NASA Technical Paper 1414

Holography Through Optically Active Windows

Arthur J. Decker

FEBRUARY 1979

NASA

NASA Technical Paper 1414

Holography Through Optically Active Windows

Arthur J. Decker
Lewis Research Center
Cleveland, Ohio

NASA
National Aeronautics
and Space Administration

Scientific and Technical
Information Office

1979

SUMMARY

By using two orthogonally polarized reference beams, holograms can be recorded through stressed windows and the virtual image reconstructed with the two reference beams will show no stress pattern. As shown analytically the stress-pattern-free hologram is recordable for any polarization state of the object illumination. Hence, the more efficient nondepolarizing diffuser can be used in performing holography through stressed windows if two reference beams are used.

There is a need for stress-pattern-free reconstructions in flow-visualization holography, where flow features appear as three-dimensional patterns. The efficient nondepolarizing diffuser is especially useful when the window is made from an absorbent material such as polysulfone. Results are presented for a pair of machined polysulfone windows intended for use in a holographic flow-visualization setup in a single-stage-compressor test rig.

INTRODUCTION

Applications of holography to flow visualization in turbomachinery require that light enter and exit the turbomachinery through windows (refs. 1 and 2). These windows must conform to the contours of the flow passages they cover and, therefore, can have complex contours and spatially varying thicknesses. The windows acquire strain distributions during both manufacturing and use. These strain distributions are highly visible in a polarimeter.

Unfortunately, convenient and useful holographic systems generally function as polarimeters (ref. 3). If a random-phase, nondepolarizing diffuser is used to provide bright illumination of the flow field, the light illuminating the windows has a definite polarization. The reference beam, obtained from the same laser as the object beam, also has a definite polarization. Strain distributions in the windows show up as annoying and confusing fringe patterns on the windows. These patterns may obscure the fringes that outline the flow features.

The simplest solution of this problem is to illuminate the object with unpolarized light by using a depolarizing diffuser. However, such a diffuser wastes the available object illumination. The depolarizing diffuser operates by multiple scattering in a volume; a nondepolarizing diffuser can achieve its effect on a surface. The loss of illumination can be troublesome. For example, if thick windows made from the high-melting-temperature, amber-colored plastic polysulfone (ref. 4) are used, a substantial fraction of the available object light is absorbed.

The solution of the strain-pattern problem described in this paper involves recording and reconstructing the orthogonal polarizations of the light wave exiting an optically active window. Several authors have described holographic recording of the orthogonal polarizations of a light wave (refs. 5 to 7). The electric-field vector at a recording plane is defined by recording two orthogonal polarizations along with their magnitudes and phases. However, contrary to the requirements of this problem, most applications of holography do not require reconstructing the entire electric-field vector of the light used to record the hologram.

The first section of this paper is an analysis of the reference- and object-illumination requirements for strain-pattern-free holography. Light from a nondepolarizing diffuser is assumed to pass through a window having positionally dependent optical activity. The second section of this paper presents an experimental confirmation of the theory for polysulfone windows with complex curvature. These windows are intended for use in a single-stage-compressor test rig at the Lewis Research Center.

ANALYSIS OF A HOLOGRAM OF A DIFFUSELY ILLUMINATED WINDOW WITH POSITIONALLY DEPENDENT OPTICAL ACTIVITY

The objective is to obtain a reconstructed image of a uniformly illuminated window free of any patterns caused by strain distributions in the window. A system for evaluating holographic techniques in the presence of optically active windows is shown in figure 1. A hologram is recorded of light exiting a thin rectangular window. The window is assumed to be thin so that the lateral deviation of light rays passing through the window can be neglected. For this analysis, the hologram is imagined to be constructed immediately in back of the window. As shown in figure 1, an image of the window is formed at unity magnification at a second location so that a reference beam can be admitted.

A rectangular coordinate system with x- and y-axes is defined in the hologram-recording plane. That plane is imagined to coincide with the window's exit plane. The window is assumed to have positionally dependent optical activity to simulate the effect of a strained window. At each point, the window has principal axes (ref. 8) defined by local rectangular coordinates. As shown in figure 2, those coordinates are labeled x' and y', where the angle between the x'-axis and the x-axis is called α. The angle α is an arbitrary function of position. In passing through the window, the phase of the x' component of the incident light wave is retarded by the angle θ relative to the phase of the y' component. The angle θ is also an arbitrary function of position. The angles $\alpha(x, y)$ and $\theta(x, y)$ define the optical activity of the window.

With the window removed, the average light intensity at the hologram-recording plane is chosen to be independent of position. The electric-field vector $\overline{E}$ in the recording plane is given by

$$\overline{E} = E_x\hat{i} + E_y\hat{j} \tag{1}$$

where $\hat{i}$ and $\hat{j}$ are unit vectors and E_x and E_y are phasors representing the x and y components of the field. If any variation from normal of the angle of incidence is neglected, the intensity is given by

$$I = a\langle \overline{E} \cdot \overline{E}^* \rangle = a\langle E_x E_x^* \rangle + a\langle E_y E_y^* \rangle \tag{2}$$

where the asterisk denotes complex conjugation, a is a proportionality constant, and the dot denotes the vector inner product. Since the incident light is to originate from a random-phase, nondepolarizing diffuser, the angular brackets are used to denote statistical averaging.

