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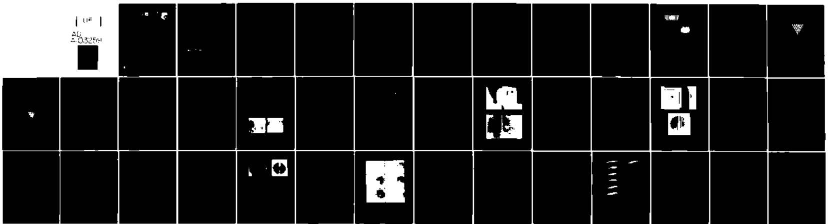

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A DEVICE TO DETERMINE THE OUT-OF-PLANE DISPLACEMENT OF A SURFACE USING A MOIRÉ FRINGE TECHNIQUE

Andrew J. Piekutowski

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Final Technical Report for Period July 1978 - April 1979

March 1981

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A brief review of various techniques to produce moiré patterns for use in making in-plane and out-of-plane displacement measurements is presented. A detailed description of a device which uses one of these techniques to obtain quantitative measurement of the out-of-plane displacement of surfaces experiencing dynamic stimulation is also given. High-speed photography of images formed by the device is used to provide a series of

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photographs which are analyzed to provide a time-sequence description of the motion of the deformed surface. Examples of measurement of the response of simulated fuel tank panels subjected to the impact of high-speed fragments and the response of aircraft transparencies experiencing a birdstrike are presented.

PREFACE

The effort reported herein was performed in the Impact Physics Group under the direction of the Aerospace Mechanics Division of the University of Dayton Research Institute, Dayton, Ohio, under Contract F33615-76-C-3103, for the Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Wright-Patterson Air Force Base, Ohio. Air Force administrative direction and technical support was provided by Mr. Richard L. Peterson, AFWAL/FEA, the Air Force Project Manager.

The work described herein was conducted during the period from July 1978 to April 1979. Project supervision and technical assistance was provided through the Aerospace Mechanics Division of the University of Dayton Research Institute with Mr. Dale H. Whitford, Supervisor and Mr. Blaine S. West, Project Engineer. Fabrication of the various moiré devices, all data reduction, analysis, and a portion of the experimental efforts were performed at UDRI. The large bird testing was performed at Arnold Engineering Development Center, Arnold Air Force Station, Tennessee.

In addition to those persons listed above, the author wishes to acknowledge Mr. Randall Watt and Mr. George Robertson of Arnold Research Organization for their support of the effort performed at AEDC.

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INTRODUCTION

The word moiré is French in origin and is used to describe a wavy or watery pattern, particularly in a fabric. More generally, a moiré is the name given to the pattern formed when two or more distinctive geometric designs are superimposed to produce a new and different design. The number and types of geometric designs that can be used to form a moiré are limitless. However, most moirés are formed using designs that are composed of straight lines, curved lines, or circles.

Moiré patterns or fringes formed by the device described in this report are produced using a pair of designs composed of parallel straight lines. These particular designs, called Ronchi rulings, are formed by etching evenly spaced parallel lines on a glass plate and filling the etched portion of the design with a black opaque material. In the Ronchi rulings used in the device, the space between black lines is equal to the width of the black lines.

SECTION II
FORMATION OF MOIRÉ PATTERNS

One method of forming moiré patterns using Ronchi rulings is shown in Figure 1(A). In this method, two rulings having slightly different pitches, or spaces between the lines are superimposed, taking care to avoid rotation of one ruling with respect to the other. Superposition of these two linear patterns results in the formation of a third linear pattern of light and dark lines or bands called fringes. Spacing of the light and dark bands in this new pattern is usually much greater than for either of the two rulings used to generate the new pattern. The location of a dark fringe and two light fringes is shown in Figure 1(A). Actual light intensity at the center of a light fringe is equivalent to that of one of the rulings used to form the fringe pattern

