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NASA Technical Memorandum 89462

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(NASA-TM-89462) REAL-TIME LASER HOLOGRAPHIC INTERFEROMETRY FOR AERODYNAMICS (NASA) 11 p Avail: NTIS HC A02/MF A01 CSCL 14E

N87-22956

Unclas

G1/35 0076082

June 1987

National Aeronautics and
Space Administration

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Abstract

Recent developments in thermoplastic recording holograms and advancements in automated image digitization and analysis make real-time laser holographic interferometry feasible for two-dimensional flows such as airfoil flows. Typical airfoil measurements would include airfoil pressure distributions, wake and boundary layer profiles, and flow field density contours. This paper addresses some of the problems and requirements of a real-time laser holographic interferometer.

Introduction

Recent developments in thermoplastics, automated digitization, and expert systems make real-time laser holographic interferometry feasible. During the past decade, laser holographic interferometry has been developed for steady and unsteady two-dimensional flows. Measurements include airfoil pressure distributions, wake and boundary layer profiles,[1-5] and flow field density contours. With real-time interferometry, measurements can be made with more efficiency and cost savings and with higher quality data. In the past, the holograms taken in the wind tunnel were reconstructed in the laboratory, which was inefficient and resulted in poorer data.

A prototype real-time interferometer must satisfy a number of requirements: (1) minimize wind-tunnel-induced vibrations, (2) process and reconstruct holograms in situ, and (3) perform online image processing and fringe analysis. Wind tunnel vibrations can be minimized with rigid optical tables and with pulse lasers. Although a ruby or Nd:YAG laser would be suitable, improvements in laser beam pointing stability and beam filtering would greatly improve the quality of the holograms. This is crucial for fast reconstructions. In situ processing and reconstruction will require either a wet photographic process done in place or a dry process using thermoplastic holograms. A thermoplastic device (TPD) was successfully tested at NASA Ames this past year. The TPD processing was dry and fast. Reconstruction was done in situ but more development work is required. The TPD is a commercial product from Newport Corp. and was modified by Spectron Development Laboratories for dual plate interferometry. Online image processing can be done by a number of commercial image processors. Ames has developed a system that is based on a DeAnza image processor and a VAX 11/780 computer. It is capable of semi-automatic digitization, image enhancement, fringe-coordinate extraction, numbering, interpolation and extrapolation of fringe functions, and conversion of fringe data into aerodynamic data. To make this system fast enough for online processing, some type of expert system needs to be designed for fringe analysis. At a minimum, the analysis must determine density gradient direction and must recognize shocks. Wake and boundary layer analysis would require a greater effort.

Airfoil flow analysis

Many problems are encountered in performing airfoil analysis with laser holographic interferometry. Some problems are: (1) reconstruction to infinite fringe, (2) noise, (3) refraction, and (4) boundary layers determination.

Figure 1 shows an interferogram that was reconstructed to the infinite fringe mode. In this mode and for two-dimensional flows, the fringes become lines of constant density which makes analysis easier. Most fringe digitization programs[6-8] have been written for this mode. To reconstruct to infinite fringe mode, the idea is to obtain one infinitely wide fringe in the freestream region where the flow is uniform. For supersonic flows, the region ahead of the nose shock wave is uniform and can be reconstructed to one or two fringes. For subsonic flows, the process is much more difficult and somewhat subjective as well as very tedious and time consuming. This is because the flow is not completely uniform in any region. At best, the regions far away from the airfoil approach uniform flow.

Noise also contributes to the difficulty of reconstructing infinite fringe interferograms. Noise causes wiggles in the fringes, merges some fringes, and adds extraneous fringes. Note that in Figure 1, wiggles and merging are more apparent in regions farther away from the airfoil. This lower signal-to-noise region will suffer larger errors than the region nearer the airfoil where there are many fringes. The noise sources are vibration, poor quality optics, misaligned optics, laser instabilities, and ambient air currents. This latter effect can be significant because beam paths in wind tunnels can be of the order of tens of meters. Figure 2 shows an ambient condition interferogram in a wind tunnel. Even under controlled conditions, a few fringes occurred.