To calculate the field at the hologram when the window is inserted, equation (1) is first transformed to the primed coordinate system. Upon transforming,

$$\overline{E} = E_x(\hat{i}' \cos \alpha - \hat{j}' \sin \alpha) + E_y(\hat{i}' \sin \alpha + \hat{j}' \cos \alpha) \tag{3}$$

In equation (3), $\hat{i}'$ and $\hat{j}'$ are unit vectors in the x' and y' directions, respectively. The phase of the x' component is retarded by θ relative to the phase of the y' component. The field becomes

$$\overline{E} = E_x(\hat{i}' \cos \alpha - \hat{j}' e^{j\theta} \sin \alpha) + E_y(\hat{i}' \sin \alpha + \hat{j}' e^{j\theta} \cos \alpha) \tag{4}$$

Equation (4) is then transformed back to the unprimed coordinate system to give the expression for the field that has passed through the window:

$$\begin{aligned}\overline{E} = \Big[E_x(\cos^2 \alpha + e^{j\theta} \sin^2 \alpha) + E_y(\sin \alpha \cos \alpha - e^{j\theta} \sin \alpha \cos \alpha)\Big]\hat{i} \\ + \Big[E_x(\sin \alpha \cos \alpha - e^{j\theta} \sin \alpha \cos \alpha) \\ + E_y(\sin^2\alpha + e^{j\theta} \cos^2\alpha)\Big]\hat{j}\end{aligned} \tag{5}$$

It can be shown that the intensity calculated by using equation (5) is unchanged from that given by equation (2).

Now, the field expressed by equation (5) is subjected to the hologram-recording process. Two reference beams are used simultaneously:

(1) The beams have orthogonal polarizations (ref. 5).

(2) The beams propagate from substantially different directions. The objective is that, upon reconstruction, the hologram formed by one beam will not diffract light from the other beam into the image.

For simplicity, the reference waves are chosen to be plane waves that are x- and y-polarized, respectively. The x-polarized reference wave is chosen to propagate along an axis in the yz-plane and is given at $z = 0$ by

$$\overline{R}_x = \hat{i} R_x e^{jk \cos(\varphi_1) y} \tag{6}$$

where φ_1 is the angle between the propagation vector of the wave and the positive y direction and k is the wave number of the light. The y-polarized reference wave is chosen to propagate along an axis in the xz-plane and is given at $z = 0$ by

$$\overline{R}_y = \hat{j} R_y e^{jk \cos(\varphi_2) x} \tag{7}$$

where φ_2 is the angle between the propagation vector of the wave and the positive x direction.

The reference waves and the wave from the window interfere at the hologram-recording plane. The intensity in the interference pattern can be derived from the Poynting vector to be

$$I = \overline{E} \cdot \overline{E}^* + \overline{\mathscr{E}}_R^* \cdot \overline{\mathscr{E}}_R + \overline{E}_R^* \cdot \overline{E} + \overline{E}_R \cdot \overline{E}^* \tag{8}$$

where by definition

$$E_{Rx} = R_x \frac{1 + \sin \varphi_1}{2}$$

$$E_{Ry} = R_y \frac{1 + \sin \varphi_2}{2}$$

$$\overline{E}_R = \hat{i} E_{Rx} e^{jk \cos(\varphi_1) y} + \hat{j} E_{Ry} e^{jk \cos(\varphi_2) x}$$

$$\mathscr{E}_{Rx} = R_x \sqrt{\sin \varphi_1}$$

$$\mathscr{E}_{Ry} = R_y \sqrt{\sin \varphi_2}$$

$$\bar{\mathcal{E}}_R = \hat{i}\mathcal{E}_{Rx} e^{jk\cos(\varphi_1)y} + \hat{j}\mathcal{E}_{Ry} e^{jk\cos(\varphi_2)x}$$

Neither the proportionality constant nor statistical averaging is shown. The angle factors absorbed in the third and fourth terms of equation (8) are typically within 10 to 15 percent of unity.

In a perfectly linear recording, the amplitude transmittance of the hologram is proportional to I. That is,

$$T = \gamma I \tag{9}$$

During reconstruction, the third term in equation (8) results in a virtual image. That term is given by

$$\begin{aligned} \bar{E}_R^* \cdot \bar{E} = {} & E_x E_{Rx}^* e^{-jk\cos(\varphi_1)y} (\cos^2\alpha + e^{j\theta}\sin^2\alpha) \\ & + E_y E_{Rx}^* e^{-jk\cos(\varphi_1)y} \sin\alpha\cos\alpha\,(1 - e^{j\theta}) \\ & + E_x E_{Ry}^* e^{-jk\cos(\varphi_2)x} \sin\alpha\cos\alpha\,(1 - e^{j\theta}) \\ & + E_y E_{Ry}^* e^{-jk\cos(\varphi_2)x} (\sin^2\alpha + e^{j\theta}\cos^2\alpha) \end{aligned} \tag{10}$$

To reconstruct the virtual image, the hologram is illuminated by waves that are proportional to the original two reference waves and that have complex magnitudes E'_{Rx} and E'_{Ry}. The x-polarized wave reconstructs an image from the first two terms of equation (10). The y-polarized wave reconstructs an image from the second two terms of equation (10).

