of holographic instrumentation to testing. TS/ER continues basic research in refinement, new techniques, materials, processes, and new applications feasibility, all oriented toward improvement of the AEDC holographic instrumentation capability. The demonstration of the feasibility of an application or technique under

controlled laboratory conditions is at best a meager beginning. To be operational in a test facility, an instrument must function in a new, often harsh environment with new constraints; it must be more reliable and more automatic, and sometimes must be operated by remote control, timed to function in the test sequence. Such problems, as well as the final data requirements themselves, are best understood by instrument groups that work directly in the facilities. Therefore test-related research and development are conducted by the facilities to bridge the gap between the feasibility study and operational capability. All activities in holography and other laser instrumentation are coordinated through the Arnold Research Organization (ARO) Laser Applications Committee, which includes representatives from each facility and TS/ER. The committee provides interfacility communication, exchange of ideas and equipment, and recommendations for concentrated research and development and future activities in laser applications.

The various tests and research activities at AEDC are well documented. In the paragraphs that follow, the basic types of instruments are described and a

summary of activities is given, with references to associated reports and publications for the reader who is interested in specific details.

APPLICATIONS OF IN-LINE HOLOGRAPHY

In-line holography is ideal for the high-resolution analysis of a dynamic, nearly transparent, three-dimensional field of light-scattering elements (ref. 1). Three-dimensional observation of many types of particle fields is required in experimental aerodynamics and mechanics (ref. 2). These areas include the development of particle, filament, or aerosol generators for the study of natural or simulated environments and for observation of the spontaneous occurrence of particulate matter in explosions, plasmas, rocket and engine exhausts, and in wind-tunnel or similar research facilities. The particulate content in any field affects its aerodynamic properties, often to the extent that it must be considered in calculating

important parameters such as heat transfer, drag, thrust, ablation rates, and mixing and burning rates. Other areas of application include the study of pollution, condensation, nucleation, and reaction phenomena. Calibration or even simple visualization of these effects has for years presented great difficulty, especially in blow-down facilities and highly dynamic events.

Figure 1 illustrates a portable in-line image holocamera of the type under discussion. The basic pulsed laser is a Korad K1QH ruby laser. Depending on the type of Q-switch used, pulsewidths range from 10^{-8} to 10^{-7} s. Recent advances can provide pulsewidths below 10^{-11} s. A low-power continuous-wave laser, F, is temporarily introduced into the system for alignment. The beam is directed into the laser cavity by mirrors B and D. After alignment, mirror D is removed and the ruby laser beam retraces the same path through the optical system. The output beam is

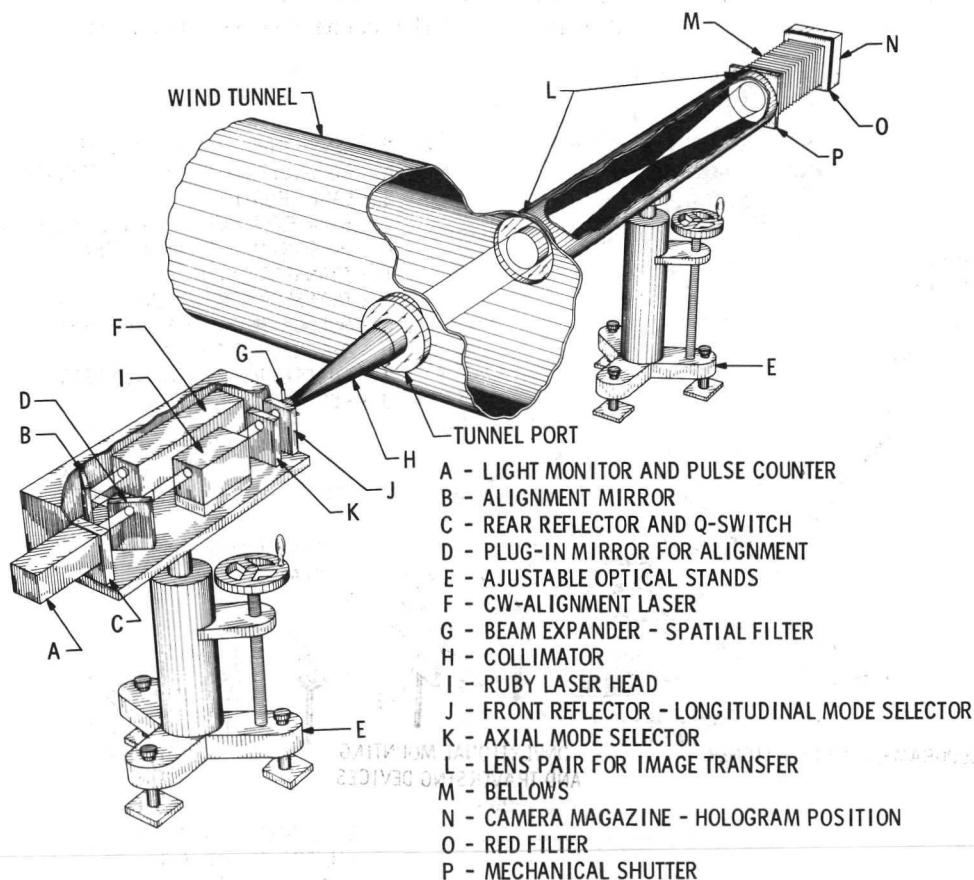


Figure 1.—In-line image holocamera.

expanded by lens G, which focuses the beam through a 0.1-mm pinhole for spatial filtering. The beam, collimated by lens H, passes through the subject field. Part of the light is scattered by particles, while the remainder passes through to serve as a reference beam. The lens pair L transfers the subject field to the vicinity of the hologram at N. There are many variations of the basic scheme, depending on test requirements, and in some cases the lens pair L is removed altogether. Filter O and shutter P allow the system to function in ambient light.

The reconstruction is performed by illuminating the hologram with light closely duplicating the reference beam. Figure 2 depicts a general hologram analysis system for either in-line or off-axis holograms. For the case under discussion, the hologram is positioned perpendicular to the collimated reconstruction beam, and the reconstructed beam is directed into the analyzer. The analyzer may incorporate a camera, a microscope, or, in the most advanced systems, a television system which is traversed through the reconstructed three-dimensional image.

The more elaborate systems include electronic circuitry to analyze the image appearing on the TV monitor and provide a complete count and size distribution analysis in a fraction of a second (ref. 3). In some cases the reconstructed is filtered by components $\ell 1$, E, and $\ell 2$ before being analyzed.

Figure 3 is a photograph of a hologram produced by the system of figure 1 in a hypersonic dust erosion facility. The hologram itself is a coherent shadowgram and, as such, provides flow field information. The bow shock on the model and shock waves associated with rebounding dust particles can be observed. The impinging and rebounding particles as well as the shock waves themselves can be located in three dimensions in the reconstruction. Figure 4 is a photograph of a plane of particles observed in the reconstructed image. The system resolution limit was $10\text{ }\mu\text{m}$. Figure 5 is a photograph of a rebounding dust particle and its associated shock as it reentered the free stream. The total depth of field in this hologram exceeded 100 cm.

The in-line reconstructed image of large objects

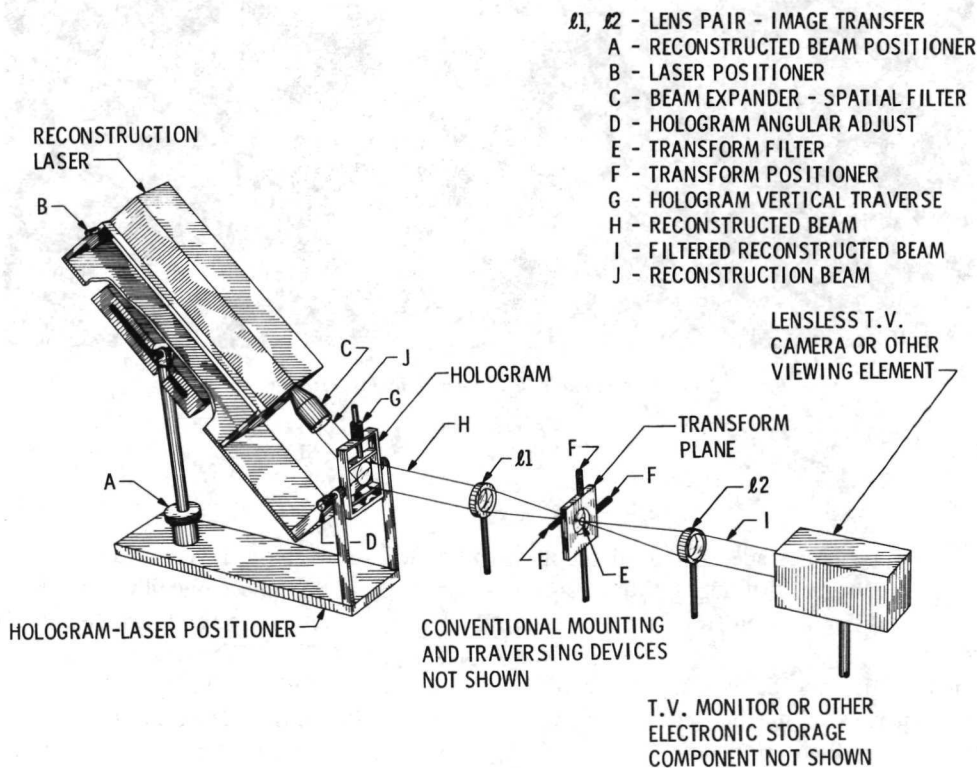


Figure 2.—Hologram analyzer.

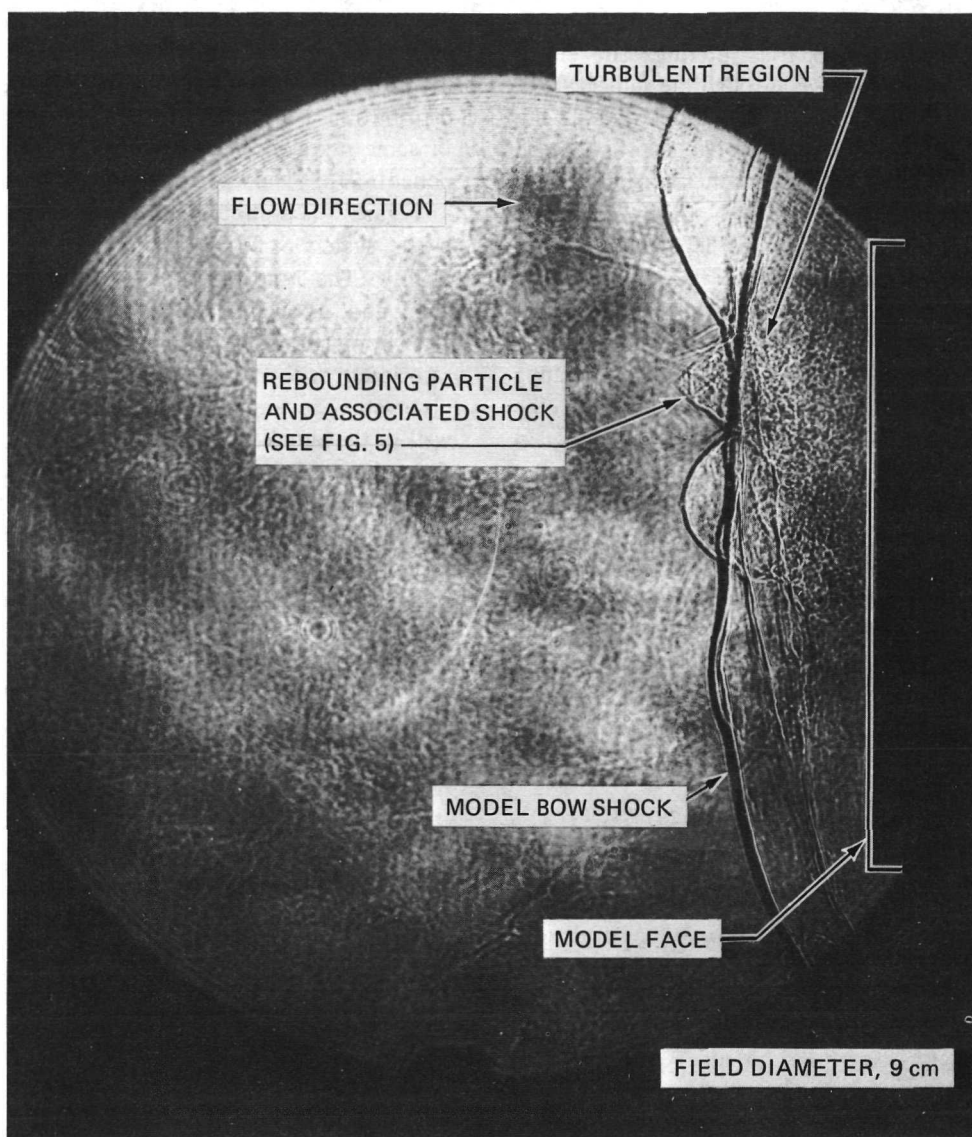


Figure 3.—Hologram made in a hypersonic dust erosion facility.

(Fresnel objects) appears degraded if viewed directly, but optical or electronic filtering techniques can virtually remove this degradation (refs. 4 and 5). The reconstructed image appears as an outline of the object which was holographed. Applications lie in the high-resolution analysis of the outline of a dynamic object such as an in-flight projectile (ref. 6). For example, in the study of ablation of projectiles in

flight, photography provides high-resolution observation only if the object location normal to the camera focusing axis is precisely known. This limitation does not apply to holography, since the viewing system can be focused accurately on the reconstructed outline. Resolution limitations caused by motion during the recording are similar for holography and photography (ref. 6). Studies have shown that the

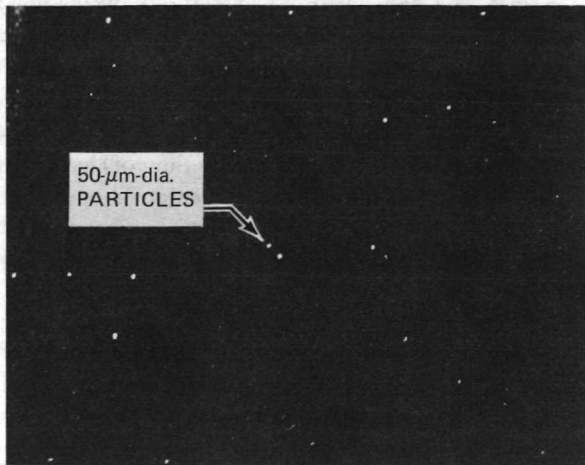


Figure 4.—Sample plane from reconstructed image of figure 3.

edge of a projectile traveling at 15 km/s can be located through holography with a motion-limited resolution of about $6\ \mu\text{m}$.

APPLICATION OF OFF-AXIS HOLOGRAPHY

Off-axis holography systems have been widely employed in aerodynamics and can be applied to almost any type of optical visualization. Some applications make an analysis simpler or more economical than conventional techniques. This is especially true in interferometry. The basic difference in most systems is the method of illuminating the object field. An illuminated optical diffuser placed behind the field of interest (fig. 6) illuminates the field from

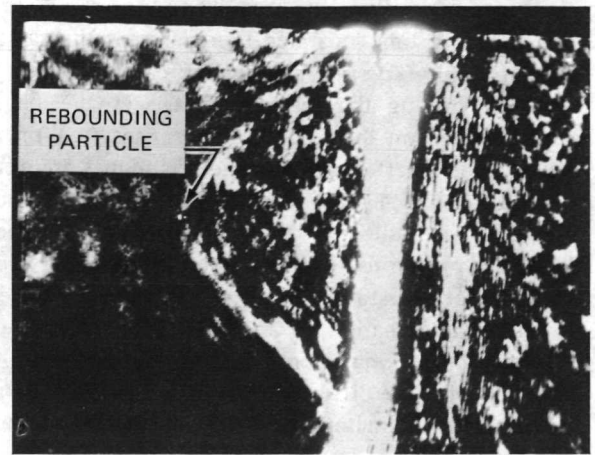


Figure 5.—Rebounding particle and associated aerodynamic phenomena (from fig. 3).

a continuity of directions. The hologram reference beam is usually passed over the test section and strikes the hologram at an angle. The reconstructed field is viewed against a diffusely illuminated background. Such systems are useful for three-dimensional display of the field of interest or for holographic interferometry.

Interferometry is accomplished by superimposing two images of the same field as it existed at separate times (time-differential interferometry). Slight changes in the optical path through the field (such as that caused by refractive index changes) cause phase differences in light emanating from the separate images and are manifested as interference fringes in

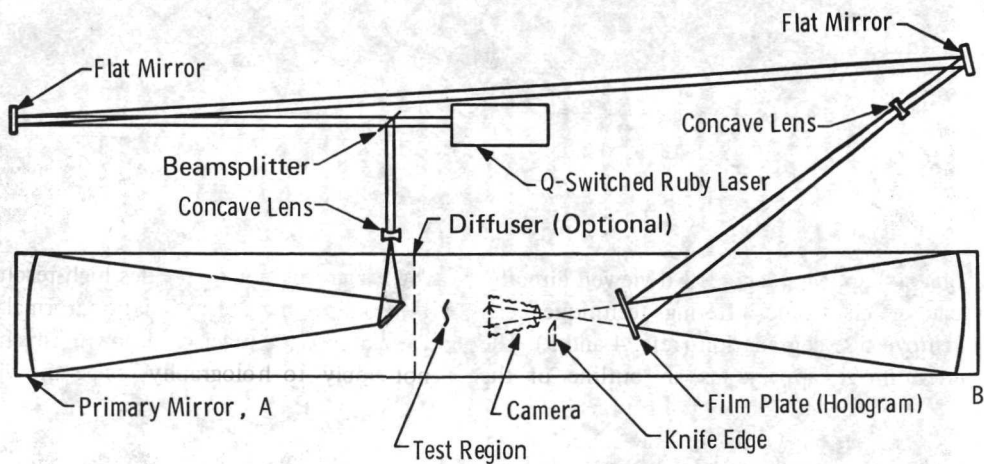


Figure 6.—Off-axis holocamera.

the superimposed images. Two common methods are (1) recording time-separated holograms of the same field (double-exposure holographic interferometry) and (2) viewing the real-time image of the field superimposed on the reconstructed image (real-time holographic interferometry). The techniques are not limited to back-lighted fields of view but can be applied to front-lighted opaque objects as well. The latter has proven useful in the study of vibration and nondestructive testing.

Direct illumination of the field (as opposed to diffuse illumination) sometimes offers advantages. Figure 6 with the diffuser removed represents such a system. The collimated light beam passes through the test field and is modulated by the objects or refractive index gradients within the tunnel. Mirror B refocuses the collimated beam onto the holographic plate, storing holographically all optical information contained in the wave. This type of system has been termed a "generalized flow visualization system"

because one can perform a variety of well known operations on the reconstructed wave to extract information. In the reconstruction setup of figure 2, a knife edge (half-plane filter) at E would provide variable Toepler schlieren visualization. Phase and amplitude filters (or combinations thereof) have been used successfully to perform mathematical operations on the reconstructed image, such as phase contrast, differentiation, addition, and schlieren interferometry.

At least six other types of interferometry are applicable using the system of figure 6. Multiple exposure of the single hologram at two different times, like the diffuse-lighted case, effects a comparison of the two reconstructed waves and provides the same information at a single viewing angle. For two-dimensional fields or axisymmetric fields, this leads to a knowledge of the temperature and density characteristics of the field. Figure 7 is an interfero-

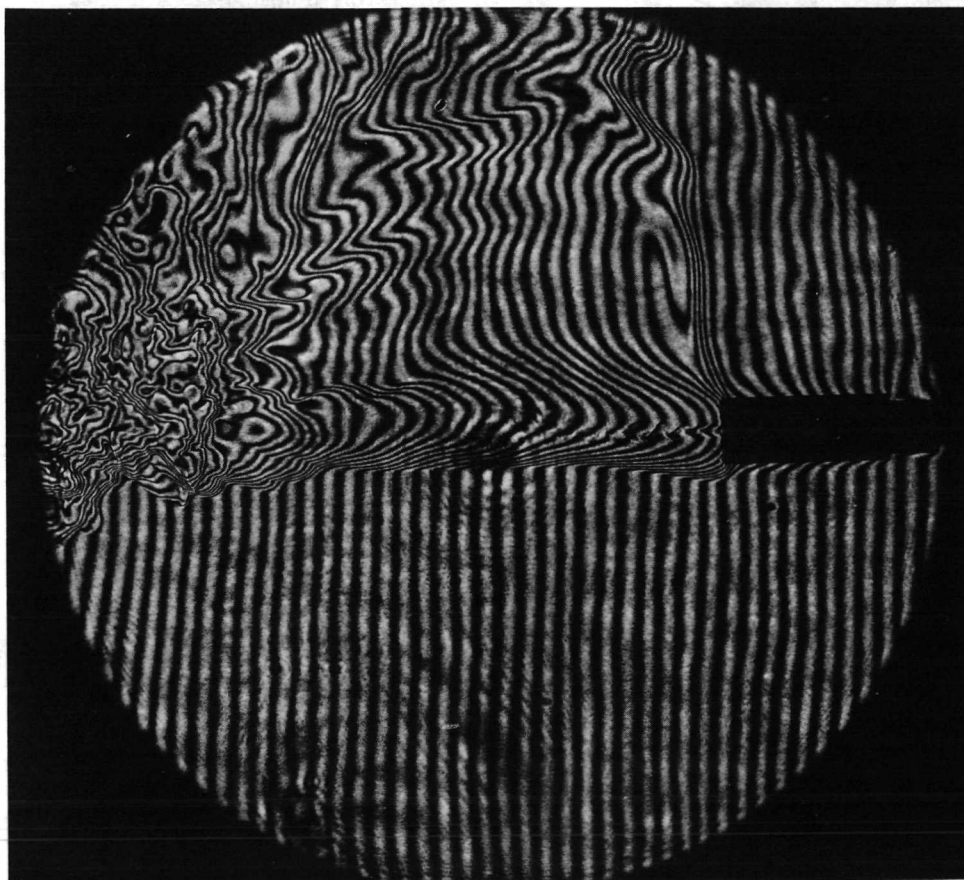


Figure 7.—Time-differential single-plate interferogram reconstruction of a torch.

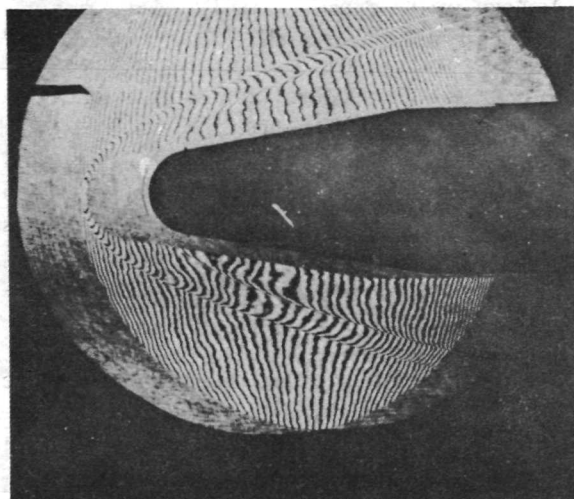


Figure 8.—Space-differential single-plate reconstruction in a Mach 8 flow field.

gram reconstruction of this type showing the temperature field of a torch. The field diameter was 50 cm.

In sheared-wavefront or space-differential interferometry, the reconstructed wave is divided and remixed, and optical pathlengths through various portions of the field are compared. Figure 8 is such an interferogram reconstruction of a spherical cone model in a Mach 8 flow. The field diameter was 50 cm.

A combination of the above two methods (space-time differential interferometry) requires two separate holograms formed at different times. The two wavefronts are reconstructed simultaneously and the resulting interferogram possesses almost complete versatility in fringe spacing and orientation by adjustment of the relative plate position during reconstruction. Figure 9 shows such an interferogram of the same model as figure 8. The above procedures have provided reliable quantitative density and temperature information, as well as other physical constants related to refractive index.

Because of associated vibration problems, real-time hologram interferometry is usually limited to smaller systems for which isolation is practical. Holography can be extended to the study of motion or velocity measurement in three dimensions through time-averaged interferometry or by multiple exposure. Holograms can be superimposed upon the same plate or in some cases used with a motion-picture camera. Multiple pulsing of ruby lasers can be accomplished

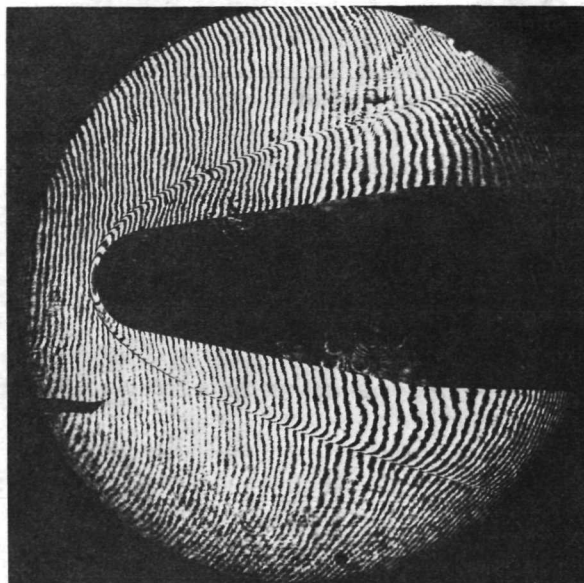


Figure 9.—Space-time differential double-plate reconstruction.

by passive and active Q-switching and by the more versatile technique of slaving two lasers together.

AEDC SYSTEMS, RESEARCH ACTIVITIES, AND TEST APPLICATIONS

Variations of the best systems described above have been employed, are currently being employed, or are in planning for practically every type of facility at AEDC. The tests and research programs using them are listed below, with the type of holography identified in parentheses after each entry, where applicable. The references provide sources for details of AEDC holography systems. Not every test series can be discussed, since some were classified or unpublished; however, the facility applications are included for all research programs to date.

Tests

1. Vaporization and condensation phenomena in fuel tanks (in-line and off-axis) (ref. 7)
2. Materials introduced into the wake of an aerodynamic model (in-line and off-axis)
3. Spray nozzle design for injection of fluid into high-speed flows (in-line) (ref. 8)
4. Analysis of droplet characteristics in a high-altitude engine icing simulation facility (in-line) (ref. 9)

5. Analysis of dust characteristics in dust erosion facilities (in-line and off-axis)
6. Characterization of the particulate contamination in wind tunnels (in-line)
7. Efficiency of particulate catchers in aerodynamic flows (in-line and motion-picture)
8. Aerodynamic flows about models (generalized holographic flow visualization) (refs. 10 thru 12)
9. Rocket exhaust particulate measurement (in-line and off-axis)

Research

1. Ablation measurement of projectiles in flight (edge-line) (ref. 6)
2. Combustion and reaction rate studies (in-line, off-axis, and generalized flow visualization) (refs. 13 and 14)
3. Nondestructive testing as a means to find defects in compressor blades (hologram interferometry)
4. Contouring for observation of flutter and vibration of test models (hologram moiré pattern)
5. Optical and electronic processing of holographic data
6. Determination of applicability of state-of-the-art materials and processes for existing system refinement
7. Determination of applicability of new holographic techniques in the AEDC instrumentation capability (refs. 15 thru 20)

CONCLUSIONS

A number of proven operational holographic systems have been described. No attempt has been made to cover the innumerable optical schemes and techniques which have evolved; however, it is clear that holographic particle sizing, outline analysis, flow visualization, and interferometry are now important tools of measurement for the aerodynamicist (as well as for those in other sciences). Moreover, the ever-increasing degree of sophistication, the almost daily introduction of new holographic techniques and applications, suggests that we are only at the beginning. A considerable amount of effort must still be concentrated in the areas of technical refinement and data retrieval and processing before we can approach the full potential of holography. It is also vital that holographic application scientists associate themselves more closely with members of the fields they support, to encourage the use of this powerful

technology in the expansion of knowledge outside the science of holography itself.

REFERENCES

1. Thompson, B. J.; Ward, J.; and Zinky, W.: Application of Hologram Techniques for Particle Size Determination, *J. Opt. Soc. Am.*, Vol. 55, 1965, p. 1566.
2. Trolinger, J. D.; and O'Hare, J. E.: Aerodynamic Holography, AEDC-TR-70-44, AD 709764, 1970.
3. π MC Particle Measurement Computer System, Catalog No. LTPB030BB, Millipore Corporation, Bedford, Mass.
4. Stroke, G. W.; *An Introduction to Coherent Optics and Holography*, 2nd ed., Academic Press, New York, 1968, p. 360.
5. Trolinger, J. D.; Belz, R. A.; and Farmer, W. M.: Holographic Techniques for the Study of Dynamic Particle Fields, *Applied Optics*, Vol. 8, 1969, p. 957.
6. Trolinger, J. D.; and Gee, T. H.: Resolution Factors in Edgeline Holography, to be published in *Applied Optics*, June 1971.
7. Anonymous, Holographic Study of Fuel Droplet Sizes, *Interavia*, 1970, p. 1106.
8. Davidson, D. L.: Unpublished AEDC Report.
9. Farmer, W. M.; Burgess, K.; and Trolinger, J. D.: Holocamera for Examination of Water Droplets in a Large High-Altitude Test Cell, AEDC-TR-70-181, 1970.
10. O'Hare, J. E.; and Trolinger, J. D.: Holographic Color Schlieren, *Applied Optics*, Vol. 8, 1969, pp. 2047-50.
11. Trolinger, J. D.; Belz, R. A.; and Farmer, W. M.: Conversion of Large Schlieren Systems to Holographic Visualization Systems, *Instrumentation in the Aerospace Industry*, Vol. 15, an ISA publication, 1969.
12. O'Hare, J. E.: A Holographic Flow Visualization System, *Proceedings SPIE 14th Annual Technical Symposium*, 1969.
13. Trolinger, J. D.; Farmer, W. M.; and Belz, R. A.: Applications of Holography in the Environmental Sciences, *Journal of Environmental Sciences*, Vol. 12, 1969, p. 10.
14. Trolinger, J. D.; Farmer, W. M.; and Belz, R. A.: Multiple-Exposure Holography of Time-Varying Three-Dimensional Fields, *Applied Optics*, Vol. 7, 1968, pp. 1640-1.
15. Trolinger, J. D.; Farmer, W. M.; and Belz, R. A.: Holographic Techniques for the Study of Dynamic Particle Fields, AEDC-TR-68-215 (AD-678 857), 1968.
16. Farmer, W. M.: Dynamic Holography of Small-Particle Fields Using a Q-Spoiled Laser, master's thesis, University of Tennessee, Aug. 1968.
17. Belz, R. A.: Resolution Limits of Fraunhofer Holography, AEDC-TR-70-23, 1970.
18. Belz, R. A.: Analysis of the Techniques for Measuring Particle Size and Distribution from Fraunhofer Diffraction Patterns, AEDC-TR-125, 1968.
19. Belz, R. A.: An Investigation of the Real Image Reconstructed by an In-Line Fraunhofer Hologram, Aperture Limited by Film Effects, Ph. D. dissertation, University of Tennessee, 1971.
20. Cody, B.: A Comparison of Various Coherent Optical Filtering Operations, master's thesis, University of Tennessee, 1971.

Page Intentionally Left Blank

Holographic Devices

H. Kogelnik and T. P. Sosnowski

Bell Telephone Laboratories, Inc.

Recently, materials have been developed in which very efficient dielectric (phase) holograms can be written. For example, simple gratings made in dichromated gelatin can have diffraction efficiencies greater than 90 percent. These materials make possible the design of a host of optical devices produced with the techniques of holography. In this talk we reviewed the principles of four holographic devices:

1. A device to couple light into thin dielectric guiding films.
2. A wavelength selector for dye lasers.
3. A distributed feedback laser structure.
4. A holographically formed fiber optic plate.

Details of the construction and operation of these devices can be found in the following references.

1. Kogelnik, H.; and Sosnowski, T. P.: Holographic Thin Film Couplers, *BSTJ*, Vol. 49, 1970, pp. 1602-1608.
2. Kogelnik, H.; Shank, C. V.; Sosnowski, T. P.; and Dienes, A.: Hologram Wavelength Selector for Dye Lasers, *Appl. Phys. Letters*, Vol. 16, 1970, pp. 499-501.
3. Kogelnik, H.; and Shank, C. V.: Stimulated Emission in a Periodic Structure, *Appl. Phys., Letters*, Vol. 18, 1971, pp. 152-154.
4. Rosenberg, R.; and Chandross, E. A.: Holographic Fiber Optics, to be published in *Applied Optics*.

Page Intentionally Left Blank

Applications of Optical Processing

A. Vander Lugt
Electro-Optics Center
Radiation, Inc.

This paper describes a hybrid optical processing system which consists of an optical processor capable of handling 5-inch film, a filter-generator for recording spatial carrier-frequency filters on either photographic film or photoplastic material, and an electronic readout system. The readout system consists of a TV camera with an image orthicon tube, a threshold device, a cell generator that partitions the output of the optical system into an array of cells, a PDP-8/I digital computer which organizes, reduces and displays the data, and a CRT display unit. The computer is also used for controlling optical processing functions. This flexible hybrid system has been used for cloud-motion analysis of ATS-III satellite imagery, for plotting of imagery, for image quality assessment, and for spatial analysis.

Applications of coherent optical systems have been made to pattern recognition, character recognition, spectral analysis, and the processing of a wide variety of optical and electrical signals. The full potential of optical processing, however, has not yet been realized. To increase the flexibility and therefore the applicability of optical processing we need (1) an input interface device which converts electrical signals or incoherent optical signals into coherent optical signals, (2) an *in situ* recording material which is reversible for constructing spatial filters in real time, and (3) an interface device which converts the optical output of the processor into an electrical signal.

In this paper I will concentrate on the second and third areas mentioned above because they are more closely linked with optical processing, and I will treat them in reverse order. I will first describe an optical processing system that is coupled to an electronic readout system and then relate the use of a reversible filter recording material to some processing applications.

The basic theory of optical spatial filtering is well developed. Figure 1 shows the key elements of an optical data processing system. The data to be processed modulate a coherent beam of light. The

light diffracted by the data is collected by a lens that displays the two-dimensional Fourier transform of the data at the image plane of the primary light source. A transparency or mask placed in the frequency plane is the spatial filter that modifies the Fourier transform of the data. The filtered data, displayed at the output plane, can then be detected for further processing.

Since the desired filtering operations frequently require the use of filters that have complex values (both phase and amplitude information), filters in which a complex-valued function is encoded as a nonnegative function can be constructed by using a technique closely related to one used in holography for recording holograms. The filter construction system, therefore, consists of (1) a single beam in which the Fourier transform of the desired impulse response is displayed and (2) an off-axis reference beam. If the sum of the reference beam and the Fourier transform is detected by a square-law detector, the recorded function can be used directly as the desired filter.

Since the optics needed to produce the Fourier transforms are the same for both processing and filter recording, it is convenient to have a single system that can perform both operations. Figure 2 shows a

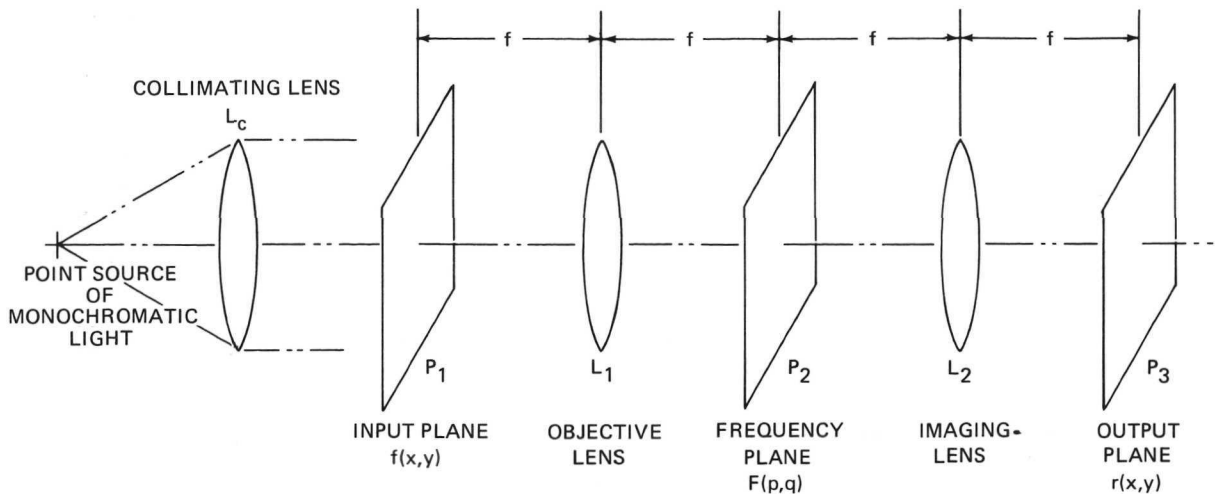


Figure 1.—Simplified diagram of an optical data processing system.

possible layout for a dual-purpose optical processing system. The laser beam is divided into signal and reference beams by a beamsplitter. Both beams are expanded and collimated. The signal beam illuminates the data, and the Fourier transform of the data is displayed at the back focal plane of a lens. The reference beam intersects the signal beam at the transform plane. Attenuators are placed in both beams so that the ratio of signal to reference beam intensity can be adjusted before filters are constructed. A photometer assembly, placed just before the transform plane, is used to measure the intensity ratio. In the processing mode the reference beam is

blocked. A second lens images the filtered data onto an image orthicon which feeds the data to the electronic readout system. The readout system consists of the image orthicon, a threshold device, a cell generator, a PDP-8/I computer, a graphics display unit, and a TV monitor.