Refraction is inherent in many airfoil flows. The bending of the light beams by refraction causes errors in the fringe data and, in the worst cases, can result in the loss of fringes. Examples are shock waves and regions of rapid expansion such as on the nose of the airfoil. Fortunately, these regions are usually small and schemes can be devised to work around the problem. Refraction in shock waves will result in a broad dark line. Obviously, fringe data is lost. More important in flow field analysis, the fringe order across the shock wave is lost; i.e., one cannot count across the shock. In the case shown in Figure 1, one can trace a fringe around the shock and then continue the digitization of the flowfield. This process is slow unless new fast software can be developed. A practical and fast way to handle shock waves would be to have orifices ahead and behind the shock to give reference fringes. Refraction near the nose will cause a bright or dark spot with a loss of fringes. Extrapolation of fringes into this region works quite well. Usually there are many well defined fringes that can be extrapolated. However, this will slow down the analysis process.

One of the principal measurements of airfoils are pressure distributions from which forces are derived. This requires digitizing the fringes on the edge of the boundary layer which is a line near the airfoil surface. The determination of this line is straightforward in some cases and somewhat subjective in other cases.

The straightforward case is shown in Figure 3. The boundary layer consists of a series of closely spaced fringes that are nearly parallel to the upper surface. Above the boundary layer, the fringes are spaced farther apart and are nearly normal to the airfoil. For this case, it is easy to define the boundary layer. It is the locus of the points at which each fringe takes a sharp turn.

A difficult case is shown in Figure 4. On the upper surface of this airfoil, the boundary layer is thin and the outer fringes are almost parallel to the surface. It is difficult to distinguish between boundary layer fringes and outer flow fringes.

An intermediately difficult case, Figure 1, is to determine the edge of the shear layer in the region behind the shock wave. Note that the fringes are much more closely spaced in the shear layer than in the inviscid flow. Note also that the outer inviscid flow fringes can vary from being parallel to being normal to those in the shear layer. For this case, the determination of the edge is not clear cut.

For all three cases, it probably requires a trained operator to define the edge for a real-time interferometry system. However research in artificial intelligence for this problem is being pursued.

Real-time interferometer requirements

The three general requirements for real-time interferometry are: (1) eliminating vibration, (2) in situ processing and reconstruction, and (3) online image processing and fringe analysis.

The wind tunnel is a high vibration, noisy environment. Every effort must be made to eliminate or reduce vibration, so optics should be mounted on vibration-isolated tables. Machines should be isolated from optics and the test section. Most important, a laser with a pulse width that is very short (compared to any vibration frequency) must be used. Finally the laser should be stable; e.g., the beam should not wander and the intensity should remain fairly constant.

Another requirement for real-time interferometry is in situ recording, processing, and reconstruction. The usual process of taking the holograms at the wind tunnel and then developing and reconstructing them at the laboratory, requires hours. In situ systems using wet or dry processing can process the holograms in less than a minute. The wet process has a self-contained film developing unit. The dry process uses a thermoplastic material that is developed by heat. Both types of processes were initially developed for nondestructive testing and are commercially available. Last year a thermoplastic holocamera[6] was modified by Spectron Development Laboratories for double-plate aerodynamic interferometry. One of its features is that vibration compensation can be done by mechanically moving one of the thermoplastic plates. It was successfully tested at Ames Research Center, and the time required for processing was less than a minute. With the two holograms remaining in place during recording, processing, and reconstruction, infinite fringe interferograms should be attained quickly. In the ideal case of no vibration or noise, infinite fringe should be attained automatically. The wet process holocameras have not yet been used in wind tunnels. One anticipated problem is that the silver halide film is flexible, which could be a source of noise. Reconstruction with flexible film (as compared to a rigid thermoplastic) would be difficult. A variation of double-plate, real-time interferometry was shown by Basler[7] in which an ambient condition holographic plate was carefully superimposed in the object beam. The technique has been used for qualitative analysis of the unsteady buffet flow over an airfoil. The disadvantage of this method is the lack of vibration compensation.

The third requirement for real-time interferometry is fast image processing and analysis. Several methods can be used to analyze the interferogram. One is direct phase measurement using heterodyne techniques[8-10] over the entire flow field. These methods have been used for measuring deformations of opaque solid surface in nondestructive testing and for surface measurements in optical quality testing. Phase shifting techniques require simultaneous recording of multiple phase-shifted images or multiple reference beam holography.