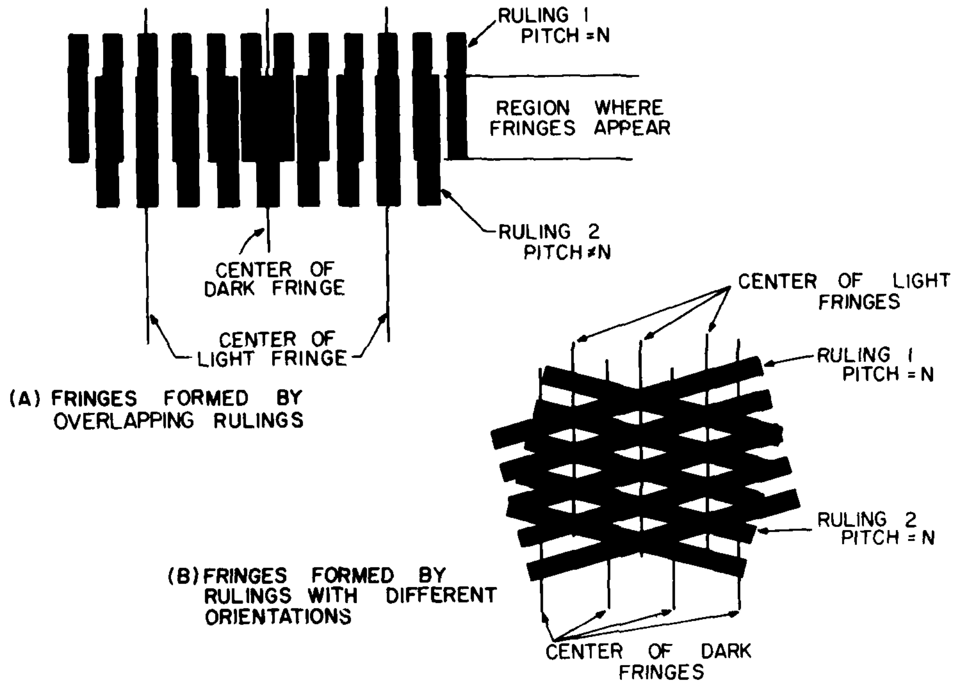


Figure 1. Two Methods of Producing Moiré Patterns Using Ronchi Rulings.

since the light fringe is formed where the light and dark portion of each ruling is exactly superimposed. Dark fringes, on the other hand, are formed where the light and dark portion of each ruling are displaced by one-half the pitch of either ruling.

A second method of forming moiré patterns using Ronchi rulings is shown in Figure 1(B). The fringe patterns are formed as the result of a difference in the orientation of one ruling with respect to the second ruling. The centers of several light and several dark fringes are identified in this figure. Relative intensities of the light and dark fringes produced using this method are the same as for those produced using the technique shown in Figure 1(A).

Moiré Methods for Determining In-Plane Motions of Surfaces. Quantitative measurements of small motions occurring in the plane of a surface can be obtained with use of the techniques for producing moire fringes shown in Figure 1. In these techniques one of the rulings, usually called the specimen ruling, is attached to the surface of the object being examined and the second ruling, usually called the master ruling, is firmly fixed adjacent to the specimen ruling. When a disturbing force or load is applied to the specimen, a change in the pitch of the specimen ruling occurs. If the deformed specimen ruling is viewed through the master ruling, a moiré pattern is observed. Subsequent analysis of the spacing of the fringes in the moiré pattern is used to determine the strain in the specimen (assuming the strain at a point in the specimen is invariant through the thickness of the specimen at the point of examination). References 1 and 2 (as well as many others) may be consulted for detailed discussions of various analytical techniques related to the use of moiré methods of strain analysis and other methods of determining motions in the plane of the surface of an object.

Moiré Methods for Determining Out-of-Plane Motions of Surfaces. Variations or extensions, to three dimensions, of the two techniques shown in Figure 1 can be used to produce moiré patterns that permit determination of out-of-plane motions of a surface. A number of moiré fringe techniques and devices have been developed for use in describing three-dimensional surfaces; for example, see References 3 through 9. However, nearly all of the techniques described in these references are for use with essentially still objects or moving objects of rather limited size, on the order of several square centimeters. The device and technique described in this document can be used to quantitatively resolve the dynamic response of relatively large surfaces (approximately 1500 to 2000 square centimeters) subjected to impulsive loading. A brief discussion of several techniques described in the previously cited references will be helpful in illustrating some of the methods for producing moiré fringe patterns that can be used to determine out-of-plane displacements of relatively large surfaces.