The function of the electronic readout system is to collect, collate, and display the processed data (see fig. 3). In a typical processing application the output of the optical system contains correlation peaks which must be detected and processed further. A basic concept in cross-correlation operations is that the output data rate can be reduced significantly

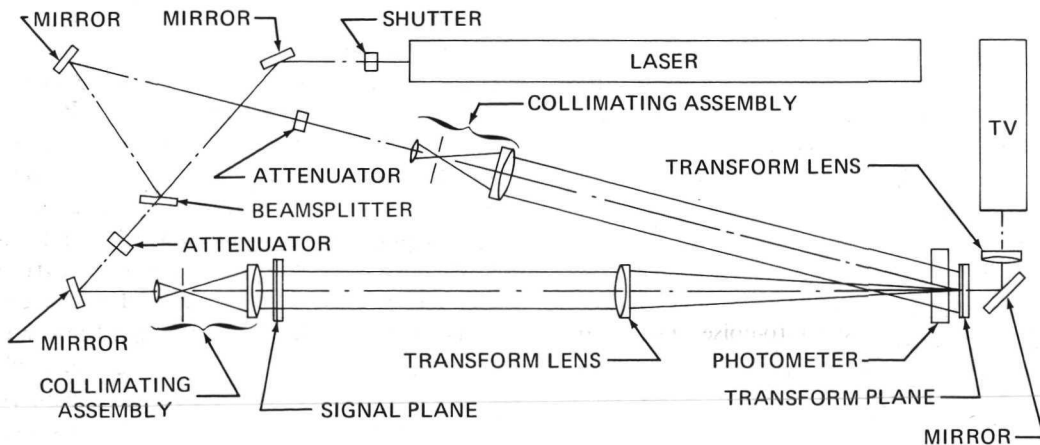


Figure 2.—Layout of optical processing system and filter generator.

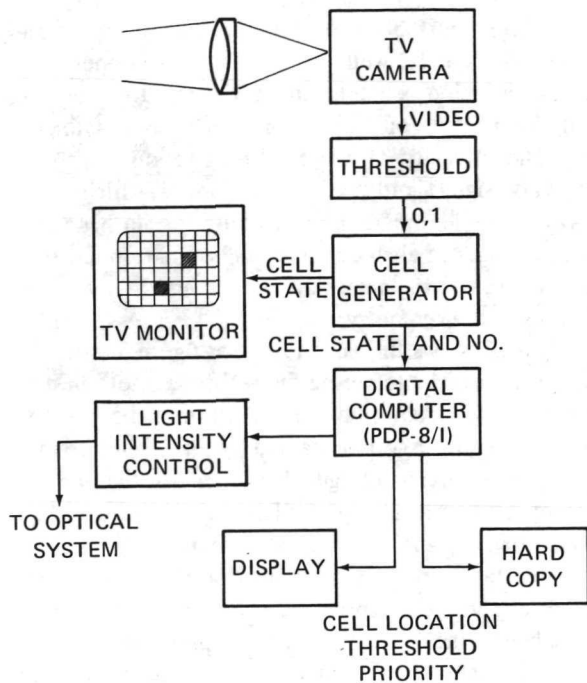


Figure 3.—Readout system.

relative to the input data rate. This concept is particularly important in optical processing because a frame of input data may contain 10^8 or more resolution elements. Since correlation is a linear operation, the output detector must have the same number of resolution elements as the input and, unless data reduction takes place, extremely high data rates may be required to transfer the processed data to the user in a useful form. For example, if a frame of imagery is processed in 1 second, data rates in excess of 10^8 bps are required at the output. Clearly such data rates cannot be handled by conventional data display systems.

Significant data reduction is possible in many optical correlation applications because the signals are isolated and cannot overlap. Therefore, after the thresholding operation, it is often adequate to locate the signal to an accuracy comparable to the signal size rather than to an accuracy comparable to the resolution of the system. Resolution must be performed so that good signal-to-noise ratios are achieved. Note that the processed data indicate the value of the maximum light intensity in a cell but do not indicate where the light peak occurred in the cell (see fig. 4). The actual size of the cells is programmable

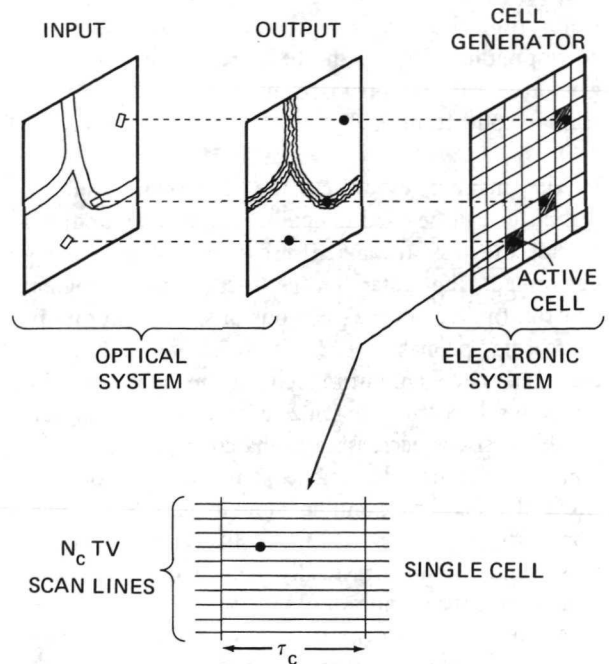


Figure 4.—Cell generator operation.

and is chosen to be comparable to the size of the signals being sought. The measurement of the light intensity, however, is carried out at a much finer resolution, comparable to the resolution of the optical system. Consequently, the readout system produces a major reduction in the bandwidth of the processed data.

An ideal detector, then, is one that has high resolution prior to thresholding but lower resolution after thresholding. Although the electronic system that we have developed is not an extremely high-resolution system (600×600) elements, it incorporates the features of an ideal detector.

The readout system includes an image orthicon TV camera, a small digital computer (PDP-8/I), and a cell-generation device. The TV camera detects the light distribution at the output plane of the optical system, and the resulting video signal is thresholded and fed into a cell generator which is a high-speed, double-buffered memory composed of shift registers and various other logic circuits. The cell generator organizes the thresholded video signal into a number of cells; each cell represents a small rectangular area at the output plane of the optical system. A cell is active if there is at least one video peak exceeding threshold in the area represented by the cell. The

state of a cell is indicated by the state (0 or 1) of the corresponding flipflop in the shift registers. The cell generator can be operated in an almost arbitrary format, but it normally creates a 32×32 array of cells.

The manner in which the data stored in the computer can be used is flexible and can be modified to suit the task at hand. If cross-correlation is being performed, the data can be used, under program control, to indicate the positions of signals in order of decreasing probability. Such information can be collected over an entire roll of imagery and the computer directed to organize a list of frame numbers on the basis of decreasing probability that there is a signal in a particular frame. This information will allow the user to examine immediately those locations where signals are most likely to be. This prescreening could drastically reduce the amount of time spent in searching sterile imagery.

At the Electro-Optics Center we have used photoplastic devices to construct spatial carrier-frequency filters *in situ* in real time. Spatial filters for use in applications such as pattern recognition, target detection, character recognition, and signature detection have usually been recorded on a nonreusable material such as photographic film. The required filters were therefore recorded before the data was processed to form a reference library.

Suppose that a reference library of map mosaics is available and we want to determine the coordinates of mission imagery relative to the stored reference data. Figure 5 shows some experimental results using photographic film for the filters. Figure 5a can be considered a frame of imagery which was recorded and stored as a spatial carrier-frequency filter to form a part of a reference library. Figure 5d shows the autocorrelation of figure 5a with 5b. Note that the cross-correlation peak has moved upwards and to the right, indicating the position of the frame of imagery relative to the stored reference function. This example shows that we do not need to use all of the mission imagery to locate its position; rather, only the portion shown in figure 5c was used. The reduced area still provides a cross-correlation peak with adequate signal-to-noise ratio to measure accurately the location of the entire frame. In this example it is not important which part of the mission imagery is

used. Every part of figure 5b contained in figure 5a correlates equally well, and each part produces a cross-correlation peak having the same location so that the position of the mission imagery is unambiguous. The intensity of the cross-correlation peak did not vary significantly as a function of which subportion was illuminated because the terrain has very small changes in elevation and in illumination. Different camera viewing angles therefore caused only small changes in the geometry.

Figure 6 shows the same results as figure 5, but the filter was constructed using the real-time photoplastic device rather than photographic film. The results shown in figure 6 were obtained by placing the frame of imagery corresponding to figure 6a into the optical system shown previously. A filter was constructed for figure 6a on the photoplastic material, and the autocorrelation peak was recorded as shown in figure 6d. The frame corresponding to figure 6b was then moved into the input plane of the processor section of the optical system, and the cross-correlation peak shown in figure 6e was immediately available for detection. The signal-to-noise ratio for the correlation peaks for both film (fig. 5e) and photoplastic (fig. 6e) is at least 20 dB.

Since the photoplastic device allows us to make filters *in situ* in real time, we can easily compare the coordinates of a frame to those of the previous frame so that the mapping process can continue even though a complete map mosaic is not available. This feature is also important in cloud motion analysis (and similar problems), where the primary interest is in obtaining relative frame-to-frame coordinates and where the time delay involved in recording filters for each frame on photographic film is unacceptable.

The hybrid optical processor, developed at the Electro-Optics Center, is therefore a flexible instrument for application to a wide variety of processing problems. The key remaining problem area is that of getting data into the system. This is no problem in those applications where the data is already recorded on film. Fortunately, progress is being made in developing input interface devices that will accept either electrical or incoherent optical data. As these devices become more fully developed, I expect to see the potential of optical data processing developed in even more processing problems.

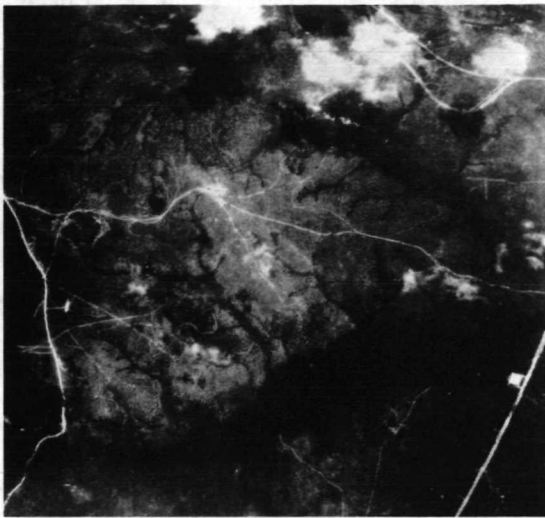
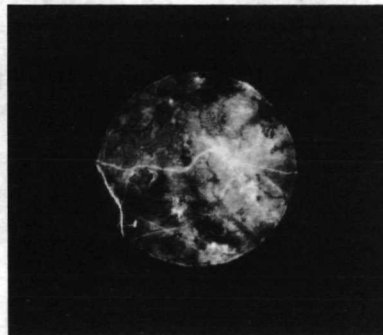
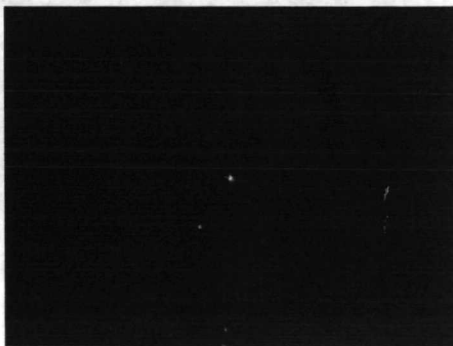
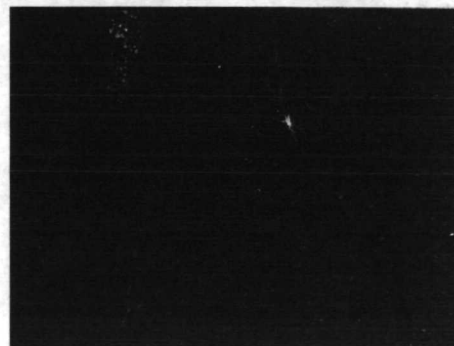
**a****b****c****d****e**

Figure 5.—Results of experiments using filter recorded on film to correlate mission imagery with stored reference map.

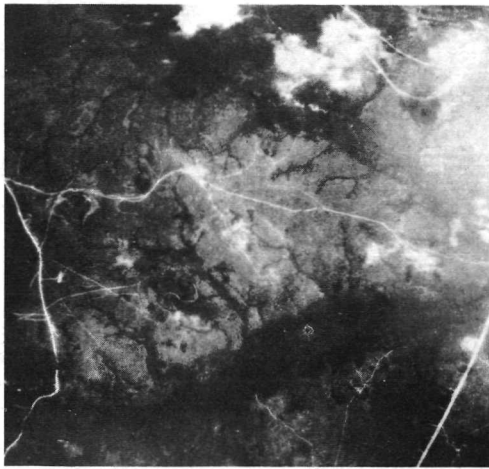
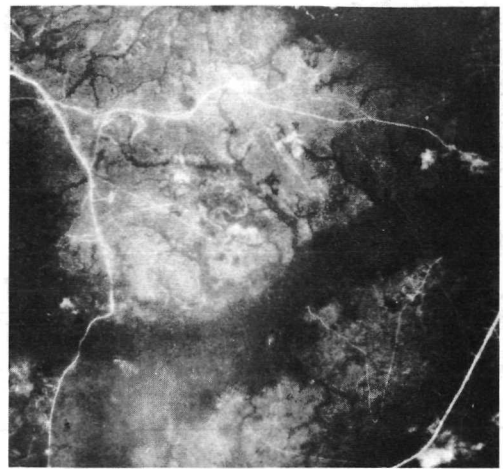
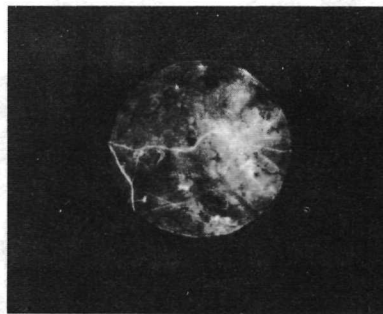
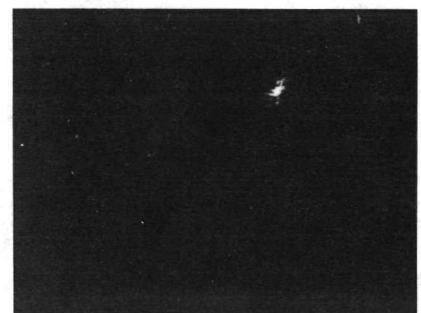
**a****b****c****d****e**

Figure 6.—Results of correlation using filter recorded on real-time photoplastic device.

Photoplastic Recording Materials in Holographic Memories

A. A. Friesem and E. N. Tompkins

*Electro-Optics Center
Radiation, Inc.*

The application of reusable, sensitive, and efficient photoplastic recording materials in read/write holographic memories is reviewed. The composition, preparation, and typical configurations of photoplastics, as well as the techniques for recording and erasing the holographic information, are described. The effects of sample thickness, exposure time, illuminating wavelength, development, and reusability on the holographic signal are examined. Experimental measurements reveal that diffraction efficiencies in excess of 10 percent can be achieved and that the exposure sensitivities and noise characteristics are comparable to high-resolution photographic emulsions. As the number of recording-erasure cycles of photoplastic holograms increases, the signal-to-noise ratio (S/N) of the holographic readout image deteriorates. However, the number of cycles can be over 100 with adequate S/N. Finally, experimental results showing the quality of the reconstructions that can be achieved from a 5X5 hologram array are presented.

Photoplastic materials are photoconductive thermoplastic media on which holograms are recorded as surface deformation. The materials are sensitized by a corona discharge to a positive or negative potential, exposed to visible radiation, and developed by heating to the flow temperature. Electrostatic forces produce deformations which are proportional to the light intensity used for exposure, and a stable hologram is formed if the photoplastic is cooled before surface tension of the plastic layer restores the original smooth surface. The hologram can be erased by heating the thermoplastic layer beyond the softening point. The surface forces then restore the smooth surface and the materials are ready for a new recording cycle. The salient features of photoplastic which make it most attractive for present holographic memories are (1) read/write/erase capabilities, (2) *in situ* recording, development, and readout, and (3) virtually real-time recording cycle (typically less than 5 s).

In the sections that follow, we briefly review the mechanism of holographic storage and erasure in

photoplastic materials and consider the details of material preparation. We then describe the procedures and results of our investigations in sufficient detail to characterize the performance of photoplastic materials in a holographic memory system. Finally, a 5X5 hologram array suitable for use in a read/write holographic memory is described and representative results from such a device are presented.

PHOTOPLASTIC HOLOGRAPHY PROCESS

Photoplastic recording materials may be made with a number of different configurations on various substrates. For the present we shall be concerned only with the configuration shown in figure 1, which can be conveniently prepared. The substrate is an optical-grade glass onto which a thin film of transparent conductor (generally tin oxide or indium oxide) has been deposited. The conductive layer is used for electrical heating and also as a ground plane for the charges deposited on the surface of the thermoplastic. An organic photoconductor layer is then coated on the transparent conductor, and the top layer consists of a deformable thermoplastic layer.

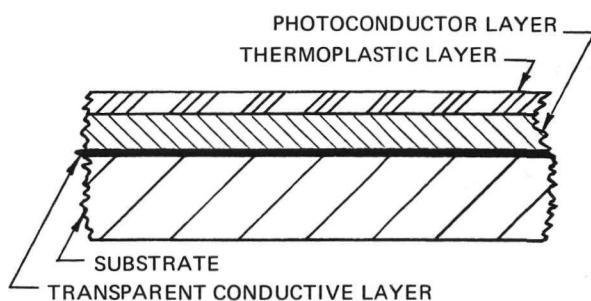


Figure 1.—Photoplastic storage medium construction.

A hologram is recorded in the photoplastic material as surface deformations corresponding to the spatial variations of the exposure pattern. The photoplastic holography process, which can be described with the aid of figure 2, consists of four basic steps:

1. The recording medium is charged (in the dark) to a uniform potential by a corona discharge device.
2. The medium is exposed to light, causing a variation of the charge pattern on the photoconductor corresponding to the variation of the illumination, and is recharged at those areas where the exposure has changed the electrostatic surface potential.
3. The medium is developed by raising its temperature to near the plastic point and then rapidly lowering the temperature to the ambient level. Surface deformations proportional to the light intensity are thus produced.
4. The recording is erased by raising the temperature level to near the melting point to even out the surface deformations.

In the first step the medium is prepared for subsequent recording. The corona discharge device, consisting of a thin wire (approximately 0.1 mm in diameter) at a voltage of 3 to 10 kV and an electrically grounded shield, deposits a uniform charge distribution on the thermoplastic. After this sensitization step, the recording material must be handled or stored in the dark. In the second step an exposure is made, and additional surface charge is added to the optically exposed areas only; the amount of the additional charge is proportional to the charge in the internal field during exposure and therefore to the impinging light pattern. Varying surface charge densities corresponding to the holographic light intensity pattern are thereby formed.

In the third step, the photoplastic medium can be developed, even in ambient light, by lowering the

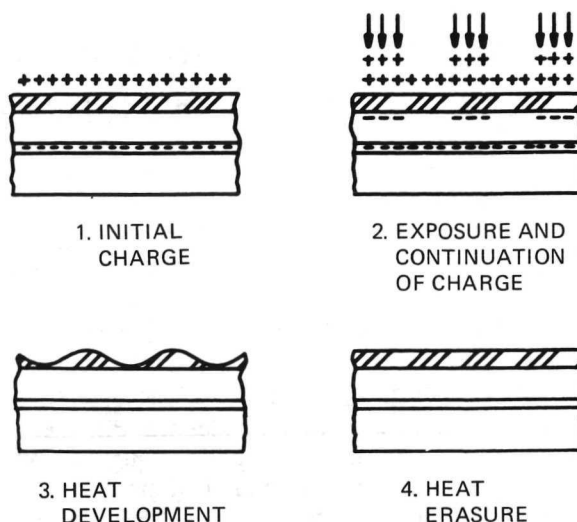


Figure 2.—Recording-erasure cycle.

viscosity of the thermoplastic layer. The material then deforms in a manner related to the surface charge density distribution. To lower its viscosity, the temperature is raised to approximately 80 °C. Rapid cooling to room temperature will result in a deformation which remains stable until intentional erasure. Heating is achieved by applying a voltage pulse across the conductive layer.

In the fourth step more heat than that used for developing is applied to the thermoplastic, either by increasing the current in the pulse or by applying the same pulse for a longer period. Erasure usually neutralizes the electrostatic charges, after which the recording process can be repeated.

MATERIAL AND SAMPLE PREPARATIONS

The holographic technique for recording information places a number of requirements on the photoplastic material. First, it must be sensitive to laser radiation. Second, it must scatter very little of the laser light. Third, it should have sufficient electrical resistance to prevent dissipation of the electrostatic charges before deformations can occur. Fourth, the glass transition temperature must be reasonably low to enable deformation with practical resistive heating, but high enough to prevent loss of deformations during storage. Finally, it must be resistant to thermal degradation. A number of materials satisfy most of these requirements, including poly-n-vinyl carbazole (PVK) sensitized with trinitrofluorenone (TNF)

photoconductor, used with Stabelite wood resin thermoplastics, on which most of our experiments have been conducted. Recently we have begun testing other thermoplastic materials, such as styrene-methacrylate copolymers and polystyrenes with various plasticizers.

The substrate for the photoplastic device is typically a glass plate coated with transparent tin oxide. The substrate is etched with zinc powder and hydrochloric acid to leave isolated squares; these squares may range in size from 1 to 100 mm on a side. Two silver electrodes along opposite edges of each square are used to connect the tin oxide squares to an electrical source which supplies the necessary current pulses to heat the square, which typically have a resistivity of 50 ohms per square. Development and erasure of a hologram are effected by resistive heating; a pulsed 60-Hz voltage is applied across each square. We use a 150-ms pulse with an average power of 20 W for developing a 10-mm square.

After chemical cleaning, the substrate is coated with a layer of organic photoconductor and a layer of thermoplastic; conventional dip coating techniques are used. To obtain a photoconductive solution suitable for coating, we mix the PVK polymer sensitized with TNF in a tetrahydrofuran solvent. The concentration of the solution and the rate of pulling are adjusted to give a coating thickness of 3 μm . The thermoplastic solution is obtained by dissolving the wood resin Stabelite in naphtha. The concentration and pulling rates are adjusted to give a thermoplastic layer thickness ranging from 0.5 to 2 μm .

The substrate and component layers are then baked in an oven at 60 $^{\circ}\text{C}$ for about an hour to evaporate the solvents. The coated plates are removed, cooled, and stored in dust-free containers until used. Figure 3 is a photograph of a typical simple photoplastic device.

EXPERIMENTAL PROCEDURE AND RESULTS

We performed experiments to determine the exposure sensitivity, spectral response, diffraction efficiency, and signal-to-average-noise ratio of various photoplastic samples. We also investigated techniques to extend the number of cycles of the photoplastic devices.

To measure the exposure and spectral sensitivity, as well as diffraction efficiency, we recorded simple interference gratings by using plane waves for both the reference beam and the signal beam. The four

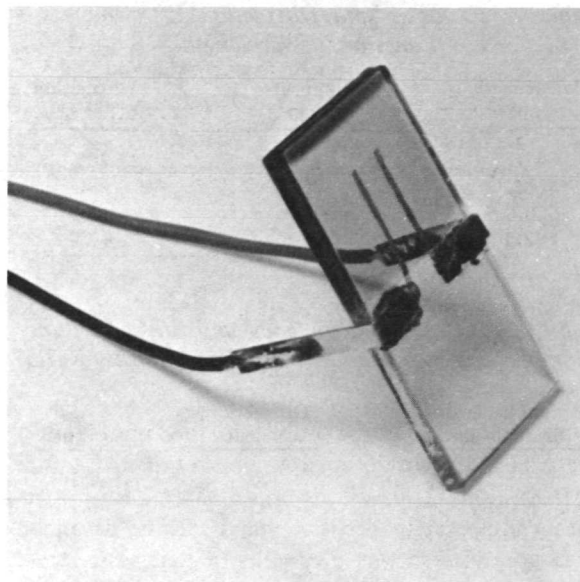


Figure 3.—Photoplastic device sample.

dominant wavelengths of the krypton laser were used to obtain the desired spectral response. During readout we measured the diffracted laser beam power, P_d , and the incident beam power, P_i , for different recording parameters. The diffraction efficiency, P_d/P_i , was then calculated from these measured values.

To measure the signal-to-average-noise ratio we holographically recorded a diffusely illuminated transparency consisting of a bright square surrounding an opaque square center. The recording geometry was arranged so that each hologram contained approximately 10^5 bits/mm². In readout a photomultiplier scanner was used to measure the intensity of the signal and noise. The average noise was determined from a scan across the dark square, and the average signal was determined from a scan across the bright area of the reconstructed image.

The results of these experiments are summarized in tables 1, 2, and 3. Table 1 shows the exposure sensitivity and diffraction efficiency as a function of wavelength. The results shown in the table were obtained with samples having a PVK-to-TNF concentration of 10:1; they demonstrate that these photoplastic samples are panchromatic. We observed that, although an exposure of 75 $\mu\text{J}/\text{cm}^2$ is generally optimum, a broad latitude of exposure is tolerable. The diffraction efficiency decreases at shorter wave-

Table 1.—Exposure and Diffraction Efficiency as a Function of Wavelength

Wavelength (nm)	Exposure ($\mu\text{J}/\text{cm}^2$)	Diffraction Efficiency
647.1	75	20%
568.2	75	18%
520.8	75	16%
482.5	75	12%

Table 2.—Diffraction Efficiency and S/N as a Function of Reference Beam/Signal Beam Intensity Ratio

Reference beam/ Signal beam	Diffraction efficiency	S/N (dB)
1:1	20%	16
10:1	16%	15
100:1	7%	14

Table 3.—Exposure Sensitivity, Diffraction Efficiency, and S/N as a Function of Sensitizer Concentration

Sensitizer concentration	Exposure ($\mu\text{J}/\text{cm}^2$)	Diffraction efficiency	S/N (dB)
100:1	1000	22%	16
10:1	75	20%	16
2:1	10	0.71%	3

lengths. We believe that the reduction is caused by the TNF sensitizer, which absorbs more of the shorter-wavelength illumination and consequently reduces the diffraction efficiency.

Table 2 shows the diffraction efficiencies and signal-to-average-noise ratio, S/N, as a function of reference-beam-to-signal-beam intensity ratio. To obtain these results we used a PVK-to-TNF concentration of 10:1, exposure values of $75 \mu\text{J}/\text{cm}^2$, and the red line of the laser. As shown, the reduction of diffraction efficiency and particularly S/N is relatively small with increasing reference-to-signal beam ratios. This fact provides great flexibility in the selection of input signals and recording parameters.

Table 3 shows the effect of PVK-to-TNF concentration on exposure, diffraction efficiency, and S/N. Although the diffraction efficiency is somewhat lower, the 10:1 concentration is obviously better for holographic recording because of its increased exposure sensitivity. Furthermore, we noted that the

recycling capabilities are poorer with the 100:1 concentration.

We tested the recycling capabilities of the photoplastic samples and found that all of the samples had limited reusability—some better than others. Although many samples could be reused for over 100 cycles with adequate S/N ratio, some failed completely after only 70 cycles. In all cases the noise characteristics degraded the reconstructions as the number of record-erase cycles increased. We attribute this deterioration primarily to thermal degradation of the thermoplastic materials, and also in some degree to dust which is attracted to the surface of the materials during the development and erasure processes. The thermoplastic undergoes cross-linking as the number of cycles increases, causing the recording characteristics to become progressively more sluggish to the point of no response.

We anticipate that the problems of thermal degradation and dust can be overcome with improved materials and operation in dust-free atmosphere.

We also noted that erasure does not completely neutralize the electrostatic charges but that a latent image of an earlier recording appears in subsequent holographic recordings. This latent image obscures the desired information and degrades the S/N of the reconstructed image. Furthermore, the latent image is particularly intense after the photoplastic material has been reused a number of times, typically after 10 recordings. We have determined that the intensity of the latent image can be reduced by using several erasure pulses rather than just one pulse. This technique, however, is not satisfactory because it extends the duration of the record-erase cycle, and it is useful only for a limited number of cycles.

A better solution for the elimination of the latent image is to charge the photoplastic during application of the erasure eliminates the surface charges of earlier recordings and leaves a uniform charge distribution at the surface. We also determined that this technique produces more consistent results when the erasure is made using a longer pulse with the same voltage as the development pulse, rather than at a higher peak voltage. This erasure technique was tested with several photoplastic materials. The testing sequence for recording and checking for latent image was to expose, develop, erase, develop, measure the intensity of the image, and then repeat the cycle. We found that no latent image could be observed even after 100 recordings.

We determined that a stationary corona device can uniformly charge the surface of a thermoplastic and be active during the entire sequence of exposure-development without adversely affecting the holographic recordings. The amount of surface charge is controlled either by varying the space between the corona device and the photoplastic surface or by varying the voltage applied to the corona device. A simultaneous rather than sequential charge-exposure-recharge mode eliminates the need for switching networks to control the charging mechanism and simplifies the recording procedure.

We also observed that the exposure sensitivity is a nonlinear function of the surface charge deposited by the corona device. In particular, by increasing the surface charge by 50 percent, the exposure sensitivity was increased by a factor of 5. However, an increase in the surface charge corresponds to an increase in the scattering noise. Because noise is generally a more serious problem than sensitivity, the surface charge should be kept at a relatively low level.

Finally, we determined that a practical operating sequence for recording each hologram is to (a) energize the corona discharge device, (b) apply an erasure heat pulse for 500 ms, (c) pause to allow cooling of the substrate, (d) expose, (e) pause to allow recharging of the photoplastic surface, and (f) apply a development heat pulse for 150 ms. The duration for the entire sequence could be about 3 seconds.

A PHOTOPLASTIC ARRAY FOR A HOLOGRAPHIC MEMORY

A simple array for recording 25 independent holograms is shown in figure 4. The storage geometry is a 5×5 array of independent holograms, each capable of storing 1.6×10^4 bits, for a total capacity of 4×10^5 bits. Each hologram pad is electrically isolated from all other pads to allow for thermal development and erasure of each hologram without adversely affecting its neighbor.

The substrate for the array is a glass plate with a transparent conductive coating of indium oxide. The substrate is etched with zinc powder and hydrochloric acid to leave a 5×5 array of isolated 3.5-by-3-mm rectangular pads. The center spacing between adjacent pads is 6 mm. Aluminum electrodes are deposited through a mask, forming the electrode structure shown in figure 4. There is one electrode common to each row of pads and 25 independent

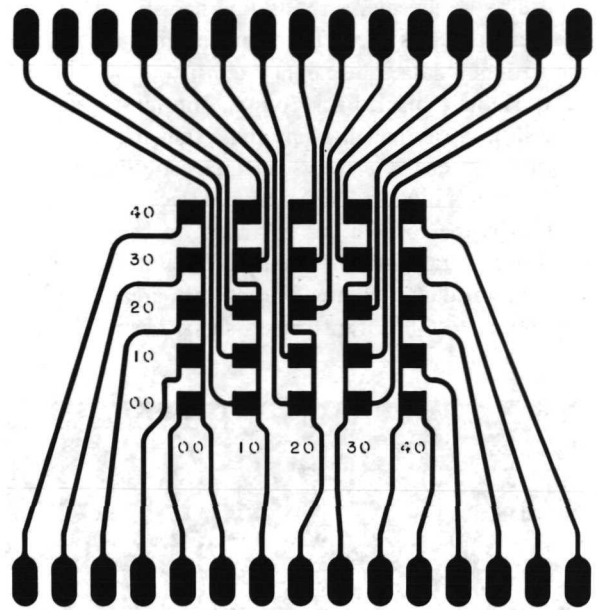


Figure 4.—Geometry of hologram array.

electrodes for controlling each pad separately. The width of each electrode is 0.5 mm, leaving a workable aperture of 2.5 by 3 mm, larger than the required hologram aperture. The electrodes are wired to a 25-position selecting switch for electrically addressing each pad. The prepared substrate is coated with a photoconductive layer of $3 \mu\text{m}$ and a thermoplastic layer of $1 \mu\text{m}$.

We tested the performance of the array with the experimental setup shown in figure 5. In this

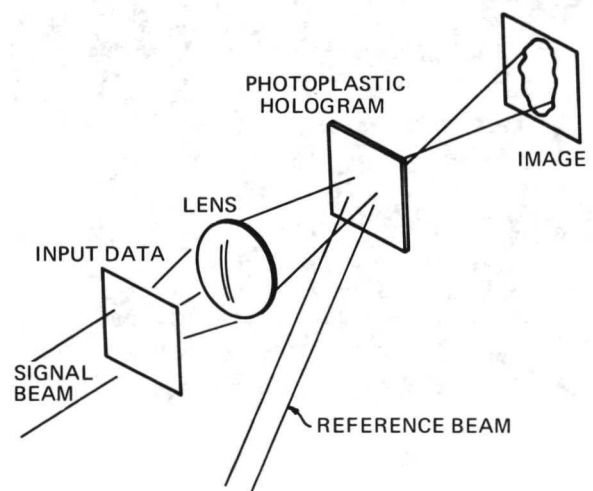


Figure 5.—Hologram recording arrangement.

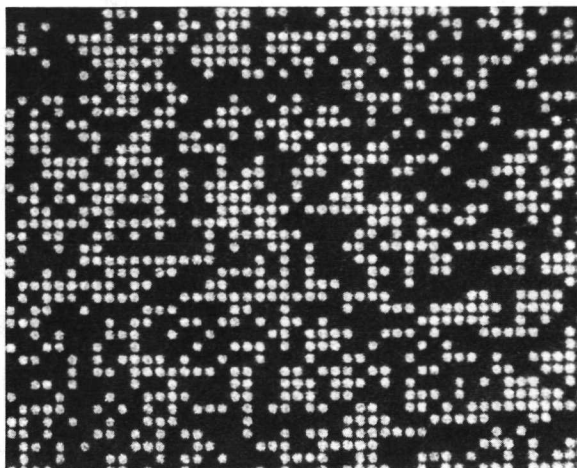
recording arrangement a modified near-Fourier transform approach is used. The signal beam is modulated by an input data transparency consisting of an array of dots on a black background. The lens system is used both as an imaging lens and a transform lens. As an imaging lens it projects an image of the original input onto a plane where a photodetector array may eventually be located. As a transform lens it forms the Fourier transform of the input data in the vicinity of the recording medium. The pattern created by the interference of the transformed signal beam with the

reference beam, both derived from the same laser, is recorded to form a hologram. In readout, the hologram is illuminated with a replica of the reference beam. Representative samples of our results are shown in figure 6. In the upper left is a photograph of a magnified portion of the original input transparency. The other photographs show the reconstructed image after 15 to 105 cycles. As is evident from these results, the S/N is significantly degraded for later cycles.