Other methods use image-processing systems to enable a computer-aided evaluation of the fringe pattern. Many fast image processors can convert a picture to digital form for computer processing. Some processors use a linear photodiode array camera and others use a high resolution camera with a frame grabber for A to D conversion. Some systems are "stand alone" and use small computers and some are connected to a larger host computer. Picture enhancement and restoration to improve blurred and noisy pictures are standard processing capabilities. Software that converts pictures into maps and quantifies the required properties can be programmed for the computer.

Several semi-automatic digital image processing codes[11-13] have been developed for aerodynamics. NASA Ames Research Center has been using Becker's code for the past few years. This system has the following capabilities: The frame is averaged to improve the signal-to-noise ratio, and the fringe pattern is digitized. Each fringe is numbered and given a coordinate; however, the user must assign the direction of the fringes and change signs as the fringe pattern bends in the opposite direction (Figure 5). The system also plays back the fringe pattern with fringe numbers on the CRT. It is easy to check to see if any fringes are missed or misnumbered. Another feature of Becker's program is zooming and merging of the magnified views. Figure 6 shows data from an interferogram that require zooming because of the lack of resolution. The data[12] with zooming of 5 sections, 3 sections and no magnification showed that zooming improved the accuracy of the results. Finally Becker's code has interpolation and extrapolation routines for regions where refraction has destroyed the fringes.

Current research into fully automated systems is being investigated. This system will utilize expert systems knowledge to detect fringes, determine fringe orders, enhance pictures where necessary, and eliminate noise. Work is progressing on developing an expert system rules base that can draw on domain-specific knowledge, relate to past experience, use information from each analysis step to assist in selecting the next step, and make intelligent guesses.

Prototype real-time interferometer

Current work toward development of real-time interferometry at NASA Ames Research Center with an application toward the study of oscillating airfoils will be presented here. Figure 7 shows a sketch of a proposed real-time system. It consists of a pulsed laser, a thermoplastic recorder mounted on a vibration-isolated table, and an image processor using a minicomputer. The pulse ND:YAG laser is made by Quanta Ray and operates at 5300 Å with a pulse width of the order of 100 nsec. This laser has been used for over 5 years and has been quite reliable. One improvement would be to redesign the filtering optics to improve the beam wandering.

Figure 8 shows a vibration-isolated optics system. All the optics, the laser, and the thermoplastic recorder are mounted on a rigid table. The effectiveness of this system for filtering vibrations will be tested. The thermoplastic holographic recorder has provisions for double-plate interferometry. It also can perform online realignment. A major effort will be to determine if realignment is necesary and if reconstruction can be done with the Nd:YAG laser. Past reconstructions were done with a He-Ne laser, which requires realignment and a more complicated procedure.

Current work in image hardware and software is progressing. Both desktop and minicomputer-based image systems are being developed. The desktop system is portable, stands alone, and could be easily moved to the wind tunnel. Its speed and memory are probably sufficient to handle the airfoil case. The faster and larger minicomputer system is being developed for more general and more complicated flows and for fully automatic operation. Its software will incorporate expert systems. This system can be tied to mainframe computers for online experimental and theoretical integration.

Concluding remarks

The state of the art in laser holographic interferometry indicates that real-time interferometry for two-dimensional flows is feasible. The main problems and requirements for a real-time system have been discussed in this paper. With a concerted effort, a prototype system could be demonstrated within a year or two.

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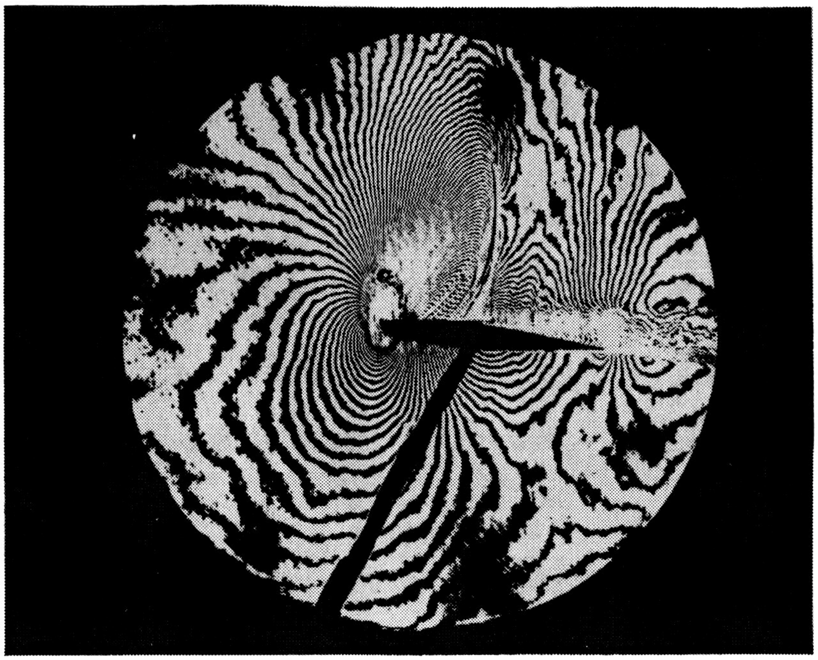