The virtual-image field $\bar{E}_i$ is given by

$$\begin{aligned} \bar{E}_i = {} & \hat{i}(E'_{Rx}E_{Rx}^*)\left[E_x(\cos^2\alpha + e^{j\theta}\sin^2\alpha) + E_y \sin\alpha\cos\alpha\,(1 - e^{j\theta})\right] \\ & + \hat{j}(E'_{Ry}E_{Ry}^*)\left[E_x \sin\alpha\cos\alpha\,(1 - e^{j\theta}) + E_y(\sin^2\alpha + e^{j\theta}\cos^2\alpha)\right] \end{aligned} \tag{11}$$

The intensity of the reconstructed light wave from the window is given by

$$I = \bar{E}_i \cdot \bar{E}_i^* = E_x E_x^* \left\{ |E'_{Rx} E^*_{Rx}|^2 + \frac{\sin^2(2\alpha)}{2} \left[\cos\theta - 1\right] \left[|E'_{Rx}E^*_{Rx}|^2 - |E'_{Ry}E^*_{Ry}|^2\right] \right\}$$

$$+ E_y E_y^* \left\{ |E'_{Ry} E^*_{Ry}|^2 + \frac{\sin^2(2\alpha)}{2} \left[\cos\theta - 1\right] \left[|E'_{Ry}E^*_{Ry}|^2 - |E'_{Rx}E^*_{Rx}|^2\right] \right\}$$

$$+ E_x E_y^* \frac{\sin(2\alpha)}{2} \left[\cos(2\alpha)\ (1 - \cos\theta) + j \sin\theta\right] \left[|E'_{Rx}E^*_{Rx}|^2 - |E'_{Ry}E^*_{Ry}|^2\right]$$

$$+ E_x^* E_y \frac{\sin(2\alpha)}{2} \left[\cos(2\alpha)\ (1 - \cos\theta) - j \sin\theta\right] \left[|E'_{Rx}E^*_{Rx}|^2 - |E'_{Ry}E^*_{Ry}|^2\right] \quad (12)$$

The proportionality constant is not shown in equation (12).

The intensity in equation (12) is, in general, a function of position through the dependence on α and θ. The pattern that results will be viewed in addition to any other pattern and may cause confusion. However, a uniform intensity is obtained simply by choosing

$$|E'_{Rx}E^*_{Rx}| = |E^*_{Ry}E'_{Ry}| \quad (13)$$

Recall that E_{Rx} and E_{Ry} contain absorbed angle factors. Then from equation (12), with statistical averaging shown explicitly,

$$I = |E'_{Rx}E^*_{Rx}|^2 \left(\langle E_x E_x^* \rangle + \langle E_y E_y^* \rangle\right) \quad (14)$$

The polarization of the object illumination can be quite general and can be chosen to satisfy any criterion. Thus, a nondepolarizing diffuser can be used for better efficiency.

EXPERIMENTAL ARRANGEMENT

The dual-reference-wave method has been attempted with a pair of windows intended for use in a single-stage-compressor test facility. These windows, because of their method of construction, are especially likely to have residual strain distributions. The windows were machined, rather than molded to the contours of the test section, from polysulfone plastic to withstand temperatures of approximately 100° C. Light is to be admitted by a large cylindrical window upstream of the rotating compressor stage. The light will then pass through the test section and out a smaller, complexly contoured window located over the compressor blade tips. This window arrangement was developed for holographic flow visualization (ref. 1). A schematic diagram of the arrangement is shown in figure 3.

The dual-reference-beam method was checked by setting up the windows in their proper configuration on a vibration isolation table. The object illumination and two reference beams were provided by an argon-ion laser. Part of the experimental arrangement is shown in figure 4. The small, complexly contoured window can be seen through the photographic plate holder. The two reference beams are aimed at the plate holder by the two beam divergers, one located left of center and one at the upper right. The reference beams originate from sufficiently different directions so that the hologram formed by one beam will not diffract much light from the other beam into the image.

Although the laser is polarized perpendicular to the table, reflections from the various mirrors in the system yield beams that have field components perpendicular and parallel to the table. Polaroids are used to select the desired polarization for a beam. In the plane of the photographic plate, the beam from the beam diverger at the right is primarily horizontally polarized. The beam from the beam diverger at the left is primarily vertically polarized. However, because the experimental setup did not duplicate the geometry studied in the analysis section, both beams have small amounts of the other component and the results are degraded slightly. Variable-density beam attenuators (not visible in fig. 4) are used to control the intensities of the reference beams.

The object beam (whose optics are not visible in fig. 4) is formed by diverging the laser beam into a nondepolarizing diffuser of sandblasted glass. So that the images reconstructed by the left and right reference beams will be equally bright, the light incident on the diffuser is first circularly polarized by passing it through a quarter-wave plate. The E_x and E_y components referred to in the analysis section are then equal in magnitude. As shown in the analysis, the polarization state of the object wave should not affect the results. The light from the diffuser passes through the large polysulfone window (also not visible in fig. 4) and then through the small window and is incident on the photographic plate.

RESULTS

The results of the dual-reference-beam test are shown in figures 5 to 8. A reticle has been placed approximately at the most distant position of the flow field from the hologram-recording plane. Figure 5 is a plain photograph of the reticle taken through the small window with the object beam used for illumination. The machining defects in the window and its complex contour degrade the image somewhat; however, the quality is adequate to show such flow features as shock waves in three dimensions. Figure 6 again shows the reticle photographed through the small window with a Polaroid placed over the camera lens. The stress pattern in the windows is clearly visible. Next, a dual-reference-beam hologram was recorded. The reference beams were adjusted to have equal intensities. Figure 7 shows the reconstructed image with only one reference beam used for reconstruction. The stress pattern is again visible and would clearly obscure any flow features. Finally, figure 8 shows the reconstructed image with both reference beams used for reconstruction. The stress pattern is much less visible. But, because each reference beam used to record the hologram had at least a slight amount of each polarization, there is some residual pattern.