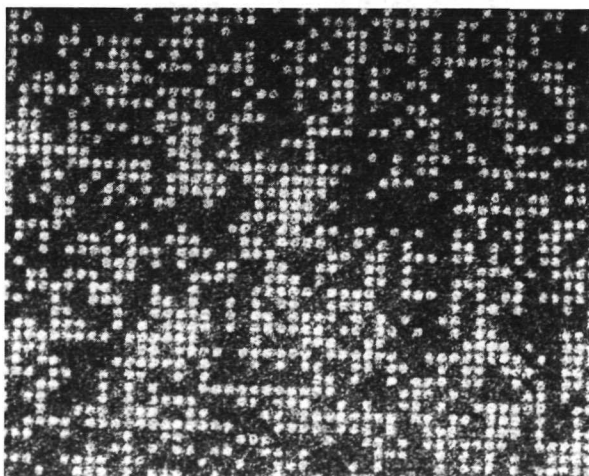
We also demonstrated that it is possible to record



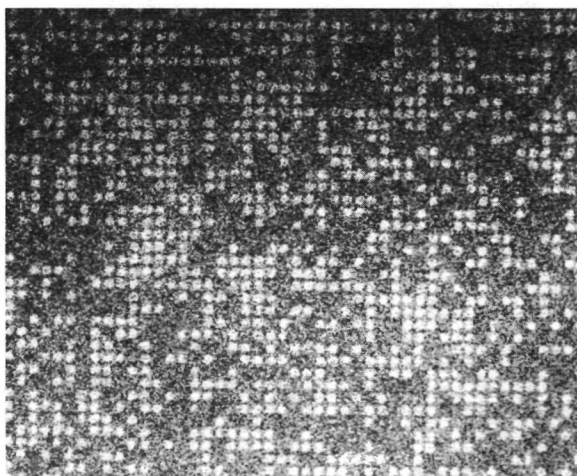
ORIGINAL



15



55



105

Figure 6.—Photographs of original and reconstructed images from holograms after 15, 55, and 105 cycles.

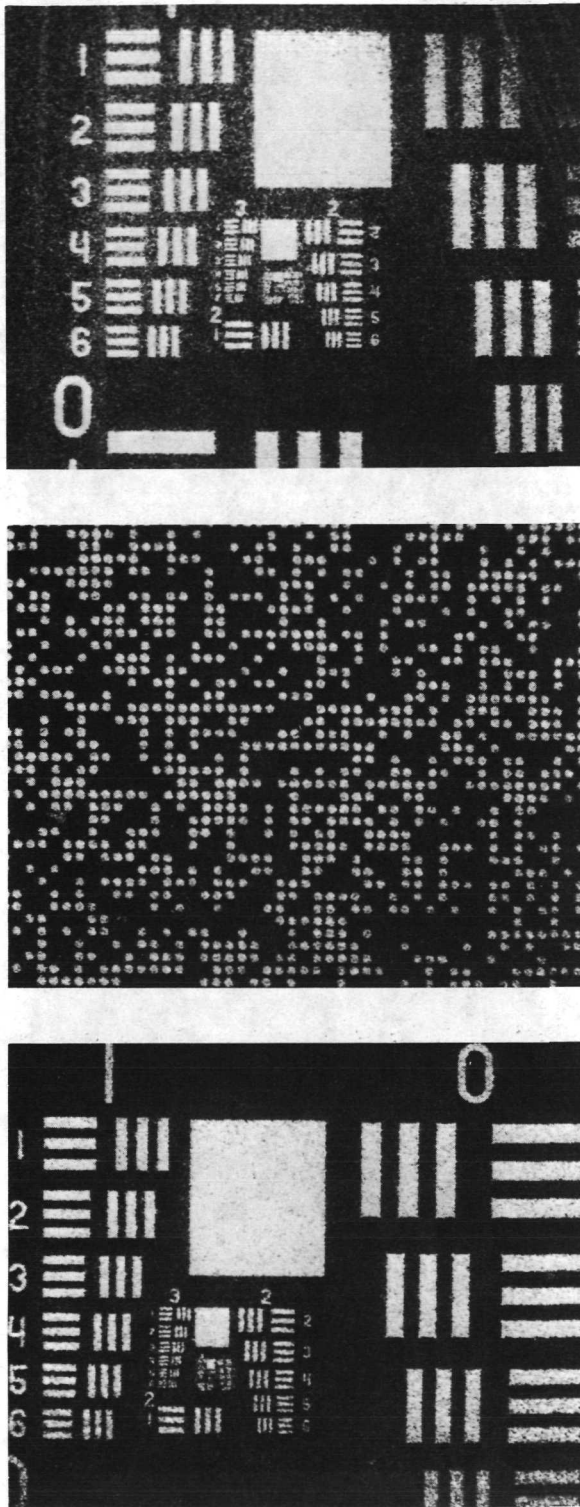


Figure 7.—Photographs of reconstructed images from successive holograms of different test patterns made on the same thermoplastic element.

and read out successive holograms with little or no interaction between them. In figure 7 we show photographs of successive reconstructed images of different test patterns from one sample. These images were obtained from the 14th, 15th, and 16th cycles. As is evident, the effect of latent imagery is negligible.

CONCLUDING REMARKS

The results of these investigations are sufficiently encouraging to suggest that some important read/write memory systems can be developed. These memories could have capacities of 10^8 to 10^9 bits with read and write capabilities using no moving parts. For some applications, where moving parts can be tolerated, these materials could also be used in larger-capacity memories. Furthermore, the photoplastic devices need not be confined to holographic memories. They could be used effectively in hologram interferometry, as holographic filters for coherent optical data processing, etc. However, to be useful in larger-capacity memories and these other applications, the properties and operational parameters of the photoplastic devices must be improved.

BIBLIOGRAPHY

1. Glenn, W. E.: Thermoplastic Recording, *J. Appl. Phys.*, Vol. 30, 1959, p. 1870.
2. Gundlach, R. W.; and Claus, C. J.: A Cyclic Xerographic Method Based on Frost Deformation, *Phot. Sci. Eng.*, Vol. 7, 1963, p. 14.
3. Gaynor, J.; and Aftergut, S.: Photoplastic Recording, *Phot. Sci. Eng.*, Vol. 7, 1963, p. 209.
4. Urbach, J. C.: The Role of Screening in Thermoplastic Xerography, *Phot. Sci. Eng.*, Vol. 10, 1966, p. 287.
5. Urbach, J. C.; and Meier, R. W.: Thermoplastic Xerographic Holography, *Applied Optics*, Vol. 5, 1966, p. 666.
6. Gaynor, J.; and Sewell, G. J.: Photocharge Process, *Phot. Sci. Eng.*, Vol. 11, 1967, p. 204.
7. Lin, L. H.; and Beauchamp, M. L.: Write-Read-Erase *in-Situ* Optical Memory Using Thermoplastic Holograms, *Applied Optics*, Vol. 9, 1970, p. 2088.
8. Anderson, H. R.; Bartkus, E. A.; and Reynolds, J. A.: Molecular Engineering in the Development of Materials for Thermoplastic Recording, *IBM J. Res. Develop.*, March, 1971.

Page Intentionally Left Blank

Application of Coherent Optical Matched Filtering for Detection of Meteor Trails*

T. H. Gee and C. W. Allen

University of Tennessee Space Institute

K. S. Clifton

*Space Sciences Laboratory
NASA Marshall Space Flight Center*

An investigation has been conducted to characterize coherent optical matched filter operation as it applies to detection of meteor trails recorded via a low-light-level television system. This paper addresses some of the practical aspects of this problem, including filter selectivity, signal-to-background contrast requirements, and filter sensitivity to rotational changes of the input plane relative to the filter plane. Theoretical results are presented along with supporting experimental data.

In order to gain information concerning the mass-flux characteristics of the near-Earth meteoroid environment, the Space Sciences Laboratory of the Marshall Space Flight Center is presently employing a low-light-level television system. Such a system can obtain optical data of faint meteors in the mass range posing the greatest hazard to long-term orbiting spacecraft such as Skylab.

The system used for such investigations consists of an intensifier-SEC (secondary electron conduction) vidicon camera chain coupled to an $f/0.75$ lens with a 105-mm focal length. Data obtained by the camera is videotaped for analysis. The entire system is portable and may be transported to different sites for optimum observing conditions. The field of view of the camera is approximately 13 by 16 degrees. Viewing at the zenith, this corresponds to an area of nearly 650 km^2 in the upper atmosphere in which meteor phenomena occur. With the low-light-level television camera, stationary objects such as stars can

be detected to the 11th magnitude. Due to the fact that a moving object with a fast writing speed across the photocathode deposits fewer photons in each resolving element, the threshold of meteor detection is limited to the eighth magnitude. Nevertheless, rates in excess of 250 meteors per hour have been obtained.

Analysis of the data is accomplished manually during the playback of the video tapes. Teams of three or more observers scan overlapping areas on a TV monitor in order to maximize the meteor detection probability. Meteors appear as moving streaks of light with brightnesses that occasionally approach the noise level of the observed scene. When an event is ascertained as a meteor, its position on the monitor, apparent direction of flight, and point of occurrence on tape (or tape index) are recorded, along with notations concerning brightness and speed. In this manner nearly 4000 meteors have been detected and logged. Although accurate, the detection procedure is tedious and time consuming, with an hour of data often requiring more than three hours of analysis. A single week of observations resulting in 30 hours of data could require as many as 270

*This work was supported by the Space Sciences Laboratory, Marshall Space Flight Center, under NASA Contract NAS8-24393.

man-hours of analysis. For this reason a means for the automatic detection of meteors is quite desirable.

One method which is being considered for automatic detection of meteors is the use of a coherent optical matched filter (ref. 1). An investigation has been carried out at the University of Tennessee Space Institute for the purpose of characterizing matched filter operation as it applies to the meteor trail detection problem (ref. 2). Results of these efforts pertaining to matched filter selectivity are presented here.

MATCHED FILTER SELECTIVITY

The theory and operation of coherent optical matched filters for pattern recognition are available to the interested reader in the open literature. A particularly good presentation of this material may be found in reference 3; therefore the filter operation will only be outlined here. Figure 1 depicts one optical configuration which may be employed to record or form a matched filter. The matched filter is recorded as a Fourier transform hologram. To process the recording medium (often photographic film) to yield a matched filter, the filter is placed in the frequency plane of an optical processor as shown in figure 2. The filter is illuminated by the Fourier-transform (performed by L_1) light-amplitude distribution of the input signal or data. Lens L_2 completes a two-dimensional cross-correlation between the signal to which the filter is matched and the input signal which is being processed. Thus, a light-amplitude distribution which is proportional to this correlation function is formed in the output plane.

A point of interest in the application of matched filters for pattern recognition purposes is the ability of the filter system to discriminate between similar signals, or its selectivity. It was demonstrated by Vander Lugt in his early work (ref. 1) and by Binns and others (ref. 4) that matched filter selectivity can be improved by stopping transmission of the lower spatial frequency information by the filter; that is, information which is common to similarly shaped signals. One method for achieving this improved selectivity is to overexpose the film to the signal component during filter formation. With reference to figure 1, this means that the signal-to-reference intensity ratio is generally greater than unity. Since the signal energy is generally concentrated near the zero spatial frequency, this technique causes the film to saturate in the low-frequency region, and con-

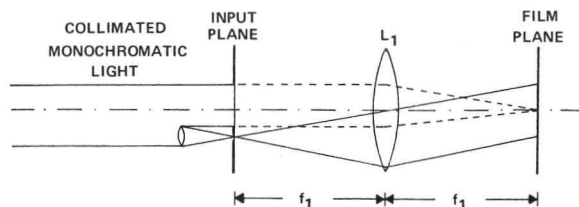


Figure 1.—Optical configuration for matched filter formation.

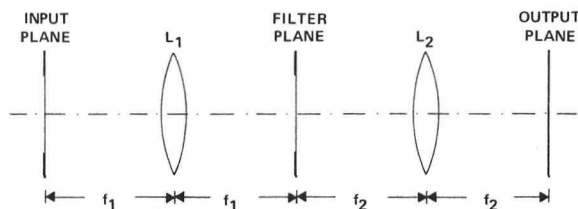


Figure 2.—Optical configuration for matched filter correlator.

sequently light transmission there is significantly attenuated.

In the meteor detection studies reported here, a narrow rectangular aperture was employed to model the meteor trail for the purpose of several theoretical and experimental phases of the investigation. An indication of the potential desirability for improved matched filter selectivity is shown in figure 3. In this figure, cross-sectional curves are shown of two-dimensional correlation intensity distributions (even functions) for several rectangular aperture sizes, where

$$\frac{a}{a'} = \frac{\text{length of input aperture}}{\text{length of aperture to which filter is matched}}$$

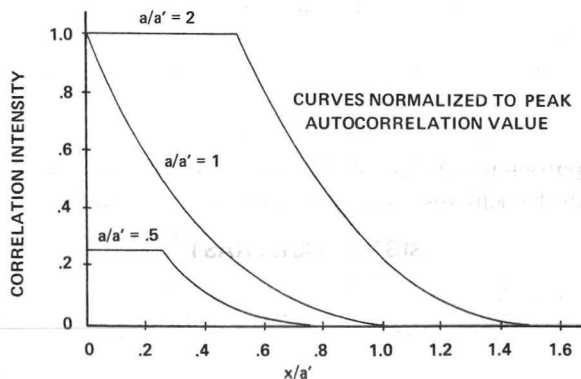


Figure 3.—Cross section of correlation intensity distributions for wideband matched filter ($a'm'=0$).

and x is the output-plane variable of a rectangular coordinate system whose origin coincides with the center of the correlation distribution. If output plane detection is accomplished by measuring the peak intensity which exceeds some predetermined threshold (e.g., via a closed-circuit TV scheme), figure 3 indicates that the matched filter system is unable to discriminate between the aperture to which the filter is matched and larger apertures. On the other hand, if the low-frequency region of the filter is masked, the output correlation functions take on a significantly different distribution, as illustrated by the cross-sectional curves of figure 4. Also, the peak intensity shown in figure 4 corresponds to the aperture to which the filter is matched only, and correct detection of that signal is possible. Curves of matched filter selectivity (a measure of the correlation central maxima) are shown in figure 5 as a function of the low-frequency cutoff, m' .

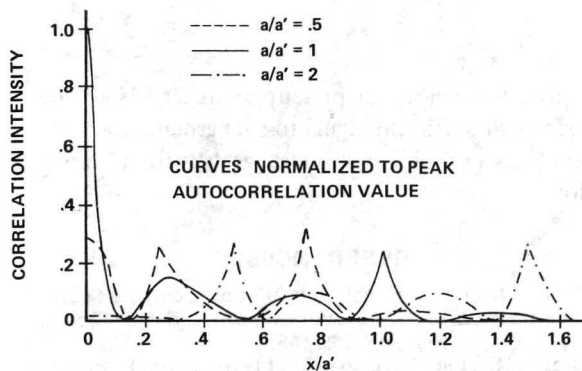


Figure 4.—Cross section of correlation intensity distributions for high-pass matched filter ($a'm'=1$).

It further has been shown that matched filter selectivity can be controlled to a large degree by use of a bandpass filter in conjunction with the matched filter (ref. 5). The presence of a high-frequency bandstop acts to make the filter less selective, and an appropriate choice of the high- and low-frequency cutoffs achieves various selectivity characteristics.

SIGNAL CONTRAST

Another factor which is of considerable importance in the operation of matched filter systems for pattern recognition is the contrast requirements for the input signals or data to be processed. The requirement here is actually related to the threshold

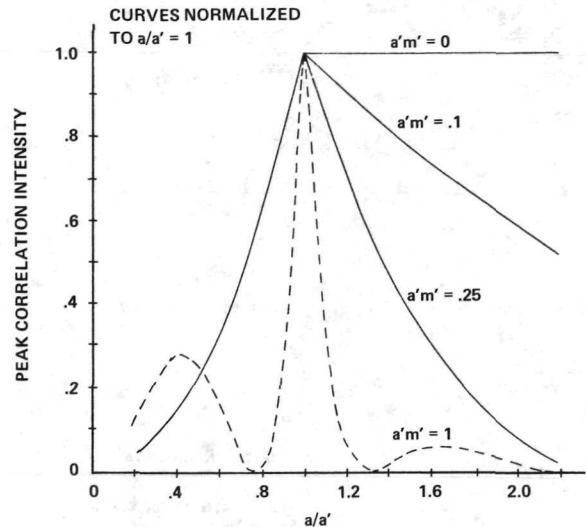


Figure 5.—High-pass matched filter selectivity.

which must be established for proper operation of the output plane detection device. Poor contrast in the input plane naturally limits the output correlation-to-background intensity ratio. For a linearly recorded, wideband matched filter with negligible noise introduced by the system, the output contrast varies in proportion with the input contrast, as shown in figure 6. In the case where the input contrast is degraded by relatively high signal background transmittance, the high-pass type of matched filter provides a contrast improvement, also shown in figure 6 (K_r is the signal-to-reference ratio used during formation of the experimental filters). This improvement is due to the presence of the low-frequency bandstopping action of the high-pass filter. Otherwise, in the case where the input signal background transmittance is low but the input contrast is still poor, the output contrast will be poor and suffer degradation due to added system noise.

ROTATIONAL SENSITIVITY

In theory, the matched filter is a shift-invariant filter; however, its operation is affected by rotation of the input signal relative to the filter itself. For meteor trail detection applications, the input signal can have various orientations. Thus, the input plane or the filter plane might require rotational alignment during each input signal frame.

The sensitivity of the matched filter to rotational misalignment is a function of the filter selectivity as

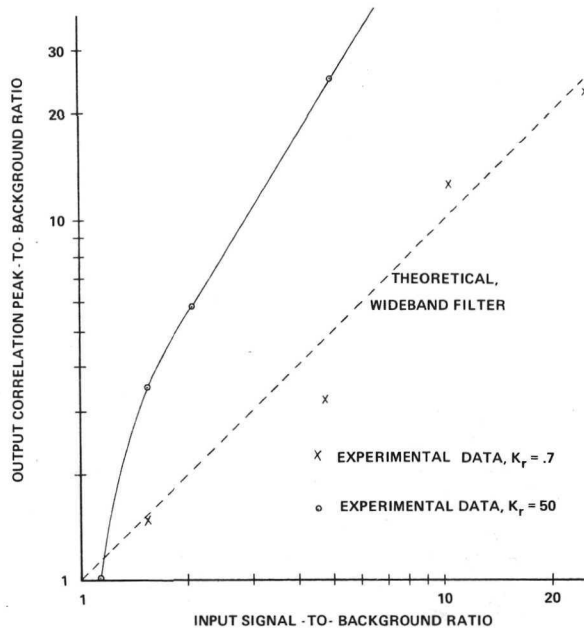


Figure 6.—Input-output contrast for unit input signal transmittance.

well as the geometrical characteristics of the signal being processed. Figure 7 illustrates the dependence for rectangular-aperture signal formats having several values of length-to-width ratio. From this figure it is apparent that matched filters exhibiting higher selectivity are more sensitive to rotational misalignment. Also it can be observed that the more narrow the rectangular aperture, the more sensitive the filter becomes to rotational changes.

CONCLUSION

The theoretical and experimental results presented here have assumed a narrow rectangular meteor trail model to determine some of the operational characteristics and limitations of the matched filter technique for detection of meteor trails. It is concluded that the most severe limitation of this technique

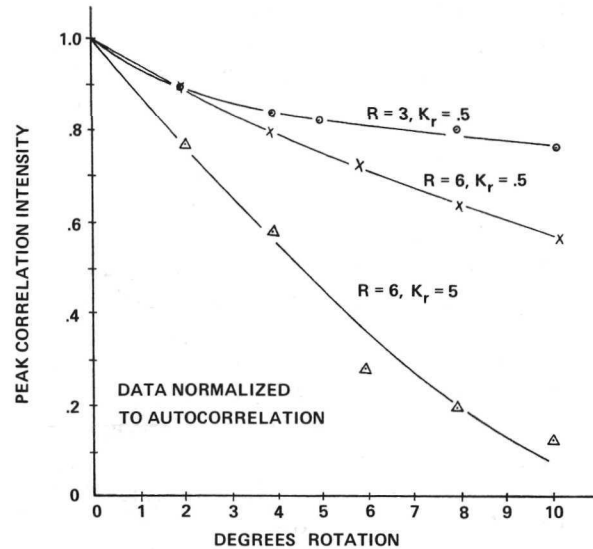


Figure 7.—Effects of input plane rotation on peak correlation intensity.

concerns the ability to present input signals to the system with sufficient signal-to-background contrast, a data transfer problem which suggests further investigation.

REFERENCES

1. Vander Lugt, A.: Signal Detection by Complex Spatial Filtering, *IEEE Transactions on Information Theory*, IT-10, April 1964, pp. 139-145.
2. Gee, T. H.; et al.: Development of Optical Data Processing Techniques Applicable to Detection and Study of Meteor Trails, NASA CR-61341, Dec. 1970.
3. Goodman, J. W.: *Introduction to Fourier Optics*, McGraw-Hill Book Co., New York, 1968.
4. Binns, R. A.; et al.: Methods of Increasing Discrimination in Optical Filtering, *Applied Optics*, 1968, p. 1047.
5. Allen, C. W.: A study of Some Signal Parameters Affecting Matched Filter Operation With Application to Meteor Trail Detection, unpublished master's thesis, University of Tennessee Space Institute, March 1971.

Holographic Pattern Recognition— New Thoughts on Old Problems

H. J. Caulfield

Sperry Rand Research Center

Two difficulties which arise in the attempt to apply holographic matched filtering to pattern recognition are (1) that the pattern location is seldom precise enough to permit matched filtering and (2) that the use of simple threshold circuits to perform the recognition is unreliable. We find that (1) when matched filtering is precluded, the next best approach is both easy and useful and that (2) more complicated recognition circuits produce an increase in system reliability. Finally, we suggest avenues for further research in these two areas.

It is well known that, in several senses, optical matched filtering is the best possible method for optical character or pattern recognition (ref. 1). Nevertheless, there remain problems which make it less than what we would desire. We will examine two of those problems: (1) the problem of similar responses to similar characters and (2) the problem of meeting the rather stringent requirements for optical matched filtering. To these problems we will offer some preliminary solutions. These "solutions" themselves present other problems, not all of which will be discussed. It is the primary thesis of this paper that there remains a great deal of work to do in arriving at a full understanding of the methods of coherent optical pattern recognition.

REVIEW OF OPTICAL MATCHED FILTERING

In order to define some notation and illustrate some problems, we must review optical matched filtering.

Consider first a lens operating to transform a wavefront in an input XY plane to an output $\xi\eta$ plane. Let both planes be a focal length f away from the lens, as shown in figure 1. We define reduced variables $u = \xi/f\lambda$ and $v = \eta/f\lambda$ for notational convenience and use the complex variable notation scheme to describe the wavefronts. We know that, except for

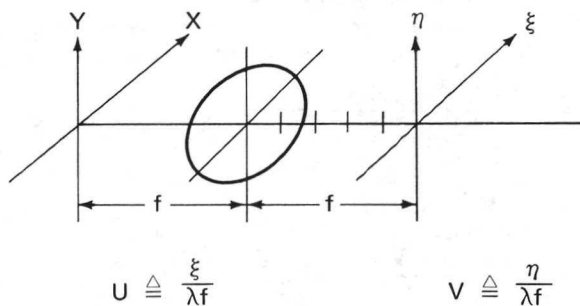


Figure 1.—The relationship between complex wavefronts in the input (x - y) and output (ξ - η) of a single-lens imaging system is given by a simple Fourier transform.

a multiplicative constant which we will ignore, an input wavefront $g(x,y)$ will be transformed into an output wavefront

$$G(u,v) = \iint_{\text{aperture}} g(x,y) \exp [-2\pi i(xu + yv)] dx dy \quad (1)$$

If $g(x,y)$ is zero outside the aperture, this is a Fourier transform of $g(x,y)$.

Now let us insert a holographic matched filter in the u - v plane. The transmission of such a hologram in one general direction is $H^*(u,v)$, i.e., the complex conjugate of the Fourier transform of some pattern

$h(x,y)$. Thus, if the input to the whole system (fig. 2) is $g(x,y)$, the wavefront leaving the u - v plane in the general direction of interest is $G(u,v)/H^*(u,v)$. The second lens Fourier-transforms that wavefront to form a final output distribution, which we call the correlation spot and represent by $S_{gh}(x,y)$. It is easy to show that $S_{gh}(x,y) = C_{gh}(-x,-y)$ where $C_{gh}(x,y)$ is the cross-correlation function of $g(x,y)$ with $h(x,y)$. The optimality of matched filtering is based on the assumption that we can measure $C_{gh}(0,0)$. Among other things, we know that

$$S_{gg}(0,0) \geq S_{gh}(0,0) \quad (2)$$

for all $g(x,y)$ and $h(x,y)$, which are normalized in the sense that

$$S_{gg}(0,0) = S_{hh}(0,0) \quad (3)$$

That is, we can insert an unknown character x and search for the highest $S_x(0,0)$ value. We then identify the unknown character with the one used to make the corresponding filter. Confusion between very similar characters such as E's and F's can still occur, e.g., $S_{EF}(0,0) = S_{EE}(0,0)$.

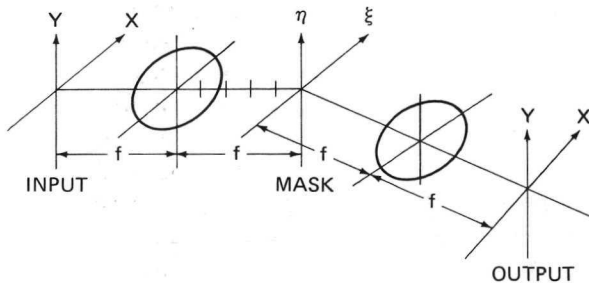


Figure 2.—Insertion of a holographic mask in the ξ - η plane can, under highly restricted conditions, lead to matched filtering of the input pattern.

PRACTICAL REQUIREMENTS FOR OPTICAL MATCHED FILTERING

There are two sets of very stringent requirements which an optical matched filtering system must satisfy. First, we must be certain that the system can produce $S_{gh}(x,y)$. Second, we must be certain that we can measure $S_{gh}(0,0)$. If either condition fails, we can relax the requirements on the other, as we will show later.

In order to assure that the system produces $S_{gh}(x,y)$, we must require negligible spurious phase contributions from the system. This means that all components, including the input transparency and the hologram, must be flat to within a fraction of a wavelength; the lenses must be diffraction limited; and the hologram must be precisely located.

In order to read $S_{gh}(0,0)$, we must read $S_{gh}(x,y)$ through a pinhole centered on $(0,0)$, the size of the hole depending on the character size and the focal lengths. If the input is translated by x_0 and y_0 , the measured signal will not be $S_{gh}(0,0)$, but $S_{gh}(-x_0, -y_0)$. Thus, we must be certain that the input is carefully located to within a fraction of the minimum resolvable input characteristic distance.

FAILURE TO ACHIEVE MATCHED FILTERING

It should now be clear that, except in some special cases, optical matched filtering is extremely difficult. Indeed, much of what is often called matched filtering is not matched filtering but something else. Suppose we cannot locate the input accurately enough to allow reading the output through a pinhole. Then a logical and common thing to do is read the whole correlation spot, i.e.,

$$\Sigma'_{gh} \triangleq \iint_{\text{aperture}} S_{gh}(x,y) dx dy \quad (4)$$

Except for a constant factor due to losses in the lens, this is equivalent to reading

$$\Sigma'_{gh} \triangleq \iint_{\text{filter}} \exp[-2\pi i(x_0 u + y_0 v)] G(y,v) H^*(u,v) du dv \quad (5)$$

Recently, Maloney (ref. 2) has shown that in this case the operation we perform is equivalent not to matched filtering of $g(x,y)$ and $h(x,y)$, but to matched filtering of the autocorrelation functions $C_{gg}(x,y)$ and $C_{hh}(x,y)$. Since the phase information about the wavefront is lost in the autocorrelation operation, the suboptimality of this autocorrelation matching follows. Nevertheless, matched filtering of autocorrelation patterns is often sufficient for adequate discrimination.

POOR ADAPTATION TO CHARACTER RECOGNITION

We use the term "pattern recognition" to describe the problem of recognizing the degree of similarity between an input pattern and a test pattern. If we

specify ahead of time that the input pattern is one from among a known alphabet of N characters, we have a new problem which we call "character recognition". Matched filtering is ideally suited to the measurement of similarities among patterns. This means that if our alphabet has within it very similar characters, e.g., O, C, G, Q, matched filtering will give nearly identical responses. Thus, we will have to distinguish among those characters on the basis of small differences among large signals. This is possible but not desirable. The question is, then, can we use the extra information given to us in the character recognition problem, namely the allowable sets of inputs, to make the response signals due to the various matched filters have a different form?

SUMMARY OF MATCHED FILTERING PROBLEMS

We can now state two questions relating to optical matched filtering.

First, in the event that system considerations preclude matched filtering, how can we take advantage of the relaxed conditions for autocorrelation matching to make pattern recognition and character recognition easier or more effective?

Second, how can we utilize the extra information in character recognition to make better filters or better use of the matched filters?

We shall indicate a few of the possible answers.

ADAPTING MATCHED FILTERING

The problem to which we refer is often called "feature selection". That is, we want to look for differences among the known characters. This assures us that identification will not depend on measurement of small differences among large signals. A highly general means for feature extraction has been given by Caulfield and Maloney (ref. 3) and extended somewhat by Caulfield and Lu (ref. 4). Without going into detail, we merely note that, if instead of the given characters $C_1, C_2, \dots, C_N$, we had new characters $\gamma_1, \gamma_2, \dots, \gamma_N$, such that

$$C_{ci\gamma_j}(0,0) = \delta_{ij} \quad (6)$$

then there would be no feature extraction problem. If the determinant of the $C_{ci\gamma_j}(0,0)$'s is nonsingular, we can solve for scalar weights W_{ij} such that

$$\gamma_i = \sum_j W_{ij} C_j \quad (7)$$

The characters $\gamma_1, \gamma_2, \dots, \gamma_N$ are normalized

features extracted to give zero cross-correlations. Furthermore, if we match the filter to γ_j , an input character C_i will lead to a signal

$$S_{ci\gamma_j}(0,0) = \delta_{ij} \quad (8)$$

These filters can be produced *a priori* (preferably using computer holography) or *a posteriori* (using measured $S_{ci\gamma_j}(0,0)$ values).

What is important to note here is that we are not bound to orthogonalize the given characters. For instance, we might choose the weights in such a way that, given the information on the distortion statistics, the expected values of the responses are orthogonalized. We can also include loss functions, *a priori* statistics, etc., by choosing weights that minimize the expected loss if we identify the character with the filter giving the highest response.

EXPERIMENTAL LIMITATIONS ON AUTOCORRELATION FILTERING

We can now begin the task of saying in what ways autocorrelation filtering is easier to perform than optical matched filtering. The most obvious advantage is insensitivity of autocorrelation matching to the transverse location of the input (assuming, of course, uniform illumination, no vignetting, no off-axis degradation of lens performance, etc.). Another obvious advantage is that, from the hologram to the detector, optical components need not be of high quality since they are merely collecting the light. Furthermore, there are other relaxations in tolerances which are harder to justify but certainly exist. Phase variations on the input transparency cause changes in the Fourier transform. Changes in phase of the Fourier transform do not affect the autocorrelation matching. Changes in the location of light in the Fourier transform are important only to the extent that the intensity pattern fails to overlap the recorded pattern. Since the recorded pattern is usually broad in the high transmission region, this effect is not as severe as it would be in optical matched filtering. Likewise, if the transforming lens forms a blurred Fourier transform pattern, we obviously cannot do optical matched filtering but we can do autocorrelation matching with reduced sensitivity.

FEATURE SELECTION IN AUTOCORRELATION MATCHING

If we assume that the input position is unknown and the phase effects are to be ignored anyway, we

are left with two possible types of feature selection. First, we can use the *a posteriori* weighting, operating on the measured Σ_{gh} values. Second, we can use Fourier transform negation masks. These are holograms which are efficient only in those regions of the Fourier transform plane where the normal hologram of that particular C_j is not efficient. That is, the Fourier transform negation mask measures light where it is not supposed to be. This type of feature selection is useful not only in character recognition (where it makes an O and a Q quite distinguishable) but also in general pattern recognition.

OUTPUT POSITION INVARIANT CONFIGURATIONS FOR AUTOCORRELATION MATCHING

There are several configurations which lead to a fixed output position for autocorrelation matching.

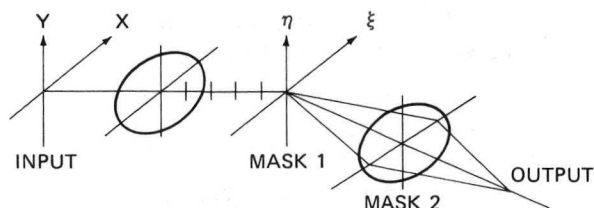


Figure 3.—If the holographic pattern recognition mask (mask 1) contains many multiplexed masks of individual characters and if all of the corresponding output wavefronts are imaged onto a single output detector, we can use a simple binary mask (mask 2) to determine which output signals are measured at any time. By reading combinations of outputs rather than single outputs, some significant improvements in signal-to-noise ratios can be made.

One configuration of greatest interest is shown in figure 3. Here we image the hologram plane onto a single detector. We can then use a binary filter near the imaging lens to determine which correlation spots are detected. We can now read many combinations of correlation spots to achieve high signals and high signal-to-noise ratios (ref. 5). It is easy to show that the orthonormalization calculations are as simple to perform on a set of linear combinations of Σ_{gh} 's as on the set of individual Σ_{gh} 's.

AN INCONCLUSIVE CONCLUSION

I hope I have demonstrated some of the problems which can be encountered in coherent optical pattern recognition. A great deal of very basic work has yet to be done. Real conclusions must wait.

REFERENCES

1. Vander Lugt, A.: Signal Detection by Complex Spatial Filtering, *IEEE Trans. Inform. Theory*, Vol. IT-10, 1964, p. 139.
2. Maloney, W. T.: Real-Time Optical Filtering of Autocorrelation Functions, *Applied Optics*, Vol. 10, 1971, p. 977.
3. Caulfield, H. J.; and Maloney, W. T.: Improved Discrimination in Optical Character Recognition, *Applied Optics*, Vol. 8, 1969, p. 2354.
4. Caulfield, H. J.; and Lu, S.: *The Applications of Holography*, Wiley, New York, 1970.
5. All work of this nature is patterned after P. Fellgett, *J. Phys.*, Vol. 28, Suppl. 3-4, C2-165, 1967.

Selectivity and Noise Effects in Application of Optical Correlation*

R. O. Webb and F. M. Shofner

The University of Tennessee Space Institute

Experimental and theoretical results describing matched filter selectivity for a particular class of signal as obtained, for example, in holographic velocimetry are reviewed. An experiment showing noise rejection is described for filters having both low and high ratios of signal to reference beam. The data presented are for transmissive signals. Best results are obtained using high-ratio filters and high-contrast signals.

Extension to signals derived from diffusely reflecting material objects is treated. By the use of proper optics, the scale-change effects of matched filtering are shown to give a quantitative measure of deformation of the strained object. Dependence of sensitivity on signal characteristics is discussed.

In the investigation of seeded flows and particle field analysis using Fraunhofer holography, the particle position information in a test section such as shown in figure 1 may be obtained from the fringe information on the hologram. For spherical wave illumination, the intensity of the far-field diffraction pattern of a small spherical particle is (ref. 1)

$$I(r) \approx \frac{A^2}{Z^2} \left[1 + \frac{Z^2 a^2}{z_0} J_1 \left(\frac{kar}{z_1} \right) - 2 \frac{Za}{z_0 r} J_1 \left(\frac{kar}{z_1} \right) \sin \frac{kr^2 z_0}{2z_1 Z} \right] \quad (1)$$

The third term contains the so-called Fresnel lens factor $\sin mr^2$, which describes the reconstruction properties of the hologram. The position information can be obtained by (1) scanning the hologram with a microdensitometer, measuring the characteristic ring radii r_n , then calculating z_1 from equation 1 (ref. 1); (2) using the reconstruction properties of the in-line hologram; and (3) matched filtering (ref. 2). The filtering operation can be described as the cross-correlation of a reference signal s_0 with an input signal s :

$$C(x_3, y_3) = s * s_0 = \iint s(\xi, \eta) s_0^*(\eta - y_3) d\xi d\eta \quad (2)$$

where x_3, y_3 are coordinates in the output plane of a standard two-lens, spherical beam correlator.

One would presume without additional information that matched filters could be prepared from a collection of linearly recorded signals as described by equation 1 and that all particles of radius a and distance z_1 from the film would produce signals which would autocorrelate with the reference signal produced with the same parameters. Linearly recorded signals yielded poor results, however, leading to the conclusion that the total signal on the film might be described as a combination of ideal signal plus background variations and film noise.