In the technique illustrated in Figure 2, a system of parallel, equally-spaced dark planes is produced where the shadows of the dark areas (as they are projected in three dimensions) of the Ronchi rulings are adjacent to one another. In this and

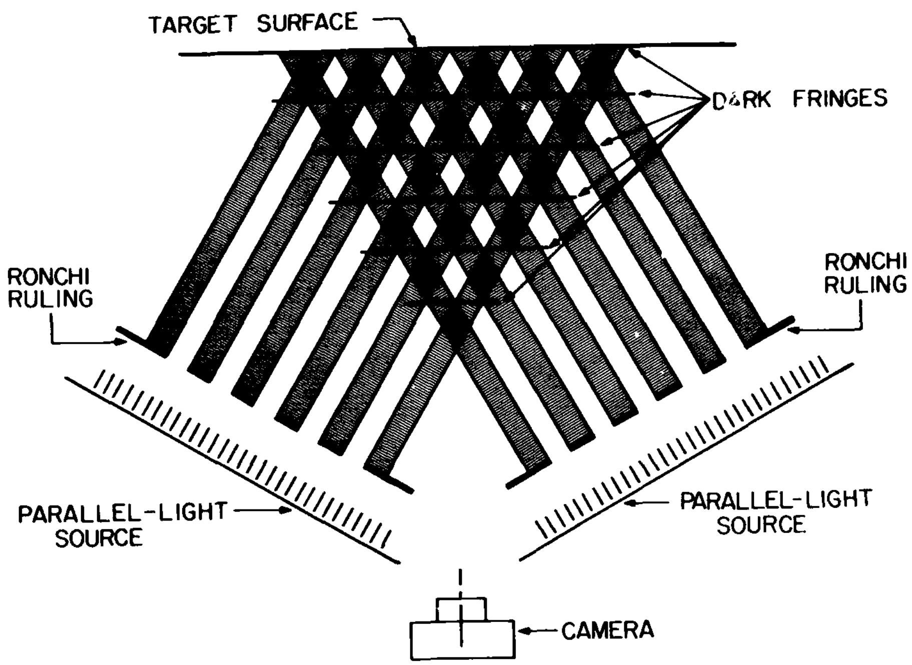


Figure 2. Technique for Producing Planar Moiré Fringe Patterns for Use in Determining the Out-of-Plane Motion of a Surface. Dark fringes are equally spaced.

succeeding illustrations the reader should assume that optical axes or surfaces of individual components have been aligned parallel and perpendicular to a reference plane, e.g., in the illustrations given, the surface of the page. These conditions must exist to prevent the dark surfaces from being skewed. If the target surface in Figure 2 displaces in an irregular manner and intersects successive dark planes, a photograph of the deformed surface would resemble a topographic map, with the dark bands defining levels of constant elevation. Interpretation of the photographic record obtained with this device is relatively simple.

Use of this technique requires Ronchi rulings and light sources that are at least as large as the surface being examined.

In actual practice, the rulings generally consist of wire or some other slender material that is held or stretched in a framework that insures proper spacing and tensioning of the individual elements. The rather large parallel light sources that are required are not as easily obtained, however, and if the target surface displaces rapidly and a high-speed camera must be used to obtain a photographic record of the deforming surface, the level of illumination which can be practically achieved with most large light sources will almost certainly limit the framing rate of the camera to low levels. Finally, the large rulings and light sources are difficult to protect from damage in dynamic events which are capable of producing dramatic and unexpected response.

The technique shown in Figure 3 overcomes several of the difficulties encountered when attempting to set up and use the preceding system. Notably, the use of two projection lens systems