CONCLUDING REMARKS

Both the analysis and the experimental results show that two orthogonally polarized reference beams are suitable for eliminating fringes due to stress patterns in windows. Consequently, a definite polarization can be tolerated in the object illumination through these windows, and the more efficient nondepolarizing diffuser can be used. This arrangement will be useful if the windows are thick and highly absorbing, as when polysulfone plastic is the window material. Of course, the depolarizing diffuser is easier to use where there is enough illumination.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 16, 1978,
505-04.

REFERENCES

1. Wuerker, R. F.; et al.: Application of Holography to Flow Visualization Within Rotating Compressor Blade Row. (AIRESEARCH-73-9489, AiResearch Mfg. Co.; NASA Contract NAS 3-15336.) NASA CR-121264, 1974.

2. Gagosz, R. M.; Whitney, G. L.; and Michael, F.: Single Pulse Holographic Flow Visualization. Engineering Applications of Holography, Society of Photo-Optical Instrumentation Engineers, 1972, pp. 251-256.

3. Fourney, M. E.; Waggoner, A. P.; and Mate, K. V.: Recording Polarization Effects Via Holography. J. Opt. Soc. Am., vol. 58, May 1968, pp. 701-702.

4. Dreger, D. R.: The Polysulfones - Heat-Resistant, Superstrong, and Ultrastable. Mach. Des., vol. 50, no. 1, Jan. 12, 1978, pp. 114-120.

5. Lohmann, A. W.: Reconstruction of Vectorial Wavefronts. Appl. Opt., vol. 4, no. 12, 1965, pp. 1667-1668.

6. Bryngdahl, O.: Polarizing Holography. J. Opt. Soc. Am., vol. 57, Apr. 1967, pp. 545-546.

7. Daendliker, R.; Marom, E.; and Mottier, F. M.: Two-Reference-Beam Holographic Interferometry. J. Opt. Soc. Am., vol. 66, Jan. 1976, pp. 23-30.

8. Yariv, A.: Introduction to Optical Eletronics. Holt, Rinehart, and Winston, Inc., 1971, pp. 11-16.

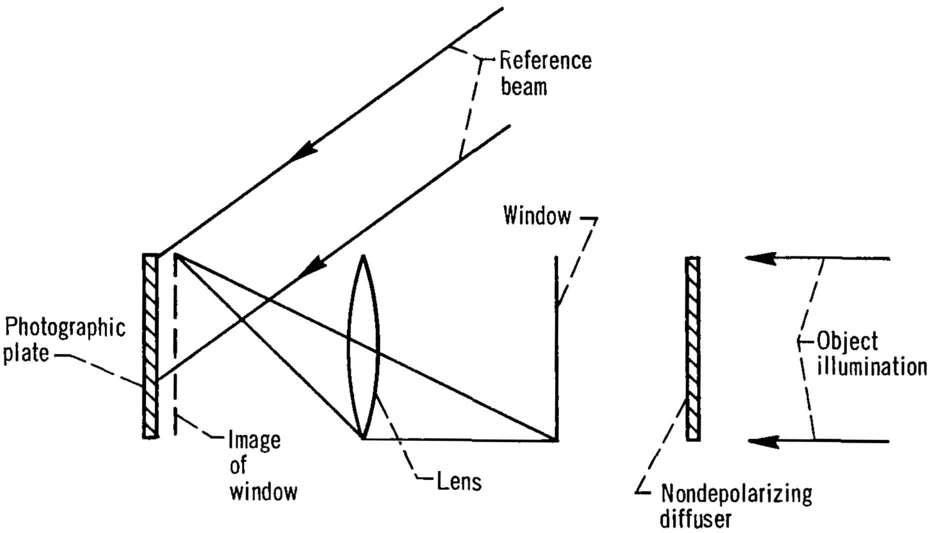

Figure 1. - Holographic system for evaluating holographic techniques in presence of optically active windows.

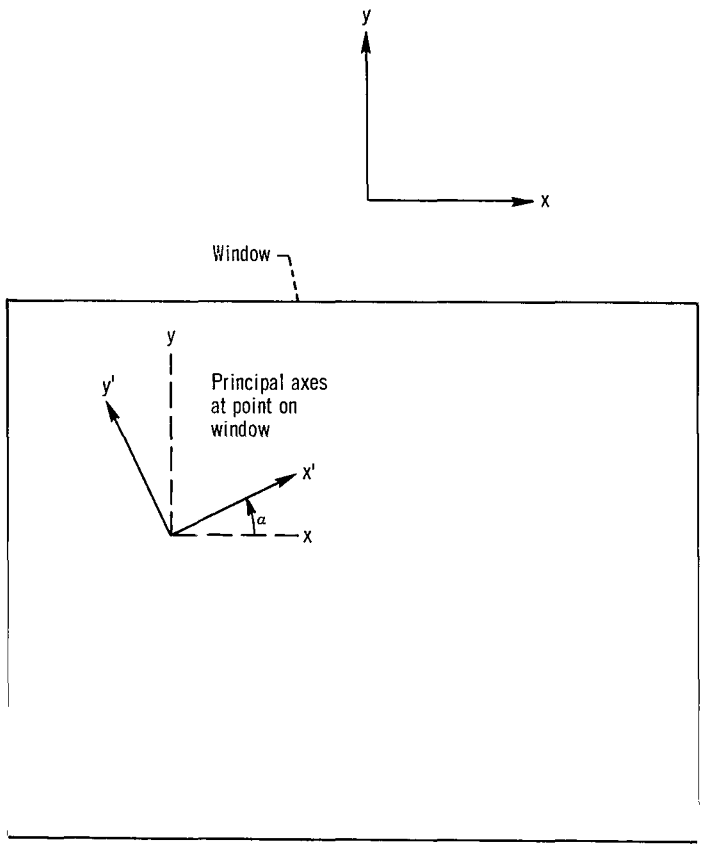

Figure 2. - Window and rectangular axes (x,y) with principal axes (x',y') at one point.