Since it was noted with interest that very little work is reported in the literature on linearly recorded (continuous-tone) signals, nonlinear recording of signals was investigated. This type of recording gave useful cross-correlation results, which are summarized in the selectivity curves of figure 2. Note that the data of complementary experiments are given, one in which various signals are cross-correlated with a single filter and the other wherein a single input signal is correlated with various filters. As an estimate of the

*Research supported by Air Force Dynamics Laboratory

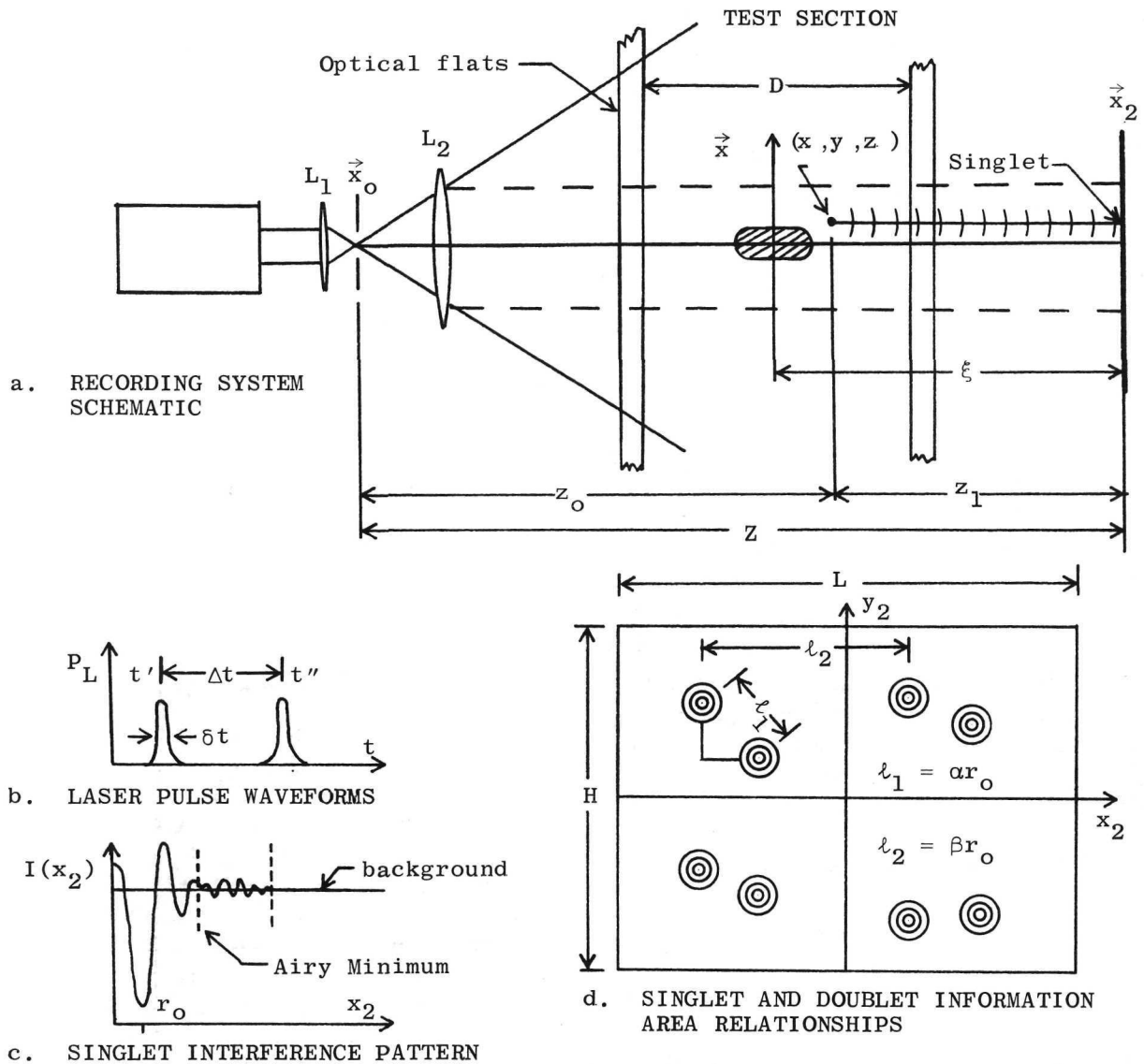


Figure 1.—Holographic velocimeter: recording phase.

width of the selectivity curves, the distance z can be found for which maximum correlation intensity is reduced to 0.9. This value from the curves is approximately ± 0.3 cm.

The experimental results can be compared with the results using a theoretical model. The signals were recorded using the saturation characteristics of the film so that the deep minimum of the second term of equation 1 produced essentially a transparent annulus upon development. Two models for this annulus based on microdensitometer traces are shown in figure 3. The rectangular model is the simpler and

more illustrative and can be used to estimate the selectivity of a linear filter. This model will predict a poorer selectivity than the experimental data, which was obtained using nonlinearly prepared filters. It has been shown that the high-ratio filters suppress low-frequency signal information and accentuate high-frequency detail and are thereby more selective (ref. 3).

MODEL SELECTIVITY

If the rectangular transmission function is used as a model of the signal, then the dimensions of the

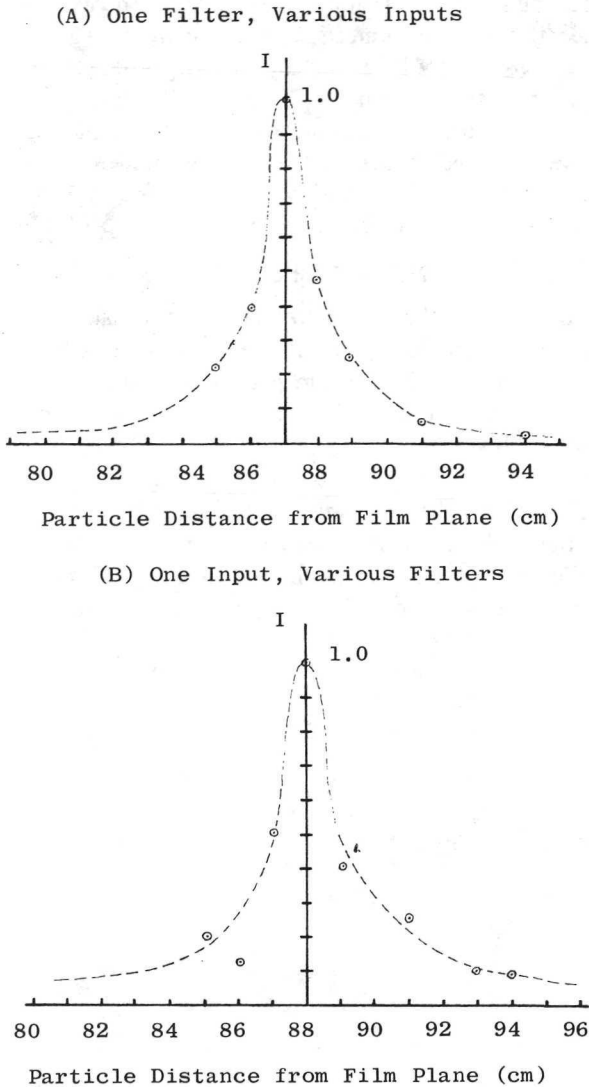


Figure 2.—Cross-correlation with nonlinearly recorded signals and nonlinear matched filters.

annulus can be obtained from a consideration of equation 1. The radius of the deep minimum of that equation is described to a good approximation by

$$r_0 = \left[\frac{\lambda z_1}{2} \frac{Z}{z_0} \right]^{1/2} \quad (3)$$

To obtain a theoretical selectivity curve, the maximum correlation of the reference annulus with signal annuli of varying dimensions must be calculated. The inner and outer radii of the signal and reference annuli are defined respectively as

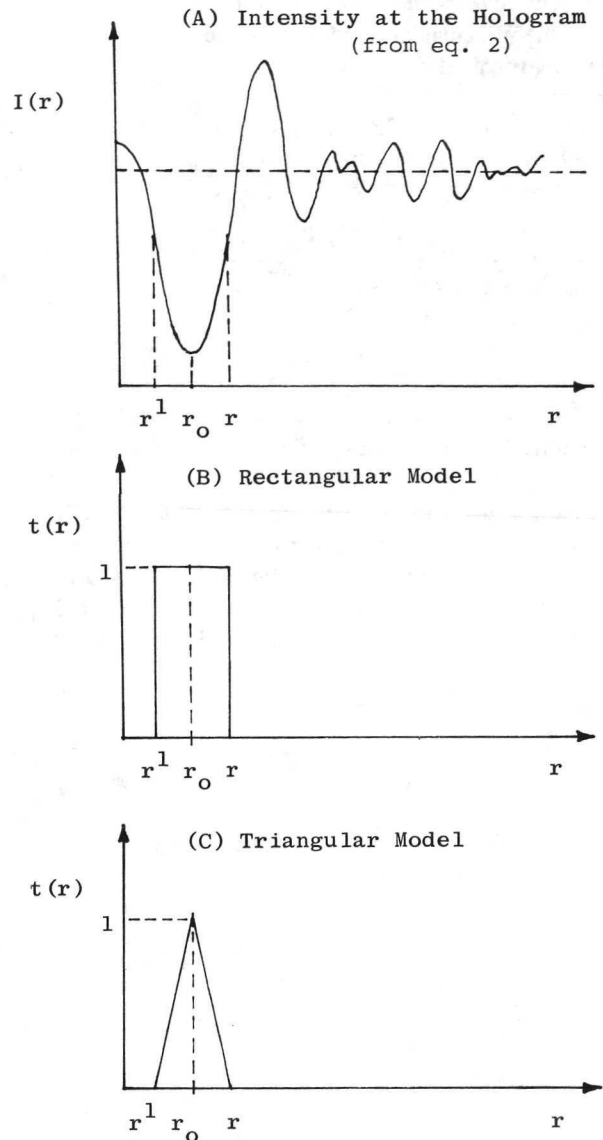


Figure 3.—Signal models.

$$r' = \alpha r_0 \quad R' = \alpha r_{00} \quad (4)$$

$$r = \beta r_0 \quad R = \beta r_{00}$$

The variables α and β depend on the saturation characteristics of the film and $r_0 = r_{00}$ for $z_1 = z_{10}$, the reference distance. It should be noted that the resultant selectivity curve will display the maximum correlation amplitude for similarly proportioned annuli, whose overall size will depend on r_0 .

The maximum correlation of two annuli according to the rectangular model is found to be a simple geometrical relationship:

$$\begin{aligned} C(0) &= 2\pi \int_0^\infty \rho t(\rho) t_0(\rho) d\rho \\ &= \frac{\pi(R^2 - r'^2)}{\pi(r^2 - R'^2)} \text{ for } z_1 \geq z_{10} \\ &= \frac{\pi(r^2 - R'^2)}{\pi(R^2 - r'^2)} \text{ for } z_1 \leq z_{10} \end{aligned} \quad (5)$$

Substituting from equation 4 and exhibiting only the case where $z_1 > z_{10}$,

$$C(0) = \frac{\pi\lambda}{2} \rho^2 \frac{Z}{z_{00}} z_{10} \left(1 - \frac{\alpha^2}{\beta^2} \frac{z_1 z_{00}}{z_0 z_{10}} \right) \quad (6)$$

This curve describes the filter selectivity for spherical wave recording and is sketched in figure 4. The plane wave case is obtained as $z_0 \rightarrow \infty$. The theoretical curve can be compared with the experimental curve given previously. For distances which correspond to the experimental data and for α and β chosen from experimental determination of r' and r_1 , the width of the curve at which it drops to 0.9 of its

maximum value is found to be ± 4.4 cm. The experimental value was found to be approximately ± 0.3 cm. The theoretical value is considerably larger because of (1) the rough approximation to $t(r)$ of the rectangular model and primarily (2) the fact that linear filtering was considered in the theoretical development. It is thus clear that substantial improvement in selectivity is achieved by using nonlinear filters.

NOISE REJECTION

In an optical processing scheme, the signal to be filtered is recorded on photographic film, which necessarily contains random grain noise. Ideally the filter contains only signal information, that is, the filter will detect only the signal to which it is matched. If any noise or extraneous elements degrade that pattern, the correlation output will be altered. Initial efforts to use matched filters to detect diffraction pattern signals showed that random grain noise affects the correlation output most when the signals are of low contrast.

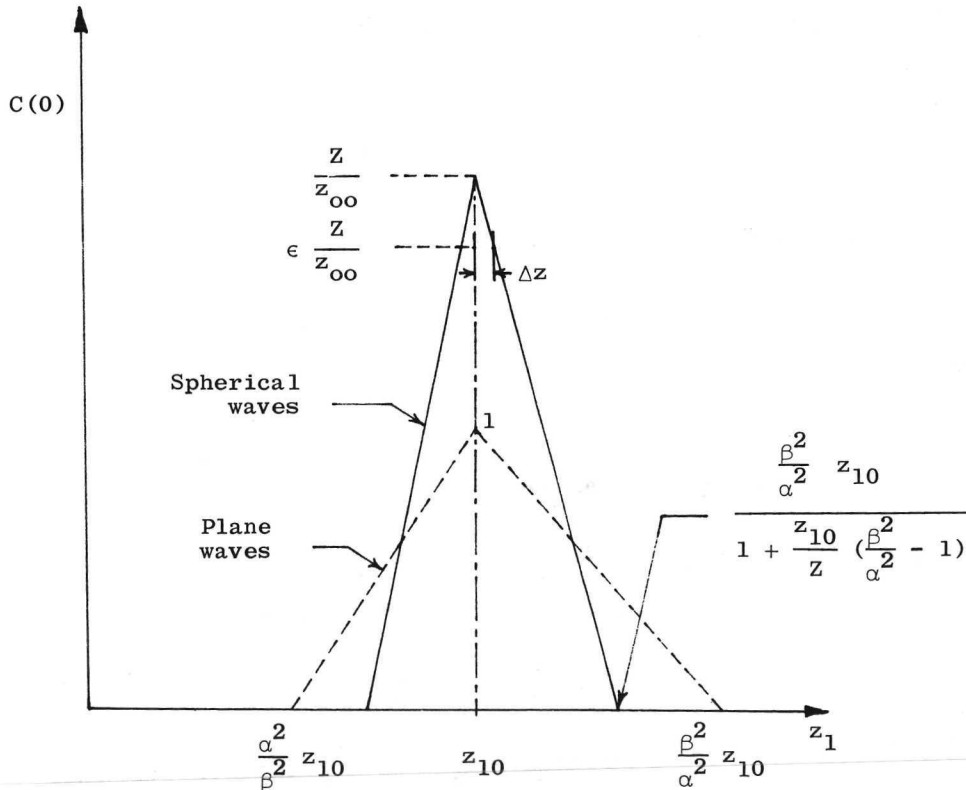


Figure 4.—Linear filter selectivity curve for rectangular $t(r)$ model.

In order to give some insight into the effect of grain noise on matched filter output, a study was conducted using an annular signal recorded on a number of films with various noise and resolution parameters. The pattern consisted of only two transmission levels; hence the characteristic curve of the film had little effect other than defining the range of the transmission step. The resultant signal took the form of a nearly transparent annulus on an opaque background. The noise in the signal was the base density granularity in the transparent portion.

To compare how film noise affected correlation, the annulus recorded on the highest-resolution film was used in making a pair of matched filters. One filter was recorded with a signal-to-reference beam intensity ratio of approximately 1:1, the other at a ratio of 1000:1. As stated earlier, the high-ratio filter filters to detail information in a signal pattern, while low-ratio, or linear, filters filter according to the gross characteristics of the pattern (ref. 4). The spectrum recorded on the filters represented that of a signal with the lowest grain noise.

One of the filters was placed in the transform plane of the correlator, and the annuli recorded on different emulsions were then placed successively into the input plane. A photomultiplier with a small aperture in front was then used to read the maximum intensity of the correlation output. These values were recorded and normalized according to the base density of the emulsion and support material of the films. The results of these readings are shown in figure 5.

This study of filter rejection with respect to noise demonstrates that the limitations of film response can seriously degrade the quality of the recorded signal. This degradation can have such a marked effect on the outcome of a detection system that a signal recorded on low-quality film may not be recognized in a matched filtering scheme.

MATCHED FILTER SELECTIVITY

The previous results apply for the matched filtering of a special type of signal, a transparent annulus on an opaque background. The theoretical selectivity

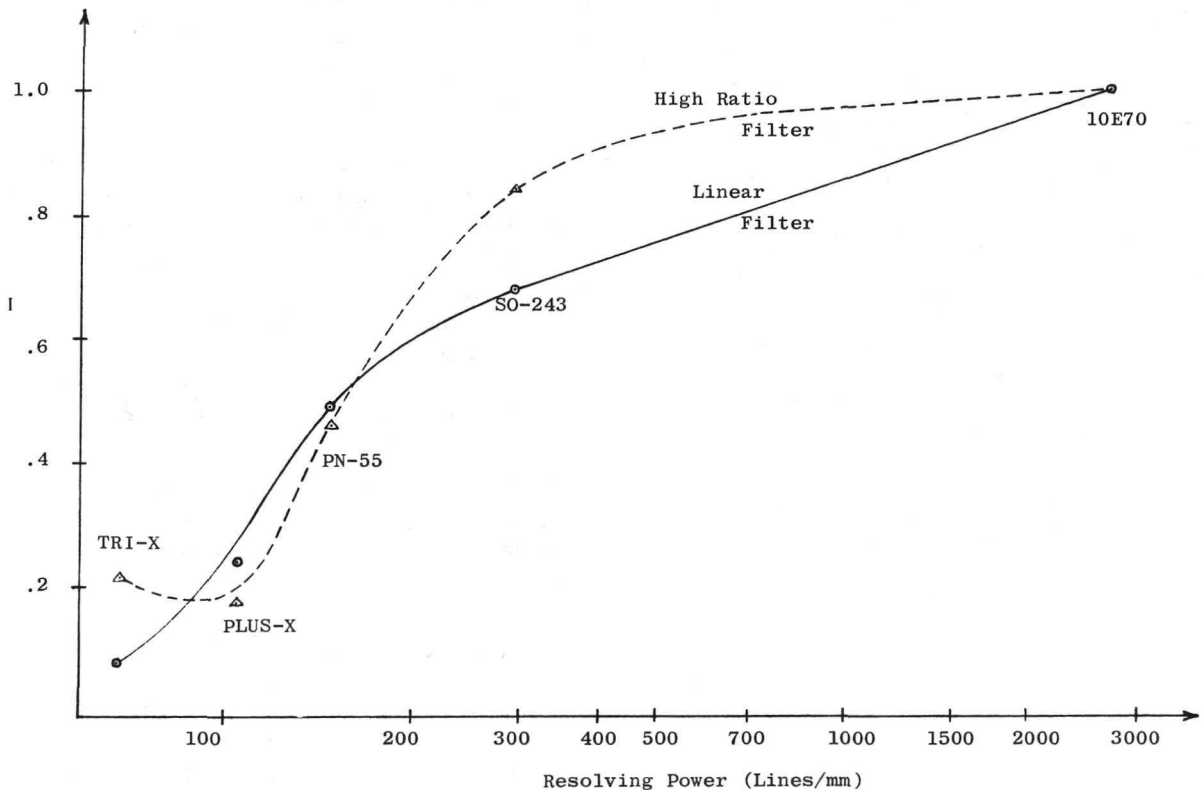


Figure 5.—Plot of normalized maximum intensity of correlation spot for signal recorded on different films.

curves were constructed from the maximum correlation intensity of two annuli whose inner and outer radii differed by a constant multiplier. The multiplier was related to the radius of the deep minimum of the Fraunhofer diffraction pattern of a small particle. These annuli are essentially a binary square-wave amplitude transmission function in the ideal case of perfect hard limiting, and therefore they contain high-frequency information associated with the abrupt transition from opacity to transparency. The frequency information of the mismatched annuli is slightly different from that of the reference, and the amount of difference accounts for the decrease in value of the cross-correlation function. The fact that the shape and slope of the selectivity curve depend on the frequency content of the signal can be seen from figure 6. This figure shows the peak correlation between a reference function and the same function whose coordinates are expanded slightly. The function is a sine wave on a bias level, and the different curves correspond to reference signals of higher frequency. It can be observed in the case of this signal that a slight expansion in coordinates produces steeper selectivity curves for signals of higher frequency content. If a number of selectivity curves are available for a particular signal with specialized frequency content, then those curves might be used to obtain a measure of the difference between the output signal and the reference signal, provided the only difference was a coordinate expansion or compression. An example of a practical use of this method, besides that of particle field analysis, is in determining the strain of materials under stress. The function in the figure might represent the reflectance of a test sample, and the selectivity curve would represent the decay of the peak correlation intensity as the sample was strained. If the reflectance were a rapidly varying function of space, then a smaller degree of strain could be detected more readily, since the correlation curve would decrease more rapidly than for low-frequency signals.

VARIABLE-SCALE OPTICS

Another optical correlation method which may be used to measure planar coordinate expansion, such as material strain, involves the use of a spherical-wave matched filter correlator such as that shown in figure 7. If we consider the problem of a transmissive signal under a uniform coordinate expansion, then it can be shown that the utilization of the scale-change effect

of this optical configuration can give a measure of the deformation. These results can be extended to diffusely reflecting planar surfaces (ref. 5). If a matched filter is made of a certain signal $s(x_1, y_1)$ using a spherical reference beam to cancel attendant quadratic phase factors, then the term of interest in the filter is given by

$$\frac{k}{\lambda f_1} S^* \left(\frac{x_2}{\lambda f_1}, \frac{y_2}{\lambda f_1} \right) \exp(-i2\pi\beta y_2) \quad (7)$$

where f_1 is the distance of the signal from the transform plane, β is the angle between the optical axis and a line from the source to the center of the x_2, y_2 plane, and K is a constant. When the film is developed and replaced in the transform plane, then it can be shown that the output of the filter is given by

$$U(x_3, y_3) \propto \frac{1}{\lambda z} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} S(\xi, \eta) s^* \left(\xi + \frac{x_3 f_1}{z}, \eta + \frac{y_3 f_1}{z} + \beta \lambda f_1 \right) d\xi d\eta \quad (8)$$

which is the autocorrelation function of the original signal centered about the point $-\beta \lambda z$ in the output plane. This output occurs under the condition

$$\frac{1}{z} = \frac{1}{f_3} - \frac{1}{f_1} \text{ and } d = f_1 \quad (9)$$

where z is the distance from lens L_3 to the output plane (x_3, y_3) , f_3 is the focal length of lens L_3 , and d is the distance of the signal from the transform plane.

If the signal in plane (x_1, y_1) then undergoes some uniform deformation α , it may be represented by $s(\alpha x_1, \alpha y_1)$, and the light distribution falling on the matched filter becomes

$$\frac{A \exp[k(x_2^2 + y_2^2)/i2d]}{\lambda d} \frac{f_2}{d} G \left(\frac{x_2}{\lambda d \alpha}, \frac{y_2}{\lambda d \alpha} \right) \quad (10)$$

Now if the signal plane is moved slightly so that $d = f_1/\alpha$, then it can be shown that the output distribution has the same form as equation 8 under a new focusing condition:

$$\frac{1}{z} = \frac{1}{f_3} - \frac{\alpha}{f_1} \quad (11)$$

If values of peak correlation are taken as the plane is shifted slightly from the reference position, along with the corresponding shift magnitude, then the amount of deformation could be found from those values of z and $|U(x_3, y_3)|^2$ which satisfied the

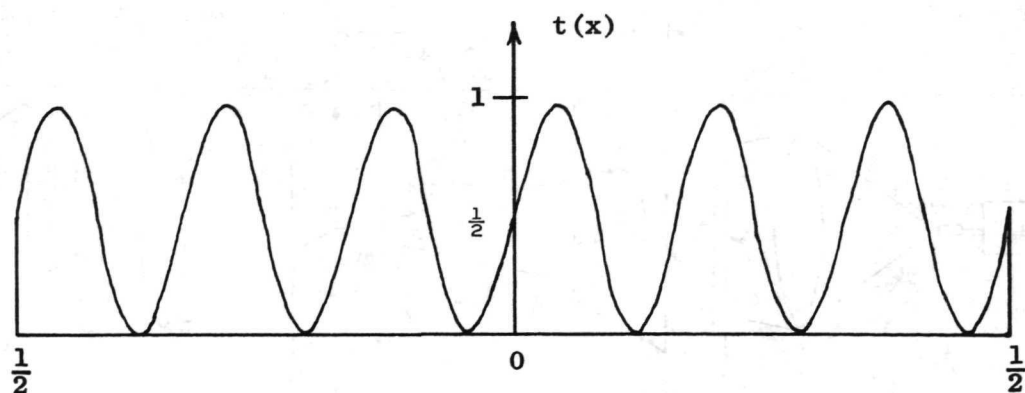
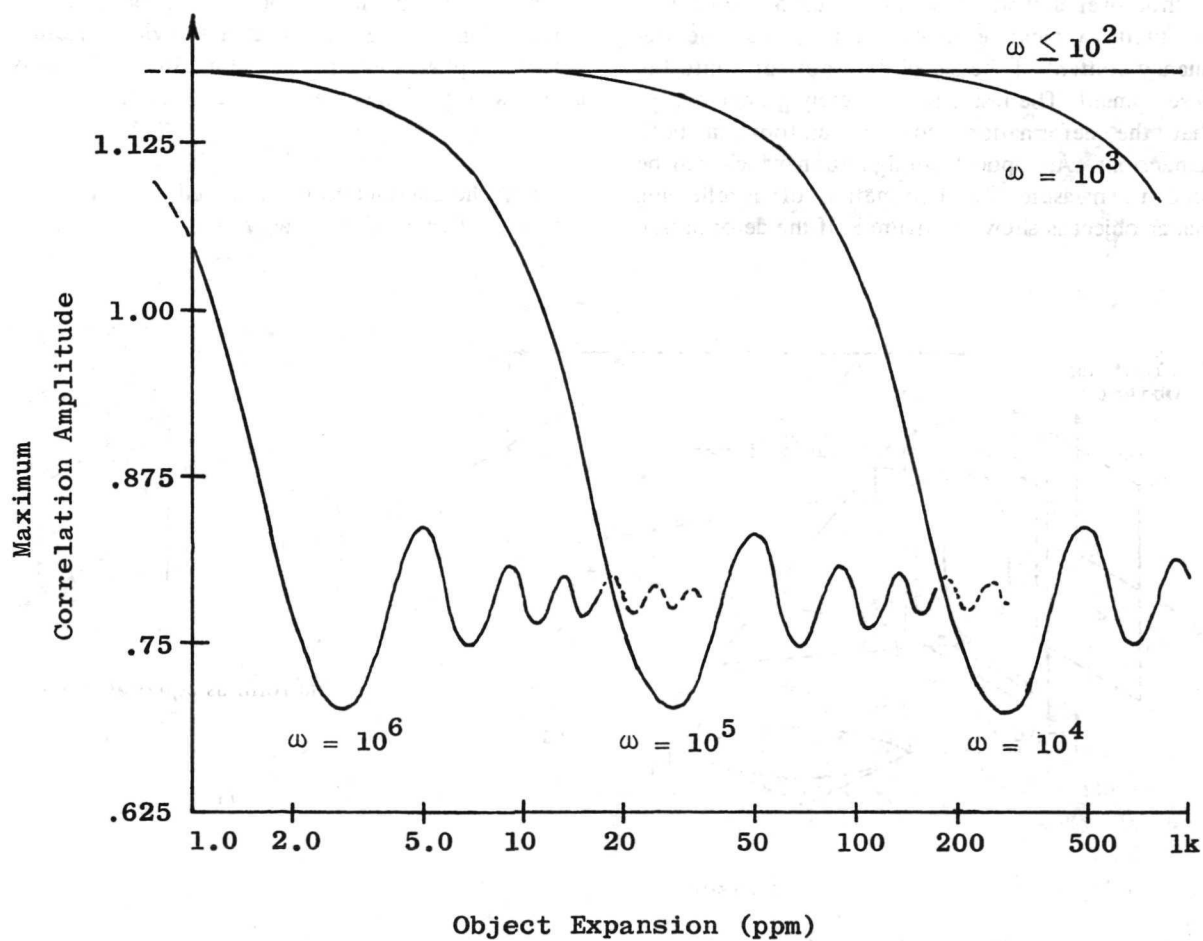
Object Transmission ($\frac{1}{2} + \frac{1}{2} \sin \omega x$)

Figure 6.—Selectivity curves for expanded coordinates.

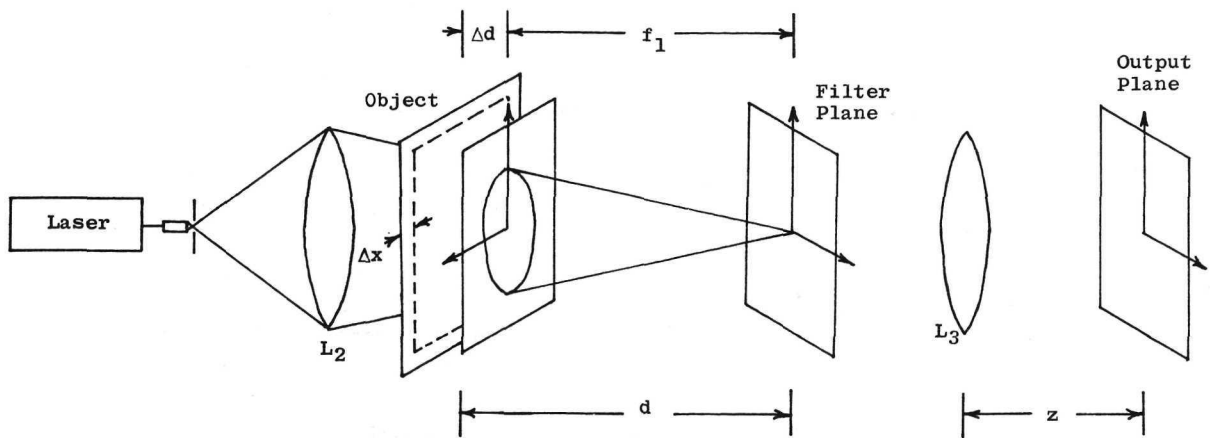


Figure 7.—Correlation of signal under uniform expansion (transmissive signal).

autocorrelation equation. The advantage of this method over that where selectivity calibration curves are used to measure deformation is that the frequency content of the signal does not enter into the development. The result is completely general except that the deformation must be uniform in both dimensions. An optical configuration which can be used to measure the deformation of a reflecting planar object is shown in figure 8. If the deformation

is to be measured in only one dimension irrespective of what occurs in the orthogonal direction, then an illumination scheme such as that shown in figure 9 may be employed when making the filter so that only a narrow strip of the object will be studied.

CONCLUSIONS

From the considerations presented here, it is clear that the effects of selectivity and noise must be

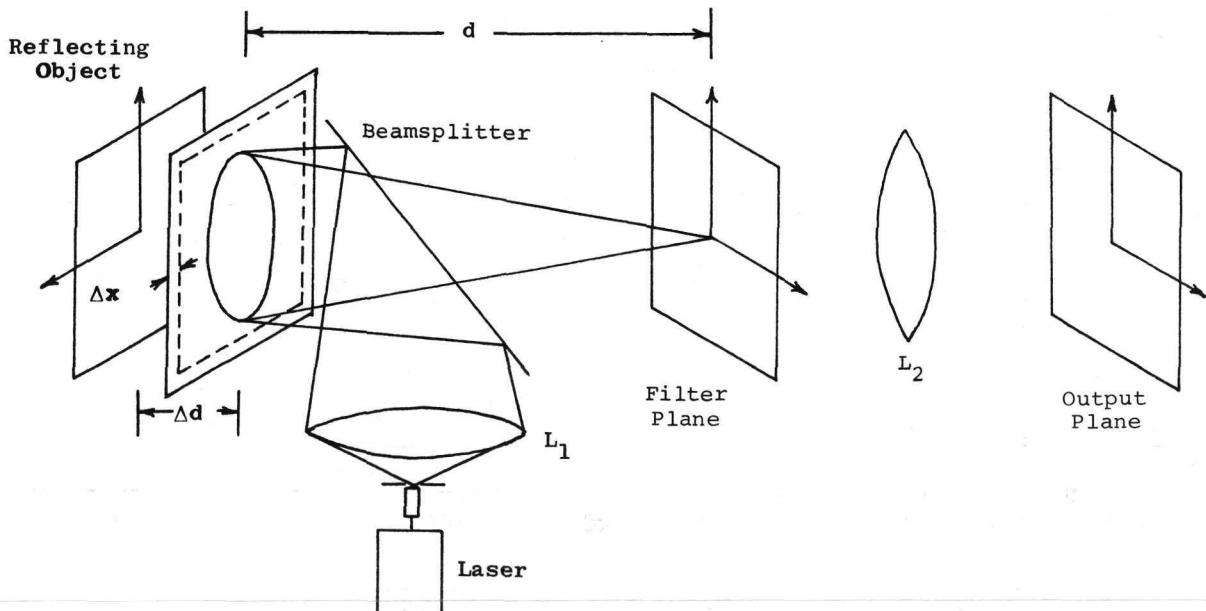


Figure 8.—Correlation of signal under uniform coordinate expansion (reflecting signal).

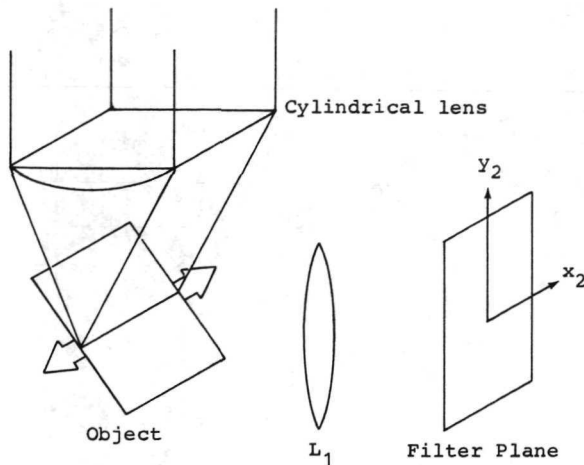


Figure 9.—Unidimensional illumination of object.

analyzed before a coherent filtering system can be used to give quantitative results concerning object deformation. Either selectivity curves or scale-change optics may be used; however, the selectivity curve is generally a function of the frequency content of the object, and hence a new set of curves may be required for each new object. The comparison of the theoretical selectivity data, based on the rectangular model of the annulus and linear filter recording, with the experimental data verified the desirability of high-ratio filters. High-ratio filters for signals with large low-frequency components lead to the blocking of these components and filtering according to detail

structure, which tends to increase the selectivity of the filtering process. The type of filter used then must also be considered in measuring the selectivity of the filtering process.

Since the high-ratio filter has greater selectivity, there was concern that it might be more sensitive to film grain noise and therefore have poorer noise rejection properties. The experimental results, however, show that the high-ratio filter has noise rejection comparable to that of the linear filter, since cross-correlation is less severely degraded by increasing film grain noise. Suppression of low-frequency noise as well as signal components leads to a net improvement in signal-to-noise ratio for the high-frequency components, even though these noise components are larger than for linearly recorded filters.

REFERENCES

1. Menzel, R.; and Shofner, F. M.: An Investigation of Fraunhofer Holography for Velocimetry Applications, *Applied Optics*, Vol. 9, 1970, pp. 2073-2079.
2. Shofner, F. M.; Webb, R. O.; and Fradenburg, R. L.: Optical Data Processors for Holographic Velocimetry, *Laser Journal*, Vol. 2, 1970, pp. 13-17.
3. Binns, R. A.; Dickinson, A.; and Wastrasiewicz, B. M.: Methods of Increasing Discrimination in Optical Filtering, *Applied Optics*, Vol. 7, 1968, p. 1045.
4. Gee, T. H.; and Linton, W. Jr.: Some Aspects of Bandlimiting in Coherent Optical Matched Filtering, *Instrumentation in the Aerospace Industry*, Vol. 16, 1970, pp. 126-130.
5. Marom, E.: Real-Time Strain Measurements by Optical Correlation, *Applied Optics*, Vol. 9, 1970, pp. 1385-1391.

Page Intentionally Left Blank

Onboard Optical Data Processing for Spacecraft

Akram S. Husain-Abidi

*Research Associate of National Academy of Science,
Goddard Space Flight Center*

Optical data processing techniques are very attractive for processing image-type data, since optical systems have two degrees of freedom. The use of hybrid optical-digital systems for use on Earth resources and planetary spacecraft is being explored. An onboard spacecraft optical system must operate on low power, be rugged and reliable, and have no mechanical or photographic links.