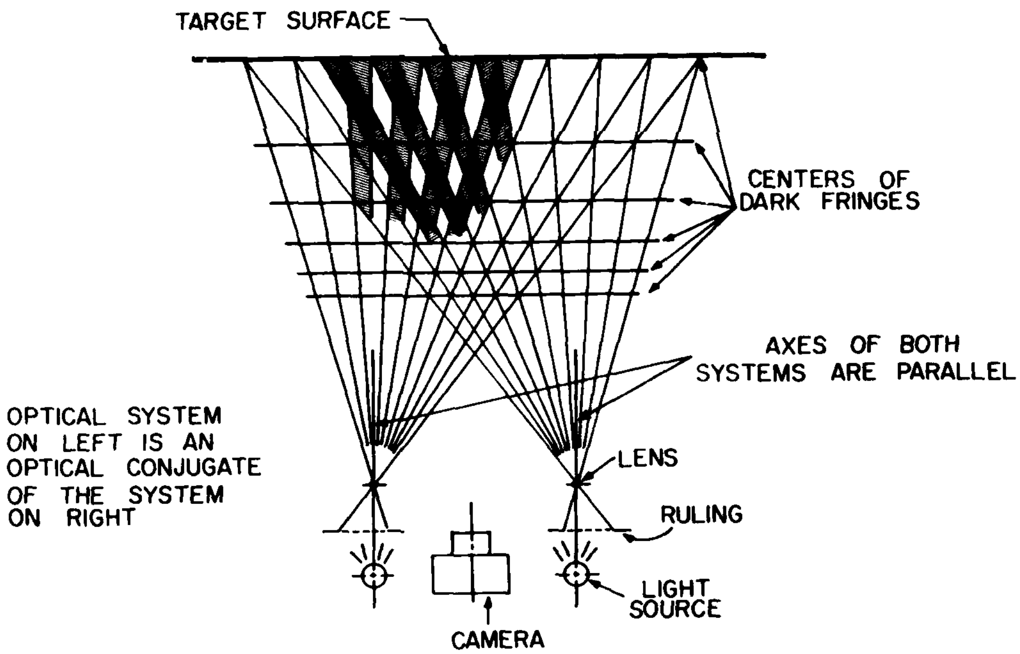


Figure 3. A Second Technique for Producing Planar Moiré Fringe Patterns for Use in Determining the Out-of-Plane Motion of a Surface. Dark fringes are not equally spaced.

permits a reduction in the size of the Ronchi rulings needed to produce the darkened regions and more conventional light sources may be used. However, these improvements come at the expense of equal spacing of the fringes. Lack of equal fringe spacing makes interpretation of photographs of a deformed surface more demanding, since identification of individual fringes with respect to the moiré device is required. Positive identification of at least one fringe in the system is needed to provide a starting point for subsequent determination of the distances between successive fringes. As shown in Figure 3, this system also does not make optimum use of the optical components, light sources, etc., since fringes are produced only in that region where the projected rulings overlap.

If the optical systems shown in Figure 3 are rotated toward each other, as shown in Figure 4, to make more efficient use of the optics in these systems, the dark surfaces are no longer