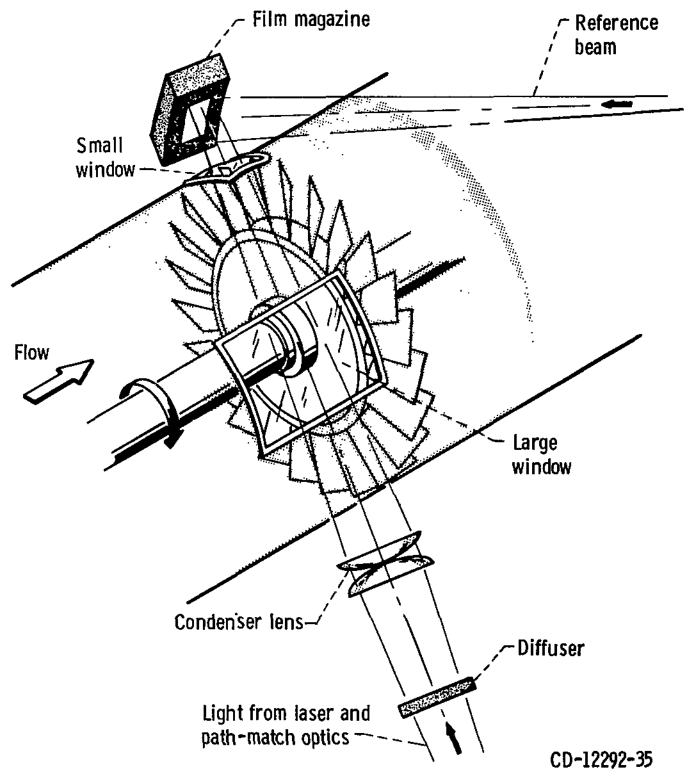

Figure 3. - Holography in single-stage-compressor test facility.

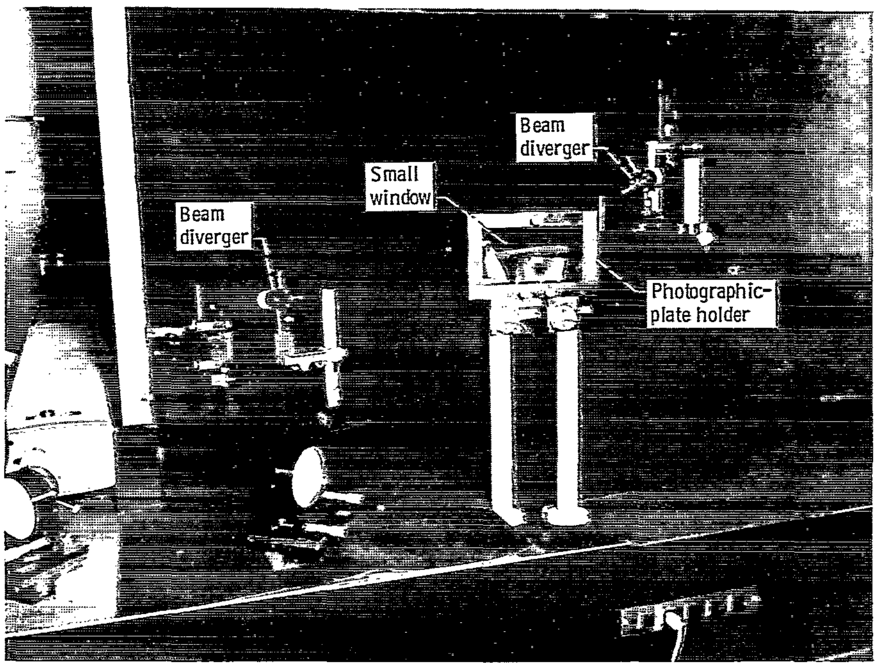

Figure 4. - Experimental arrangement for evaluating windows. (Object-beam optics not visible.)