With onboard satellite use in mind, a unique system has been designed. The main features of the system are the use of off-axis parabolic mirror segments as collimating Fourier-transforming and image-reconstructing elements, and a gallium arsenide laser diode as a point source of coherent electromagnetic radiation. The performance of this system in generating Fourier transform relationships and spatial filtering is very encouraging.

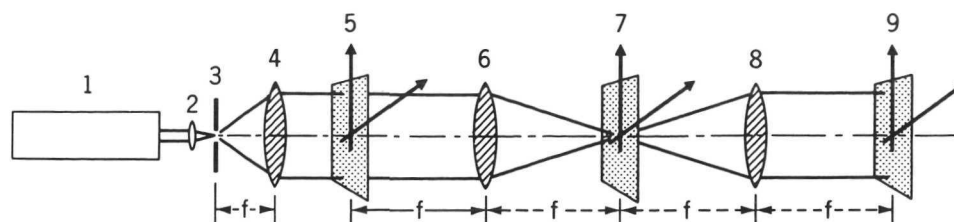
Earth resources satellites and the Earth resources experiments aboard space stations will sense a very large number of images. According to a rough estimate, the total data rate may be as high as 10^{12} bits per second. In order to extract usable information from this enormous amount of data, we believe that optical data processing techniques are ideally suited, since they have two degrees of freedom (as contrasted with electronic techniques, which have inherently only one degree of freedom). Optical techniques are extremely useful for the performance of linear mathematical operations such as spectral analysis, complex spatial filtering, matched filtering, autocorrelation, and cross-correlation.

An onboard spacecraft optical data processing system will be very useful because it will allow transmission of processed data rather than raw data, resulting in an enormous saving of transmitter bandwidth. The development of these techniques will be useful for NASA missions to other planets, as well as Earth-orbital missions.

The published account of optical data processing techniques goes as far back as 1873, when Ernst Abbe demonstrated in his classical paper that the diffraction

pattern in the focal plane of a lens has all the characteristics of a two-dimensional Fourier transform of the light distribution in the input information. He also recognized the spatial filtering phenomenon. Porter in 1906 reported the experimental evidence of spatial filtering by manipulating the diffraction pattern in the Fourier transform plane to enhance or suppress certain features of the input information. During the period of 1954 to 1964 a number of papers appeared in the literature, perhaps the most important of which was the one by O'Neill in 1956. This paper demonstrated that the optical analog of a number of electrical concepts, such as edge-sharpening and detection of periodic and isolated signals in the presence of noise, can conveniently be performed. The published work of Vander Lugt in 1964 on recording techniques of complex spatial filters was largely responsible for a reevaluation of optical data processing techniques.

Figure 1 illustrates the conventional configuration of an optical system normally used for coherent optical data processing. Light from a He-Ne laser radiating at a wavelength of 632.8 nm is brought to a point focus by a microscope objective. A pinhole is



- | | |
|---------------------|-------------------------------|
| 1. He-Ne GAS LASER | 6. FOURIER TRANSFORMING LENS |
| 2. MICROSCOPIC LENS | 7. FOURIER TRANSFORM PLANE |
| 3. PIN HOLE | 8. IMAGE RECONSTRUCTING LENS |
| 4. COLLIMATING LENS | 9. IMAGE RECONSTRUCTION PLANE |
| 5. INPUT PLANE | |

Figure 1.—The conventional optical data processing system.

placed in this focal plane to eliminate laser beam noise and to exclude stray light. Another lens is placed a focal length away from this plane to collimate the laser light. The input information is then placed a focal length away from a converging lens. This lens in its focal plane produces the Fraunhofer diffraction pattern of the input information in two dimensions. This diffraction pattern has all the characteristics of a two-dimensional Fourier transform of the light distribution in the input information. If an arbitrary function is introduced in the input plane, a two-dimensional spectrum of that function can be obtained in the Fourier transform plane. Spatial frequency filtering can also be performed in the Fourier transform plane by manipulating the diffraction pattern. If a complex spatial filter is placed in the Fourier transform plane, the system can be used for autocorrelation or cross-correlation.

This optical system works well in the laboratory environment, and its performance in spectral analysis, spatial and complex spatial filtering, autocorrelation, and cross-correlation has been reported in the literature. For processing data aboard spacecraft, however, this system has two main drawbacks. The first is the low efficiency and bulkiness of the He-Ne gas laser, and the second is the axial symmetry of the optical system.

A solid-state GaAs laser has been used to overcome the first drawback. This laser is at least 10 000 times better in efficiency and probably the same order of

magnitude smaller in overall volume. Furthermore, since a GaAs laser system does not require the microscopic lens and pinhole spatial filter, optical alignment problems are minimized.

To overcome the second problem, paraboloidal mirror segments are used. It has been found that paraboloidal mirror segments not only overcome the axial symmetry problems but have a number of significant advantages over lenses. Let us start by considering the problems associated with lenses.

The quality and resolution of Fourier transform relationships in the focal plane of a lens is very much affected by the lens aberrations and the optical refracting material. The three types of aberration that are primarily responsible for the degradation of Fourier relationships are spherical aberration, astigmatism, and coma.

Besides overcoming these aberrations, the other critical problem is the choice of the proper optical material. For an ultrahigh-quality lens suitable for data processing, the optical material should be:

1. homogeneous to a very high degree. (It is very important that the refractive index of the lens be constant throughout the material.)
2. free from thermal and mechanical strains.
3. optically isotropic (i. e., the index of refraction at any point must be constant regardless of the direction in which the radiation is passing the point).

Therefore, for a good optical system with lenses, it is necessary to rectify all the aberrations and to insure the selection of proper optical material. Both of these requirements are extremely difficult and costly to satisfy.

Additional disadvantages of lens systems are front surface reflections, which are unavoidable, and the requirement for axial symmetry of the system (i. e., the optical system with lenses cannot be folded).

Let us now consider the paraboloidal mirror as a linear element in an optical data processing system. Referring to figure 2, light rays entering from the right parallel to the z axis are reflected from the mirror and intersect the z axis at the focal point f . The relationship between the incident and reflected scalar light fields at any point in the (x, y, z_0) plan can be described in terms of a transfer function, $t(x, y, z_0)$. For mirrors (as well as for lenses) the transfer function is strictly a phase function, and we have

$$\begin{aligned} t(x, y, z_0) &= e^{[i\phi(x, y, z_0)]} \\ &= e^{[ik\Delta(x, y, z_0)]} \end{aligned} \quad (1)$$

where $\phi(x, y, z_0)$ is the phase difference in radians between the incident and reflected fields, k is the wave number $2\pi/\lambda$, and $\Delta(x, y, z_0)$ is the difference in pathlength between the incident and reflected waves.

Again referring to figure 1, we see that the total path difference is

$$\Delta(x, y, z_0) = 2(z_0 - \Delta z) \quad (2)$$

(This assumes no ray bending to the left of the (x, y, z_0) plane, analogous to the thin-lens approximation in lens analysis.)

Now from the equation for a paraboloid of revolution,

$$\Delta z = \frac{x^2 + y^2}{4f} \quad (3)$$

Therefore,

$$\begin{aligned} t(x, y, z_0) &= e^{[ik\Delta(x, y, z_0)]} \\ &= e^{[i2kz_0]} e^{-ik\left[\frac{x^2 + y^2}{2f}\right]} \end{aligned} \quad (4)$$

In the case of a spherical thin lens, if the paraxial approximation is made, i. e., if we consider only light rays close to the lens axis, the transfer function is found to be

$$t(x, y, z_0) = e^{[iknz_0]} e^{-ik\left[\frac{x^2 + y^2}{2f}\right]} \quad (5)$$

Here n is the index of refraction of the lens material, and z_0 is the lens thickness along the optical

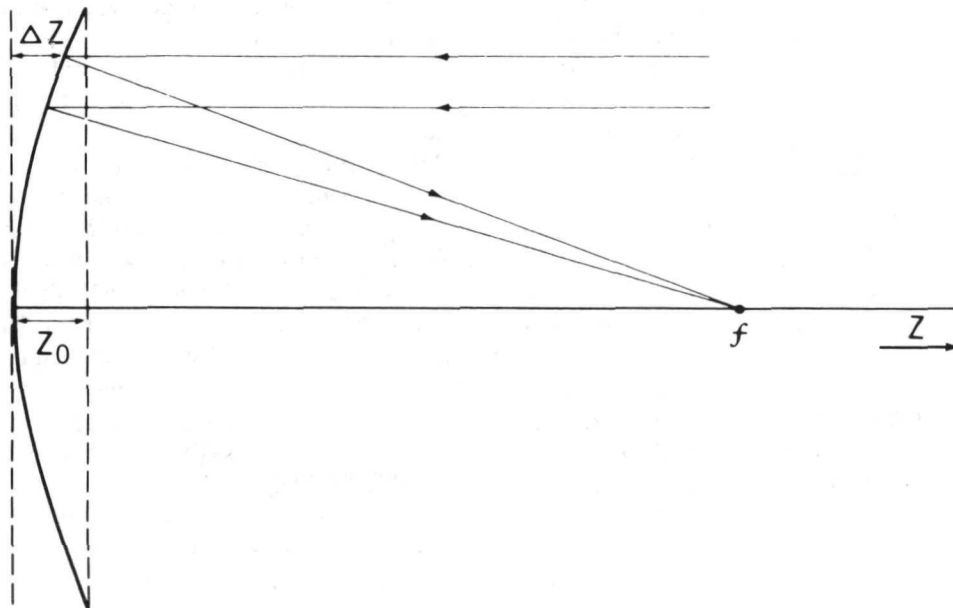


Figure 2.—Transfer function for a parabolic mirror.

axis. It is important to note that the focal length f of a lens is a function of the index of refraction of the lens material.

Referring to the derivation of the transfer function, several points can be made for the parabolic mirror as a system element. First, since the focal length f of a mirror is not a function of index of refraction, the parabolic mirror system will not have the chromatic aberration that is inherent in the lens system. Secondly, *all* the light rays parallel to the z axis will intersect the point f for a parabolic mirror, while only the *paraxial* rays will intersect the focal point for a spherical lens. This means that the parabolic mirror is inherently free from spherical aberrations (while the lens, of course, is not).

The absence of paraxial approximation for mirrors has several practical advantages, such as that the aperture of the optical signal being processed can be larger for a parabolic mirror than for a lens of the same diameter. More important, it means that off-axis segments can be cut out from a parabolic mirror, and these segments will have the same transforming properties of the original mirror and the same relative axis. Thus one can construct a folded optical processing system.

Two other aberrations also deserve some attention. Let us consider astigmatism. This aberration occurs when the incoming light rays make a large angle with the z axis of a mirror. This is not a serious drawback, however, since for most optical signal processing, the incoming light is a coherent plane wave whose rays are parallel to the z axis. Furthermore, all inter-element light paths can be kept at very small angles with respect to the element axes. Astigmatism therefore can be made negligible in a parabolic processing system.

The second aberration is coma, the aberration that occurs for light rays at small angles to the z axis. In experiments using parabolic mirrors as Fourier transforming elements, the effects of coma were not observable at the normal working angles.

Figure 3 illustrates an optical data processing system using paraboloidal mirror segments. The coherent light source (1) is a p-n gallium arsenide laser with an effective radiating area of 0.0015 mm^2 . The laser operates at room temperature at a wavelength of 900 nm . It is placed in the focal plane of the paraboloidal mirror (3). The coherent light (2) from the laser diverges and typically forms a 30° angle. Since the coherent light source is almost a

point source and since it is in the focal plane of the paraboloidal mirror (3), the light reflected from the paraboloidal mirror segment (4) is collimated.

To perform a two-dimensional spectrum analysis, the information to be analyzed is recorded on a transparency (either by taking a photograph or by electronically generating the object image). The transparency (6) is placed in the collimated beam (5), a focal length away from the paraboloidal mirror (7). The paraboloidal mirror segment (8) converts the information of the transparency into a diffraction pattern that has all the properties of a Fourier transform in the plane (10) centered at the point (9) which is the focal point of the paraboloidal mirror (7). The information in the diffraction pattern can be converted into electrical signals by placing an appropriate photon detector (11) in the plane (10). The photon detector can be of any suitable geometry, such as in the form of wedges or concentric rings.

Spatial filtering can also be performed in the plane (10). For example, the two basic types of filtering, bandpass and bandstop, can be performed by having a transparent or an opaque region at a desired place in the plane (10). Optical filters in the form of wedges, annuli, or opaque disks are used in the plane (10). The light transmitted through the filter/detector (11) is reflected by a paraboloidal mirror segment (13) of paraboloid (14), placed a focal length away from the plane (10). The input information is reconstructed at the plane (15), which is a focal length away from the paraboloidal mirror (14).

Figure 4 shows how the system could be housed in an enclosure 15.25 cm long, 9 cm high, and 4 cm wide.

Experimental performance of the paraboloidal mirror segment system was evaluated by first monitoring the Fourier transform relationship in the focal plane of the mirror segment. As examples of single simple shapes, figure 5 shows the Fourier transforms of a circular, a rectangular, and a triangular aperture. The well known Airy disk can be seen distinctly in the center of the transform of the circular aperture. Figure 5 also illustrates (d thru f) an example of multiple simple shapes. (A He-Ne laser was used for these experiments.)

Figure 6 shows an example of spatial filtering. The Fourier transform of a triangle and its reconstructed image are shown in figure 6 (top). To filter out one of the sides of the triangle, a narrow wedge was placed in the Fourier transform plane so that one of the

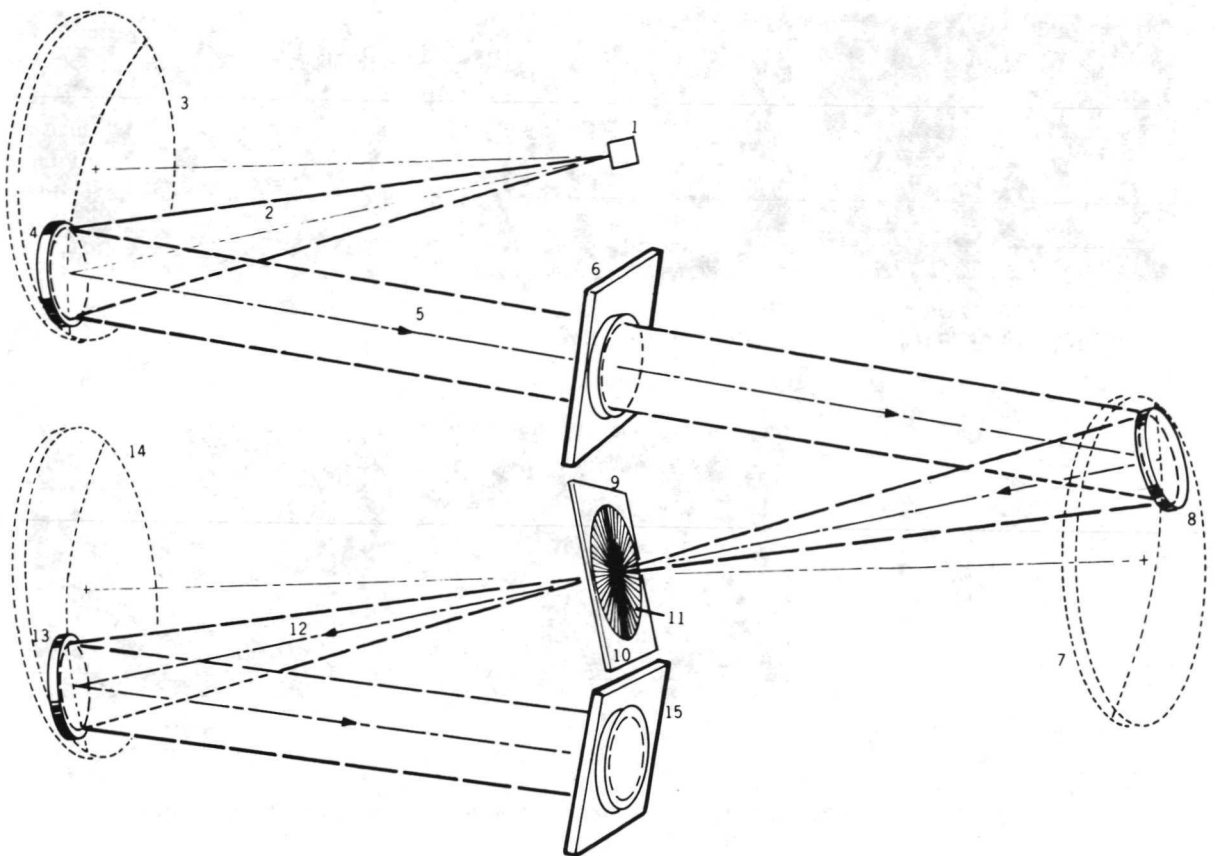
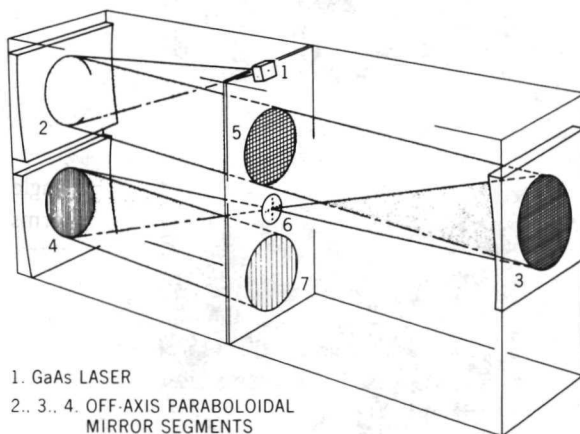


Figure 3.—An optical data processor using parabolic mirror segments.



1. GaAs LASER
- 2.. 3.. 4. OFF-AXIS PARABOLOIDAL MIRROR SEGMENTS
5. INPUT PLANE
6. FOURIER TRANSFORM PLANE
7. RECONSTRUCTION PLANE

Figure 4.—A packaging concept for the optical system.

components of the Fourier transform was blocked. The effect of blocking the Fourier component is shown in figure 6 (bottom), where it can be seen that the reconstructed image is without one side. The missing side has been filtered, or more correctly, suppressed in the Fourier transform plane.

Figure 7 shows another example of spatial filtering. In this experiment a He-Ne gas laser was used as a source of coherent radiation mainly because the resolution of the image converter tube used in the image reconstruction plane was very low. A wire grid was chosen as an object (fig. 7a). The Fourier transform of this object is shown in figure 7b. For spatial filtering purposes, a slit was placed in the Fourier transform plane so that only the vertical structure of the Fourier transform was allowed to pass through the Fourier transform plane. The reconstructed filtered image (fig. 7c) is without any vertical

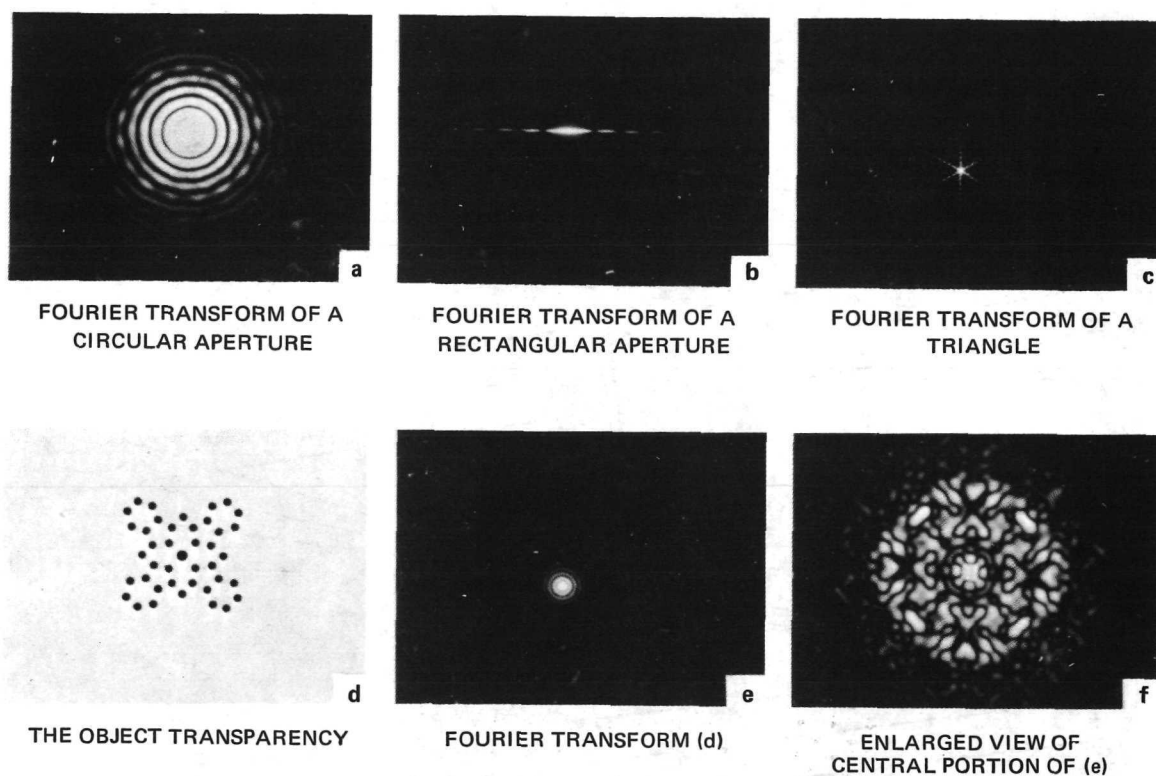


Figure 5.—Experimental results of using parabolic mirror segments as Fourier transforming elements.

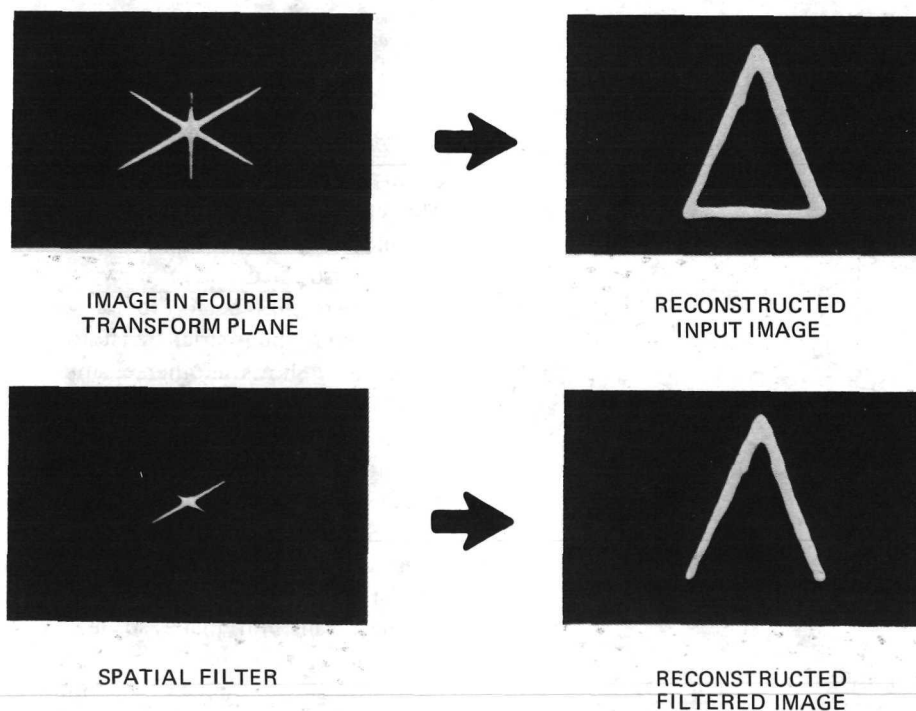


Figure 6.—Examples of coherent optical processing using a gallium arsenide laser source.

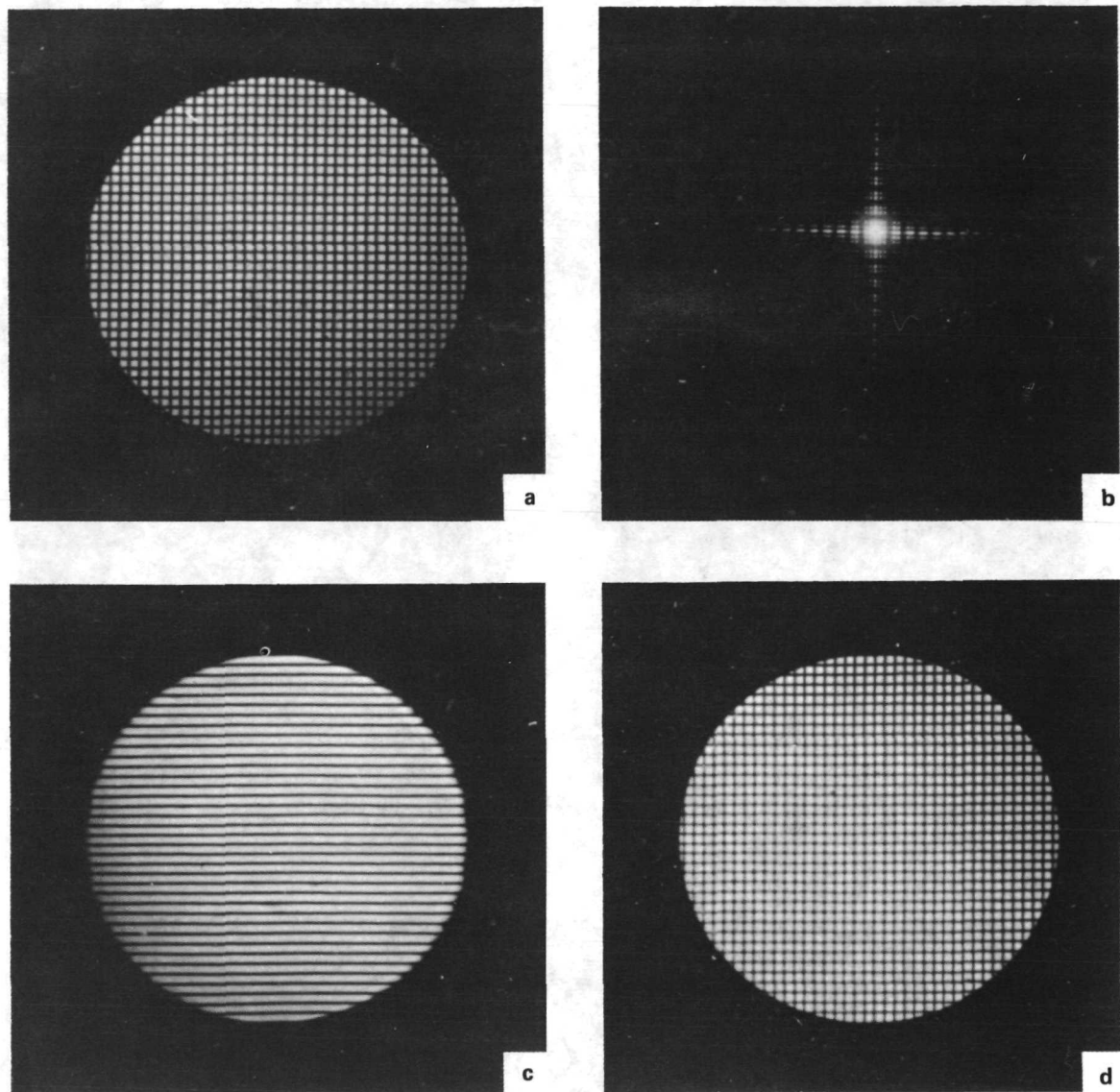


Figure 7.—Results of a spatial filtering experiment: (a) object transparency (a wire grid in a circular aperture); (b) Fourier transform of (a); (c) the filtered reconstructed image; (d) the unfiltered reconstructed image.

information. Figure 7d shows the reconstructed image without any spatial filtering.

Optical correlation experiments using paraboloidal mirror segments were also performed. Figure 8 illustrates the optical correlator. The input transparency was placed in the input plane. A Fourier transform hologram was recorded in the complex spatial filter plane. The photographic film was developed and placed back in exactly the same place it

occupied during the exposure. The reference beam was blocked and the hologram was illuminated by the signal beam only.

Another off-axis paraboloidal mirror segment was used to Fourier-transform the field transmitted by the hologram. The correlation plane, which is located a focal length away from the off-axis mirror segment, displays the convolution, geometrical image, and correlation function. The autocorrelation has a bright

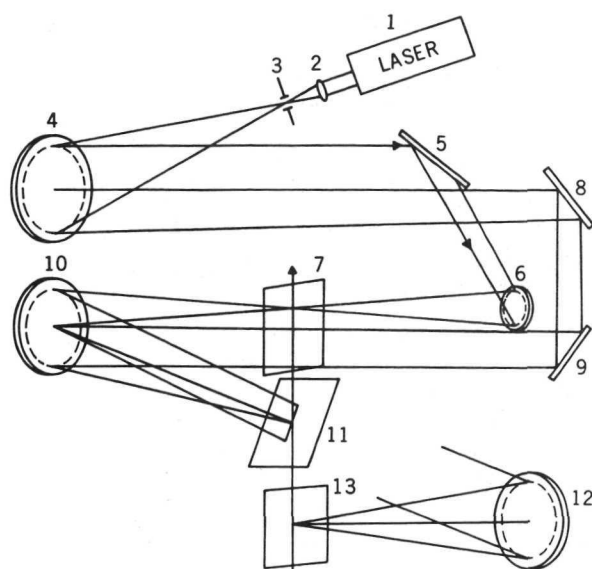


Figure 8.—Optical correlator using paraboloidal mirror segments: (1) He-Ne laser; (2) microscope lens; (3) 6- μ m pinhole; (4) collimating parabolic mirror; (5) front-surface mirror; (6) focusing parabolic mirror (off-axis segment); (7) input plane; (8) front-surface mirror; (9) front-surface mirror; (10) off-axis paraboloidal mirror segment for Fourier transforming; (11) complex spatial filter plane; (12) off-axis paraboloidal mirror segment for Fourier transforming; (13) correlation plane.

central peak that can be detected. In the example shown in figure 9, the geometrical image of the input transparency and the bright central peak of the autocorrelation function can be seen.

A computer-aided optical correlator system presently under development is shown in figure 10. The correlation spot is monitored by an image dissector tube. The output of this tube is interfaced with an

IBM 1800 computer, which controls the physical position of the input information. The correlation spot can be brought to a desired point by adjusting the position of the input information.

In conclusion, the results obtained so far have shown that a low-power, rugged, compact optical system capable of onboard spacecraft data processing can be constructed using off-axis paraboloidal mirror segments.

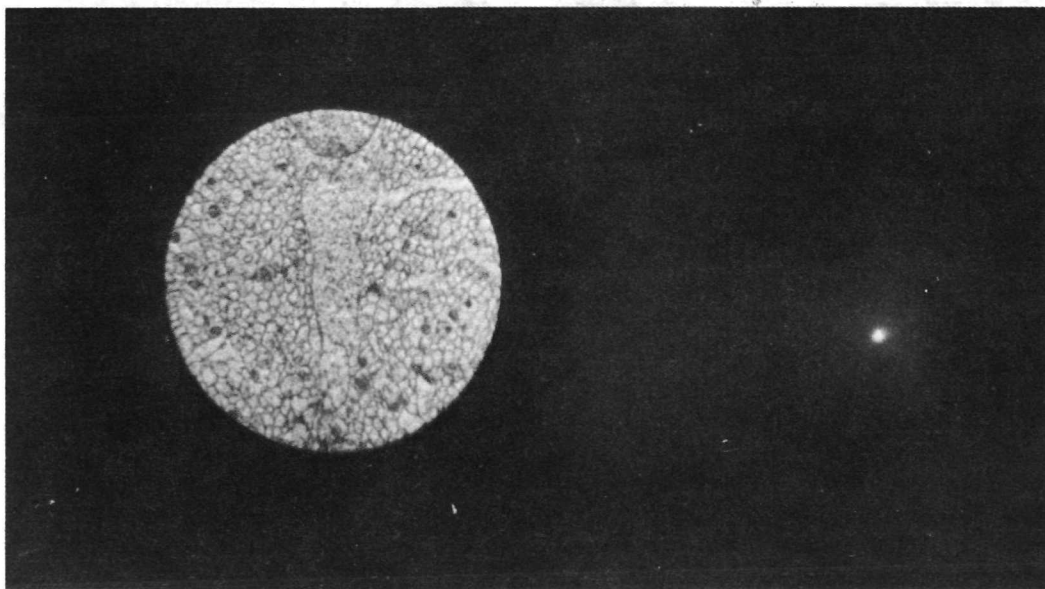


Figure 9.—Results of optical correlation experiment: Seen at right is bright central peak of autocorrelation function of input transparency at left.

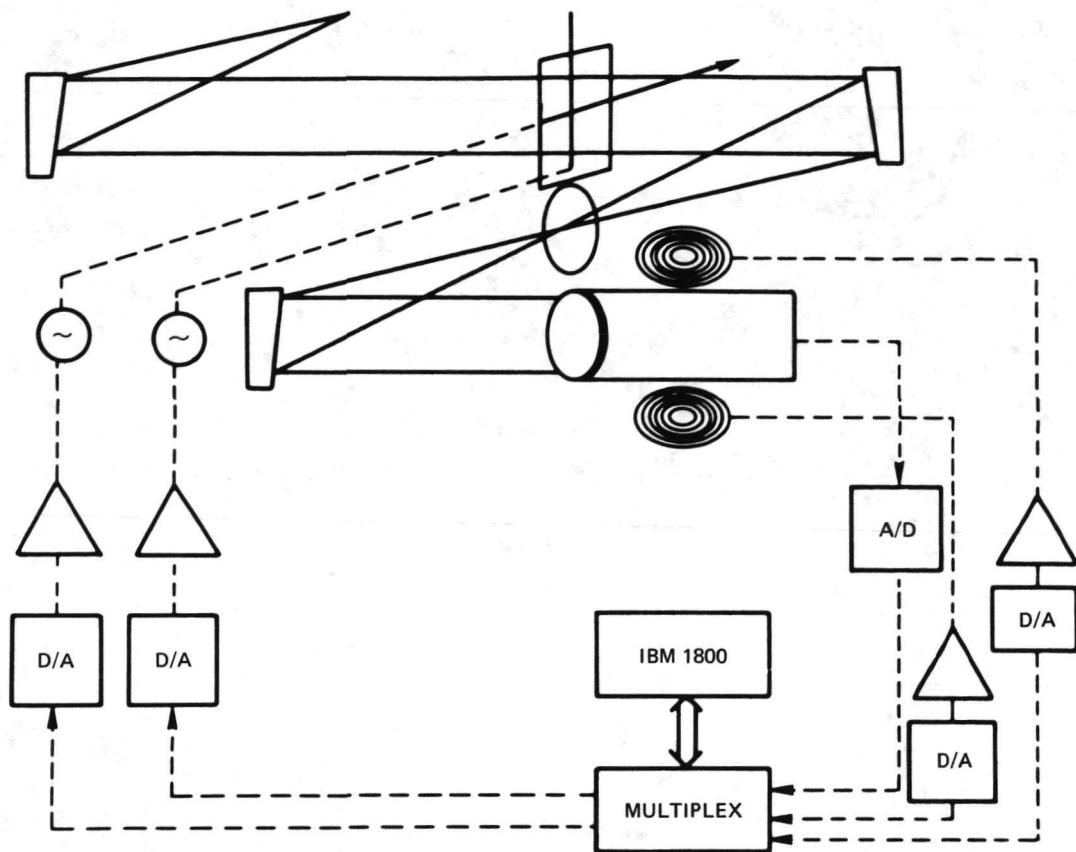


Figure 10.—An automatic optical correlator.

Page Intentionally Left Blank

Holographic Image Deblurring Methods*

George W. Stroke

Electrical Sciences Department

State University of New York

Greatly sharpened images may be extracted from photographs which have been blurred, either by accident or deliberately (e.g., when coded for special image processing applications). In simple words, it has recently become truly possible to turn a bad photograph into a good image in a great number of situations, notably those of interest in space imaging. Examples in the first category (accidentally blurred) include photographs blurred by motion, imperfect focus, instrumental defects, and atmospheric turbulence, among other causes. Examples of the second category (deliberately coded) include the synthesis of multiple pinhole camera X-ray photos for the purpose of S/N increase. The results obtained illustrate new extensions of the basic holographic Fourier-transform division method first described by G. W. Stroke and R. H. Zech in 1967 for the first category, and of the method described by G. W. Stroke in 1968 for the second.

*Work supported by NASA Grant NGR-33-015-068.