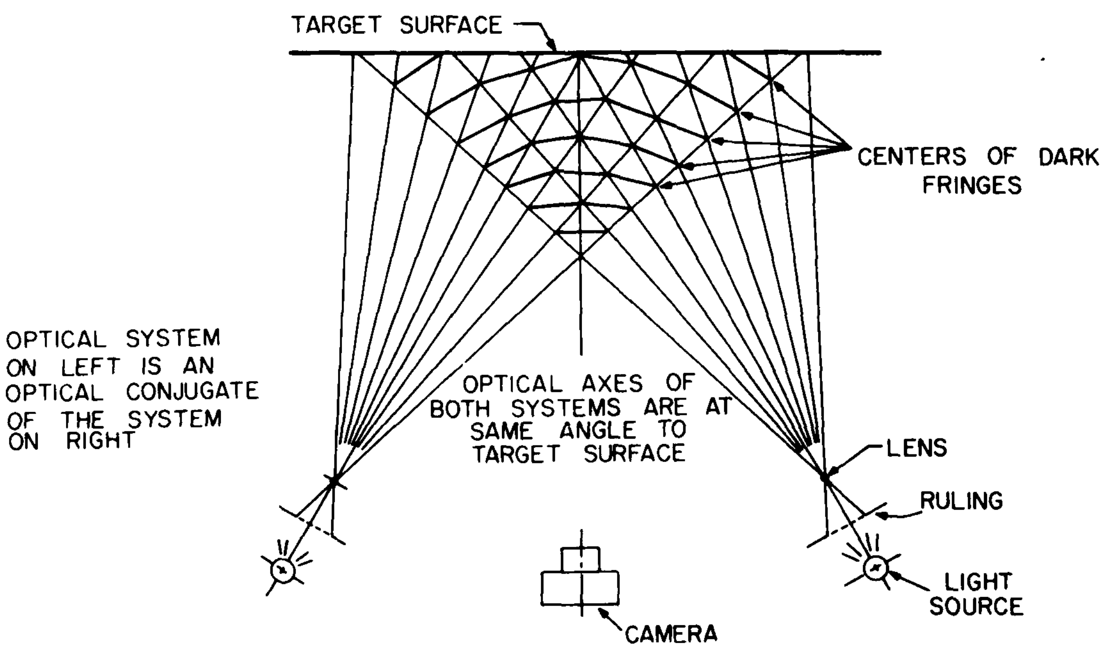


Figure 4. Technique for Producing Curvilinear Moiré Fringe Patterns for Use in Determining the Out-of-Plane Motion of a Surface. Dark fringes are symmetric but not equally spaced.

planar. (Note: In this and the succeeding figure, detailed structure of the projected ruling is eliminated and only the boundaries between selected light and dark segments of the rulings are shown as lines or rays.) Interpretation of fringe patterns obtained with the system shown in Figure 4 becomes more complicated since the elevation of the surface along a particular dark band varies as a result of the curvature of the fringes, but most practical difficulties associated with the formation of moiré fringe patterns in a hostile environment have been overcome. In actual practice, however, the level of illumination of the target surface may still be below that required to expose film in a high-speed camera operating at framing rates as high as 6000 to 7000 pictures per second.

In Figure 5, the light source on the left in Figure 4 has been removed and replaced with a camera. In addition, a

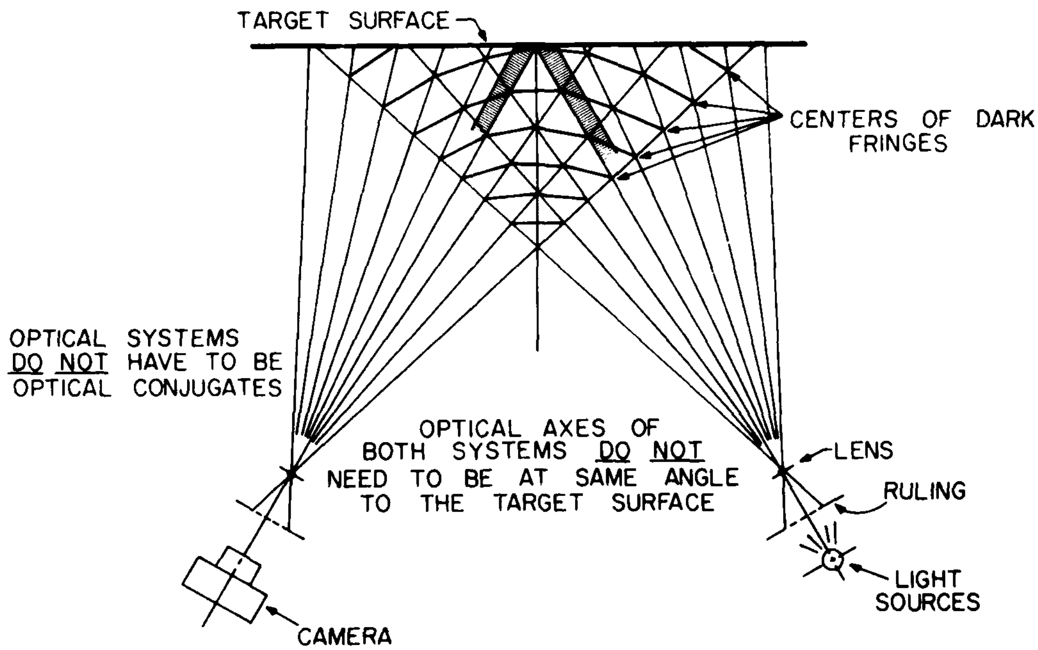


Figure 5. Technique for Producing Moiré Fringe Patterns Using the Device Described in this Document. Fringes may not be symmetric and are not equally spaced.