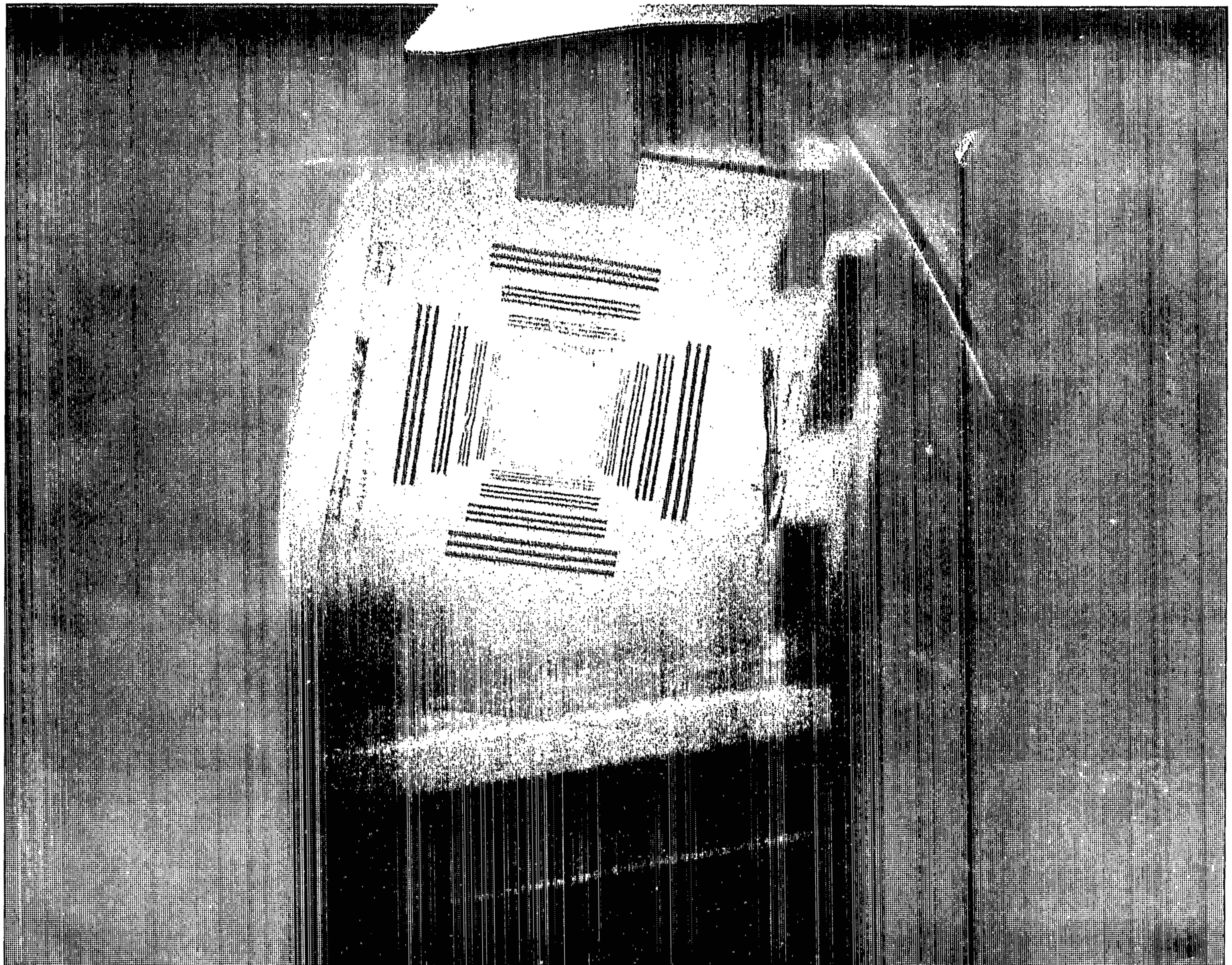

Figure 5. - Recticle photographed through small window with object illumination.