Page Intentionally Left Blank

Elimination of Coherent Noise in a Coherent Light Imaging System

Gerald J. Grebowsky, Robert L. Herman,
Hugh B. Paull, and Arnold R. Shulman

NASA Goddard Space Flight Center

Optical imaging systems using coherent light introduce objectionable noise into the output image plane. Dust and bubbles on and in lenses cause most of the noise in the output image. The noise usually appears as bull's-eye diffraction patterns in the image. By rotating the lens about the optical axis, these diffraction patterns can be essentially eliminated. The technique does not destroy the spatial coherence of the light and permits spatial filtering of the input plane.

Page Intentionally Left Blank

Optical Correlation Evaluation of Surface Deformation Due to Fatigue

Robert L. Bond

University of Arkansas
Graduate Institute of Technology

Robert E. Beissner, James Lankford, Jr.,
and William W. Bradshaw

Southwest Research Institute

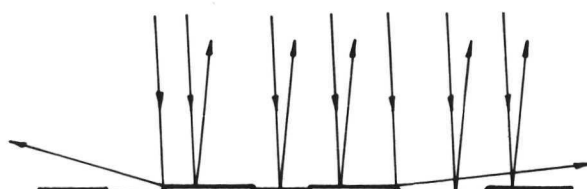
Coherent optical correlation techniques have been applied to the detection and evaluation of microstructural surface alterations during cyclic stressing of Fe-3Si. Correlation data were obtained by measuring the light intensity in the central portion of the optical correlation function, at various cyclic intervals, using a holographic filter made with the wavefront reflected by the specimen in its original uncycled, preload condition. The changes in correlation intensity were supplemented by measurements of the spatial frequency spectrum of the reflected beam, and changes in both sets of measurements were correlated with optical microscopy and surface interferometry, and also with electron replica microscopy, of the surface topography. The results are discussed in terms of cumulative fatigue damage and ultimate fatigue crack initiation.

One of the major enigmas associated with the basic mechanism of crack formation during metal fatigue is the inability to predict *a priori* when and where a crack will form. Slip lines, bands, or microcracks at the surface of the metal result from fatigue cycling. Cracks can form at local corrosion or oxidation sites, at grain boundaries having a high energy configuration, or at local stress raisers such as inclusions. Whatever the cause of crack formation, it is not currently feasible to establish where and when the crack will form early enough to do anything about it. Indeed, it is not possible to predict that the crack will form at all.

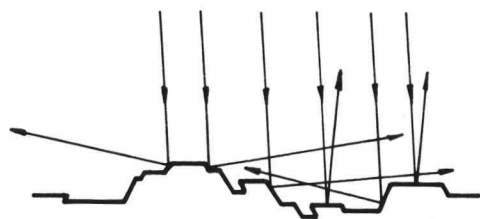
It is the purpose of this paper to present an optical method for the study of fatigue. Optical correlation, coupled with spatial frequency analysis, and standard metallurgical techniques were used to relate the

correlation and frequency analysis data to known surface effects. The high sensitivity of optical correlation offers the possibility of capitalizing on the subtle differences in surface characteristics. These differences *may* precede the formation of microcracks which will lead to the formation of propagating cracks causing the ultimate failure of the metal undergoing cyclic stress. Coherent light reflected from a specimen that is undergoing fatigue will experience small phase changes as a result of surface alterations.

Optical correlation permits the comparison of every point in a given space with every other point in that or any other space. Figure 1(a) shows a wave front, $f(x,y)$, reflected from an uncycled specimen. Figure 1(b) shows a wave front, $g(x,y)$, reflected from the same specimen after it has been fatigued. By using



(a) Light amplitude reflected by unstressed specimen = $f(x,y)$



(b) Light amplitude reflected by stressed specimen = $g(x,y)$

Figure 1.—The spatial correlation approach to the measurement of surface deformation (correlation function = $\int f^*(x,y)g(x+\xi,y+\eta)d\xi d\eta$ = measure of surface deformation).

optical correlation, as in the system shown in figure 2, it is possible to convolve these two signals to yield a function which is indicative of the magnitude and type of surface changes. This correlation function is given by

$$\phi = \iint f^*(x,y)g(\bar{x}+x,\bar{y}+y)dx dy$$

Minute phase differences reflect a change in the correlation function of the specimen under study. By measuring this loss in correlation, it is possible to get a semiquantitative measurement of the deterioration of the fatigued surface. That is, as surface perturbations appear, they change the frequency spectrum of

the metal surface and lead to a subsequent change in the correlation function. By careful analysis of the correlation function, it is possible to get a good idea of the surface changes which have occurred. Additional information about the surface characteristics is given by the frequency spectrum itself.

Marom and Mueller (ref. 1) have reported a study of the fatigue of aluminum specimens by optical correlation techniques. It was our goal to extend their study by relating the complete correlation process to surface effects by the use of standard nondestructive metallurgical techniques such as optical and electron microscopy, Nomarski interference microscopy, and Michelson interferometry. The work has shown good agreement with observed microscopic alterations in surface profile caused by fatigue-generated dislocation (linear atomic imperfection) configurations. It has yielded some additional information concerning the sensitivity of the correlation technique as well as indicated some potential uses in both applied and basic research and in field applications.

EXPERIMENT

Silicon iron (Fe-3Si) was used in the reported studies. The specimen was rolled, machined, annealed, polished, etched, and electropolished. Annealing at 800 °C for 2 hours yielded grains about 200 μm in diameter. The Fe-3Si specimen was mounted in a stressing fixture with a small preload so that it would be supported firmly throughout the stress cycle. The device used to fatigue the specimen is shown in figure 3. Cyclic stress (fatigue) was applied via an eccentric cam driven by a synchronous motor. The cam was connected to a yoke which held

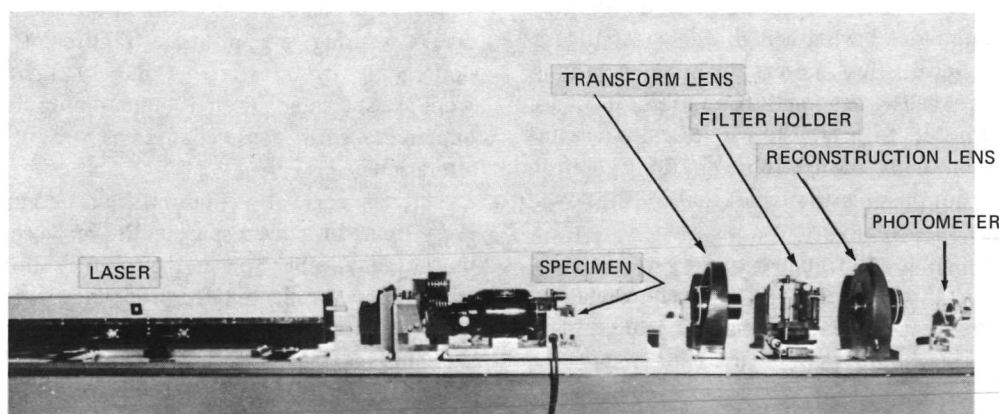


Figure 2.—Experimental arrangement for reflected light correlation measurement.

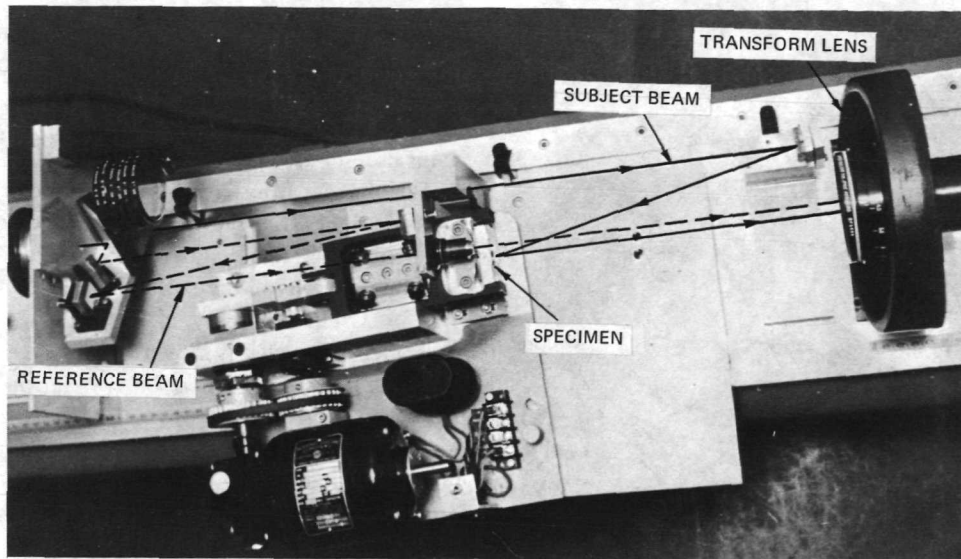


Figure 3.—Stressing fixture and optical paths of reference and subject beams.

the specimen firmly against a stationary anvil opposite the sampling laser beam. The sampling laser beam illuminated the center of the specimen which had an hourglass shape.

The beam of coherent light scattered from the uncycled specimen was collected by a lens which formed the Fourier transform on a high resolution film plate. A reference beam was superimposed on the Fourier transform, forming a Fraunhofer hologram which is the matched filter. After photographic processing, the filter was replaced in the original location, and the autocorrelation function was measured with a photodiode. The specimen was then cycled as the correlation function was monitored with a solid state photodiode.

As the specimen was fatigued, readings of the correlation function were made at various cyclic intervals. The results are shown in figure 4. Several times during the fatigue cycling the specimen was removed and examined using optical and electron replica microscopy in an attempt to establish the metallurgical micromechanisms responsible for the changing correlation. Though slip lines began to form after approximately 200 cycles (fig. 5), there were practically no additional visible effects in the sampling region throughout the lifetime of the specimen. Indeed, there were few visible changes in the entire specimen until at about 500 000 cycles a crack formed near the edge of the specimen. It was assumed that the plastic strain was accommodated by the

intensification of the existing surface slip bands. Compare figure 6 made after 200 000 cycles with figure 5 made after 200 cycles.

Electron replica microscopy revealed that within those matrix regions bounded by strong slip bands extensive fine slip occurred in the form of long, straight, small amplitude slip lines. The slip lines generally formed from 45° to 90° with reference to

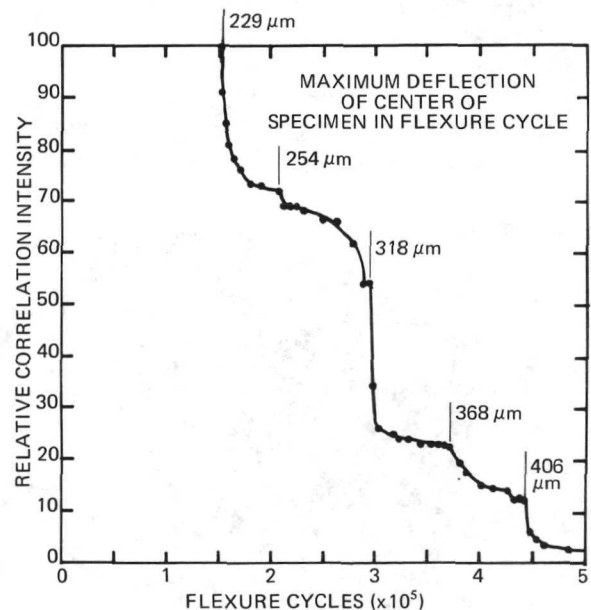


Figure 4.—Optical correlation intensity as a function of flexure cycles.

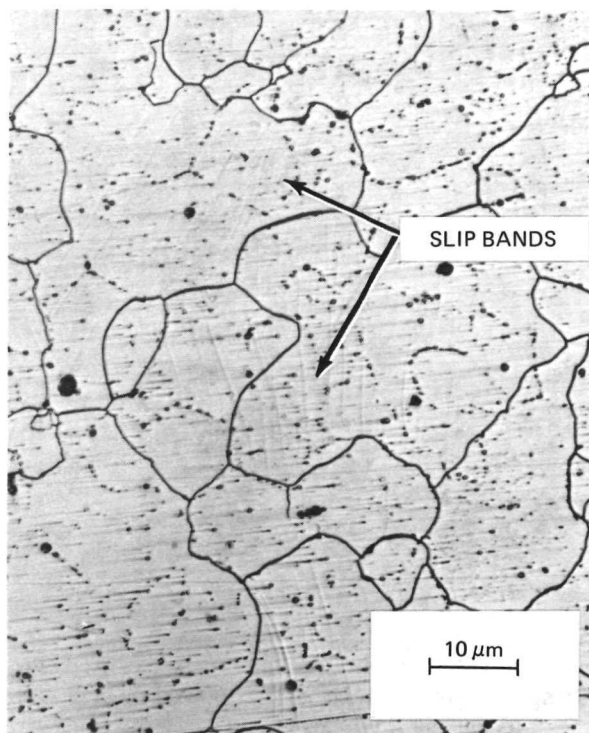


Figure 5.—Slip structure after 200 cycles.

the stress axis. As deformation proceeded, the development of these closely spaced strain centers apparently produced the spatial frequency diffracting centers which account for the decrease in correlation with fatigue cycles.

The visible effects of fatigue show up mainly as slip bands of relatively low density, as grain boundary distortion, and as a severe surface perturbation near the edge of the specimen. The loss of correlation was

not caused by these permanent *gross* changes in the specimen but by micrometer and submicrometer size changes. Electron micrographs confirmed that there was significant slip line intensification within the grains used in the correlation studies.

A Nomarski interference microscope was used to determine the true phase characteristics of the surface. The result was compared with a standard bright field micrograph of the surface after 200 000 cycles (fig. 7). Grain boundary distortion does not occur until 500 000 cycles as shown in figure 8. Apparently the final catastrophic loss of correlation shown in figure 4 corresponds to the nucleation and propagation of the edge crack shown in figure 9. This probably was caused by crack nucleation. The interferogram made with a Michelson interferometer shown in figure 10 illustrates the degree of gross distortion caused by the crack formation.

Figure 11 shows the shift in frequencies as a result of the deterioration of the microstructure of the specimen. It is obvious that there is a significant breakup of the dc spike and a shift of the low frequency terms toward much higher frequencies. This fine structure is not visible in optical microscopy but is visible under electron microscopy. The last frame of figure 11 indicates a complete disruption of the dc terms indicative of high efficiency forward Mie scattering. It is obvious from these figures that a simple frequency shift causes part of the correlation loss.

It is important to note that the correlation technique was able to detect the fatigue crack forming at a point remotely located from the segment of the specimen under study.

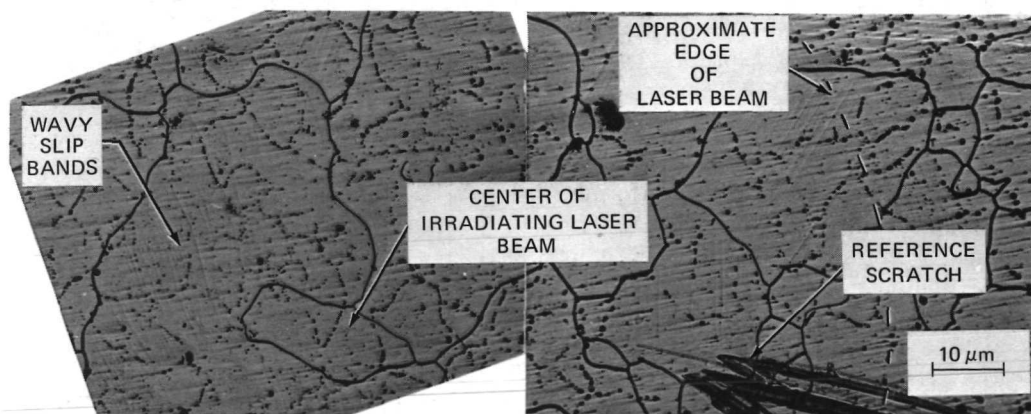


Figure 6.—Slip structure after 200 000 cycles.

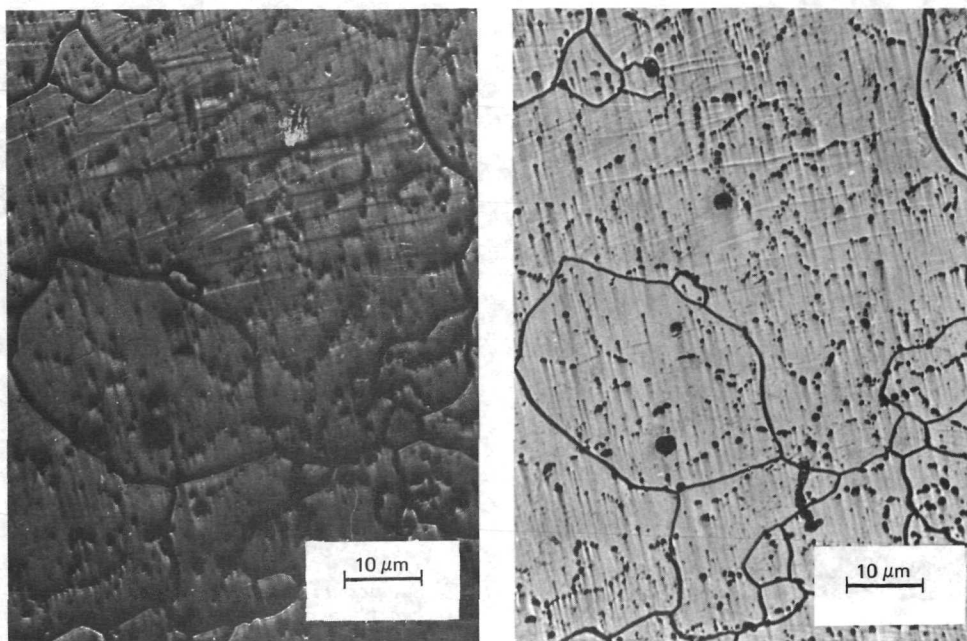


Figure 7.—Interference (left) and bright field photomicrographs of typical region after 200 000 cycles.

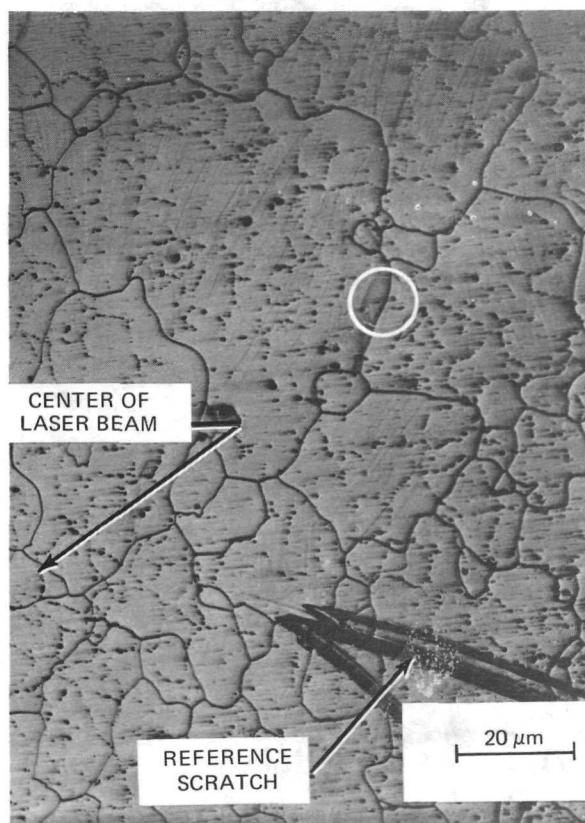


Figure 8.—Photomicrograph after 500 000 cycles. Circled area shows grain boundary distortion.

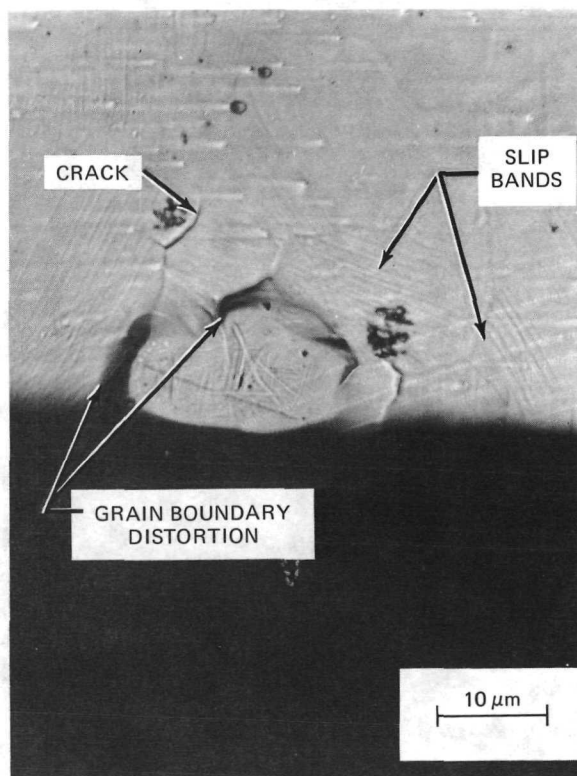


Figure 9.—Crack detected after 500 000 cycles.

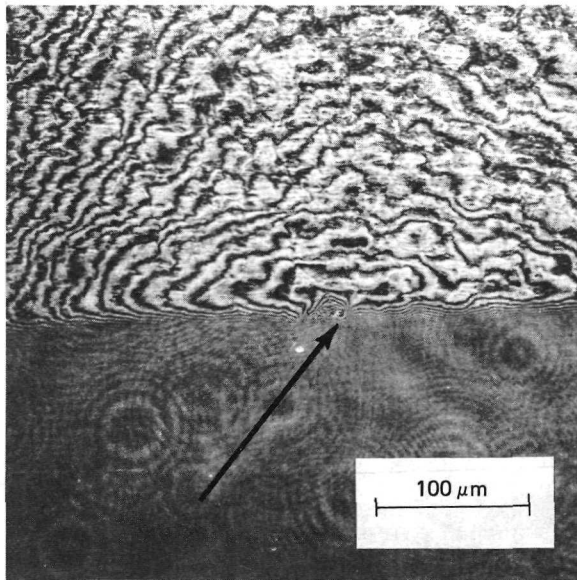


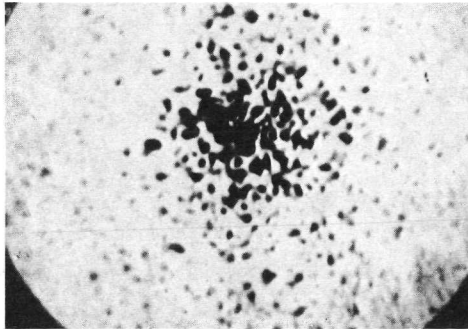
Figure 10.—Interferogram of surface after 500 000 cycles (arrow indicates distortion caused by crack formation).

CONCLUSIONS

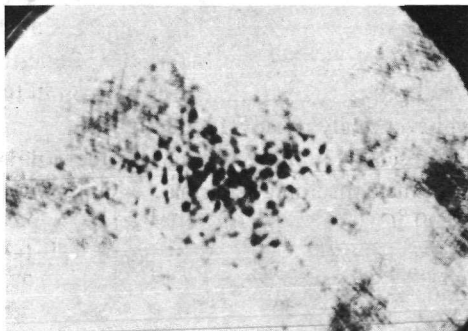
It is clear that the correlation technique is adaptable to the early prediction of metal fatigue crack formation. Indeed, *a priori* prediction of crack formation is possible before visible signs of such nucleation occur and under certain circumstances without having to scan large areas of a specimen undergoing fatigue. This noncontacting method offers the possibility of studies of fundamental fatigue mechanisms in air, as well as in vacuum and other controlled environments.

REFERENCE

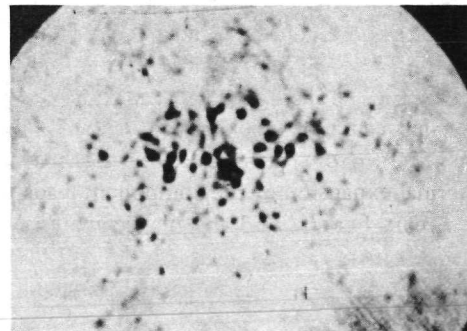
1. Marom, E.; and Mueller, R. K.: *Proceedings of the Sixth Symposium on Nondestructive Evaluation of Aerospace and Weapons Systems Components and Materials*. Western Periodicals Co., North Hollywood, California, 1967, p. 79.



200 CYCLES



200 000 CYCLES



500 000 CYCLES

Figure 11.—Photographs of holographic filters showing increase in angular dispersion of subject beam as number of stress cycles is increased.

Solder Joint Fatigue Measurement by Optical Cross-Correlation

Rodney W. Jenkins and Melvin C. McIlwain
NASA Marshall Space Flight Center

As space flights increase in duration, the demand for longer component/system lifetime increases dramatically. Coupled with the need for increased lifetime is the need to accurately predict whether a component will function for the duration of the space flight. The failure of printed circuit boards, a component common to nearly all flight vehicles and payloads, has been costly to NASA. Although the design of these printed circuit boards must be tested over thousands of thermal cycles to qualify for flight, because of the destructive nature of these tests and the time involved, this type of testing cannot be used as an inspection technique or for assuring the reliability of printed circuit boards over very long time periods.

Optical cross-correlation, because of its nondestructive nature and shorter time requirement, offers promise as both a qualifying test for the design of printed circuit boards and an inspection test for the boards to be used on space flights. Using optical cross-correlation, measurements can be made of the relative component movements and deterioration of the solder joint surface under thermal loading. The results obtained in a program using these techniques are presented.

The complex electronic checkout, control, and telemetry systems of the Saturn V launch vehicle have been plagued by failures caused by cracking of solder joints on printed circuit boards. While these failures have not caused a loss of mission objectives, they have generated considerable concern and led to extra costs in repair and replacement of defective boards. As the space program matures and the emphasis turns to long-duration missions and reusable vehicles, the reliability of these soldered electrical connections becomes more and more critical.

Various in-house and contract studies undertaken to improve the reliability of solder joints have pointed to strains developed during thermal fluctuation as the prime cause of cracking failure (ref. 1). These strains result from differences in the coefficients of thermal expansion of the component leads, the printed circuit boards, and the plastic material making up the solder joint system (fig. 1). As the temperature changes, the printed circuit board and

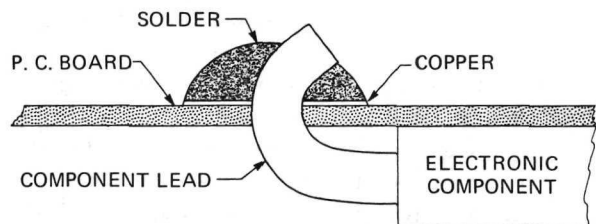


Figure 1.—Cross section of typical solder connection.

conformal coating undergo a greater expansion or contraction than does the component lead, thus imposing a load on the solder joint. Repetition of this loading due to operational fluctuation in temperature will eventually cause a fatigue failure.

Presently, lifetime testing of solder joints is limited to time-consuming thermal cycling from -55 to $+100^{\circ}\text{C}$, at approximately 2 hours per cycle. A solder joint design is considered satisfactory if it survives 200 cycles without cracking. This type of

test is effective in determining the average life of a joint design, but because of its destructive nature it cannot be used as an inspection technique. To assure the reliability of solder joints over long time periods, it is necessary to have a nondestructive test which can accurately predict the fatigue life of a joint under operational conditions.

Since the fatigue mechanism which causes solder joint cracks is strain limited, any techniques which are used to predict life should be based on strain measurements. Holographic techniques, due to their ability to measure extremely small strains in a limited area, were selected as the most promising system for development of a solder joint cracking lifetime prediction test.

Holographic interferometry (refs. 2 thru 4) is one way to measure deformation occurring in materials. However, measuring the deformation quantitatively by fringe analysis is at best tedious and complicated. A simpler way to measure the change is by optical cross-correlation (refs. 5 and 6). Instead of adding the two functions associated with the component before and after deformation, a cross-correlation of the two functions is performed. The amplitude of the cross-correlation integral evaluated at the origin is a measure of the difference between the two functions.

THEORY

Figure 2 is a block diagram of an optical data processing system whose output amplitude is a measure of the deformation that has occurred in the test material. This particular system requires a highly coherent and relatively intense light source. For this reason, a laser is used for the light source. The optical input is the wavefront that is backscattered off the test material. The amplitude and phase of the input can be described by a complex amplitude distribution $h(x,y)$, where the x - y plane is parallel to the face of the test material. By the use of a lens, the function $h(x,y)$ is operated on to produce its Fourier transform (ref. 7). Then, with a matched filter (ref. 8), the Fourier transform of $h(x,y)$ is multiplied by the complex conjugate of the Fourier transform of the complex amplitude $s(x,y)$, representing the value of the input when the material is unstressed. Using another lens, a Fourier transform is performed on the product. By the convolution theorem (refs. 9 and 10) this is equal to the cross-correlation of $h(x,y)$ and $s(x,y)$, which is described by

$$\iint_{-\infty}^{\infty} h(\xi, \eta) s^*(\xi - x, \eta - y) d\xi d\eta$$

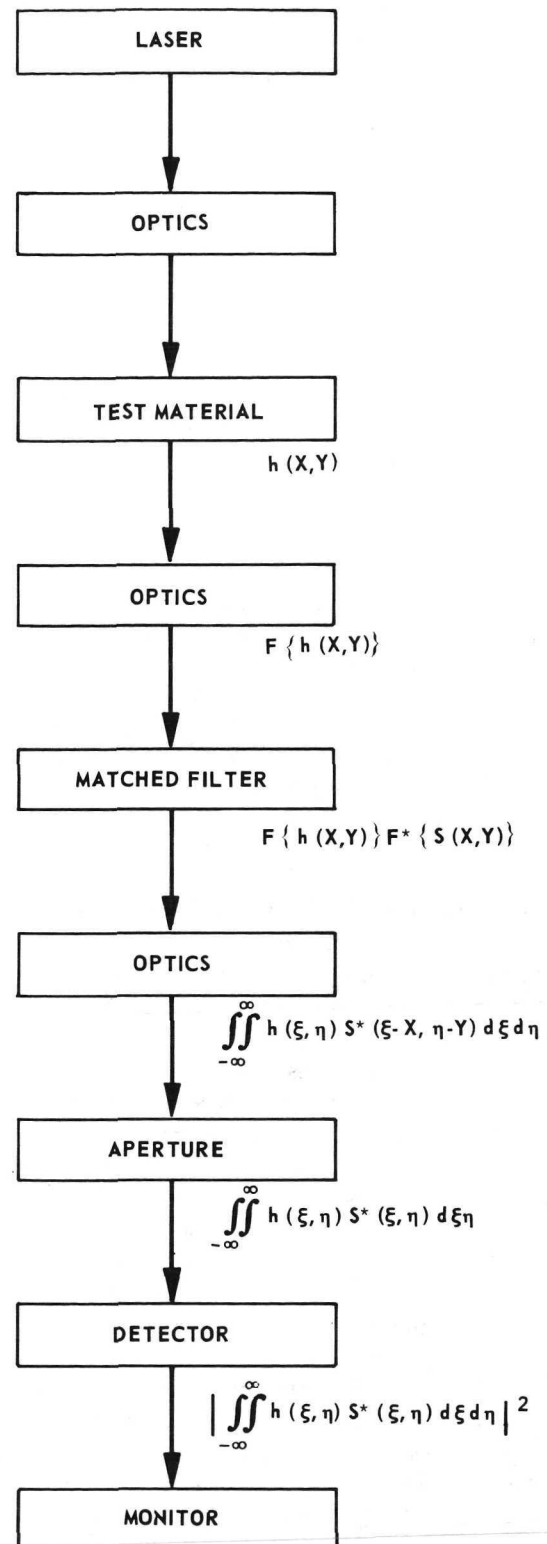


Figure 2.—Block diagram of optical cross-correlation system.

By the use of an aperture (a 50- μm pinhole) placed at the origin of the x - y plane (i.e., along the optical axis), the values of x and y are chosen to be zero. This is the final optical output. Its properties are that it is greatest when $h(x,y)$ is equal to $s(x,y)$, i.e., when the test material is unstressed. It decreases rapidly as $h(x,y)$ becomes increasingly different from $s(x,y)$. The final optical output is converted into an electrical output by a detector such as a photomultiplier tube.

To realize such a system is not difficult, the greatest difficulty lying in the synthesis of the matched filter with the correct amplitude transmittance. This is accomplished by making a Fourier-transform hologram of the unstressed test material.

MATCHED FILTER SYNTHESIS

The Fourier-transform hologram is recorded using the configuration shown in figure 3. If the complex amplitude distribution at the photographic plate due to the reference wavefront is $R(x,y)$ and the distribution due to the signal wavefront is the Fourier transform of $s(x,y)$, then the intensity, $I(x,y)$, at the plate will be

$$\begin{aligned} I(x,y) &= |R(x,y) + F\{s(x,y)\}|^2 \\ &= |R(x,y)|^2 + F\{s(x,y)\}|^2 + R^*(x,y)F\{s(x,y)\} \\ &= |R(x,y)|^2 + F^*\{s(x,y)\} \end{aligned}$$

If the emulsion is to respond linearly to the amplitude distribution of the signal wavefront, $|F\{s(x,y)\}|$ must be much less than $|R(x,y)|$ and $|R(x,y)|$ must be such that

$$|R(x,y)|^2 + |F\{s(x,y)\}|^2 = E_0/t$$

where (E_0, T_0) is a point that falls in the middle of the linear section of the amplitude transmittance-versus-exposure curve (E_0 being the mean exposure). In this case, the transmittance modulation will be linearly proportional to the intensity modulation. Therefore, the amplitude transmittance, $T_a(x, y)$, of the plate can be written

$$T_a(x,y)=T_0+Bt[R^*(x,y)F\{s(x,y)\}+R(x,y)F^*\{s(x,y)\}]$$

where B is the slope of the curve at (E_0, T_0) and t is the exposure time.

If the plate is illuminated with the complex amplitude distribution $F\{h(x,y)\}$ (fig. 4), the transmitted amplitude can be written $F\{h(x,y)\}T_a(x,y)$. If the reference wavefront is a plane parallel beam of

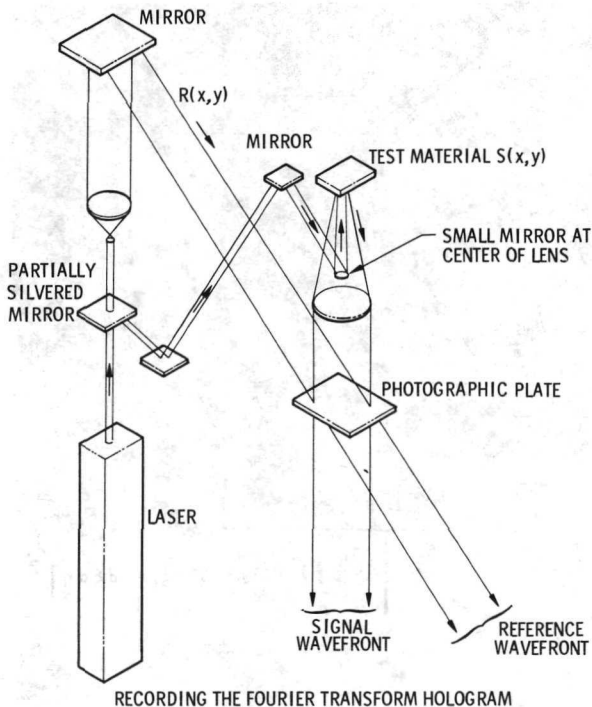


Figure 3.—Arrangement for recording the Fourier-transform hologram.

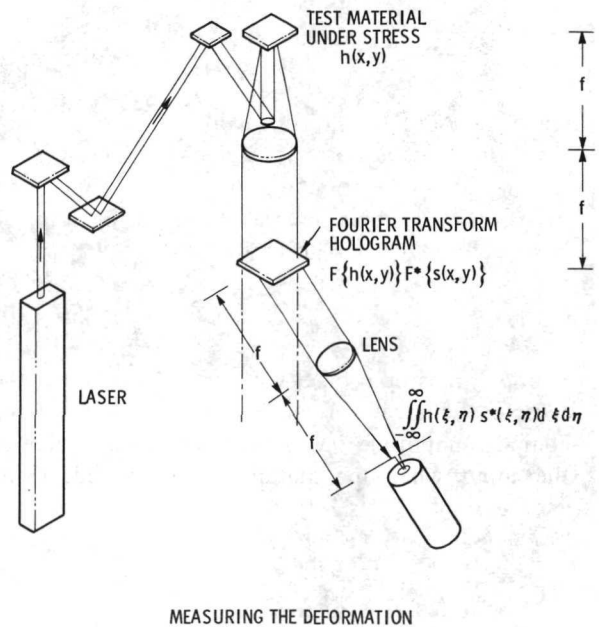


Figure 4.—Arrangement for measuring the deformation.

constant amplitude inclined at an angle θ with respect to the optical axis, it can be written

$$R(x,y)=A \exp(-i2\pi \sin \theta y/\lambda)$$

Then the transmitted amplitude will be

$$F\{h(x,y)\} T_a(x,y)=BtA F\{h(x,y)\} F^*\{s(x,y)\} \exp(-i2\pi \sin \theta y/\lambda)+\dots$$

where the other terms are separated by an angle from the first term because the $\exp(-i2\pi \sin \theta y/\lambda)$ term serves to incline the desired transmitted amplitude off axis at the angle θ . Dropping the exponential term and the constants, the off-axis transmitted amplitude is written

$$F\{h(x,y)\} T_a(x,y)=F\{h(x,y)\} F^*\{s(x,y)\}$$

Effectively, the amplitude transmittance of the developed photographic plate (hologram-matched filter) is $F^*\{s(x,y)\}$, which is the desired value.