Figure 1. Infinite fringe interferogram

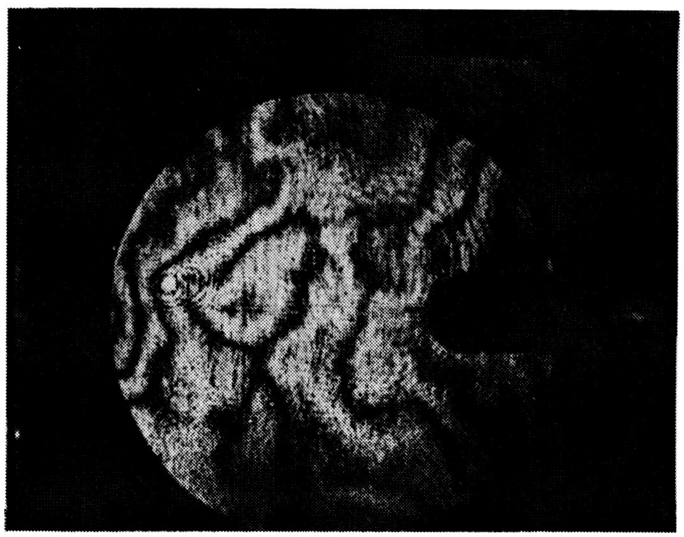

Figure 2. Ambient condition interferogram

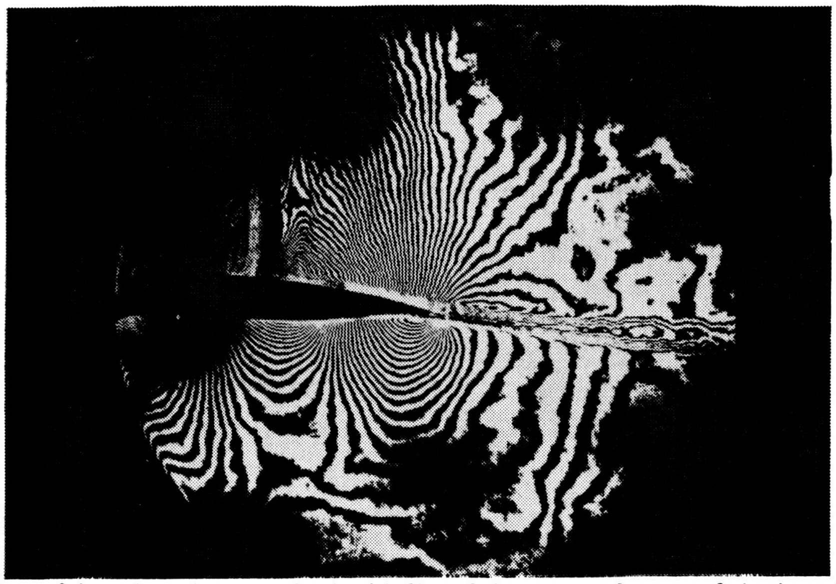

Figure 3. Detection of boundary layer: inviscid flow fringes nearly normal to boundary layer fringes