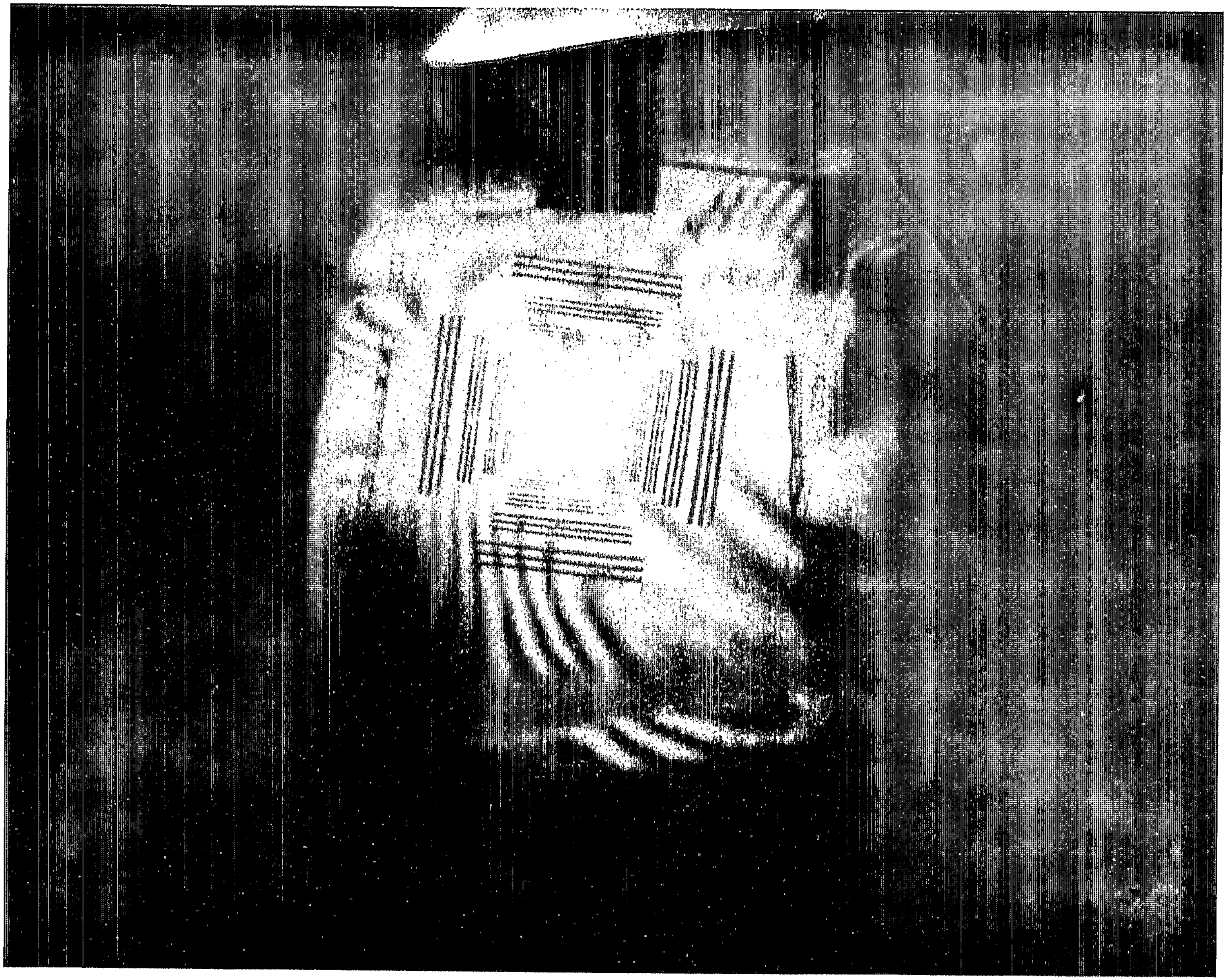

Figure 6. - Reticle photographed through small window in single polarization.

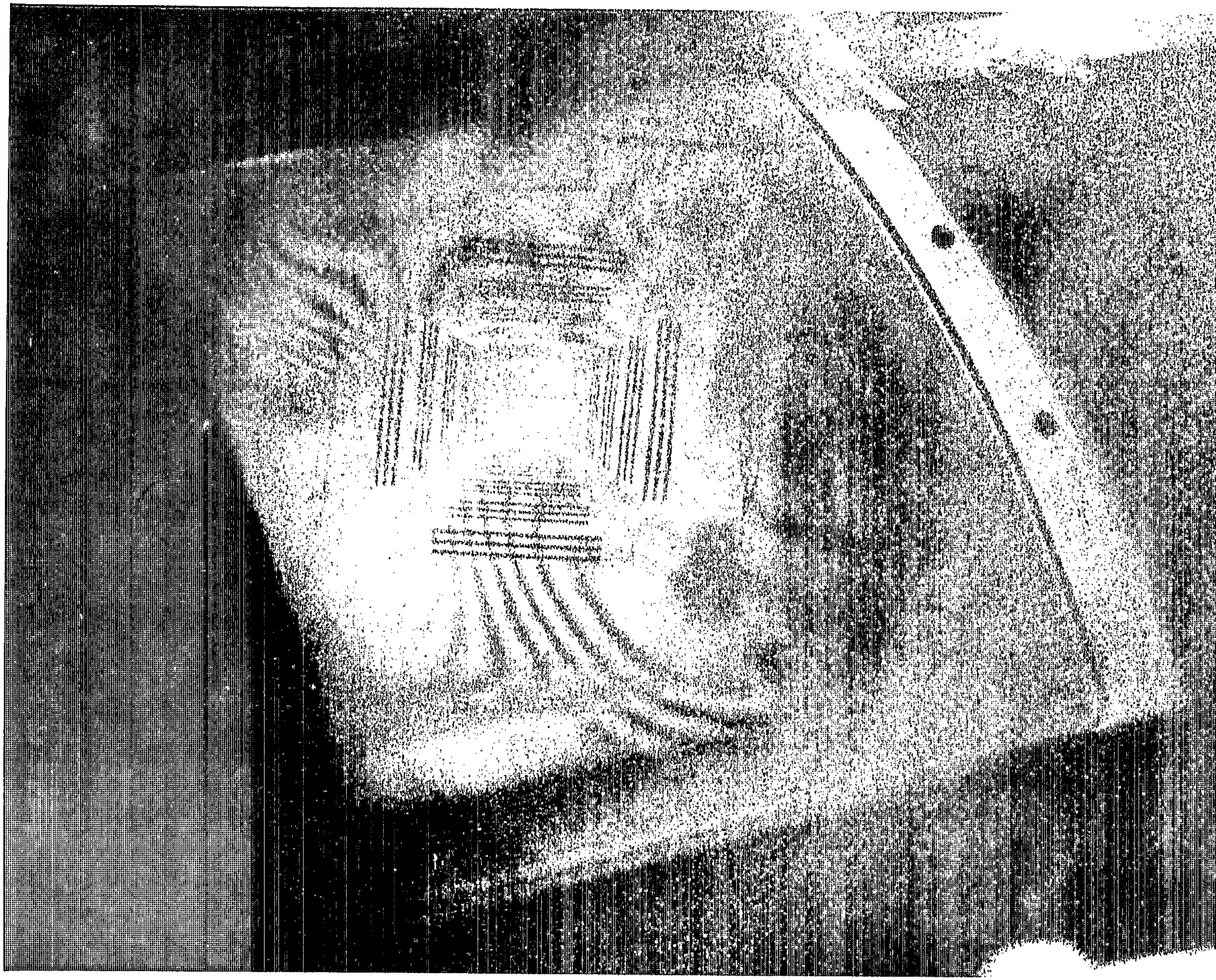

Figure 7. - Image reconstructed with only one reference beam.