EXPERIMENTAL RESULTS

Since thermal fluctuation has been determined to be the main cause of solder joint failure, an experi-

ment was set up to monitor the cross-correlation output while the solder joint was thermally stressed by a heat lamp mounted behind the printed circuit board. The experiment was performed using a cold-cathode 70-milliwatt He-Ne laser. The laser was allowed to stabilize for an hour before any exposures or tests were made. The entire setup was mounted on a granite table which was supported by three air-mounts to isolate the system from building vibration (fig. 5). The photographic plate (Agfa 10E70) was held by a precision plateholder with x-y translation adjustment. The second transform lens could be translated along its optical axis and the pinhole aperture could be translated in its x-y plane.

The second purpose of these adjustments was to correct for the drop in cross-correlation amplitude due to the linear translations and rotations of the solder joint caused by the buckling of the printed circuit board when heated. In-plane shifts of 25 μm , on-axis shifts of 1 mm, and rotations of 100 arc seconds cause no loss of output when corrected by the appropriate movement of either the matched filter, the second transform lens, or the pinhole. Furthermore, the amount of adjustment necessary is

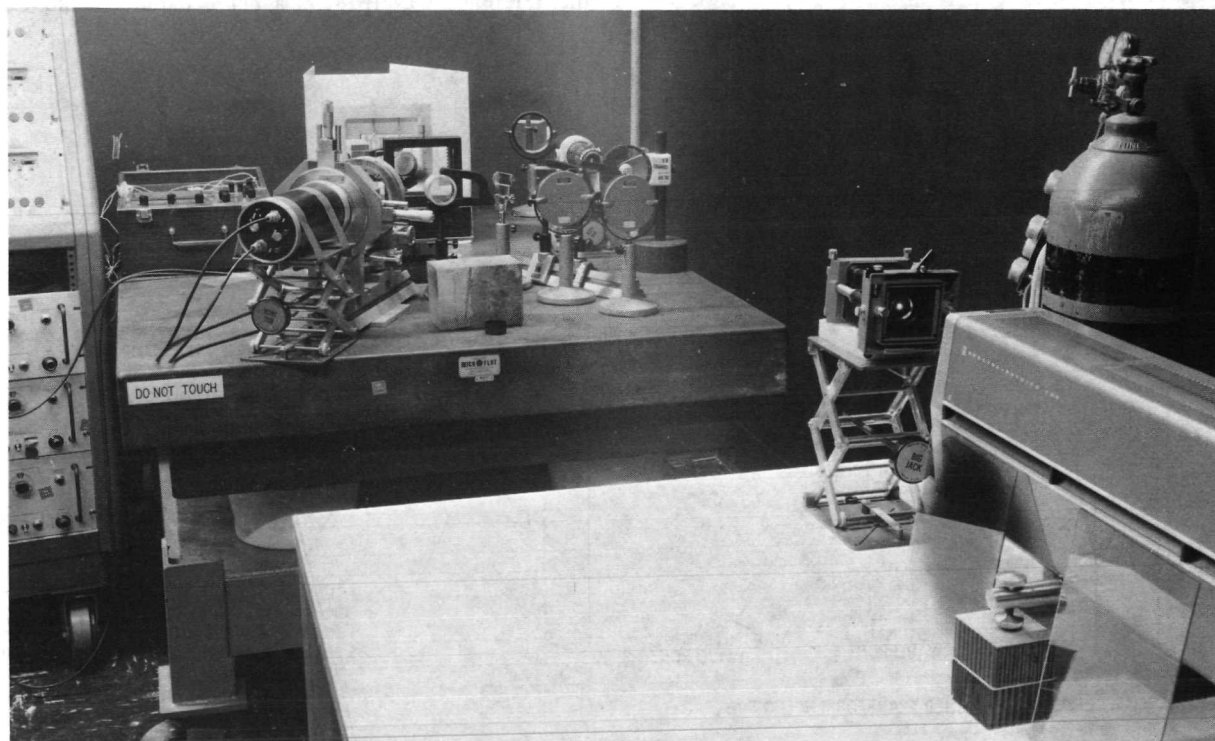


Figure 5.—Laboratory setup.

a quantitative measure of the movement of the solder joint. If the solder joint shifts by an amount Δx and Δy , the autocorrelation output will remain unchanged if the pinhole is translated by $-\Delta x$ and $-\Delta y$. Similarly, if the solder joint shifts along the optical axis, correction can be made by moving the second transform lens along its optical axis. Also, small rotations of the joint are easily compensated for by displacement of the matched filter in its x - y plane. Solder joint shifts as small as $1\text{ }\mu\text{m}$ and rotations of less than 1 arc second can be measured using this technique. Therefore, while small translations and rotations of the solder joint can be measured, they do not affect the actual deformation measurement obtained from the cross-correlation output.

Figures 6, 7, and 8 show how the autocorrelation intensity drops as the solder joint is rotated or translated and how well these movements are compensated by the adjustment of the position of the

matched filter, the second transform lens, and the pinhole. The dashed lines show how the intensity falls off with movement of the solder joint. The solid vertical lines indicate the intensity increase due to the adjustment of the *appropriate* optical components. The dotted vertical line indicates the intensity increase due to the additional adjustment of the other two components. Since this last combined adjustment did cause the intensity to rise, apparently we did not have pure translational or rotational movement.

After the photographic plate was exposed, processed, and replaced in the precision plateholder, the reference beam was blocked and the plate was precisely positioned in its x - y plane for maximum autocorrelation. The printed circuit board was then heated in place for 12 minutes (raising its temperature from 23 to 80°C) and allowed to cool to room temperature. Figure 9 is a plot of the cross-correlation intensity versus time with the matched

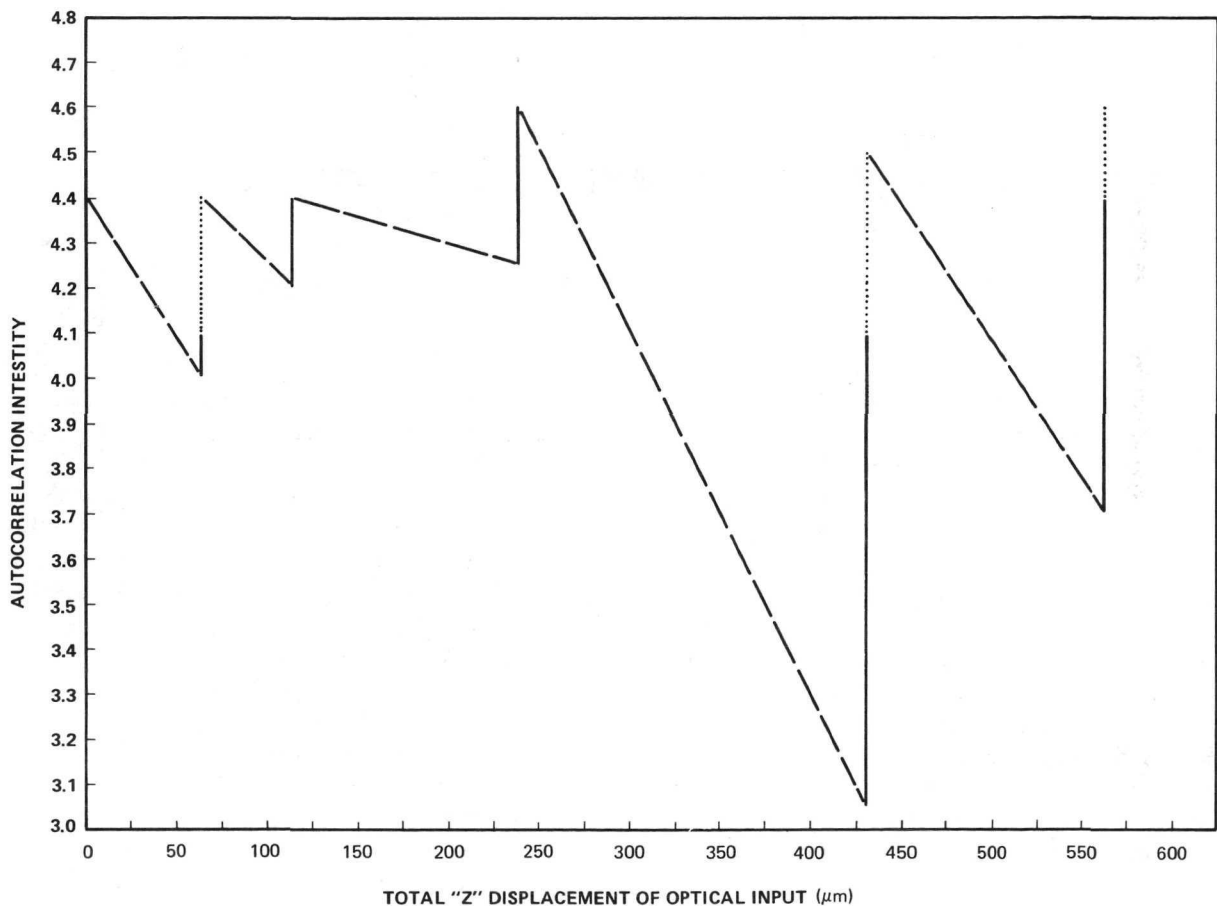


Figure 6.—Autocorrelation intensity as a function of optical input displacement along z axis.

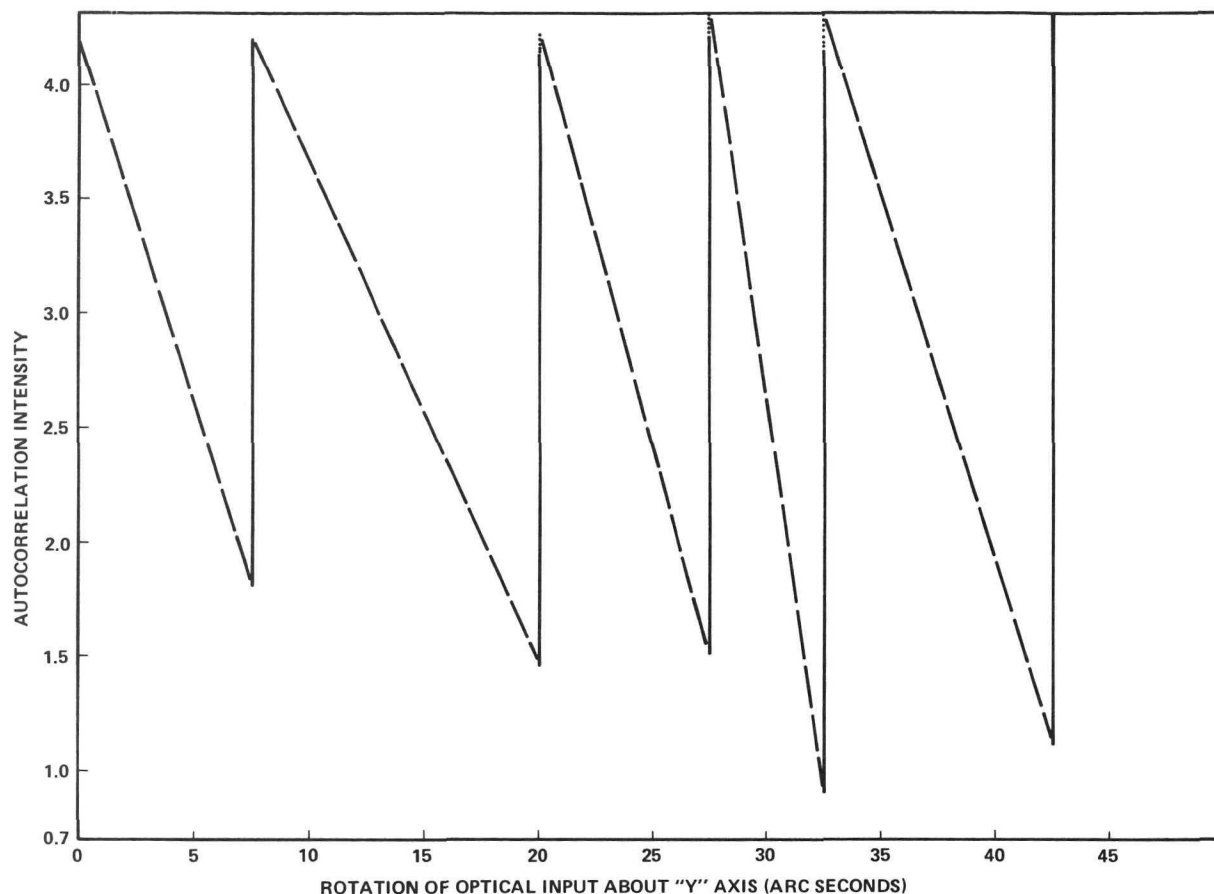


Figure 7.—Autocorrelation intensity as a function of optical input rotation about y axis.

filter, the second transform lens, and the pinhole adjusted for maximum cross-correlation each reading. The greatest drop in the cross-correlation intensity is a measure of the elastic plus plastic deformation that occurs in the solder joint during a thermal cycle. As the solder joint cools, the elastic strain is removed, but the solder joint will not return to its original state if it has been strained beyond its elastic limit. The difference between the autocorrelation intensity before heating and after the joint has cooled to room temperature is a measure of the permanent or plastic deformation. Therefore, if the cross-correlation intensity after each thermal cycle is plotted versus thermal cycles, a curve characteristic of the plastic strain occurring in the particular solder joint will be obtained (fig. 10).

Since it was postulated that the source of the strain in a solder joint during a thermal cycle is the

difference in the coefficients of thermal expansion of the board material and the component lead, to find out quantitatively the sensitivity of the technique, it was decided to strain the solder joint by physically pulling on the component lead. Figure 11 shows the cross-correlation intensity plotted against the displacement of the end of the solder lead. This graph can be related to an equivalent temperature change in a thermal cycle by the equation

$$\Delta T = \delta / L(a_b - a_a)$$

where ΔT = temperature change

δ = displacement

L = length of the lead

a_a = coefficient of expansion of the wire

a_b = coefficient of expansion of the board material

To further test the cross-correlation technique, an

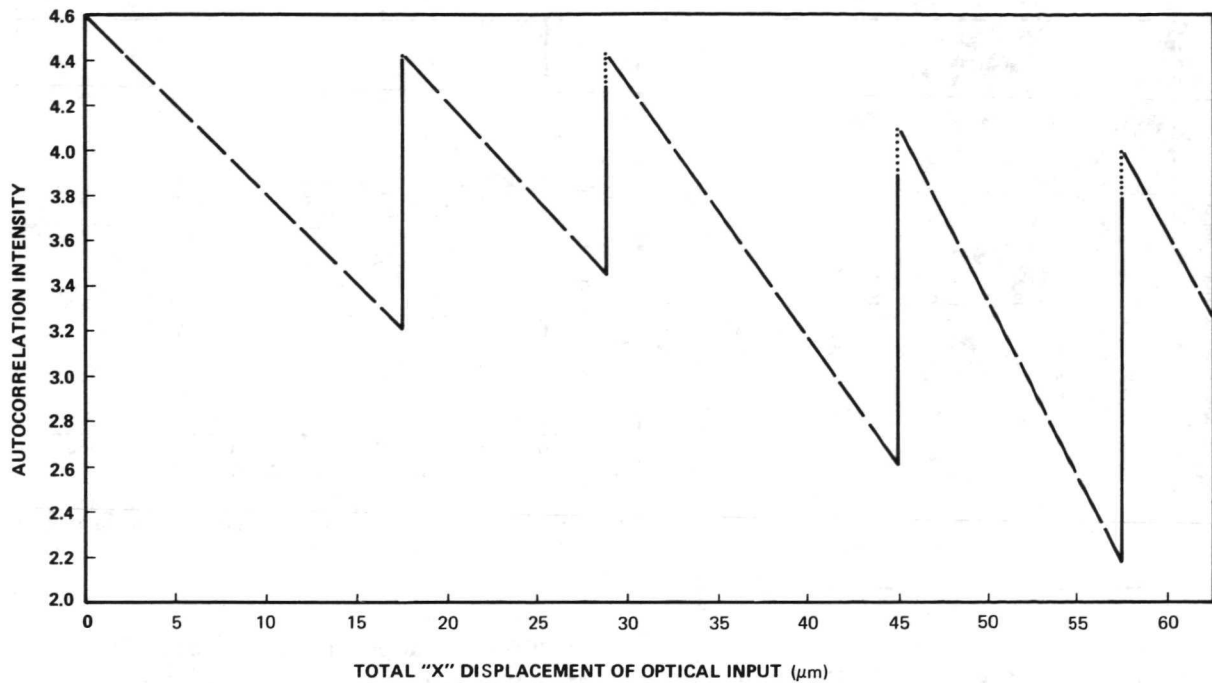


Figure 8.—Autocorrelation intensity as a function of optical input displacement in x direction.

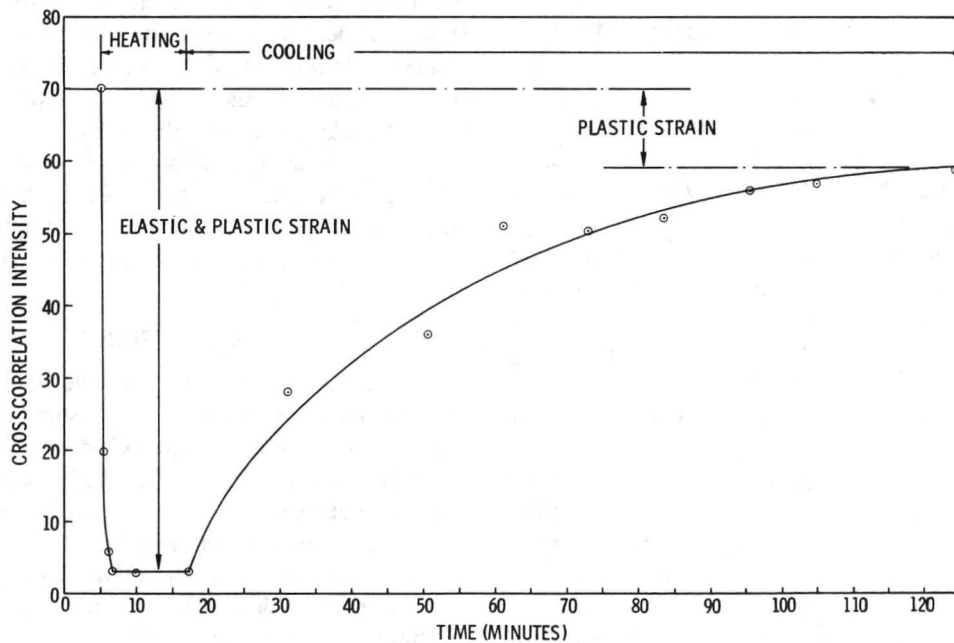


Figure 9.—Cross-correlation intensity as a function of strain during a thermal cycle.

experiment was set up to monitor three solder joints, each of a different type. The purpose was to predict which solder joint would fail first in normal use. The

solder joint whose cross-correlation amplitude dropped fastest when plotted versus thermal cycles would be said to be undergoing the greatest

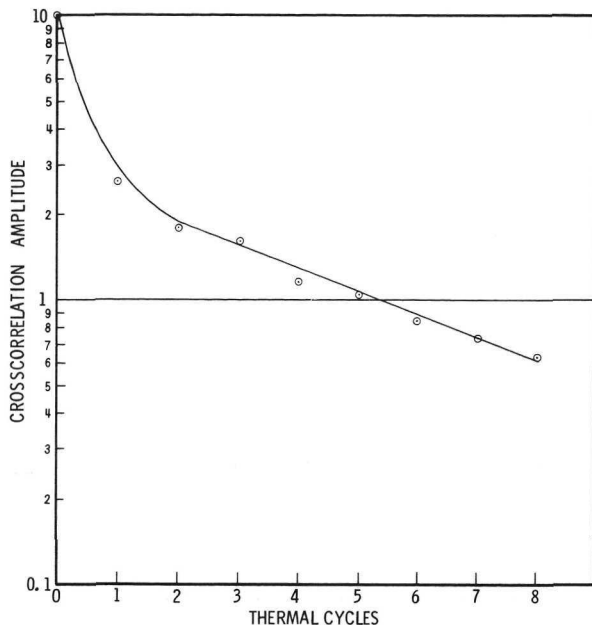


Figure 10.—Cross-correlation amplitude as a function of thermal cycling.

permanent deformation and therefore be likely to fail before the others.

The laser beam directed toward the printed circuit board was split into three separate beams, each directed to one of the three solder joints being tested. One Fourier-transform hologram was recorded for all three solder joints. By blocking two of the three beams illuminating the printed circuit board, the cross-correlation for each solder joint could be recorded and plotted versus the number of thermal cycles undergone by the printed circuit board. Using a heat lamp, the temperature was raised from 24 to 39 °C and then allowed to cool to 24 °C during each cycle.

Typical results obtained from this procedure are plotted in figure 12. The type B solder joint had the steepest slope, and the type A joint had the least decrease in cross-correlation amplitude. Therefore, it was postulated that type B was the worst of the three and type A was the best. These predictions were found to agree with results obtained from destructive testing of the same types of joints.

The destructive testing procedure was to cycle the printed circuit boards from -50 to +80 and back to -50 °C many times, counting the number of joints which showed effects of strain, suffered simple

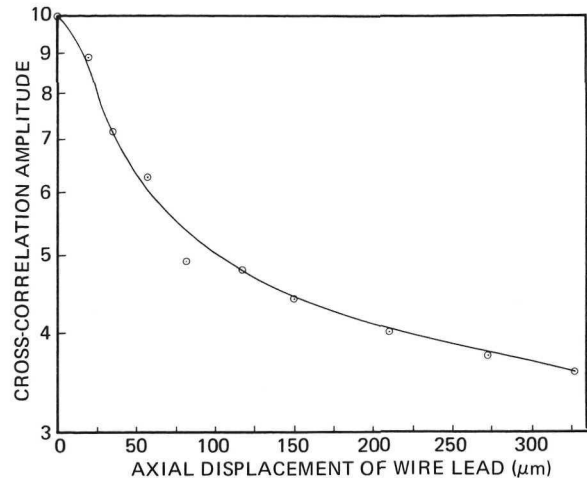


Figure 11.—Cross-correlation amplitude as a function of axial displacement of the wire lead.

cracks, or contained an isolated crack. (An isolated crack is defined as a 360° crack about the lead. This is a case of complete failure.) The results of these tests are shown in figure 13. It was found, as predicted by the cross-correlation measurements, that type B solder joints were by far the worst of the three solder joint types. It was the only one which went to isolated cracking. Also in agreement with prediction, type A solder joints were the best of the three. (While the testing procedure does not duplicate the thermal cycling experienced under operational conditions, results from extensive destructive testing were found to agree with data from solder joint failure during actual use.)

CONCLUSIONS

Solder joint shifts, elastic and plastic deformation, and creep can be observed and measured using optical correlation. In addition, the experiment shows that it may be feasible to subject printed circuit boards to nondestructive testing to detect bad solder joints and to assign lifetime predictions based on the slope of the cross-correlation-versus-thermal-cycles curve.

The primary limitations of the cross-correlation technique relate to the stability that is required for recording the matched filter and for obtaining the cross-correlation measurement. The system must be isolated from vibration, and the test material must be rigid. Materials which are too large and flexible will deform under their own weight, making the cross-correlation measurement almost meaningless.

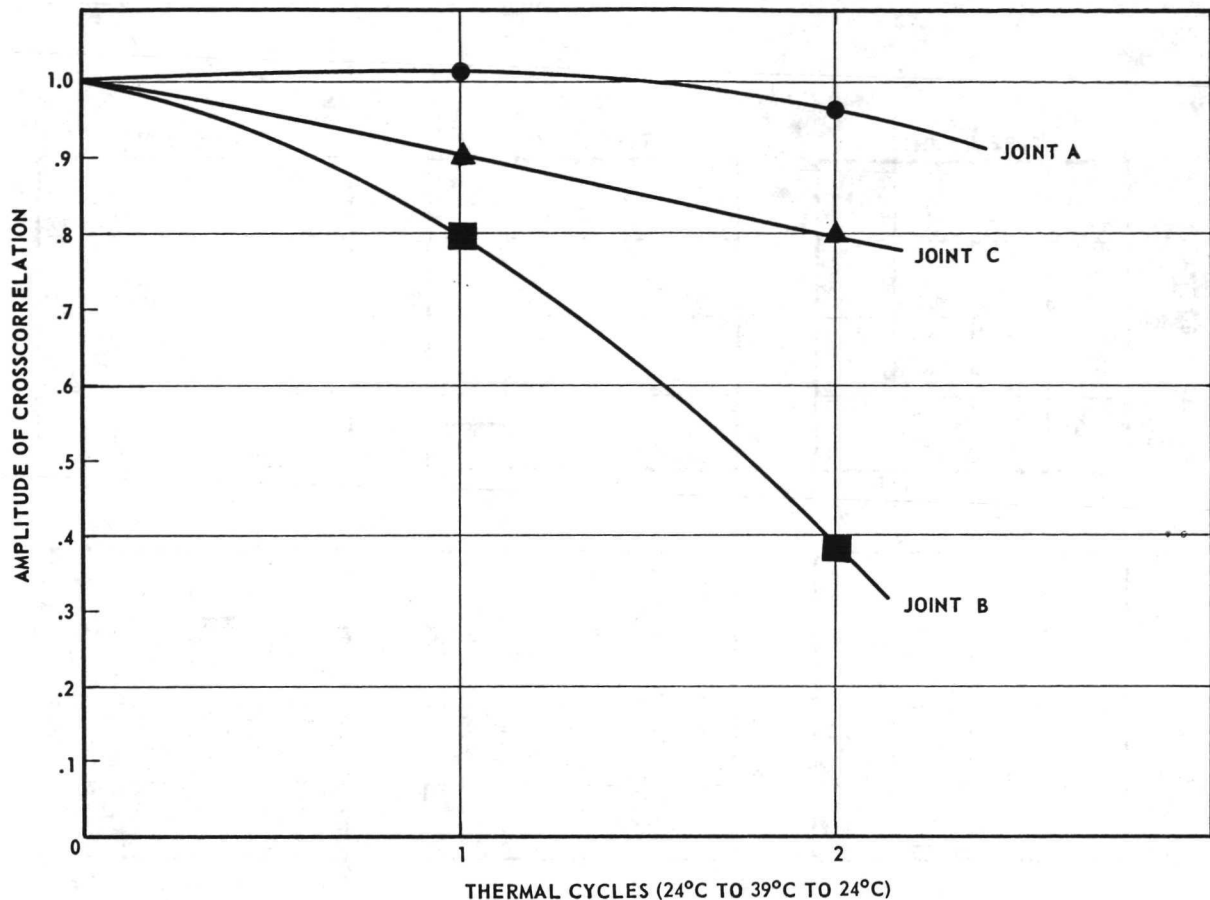


Figure 12.—Results obtained from nondestructive testing of three types of solder joints.

However, for rigid materials, there are several advantages. In most other nondestructive testing, the faults must be fairly large before they can be detected. With this system the faults are detected before they occur, and the material needs to be only barely stressed to detect material fatigue, thereby maintaining the integrity of the material.

REFERENCES

1. Westinghouse Defense and Space Center, Development of Highly Reliable Soldered Joints for Printed Circuit Boards, NASA Contract No. NAS-21233, 1968.
2. Powell, R. L.; and Stetson, K. A.: Interferometric Vibration Analysis by Wavefront Reconstruction, *J. Opt. Soc. Am.*, Vol. 55, 1965, p. 1593.
3. Heflinger, L. O.; Wuerker, R. F.; and Brooks, R. E.: Holographic Interferometry, *J. Appl. Phys.*, Vol. 37, 1966, p. 642.
4. Haines, K. A.; and Hildebrand, B. P.: Surface Deformation Measurement Using Wavefront Reconstruction Technique, *Applied Optics*, Vol. 5, 1966, p. 595.
5. Chuang, K. C.: Application of the Optical Correlation Measurement to Detection of Fatigue Damage, *Materials Evaluation*, Vol. 26, 1968, p. 116.
6. Marom, E.: Real-Time Strain Measurements by Optical Correlation, *Applied Optics*, Vol. 9, 1970, p. 1385.
7. Goodman, J. W.: *Introduction to Fourier Optics*, McGraw-Hill Book Co., New York, 1968, pp. 83-87.
8. Vander Lugt, A.: Signal Detection by Complex Spatial Filtering, *IEEE Transactions on Information Theory*, Vol. 10, 1964, p. 139.
9. Papoulis, A.: *Systems and Transforms with Applications in Optics*, McGraw-Hill Book Co., New York, 1968, pp. 91-92.
10. Stroke, G. W.: *An Introduction to Coherent Optics and Holography*, Academic Press, New York, 1969, pp. 174-177.

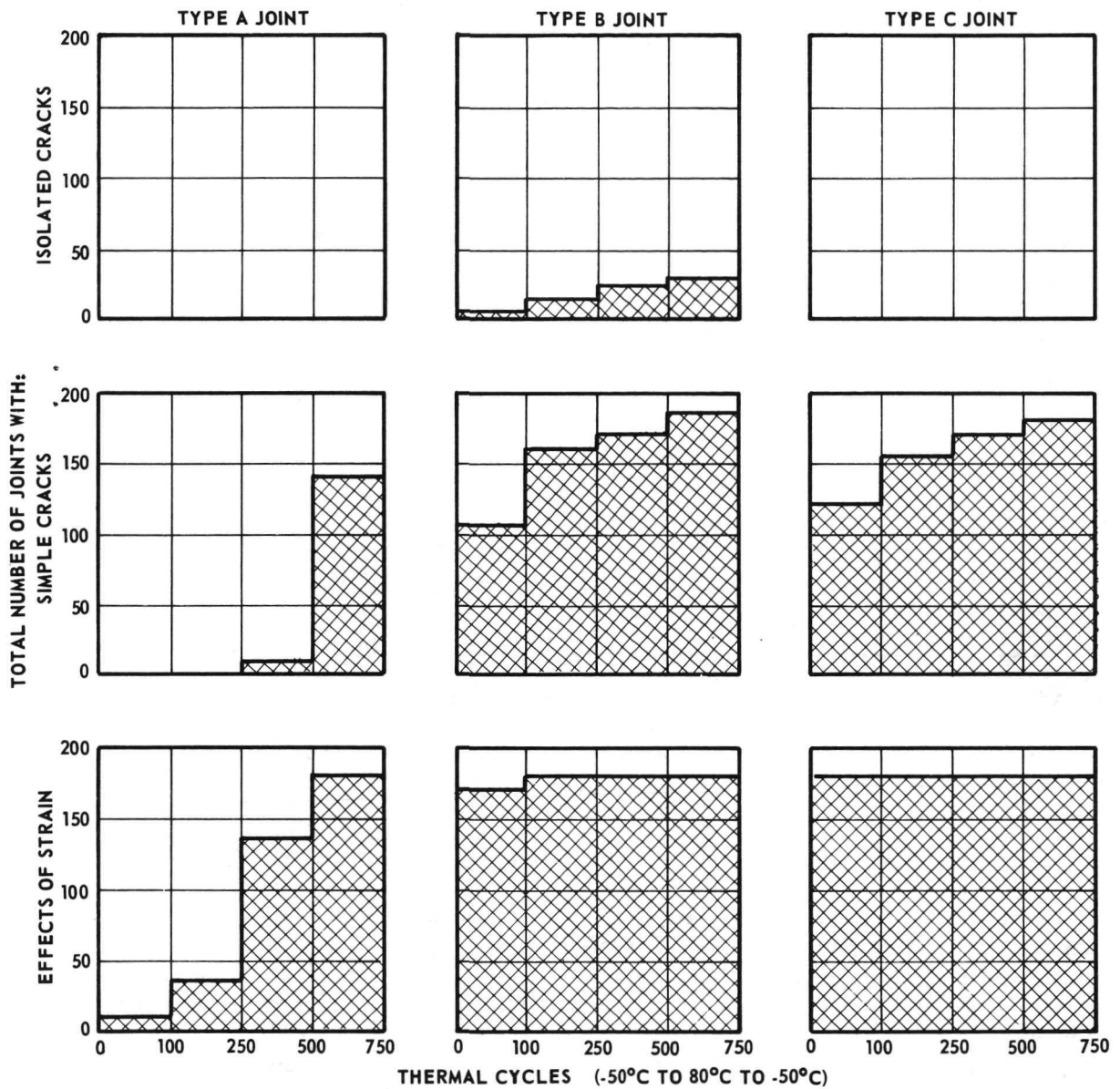


Figure 13.—Results of destructive testing of same three types of solder joints.

An Investigation of the Real Image of an Aperture-Limited, In-Line Fraunhofer Hologram*

Ronald A. Belz

Arnold Research Organization, Inc.

In-line holography is a convenient technique for investigating size distributions and velocities in a particle field. However, the errors inherent in the measurement of these parameters must be known. In this paper the intensity distribution in the neighborhood of the real image of an aperture-limited, in-line Fraunhofer hologram is described. Theoretical data are presented in the form of isophote diagrams. Each diagram is dependent only on the amount of particle information recorded and not on the recording parameters. Diagrams of the intensity along the reconstruction axes are included. From the theory; the conditions under which the image size measurement error is zero are found. In addition, the depth of field of the image is also determined and is found to be similar to that of the real image of a thin lens. The theoretical analysis shows excellent agreement with experimental data.

In-line holography is applicable to particle field analysis for the determination of the size and velocity distributions within a volume of dynamic particles. This technique has been used at the Arnold Engineering Development Center and the University of Tennessee Space Institute (refs. 1 and 2). As a consequence of this work, it was determined that the errors inherent in the measurements of the reconstructed images must be known for the size data and the image positions in the volume. Therefore the real image in the hologram reconstruction was investi-

gated in terms of a limiting aperture in the recording. The limited-aperture concept results from the fact that the film is unable to record all of the light diffracted by the particles. Consequently, each image is reconstructed from a finite amount of holographic information. The effects of this information on the image characteristics and on the measurements will be discussed.

In this analysis it is assumed that a circular opaque particle is illuminated with monochromatic plane waves. The interference pattern arising from this illumination is used to find the light distribution in the reconstruction. Analysis of the intensity in the reconstruction consequently yields the effects of the limited information on the reconstructed image. Criteria can then be chosen to indicate the errors inherent in the size measurement and the depth of field of the hologram.

REAL IMAGE INTENSITY DERIVATION

A circular opaque particle of radius a , illuminated

*The research reported in this paper was sponsored by the Arnold Engineering Development Center, Air Force Systems Command, Arnold Air Force Station, Tennessee, under Contract No. F40600-72-C-003 with ARO, Inc. The author was a research assistant with the University of Tennessee Space Institute. This work constitutes one part of his dissertation submitted to the Graduate School of the University of Tennessee, in partial fulfillment of the requirements for the Ph. D. degree in electrical engineering. Further reproduction is authorized to satisfy the needs of the U.S. Government.

with plane waves as illustrated in figure 1a, produces an intensity distribution in a plane z_1 , which is given by

$$I(r, z_1) = 1 + \frac{a^2}{r^2} J_1^2\left(\frac{kar}{z_1}\right) - 2\left(\frac{a}{r}\right) J_1\left(\frac{kar}{z_1}\right) \sin\left(\frac{kr^2}{2z_1}\right) \quad (1)$$

where r is the radial coordinate in the recording, k is the wave number, and J_1 is a first-order Bessel function of the first kind. This intensity pattern is recorded on film so that the amplitude transmittance of the developed negative is proportional to the intensity; that is, the background exposure lies in the linear region of the amplitude transmittance-versus-exposure (T_A - E) curve. Illuminating this hologram with a monochromatic plane wave of wavelength λ produces behind the hologram a light distribution given by (ref. 3)

$$\psi_R = \frac{1}{i\lambda} \int_h \psi_A \frac{e^{ikR}}{R} \cos \theta' d\bar{r} \quad (2)$$

where $i = \sqrt{-1}$, $d\bar{r} = r dr d\theta$, ψ_A is the field immediately behind the hologram, R is the distance between a point on the hologram and a point in the reconstruction plane (see fig. 1b), and θ' is the angle between R and the normal to the hologram.