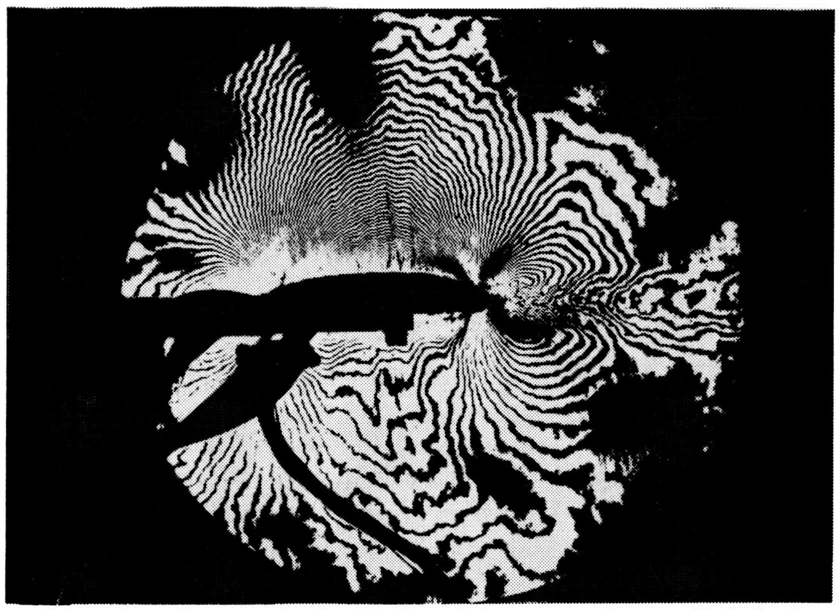

Figure 4. Detection of boundary layer: inviscid flow fringes nearly parallel to boundary layer fringes

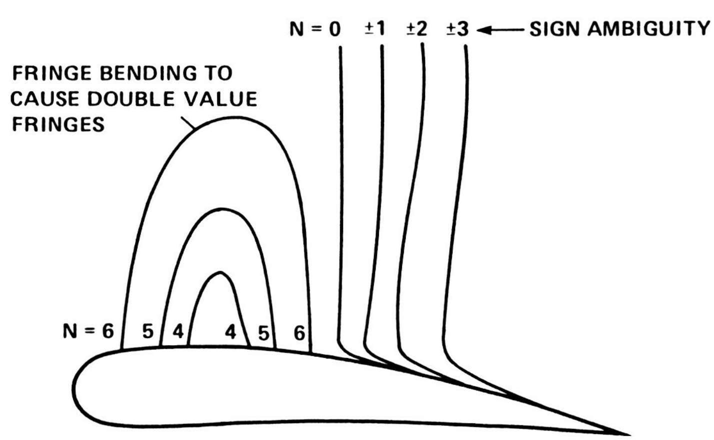

Figure 5. Sign ambiguity and double value fringes

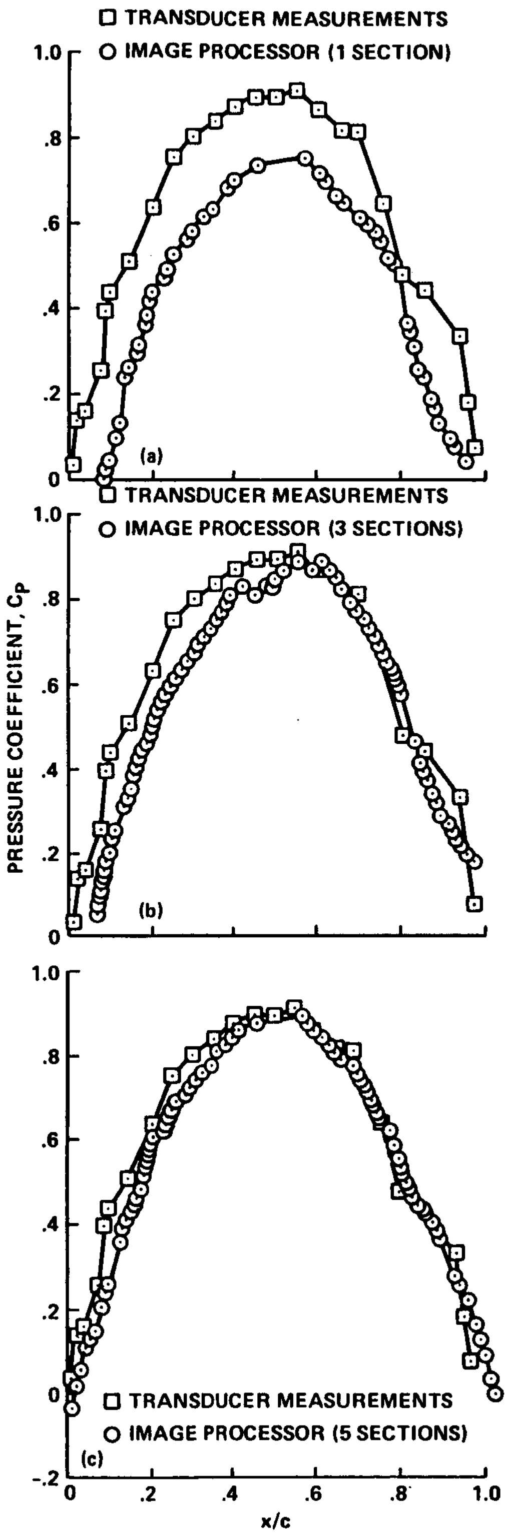

Figure 6. Effects of magnification. a) no magnification, b) three times magnification, c) five times magnification