fundamental change in the way the moiré pattern is produced has occurred. In preceding examples, the moiré pattern was formed on the target surface. The device being described in this document makes use of the technique shown in Figure 5 to produce a moiré pattern at the Ronchi ruling in front of the camera. As discussed previously, a moiré pattern is produced when two or more distinctive geometric patterns overlap. The optical system on the right in Figure 5, called the projection side, projects an image of the Ronchi ruling in this system onto the target surface. The lens in the left optical system, called the viewing side, focuses an image of the target surface (and its projected Ronchi ruling) onto the Ronchi ruling in the viewing side optical system. As a result, the moiré pattern is formed where this image and the viewing side Ronchi ruling are superimposed. The lens of a high-speed camera (or any other camera) is then focused on this composite image/ruling and the camera is used to record changes in the moiré pattern. Each pattern can then be analyzed to determine the out-of-plane displacement of the target surface.

The light-gathering characteristics of the lens in the viewing side serves to increase the intensity of the light available to expose film in the camera. When large flashlamps (GE#50's or similar) are used as the light source, framing rates of up to 7000 pictures per second in a 16-mm high-speed camera are possible. This framing rate is suitable for recording the dynamic response of many surfaces of practical interest that have been subjected to an impulsive load.

As noted in Figure 5, the projection and viewing systems do not have to be optical conjugates. In addition, each of the systems does not have to be at the same angle of inclination with respect to the target surface. As shown in Figure 5, a dark fringe is formed where short segments of two shaded regions intersect the target surface. When viewing this figure note that these shaded regions lie on the left and right side of the viewing and projection system optical axes, respectively. Further discussion of the use of these particular segments of the Ronchi ruling will be given in Section IV.

Properties of Moiré Patterns. Before proceeding to a description of the moiré fringe device, some comment regarding the nature of the fringes produced by the device is appropriate. Provided care has been taken during the alignment of the optical components used in the assembly of the device, the light and dark fringes will appear as a system of surfaces that are curved in two dimensions, each surface having a slightly different curvature and spacing from its neighbor. In addition, any line normal to the reference plane and through the center of any light or dark region will remain at the center of the appropriate region, regardless of elevation above the reference plane.

Fortunately, Mother Nature has provided a material which can be used to more clearly illustrate how a system of such fringes would appear to an observer. In the block of wood shown in Figure 6(A), the reference plane should be taken as one normal to the surface of the block of wood and parallel to the top and bottom edge of the block. End grain structure of this piece of

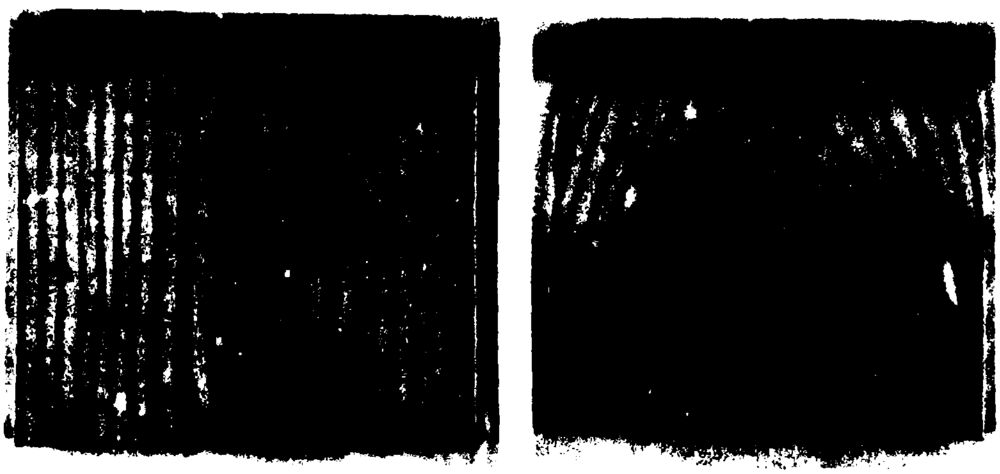


Figure 6. Nature's Analogy to a System of Moiré Fringes Produced Using the Techniques Shown in Figure 4 and 5. (A) System cut parallel to fringes. (B) System cut at an angle to fringes.