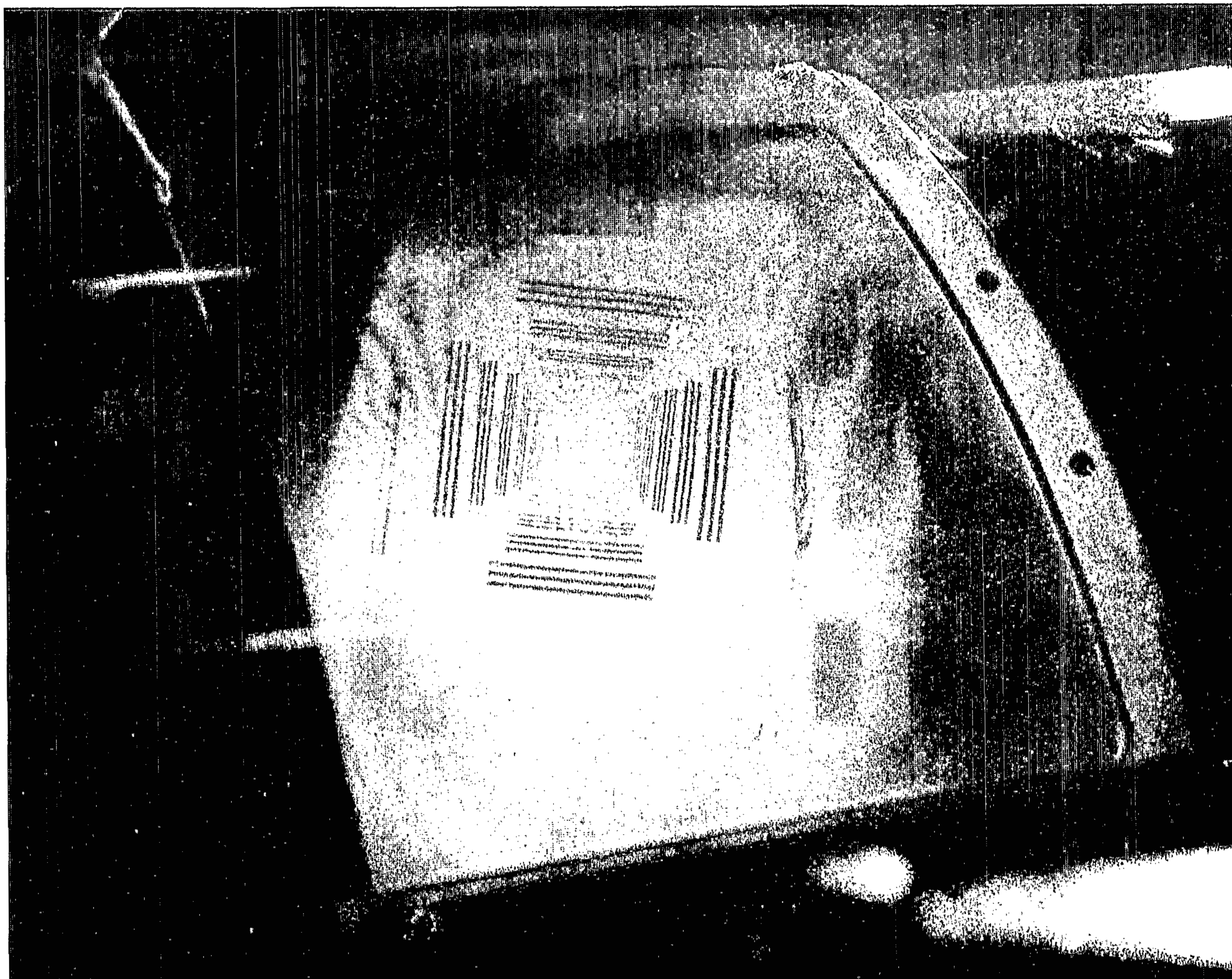

Figure 8. - Image reconstructed with both reference beams.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TP-1414		
4. Title and Subtitle HOLOGRAPHY THROUGH OPTICALLY ACTIVE WINDOWS		5. Report Date February 1979
		6. Performing Organization Code
7. Author(s) Arthur J. Decker		8. Performing Organization Report No. E-9808
		10. Work Unit No. 505-04
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Paper
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

By using two orthogonally polarized reference beams, holograms can be recorded through stressed windows and the reconstructed virtual image will show no stress pattern. As shown analytically the stress-pattern-free hologram is recordable for any polarization state of the object illumination. Hence, the more efficient nondepolarizing diffuser can be used in performing holography through stressed windows if two reference beams are used. Results are presented for a pair of machined polysulfone windows intended for use in a holographic flow-visualization setup in a single-stage-compressor test rig.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Holography Optical activity Flow visualization Windows Compressor rotors	Unclassified - unlimited STAR Category 35

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	17	A02

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

NASA-Langley, 1979

National Aeronautics and
Space Administration

Washington, D.C.
20546

Official Business
Penalty for Private Use, $300

SPECIAL FOURTH CLASS MAIL
BOOK

Postage and Fees Paid
National Aeronautics and
Space Administration
NASA-451

U.S.MAIL

7 1 1U,D, 020279 S00903DS
DEPT OF THE AIR FORCE
AF WEAPONS LABORATORY
ATTN: TECHNICAL LIBRARY (SUL)
KIRTLAND AFB NM 87117

NASA

POSTMASTER: If Undeliverable (Section 158 Postal Manual) Do Not Return