Considering only the real image, making the usual approximations (the Fresnel approximation, $\cos \theta' \approx 1$, etc.), and neglecting the effects of the second term in equation 1, the integration becomes

$$\psi_R(w, z_2) = \frac{1}{i\lambda^2} \frac{a\beta T}{z_2} e^{ik\left(z_2 + \frac{w^2}{2z_2}\right)} \int_0^H J_1\left(\frac{kar}{z_1}\right) J_0\left(\frac{kwr}{z_2}\right) e^{-\frac{ikr^2}{2}} \left(\frac{1}{z_1} - \frac{1}{z_2}\right) dr \quad (3)$$

where β is the slope of the linear region of the T_A - E curve of the film, T is the exposure time, z_2 is the distance from the hologram to the plane of interest in the reconstruction, and w is the radial vector in the z_2 plane. The zeroth-order Bessel function results from integration over the polar angle θ on the hologram.

The upper limit H is the limiting aperture radius of the hologram. Beyond this radius, the intensity is assumed to be the background, a constant. Therefore only a finite amount of the information contributes to the formation of the image in the reconstruction. Utilizing Euler's formula and

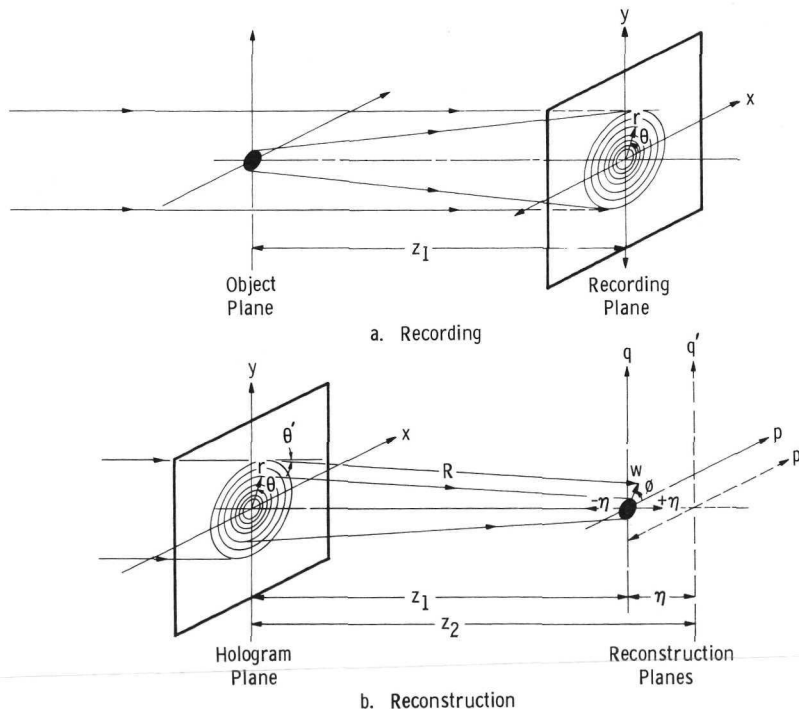


Figure 1.—Plane-wave recording and reconstruction geometry for an in-line hologram.

$$I_R = \psi_R \psi_R^* \quad (4)$$

where ψ_R^* is the complex conjugate of ψ_R , then

$$I_R(w, z_2) = c^2 \left\{ \left(\int_0^H J_1 \left(\frac{kar}{z_1} \right) J_0 \left(\frac{kwr}{z_2} \right) \cos \left[\frac{k}{2} \left(\frac{1}{z_1} - \frac{1}{z_2} \right) r^2 \right] dr \right)^2 + \left(\int_0^H J_1 \left(\frac{kar}{z_1} \right) J_0 \left(\frac{kwr}{z_2} \right) \sin \left[\frac{k}{2} \left(\frac{1}{z_1} - \frac{1}{z_2} \right) r^2 \right] dr \right)^2 \right\} \quad (5)$$

where $c = (a\beta T / \lambda^2 z_2)$. This equation describes, under the focusing condition ($z_1 = z_2$), the intensity of the real image as well as the intensity distribution in the neighborhood of this image.

Normalization of the upper limit by $r = H\rho$ results in

$$I_R = c^2 H^2 \left\{ \left[\int_0^1 J_1(\Omega\rho) J_0(V\rho) \cos \left(\frac{U}{2} \rho^2 \right) d\rho \right]^2 + \left[\int_0^1 J_1(\Omega\rho) J_0(V\rho) \sin \left(\frac{U}{2} \rho^2 \right) d\rho \right]^2 \right\} \quad (6)$$

where

$$\Omega = \frac{kaH}{z_1} \quad (7)$$

$$V = \frac{kwH}{z_2} \quad (8)$$

and

$$U = kH^2 \left(\frac{1}{z_1} - \frac{1}{z_2} \right) \quad (9)$$

The argument of the J_1 function at $\rho = 1$ coincides with the argument of the same function in the interference equation (eq. 1) at the upper limit H . Consequently, this coefficient indicates the amount of information about the particle that is recorded. It is constant in the reconstruction and is fixed in the recording. The distance from the hologram to the plane of interest, z_2 , in the reconstruction can be written in terms of the real-image focal plane as

$$z_2 = z_1 + \eta \quad (10)$$

Figure 1b illustrates the geometry pertaining to this definition of z_2 . Solving for H in equation 7 and substituting along with equation 10 into equations 8 and 9 gives

$$U = \frac{\lambda}{2\pi} \frac{\Omega^2}{a^2} \frac{z_1 \eta}{z_1 + \eta} \approx \frac{\lambda}{2\pi} \frac{\Omega^2}{a^2} \eta \quad (11)$$

$$V = \frac{\Omega}{aw} \frac{z_1}{z_1 + \eta} \approx \frac{\Omega}{aw} \quad (12)$$

The approximations are valid for η much less than z_1 . From these equations, U and V are seen to be functions of the horizontal (η) and radial (w) axes, respectively. Therefore the solution of equation 6 with Ω a constant and U and V varying will produce reconstruction data applicable to all holograms which have recorded particle information up to the same value of Ω independent of the particle size, recording distance, and wavelength. The data are applicable even to the case where recording and reconstructing are done with spherical waves (ref. 4). However, the relationships between U and V and the recording parameters will change.

To observe the relative intensity variations, equation 6 is normalized to the intensity at $U = 0$ and $V = 0$, i.e., the center of the in-focus image. Therefore

$$I_{R(\text{norm})} = \frac{\Omega^2}{[1 - J_0(\Omega)]^2} \left\{ \left[\int_0^1 J_1(\Omega\rho) J_0(V\rho) \cos \left(\frac{U}{2} \rho^2 \right) d\rho \right]^2 + \left[\int_0^1 J_1(\Omega\rho) J_0(V\rho) \sin \left(\frac{U}{2} \rho^2 \right) d\rho \right]^2 \right\} \quad (13)$$

THEORETICAL DATA RESULTS

In general, equation 13 must be solved numerically. A 96-point Gaussian quadrature numerical integration technique was used to evaluate the integrals (ref. 5). The resulting data are presented on isophote diagrams with U and V as the horizontal and vertical axes, respectively. These diagrams indicate lines of constant intensity about the real image. Figures 2, 3, and 4 are the isophote diagrams for $\Omega = 13.324$, respectively (the second, third, and fifth zeros of J_1). The in-focus image intensity lies along the V axis with the edge of the image ($w = a$) at $V = \Omega$ (from eq. 12).

The positions of the intensity variations in the reconstruction are found by translating the data from the diagrams to the coordinate axes, η and w , where

$$\eta = \frac{2\pi a^2 z_1 U}{z_1 \lambda \Omega^2 - 2\pi a^2 U} \approx \frac{2\pi a^2}{\lambda \Omega^2} U \quad (14)$$

and

$$w = \frac{z_1 \lambda \Omega a V}{z_1 \lambda \Omega^2 - 2\pi a^2 U} \approx \frac{a V}{\Omega} \quad (15)$$

where the approximations result when $U \ll 2N\Omega^2/\pi$. (N is the far-field number; one far field is defined as $4a^2/\lambda$.) The isophote diagram is symmetrical about

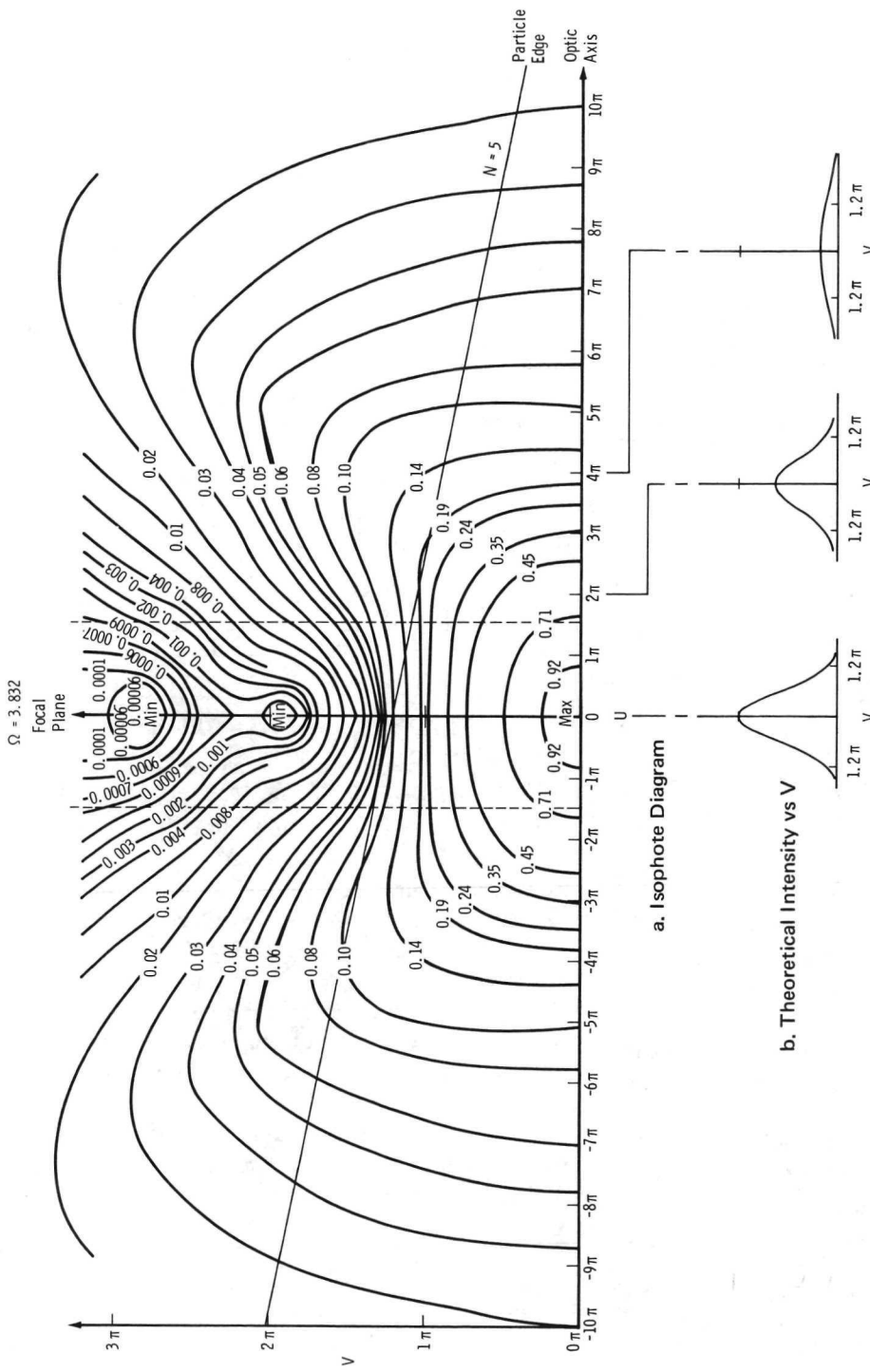
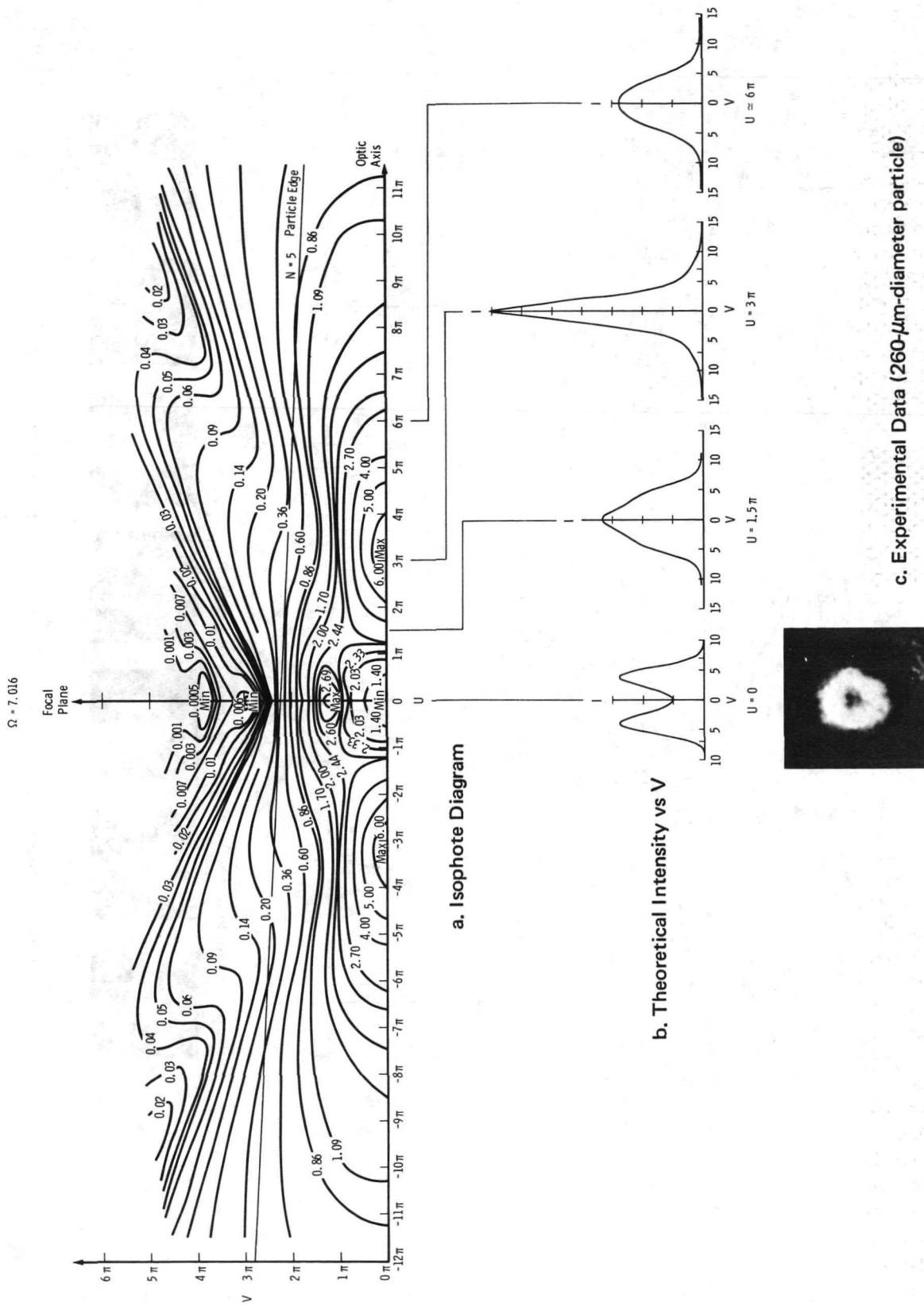


Figure 2.—Intensity variations in the neighborhood of the real image for $\Omega=3.832$.


 Figure 3.—Intensity variations in the neighborhood of the real image for $\Omega = 7.016$.

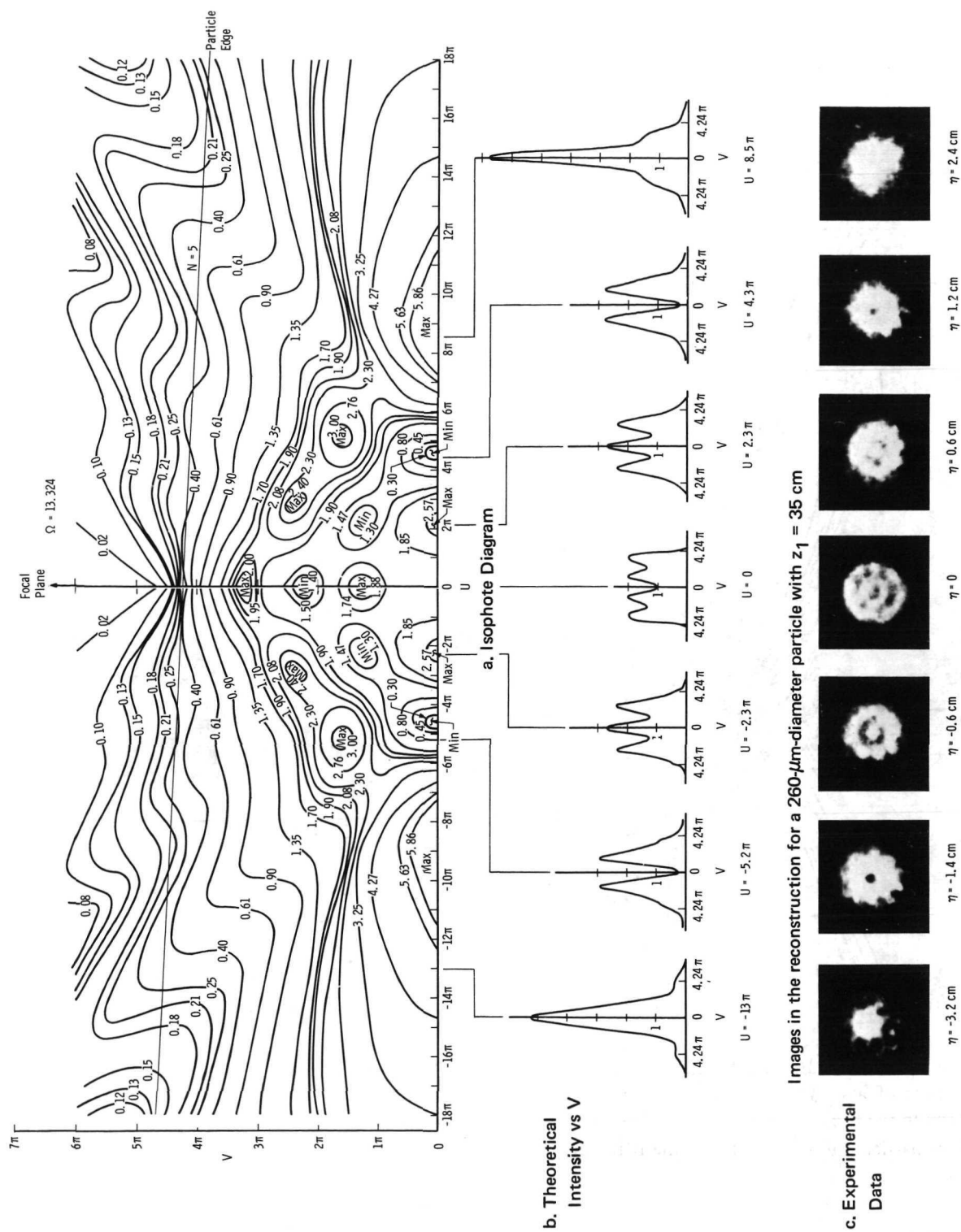


Figure 4. —Intensity variations in the neighborhood of the real image for $\Omega=13.324$.

both axes because the integrals in equation 13 are squared; however, the intensity distribution in the reconstruction is asymmetrical about the focal plane. This is evident from equations 14 and 15, where both η and w are functions of U . Substituting equation 14 for η into equation 12, the isophote diagram axes are found to be related as

$$V = \left(\Omega - \frac{\pi}{2N\Omega} U \right) \frac{w}{a} \quad (16)$$

Thus V and U are linearly dependent with a slope that is a function of Ω and the far-field number, N . Consequently, the amount of asymmetry in the reconstruction can be indicated on the isophote diagram. The equation is plotted for $w=a$ and $N=5$ on the diagrams. In figures 2a and 3a, the line has a pronounced slope. In figure 4a it is approximately parallel to the horizontal axis, indicating that within the region shown on the isophote diagram the reconstruction is approximately symmetrical and follows the intensity distribution on the diagram. Some idea of the intensity variation in the reconstruction can be obtained by mentally rotating the line so that it is parallel to the horizontal axis. Then the intensity between the hologram and the focal plane is visualized to be compressed as compared to that on the diagram, while beyond the focal plane it is expanded.

To better observe the variations of the intensity across the image when it is in and out of focus, I_{norm} versus V is plotted in part b of figures 2, 3, and 4 for various values of U . For $\Omega=3.832$, figure 2b shows that the reconstructed image will contain a single peak which is maximum when in focus and decreases to the background (zero on the diagram) when out of focus. The in-focus image intensity, shown in figure 3b for $\Omega=7.016$, is a minimum at the center. It increases to a maximum before decreasing to the background near the geometrical edge. As the image is moved out of focus, the central intensity will increase to a maximum and the out-of-focus image will consist of a single peak which, further along U , decreases to the background.

When particle information up to the fifth zero of J_1 is recorded, the in-focus image will contain four extrema radially from the center (or seven extrema across the diameter) as shown in figure 4b. In out-of-focus planes, the center intensity increases to a maximum, where now the number of extrema on the image has decreased to a minimum and the variations

on the out-of-focus image are seen to coincide with those on the in-focus image for $\Omega=7.016$. This intensity then increases further along the horizontal axis until it has reached a single peak. Beyond, it decreases to the background. The data therefore indicate that the in-focus image is characterized by the number of J_1 zeros that were recorded. In general, it is found that the number of extrema radially on the image will always be one less than the number of J_1 zeros recorded (ref. 6). Data for intermediate values of Ω will exhibit characteristics of the J_1 zeros they lie between.

When more information about the particle is recorded, i.e., at larger values of Ω , the extrema on the in-focus image not only increase in number but also decrease in amplitude to an average value. The frequency of occurrence of the extrema on the out-of-focus image also increases as the image is brought near focus. In the limit as Ω goes to infinity, it approaches infinity near the in-focus image (ref. 4).

EXPERIMENTAL RESULTS

The theoretical results were verified experimentally by physically aperturing in-line Fraunhofer holograms during the recording. The recording and reconstructing systems are illustrated in figure 5. All of the holograms were taken on Agfa-Gevaert Scientia 8E75 film, which has a cutoff frequency of 3000 lines per millimeter. For a fixed aperture radius ($375 \mu\text{m}$), the amount of information recorded on the hologram was controlled by varying the distance from the film to the object, a black spray-paint particle mounted on a glass plate. The reconstructed images are shown in part c of figures 2, 3, and 4. These data were taken from the monitor of a high-resolution (1225 lines) closed-circuit television (CCTV) system. No lenses were used in the recording or in the reconstruction of the hologram.

The slow decay of the intensity near the edge of the $102\text{-}\mu\text{m}$ image in figure 2c gives it a fuzzy appearance. This represents the minimum resolution of the aperture. In figure 3c the in-focus image of a $260\text{-}\mu\text{m}$ -diameter particle appears doughnut-shaped. Experimental data for the fifth zero of J_1 are presented in figure 4c for planes out of focus as well as the focal plane. The positions of the out-of-focus images correspond to the theoretical curves in part b of the figure. The data are seen to coincide well with the theory.

In order to observe the natural aperturing effects

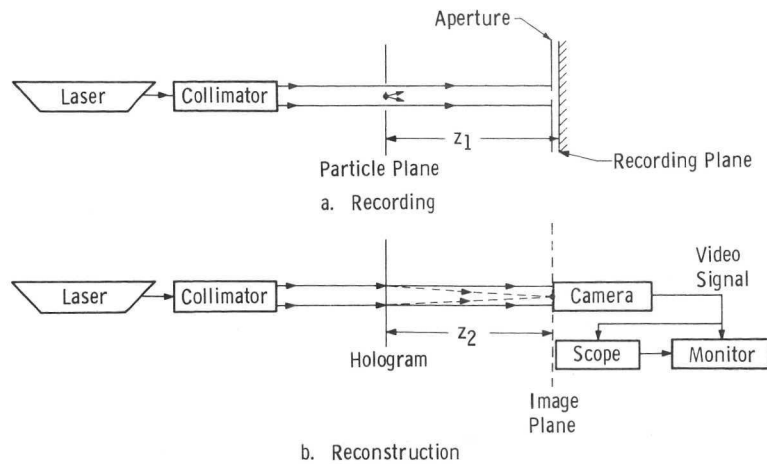


Figure 5.—Experimental geometry for recording and reconstructing the in-line hologram.

in the recording, holograms of the 260- μm -diameter particle were taken on Kodak Royal Pan and Kodak SO-243 films. Figure 6 shows the in-focus images and the experimentally determined intensity variations reconstructed from each in-line hologram. No physical aperture was placed in the recording or reconstruction systems. The image on the left is characteristic of the fifth zero of J_1 , and that on the right is characteristic of the third zero. These photographs show that the limiting-aperture concept, with the resulting characteristic image variations, is not an artificial one and that the results are valid for practical considerations. For example, by noting the number of intensity peaks (rings) on the in-focus image, the approximate bandwidth of the hologram recording can be determined. It is believed that the cause of the limiting aperture in both cases is the film grain noise (ref. 4). This noise is apparent in the reconstruction as intensity variations (speckle) on and around the image of the Royal Pan hologram.

THEORETICAL RESOLUTION

From the foregoing theoretical data, criteria can be established for the measurement of the size of the reconstructed image and for the determination of the depth of field. Errors inherent in the measurement can then be found from the theoretical data.

The distance from the geometrical edge of the image to some point coinciding with a predetermined intensity value near the edge can be obtained from the isophote diagrams, and the errors inherent in the measurement of the particle diameter at this point

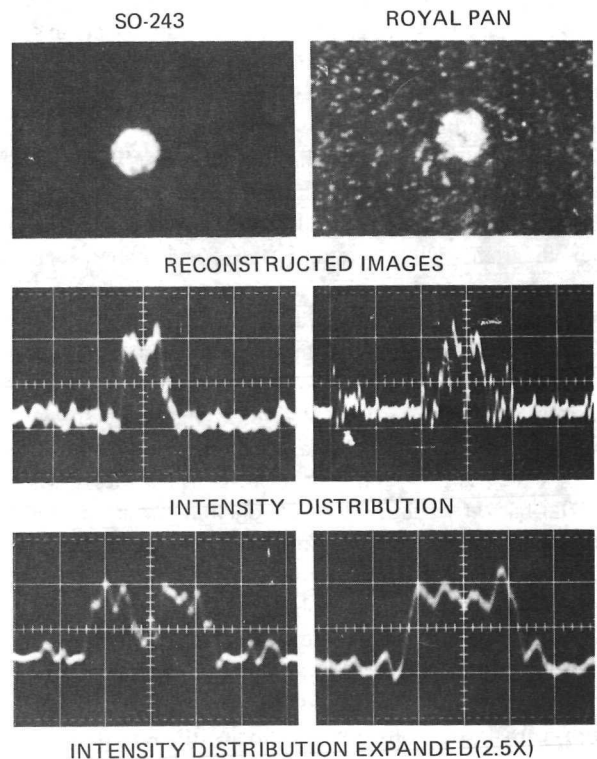


Figure 6.—Reconstructed images and corresponding intensity distributions from two films where $z_1=91$ cm and $a=130$ μm .

can be determined. This distance, Δw , from equation 15 is

$$\Delta w = \frac{\Delta V}{\Omega^2} a \quad (17)$$

where ΔV represents the distance on the isophote diagram from the image edge ($V=\Omega$) to some specified intensity.

At the edge of the image, the intensity can be found from equation 13 with $V=\Omega$ and $U=0$ as

$$I_{\text{norm}} = \frac{1}{4} [1 + J_0(\Omega)]^2 \quad (18)$$

Consequently, by measuring the image where the edge intensity is 25 percent of the center intensity, zero error results, theoretically, when the maximum argument of J_1 recorded on the hologram is a zero of J_0 . This measurement is indicated by W_1 on the theoretical intensity of the in-focus image for $\Omega=19.616$ in figure 7. The maximum error is found to occur when Ω is a zero of J_1 , since this is where J_0 is a maximum. Table 1 lists these errors for five zeros of J_1 . It should be noted that this measurement will yield sizes that are both too large (indicated by the positive signs) and too small (indicated by the negative signs), depending on the value of Ω . The error is given as a percentage of particle radius, which follows directly from equation 17. It is seen that the particle size measurement error is a function only of

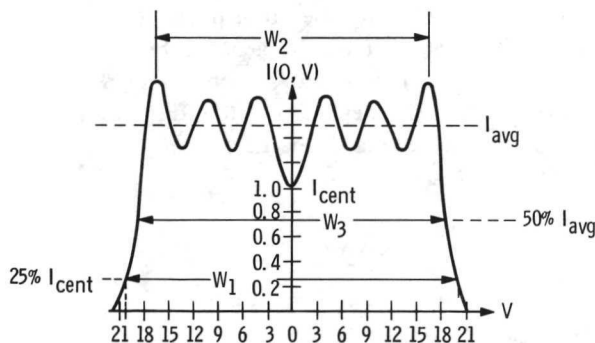


Figure 7.—Measurements of particle image diameter for an in-focus image resulting when $\Omega=19.616$.

Table 1.—Theoretical Size Measurement Errors

Ω	$W_1(\%)*$	$W_2(\%)*$	$W_3(\%)*$
3.832	-22.0		-44.3
7.016	+6.0	-47.0	-8.0
10.173	-4.78	-31.3	-9.6
13.324	+2.05	-19.8	-6.0
19.616	+1.22	-17.8	-3.7

*Positive and negative signs indicate whether the image is larger (+) or smaller (-) than the actual particle size.

the maximum value of Ω . However, Ω will change for each hologram depending on the recording parameters.

Another size measurement is indicated in figure 7 by W_2 . In this case the separation between the outermost peaks is measured. The errors listed in table 1 are larger than those of the previous method, and the sizes are seen to be smaller. As a third-image size measurement, the width W_3 is measured (fig. 7) where the intensity at the edge is 50 percent of the average image intensity. The errors inherent in this measurement, listed in table 1, lie between those of W_1 and W_2 .

Particle diameter measurements W_1 and W_3 were taken of three different-size particle images reconstructed from apertured holograms containing a predetermined value of Ω , and the data are presented in table 2 along with the theoretical errors for comparison. These data were taken by observing the video signal of a single horizontal scan line on the CCTV. Experimental errors for W_1 are close to the theoretical errors for the 520- μm particle. However, for the larger values of Ω for this particle and for the 102- μm particle, the errors differ. It is believed that this difference is due to the limited bandwidth (10 MHz) of the readout system (the CCTV and an oscilloscope), which could not pass the high frequencies of the image signals. However, the measurement W_3 produced experimental measurement errors for these data that were much smaller than those predicted by the theory. Although the theoretical errors are large for this measurement, they compensated for the errors introduced by the limited bandwidth.

Table 2.—Experimental and Theoretical Data for Particle Image Size Measurements

Particle diameter (μm)	Ω	W_1		W_3	
		Measured diameter (μm)	Error* (%)	Measured diameter (μm)	Error* (%)
102	3.832	121	18.7 (-22.0)	99	0.98 (44.3)
	7.016	128	25.5 (6.0)	99	0.96 (8.0)
260	3.832	292	11.8 (-22.0)	198	24.1 (44.3)
	7.016	285	8.8 (6.0)	245	6.13 (8.0)
	10.173	289	10.7 (-4.8)	256	1.92 (9.6)
520	13.324	285	8.8 (2.1)	268	2.68 (4.9)
	7.016	583	10.8 (6.0)	478	8.1 (8.0)
	10.173	499	-4.0 (-4.8)	441	15.1 (8.0)
	13.324	528	1.5 (2.1)	484	6.9 (4.9)

*Theoretical errors are given in parentheses.

The ability to locate the position of the focal plane of the reconstructed in-focus image from the hologram can be indicated in terms of the depth of field, $\Delta\eta$. A common measurement of this parameter assumes that a 20-percent intensity change at the center of the image can be detected (ref. 7). From equation 14, for small values of U ,

$$\Delta\eta = \pm K_h (\Omega)^2 \frac{a^2}{\lambda} \quad (19)$$

where

$$K_h = \frac{2\pi^2}{\Omega^2} \left(\frac{\Delta U}{\pi} \right) \quad (20)$$

and $\Delta U/\pi$ is the incremental length representing a 20-percent change on the appropriate isophote diagram. Values of the constant K_h are listed in table 3. Equation 19 is of the same form as that obtained for a thin lens equal to z_1 and a radius equal to the maximum radius of the apertured hologram (ref. 4).

Table 3.—Values of K_h for the Depth-of-Field Calculation

Ω	K_h
3.832	1.790
7.016	0.161
10.173	0.150
13.324	0.119

If Ω is the same in holograms of different particle sizes, then the depth of field will become smaller with decreasing radii. Even when Ω is not constant, as for example on film that has recorded holograms of particles of various sizes in a single plane, the smaller images are observed to have a more rapid intensity change than the larger ones, thus allowing the focal plane to be determined more accurately.

SUMMARY AND CONCLUSIONS

It has been shown that the reconstructed real image of the aperture-limited hologram is characterized by the amount of particle information that was recorded on the hologram. In particular, the number of extrema from the center of the in-focus image is equal to $n-1$, where n is the number of J_1 zeros that were recorded and are effective in the reconstruction. It was assumed in the theoretical derivation that a finite amount of information is recorded. The radius of an aperture defines the upper limit of this

information. Experimental verification of the theory with a physical aperture in the recording and by holograms taken on relatively poor films illustrated the practicality of the limiting-aperture concept for in-line holography. The reconstructed image can be used as an indication of how much information is recorded on the film, provided the intensity variations are observable. The number of rings on the in-focus image will indicate how much of the interference pattern is recorded.

From the theoretical data presented on the isophote diagrams, criteria were established for measuring the reconstructed particle image size and the depth of field. It was found theoretically that the image size measurement will have zero error when the image width is measured where the edge intensity is 25 percent of the center intensity. However, in some cases, because of experimental limitations, the measurement at the edge where the intensity is 50 percent of the average image intensity proved to have smaller errors. A worst-case measurement of the separation of the outermost peaks on the image was also considered. The depth of field of the reconstructed image was found to be comparable to that of a thin lens. For a constant value of Ω , it decreases for smaller particle radii, allowing the focal plane to be determined more accurately. In general, however, the amount of information recorded on a hologram of a given particle will depend on the film used, the recording distance, and the particle size.

REFERENCES

- Farmer, W. M.; Burgess, K. S.; and Trolinger, J. D.: Holocamera for Examination of Water Droplets in a Large High-Altitude Test Cell. AEDC-TR-70-181, December 1970.
- Menzel, R.; and Shofner, F. M.: An Investigation of Fraunhofer Holography for Velocimetry Applications, *Applied Optics*, Vol. 9, 1968.
- Goodman, J. W.: *Introduction to Fourier Optics*, McGraw-Hill Book Co., New York, 1968.
- Belz, R. A.: An Investigation of the Real Image Reconstructed by an In-Line Fraunhofer Hologram Aperture-Limited by Film Effects, Ph. D. dissertation, University of Tennessee, August 1971.
- Carnahan, B.; Luther, H.; and Wilkes, J.: *Applied Numerical Methods*, John Wiley and Sons, New York, 1969.
- Belz, R. A.; and Shofner, F. M.: Characteristics and Measurements of an Aperture-Limited In-Line Hologram Image, to be published in *Applied Optics*.
- Born, M.; and Wolf, E.: *Principles of Optics*, Pergamon Press, New York, 1965.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE \$300

SPECIAL FOURTH-CLASS RATE
BOOK

POSTAGE AND FEES PAID
NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION
NASA-451



POSTMASTER : If Undeliverable (Section 158
Postal Manual) Do Not Return

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons. Also includes conference proceedings with either limited or unlimited distribution.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include final reports of major projects, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546