wood is shown in the small piece of wood attached to the top of the larger block. Alternate light and dark grain rings in this small piece are analagous to the light and dark regions which an observer would see if he were viewing the moiré fringes produced using the techniques illustrated in Figures 4 and 5. If the system of light and dark annual growth rings in this piece of wood is intersected by a plane surface, e.g., the front surface of the block, then that surface will exhibit a grain pattern which is exactly analagous to that produced on the surface of the targets shown in Figures 4 and 5. When the intersecting surface passes through the system in some other manner, e.g., the diagonal cut made in the block of wood shown in Figure 6(B), then a different pattern of fringes will appear. In the case of Figures 6(A) and 6(B), cuts made at various other depths below the surfaces shown would reveal grain patterns (or moiré-like patterns) that were unique for each of the new surfaces.

SECTION III
DESCRIPTION OF MOIRÉ DEVICE

The moiré device consists of two optical systems: a projection system and a viewing system. Each of these systems is rigidly attached to a single support structure as shown in Figure 7. The projection system consists of (1) an optical head in which the projection lens and Ronchi ruling are mounted, and (2) a light source that contains a condensing lens system and an enclosed light holder. The viewing system consists of an optical head which is identical to the projection head. As specific experimental conditions require, either head can be used as the projection head by simply installing the light source in the desired location.

Selection of nominal characteristics of the optical components used in the moiré device, i.e., focal length and diameter of the lenses, Ronchi ruling pitches, spacing of lens and ruling with respect to the target (magnification of system),

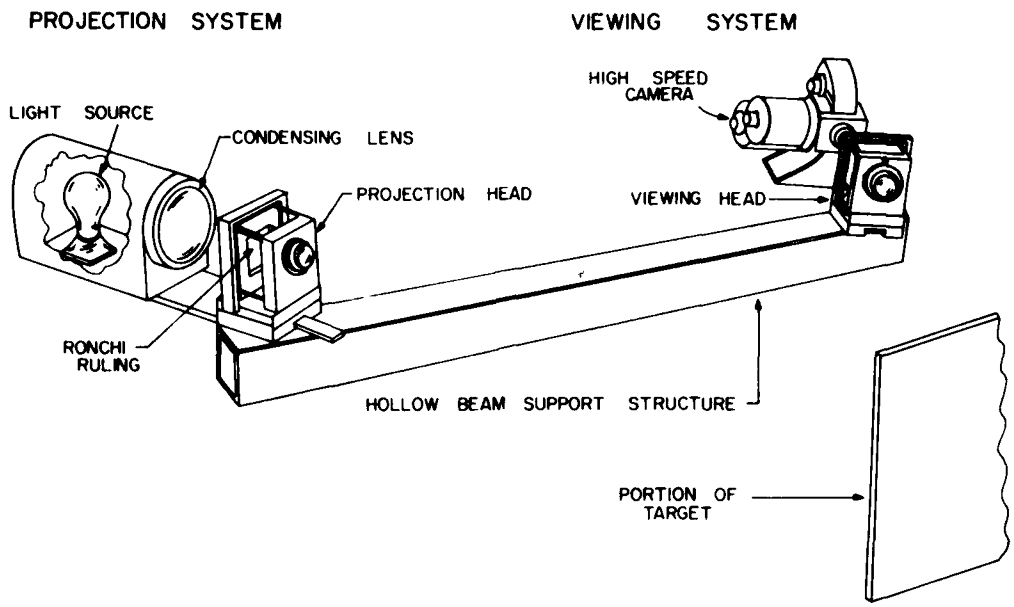


Figure 7. Schematic View of Moiré Device Illustrating Components and Their Relationship to Target Surface.

and angles of the optical axes with respect to the target surface (or support structure), is made with the aid of several nomographs that illustrate the effect of changes in one or more of these interdependent characteristics. Use of these nomographs permits the designer to select those combinations of fringe spacing and curvature which optimize the measurement of the anticipated ranges of out-of-plane displacement of the target surfaces. Actual values for these characteristics are determined from measurements made during and after the alignment procedure and are used to specify various parameters which describe the geometrical relationships of all components in the device.