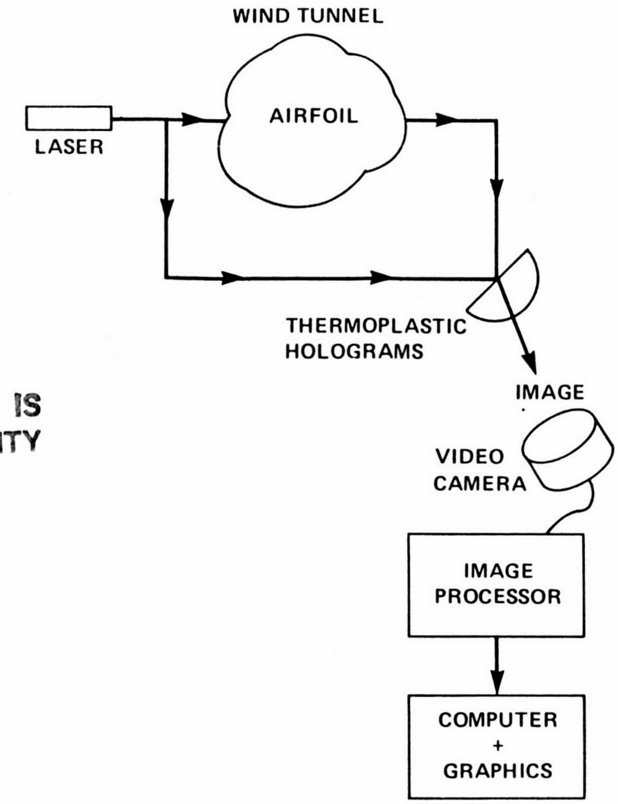

Figure 7. Prototype real-time interferometer

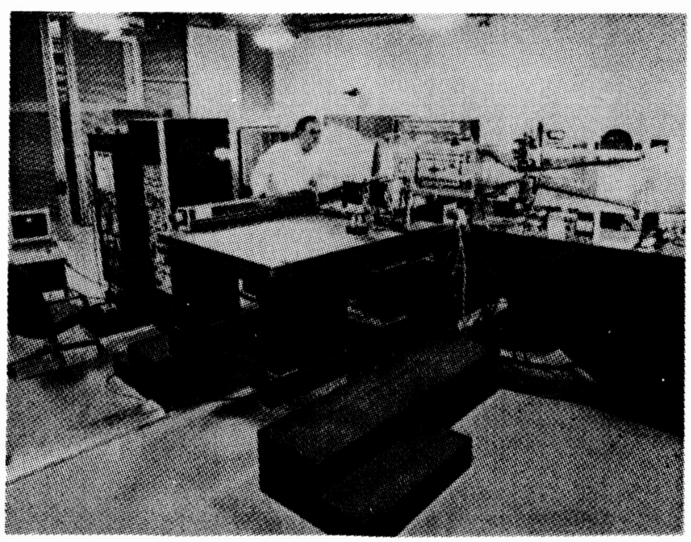

Figure 8. Vibration-isolated optical-table

Report Documentation Page

NASA
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1. Report No. NASA TM 89462	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Real-Time Laser Holographic Interferometry for Aerodynamics		5. Report Date June 1987
		6. Performing Organization Code
7. Author(s) George Lee		8. Performing Organization Report No. A-87205
		10. Work Unit No. 505-61-01
9. Performing Organization Name and Address Ames Research Center Moffett Field, CA 94035		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001		14. Sponsoring Agency Code

15. Supplementary Notes

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Presented at SPIE 1987 International Symposium Southeast on Optics, Electro-Optics and Sensors, Orlando, Florida, May 17-22, 1987.

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Real-time interferometry Holography	Unclassified-Unlimited Subject Category-35

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	9	A01