Proper alignment of the various optical components used in the construction of the device is accomplished through a sequence of carefully performed adjustments that are made as each head is being assembled. As stated previously, these alignment procedures are necessary to insure that fringe surfaces are not skewed and that interpretation of fringe patterns is accurate. All adjustments related to alignment of the device are performed on a large granite surface plate using toolmakers angle plates, squares, and sine bars to verify that alignment has been performed properly and that cumulative effects of small misalignments are minimized. Adjustments are made after an examination of the image of the Ronchi ruling that is projected onto a large, flat metal plate which has been painted to serve as a screen.

The projection system--the optical head and an enclosed lens/light source--and a portion of the support beam of the moiré device are shown in Figure 8. As shown in this figure, the optical head consists of two components, a lens/ruling holder and an adjustable base. The lens/ruling holder is machined from a solid block of metal and has provisions for mounting a lens and a Ronchi ruling and adjusting the position of the Ronchi ruling with respect to the optical axis of the lens. The adjustable base has provisions for moving the lens/ruling holder with respect to the lower portion of the base after this holder has been solidly attached to the upper portion of the base. A dovetail slot machined in the bottom of the base is used to position and attach the assembled head to the support beam.

Alignment of the device is begun by properly locating the Ronchi ruling on the optical axis of the lens. This is accomplished using a special fixture which permits the assembled head to be rotated about the optical axis of the lens and a selected boundary between a specific light and dark region of the Ronchi ruling. Identification of that particular boundary is facilitated by filling the clear space between a pair of dark lines at the center of the ruling, leaving two small interruptions near the center of the line. These interruptions, as well as the blackened locator line on the Ronchi ruling, are shown in the projected image of the Ronchi ruling illustrated in Figure 9. The particular boundary between a light and dark region that is to be

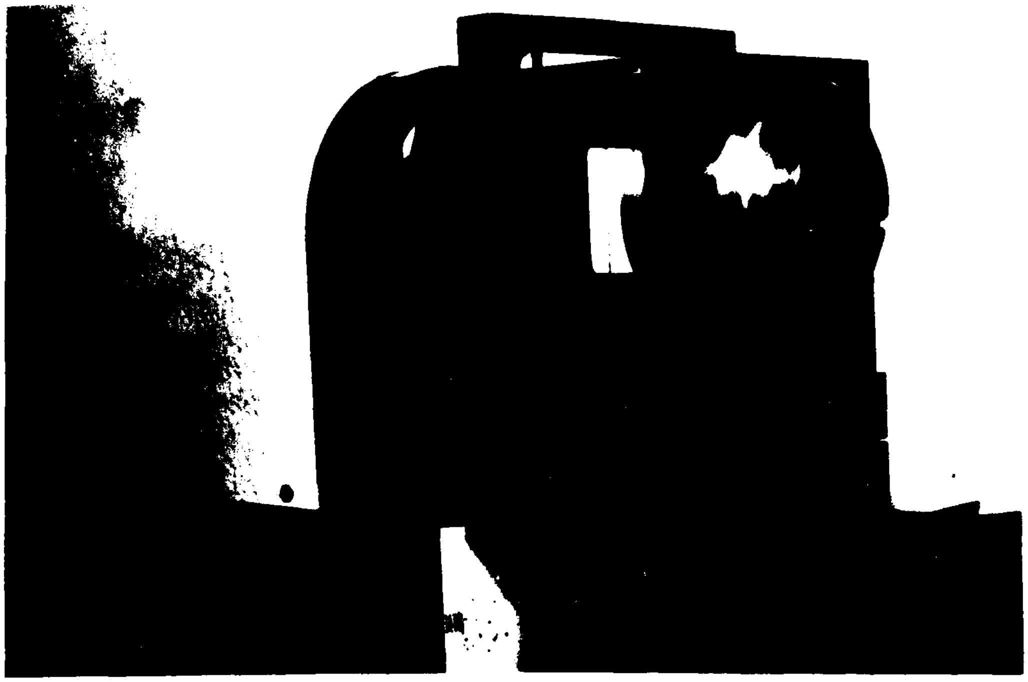


Figure 8. View of a Portion of the Moiré Device, Showing Projection System and a Part of the Support Beam.

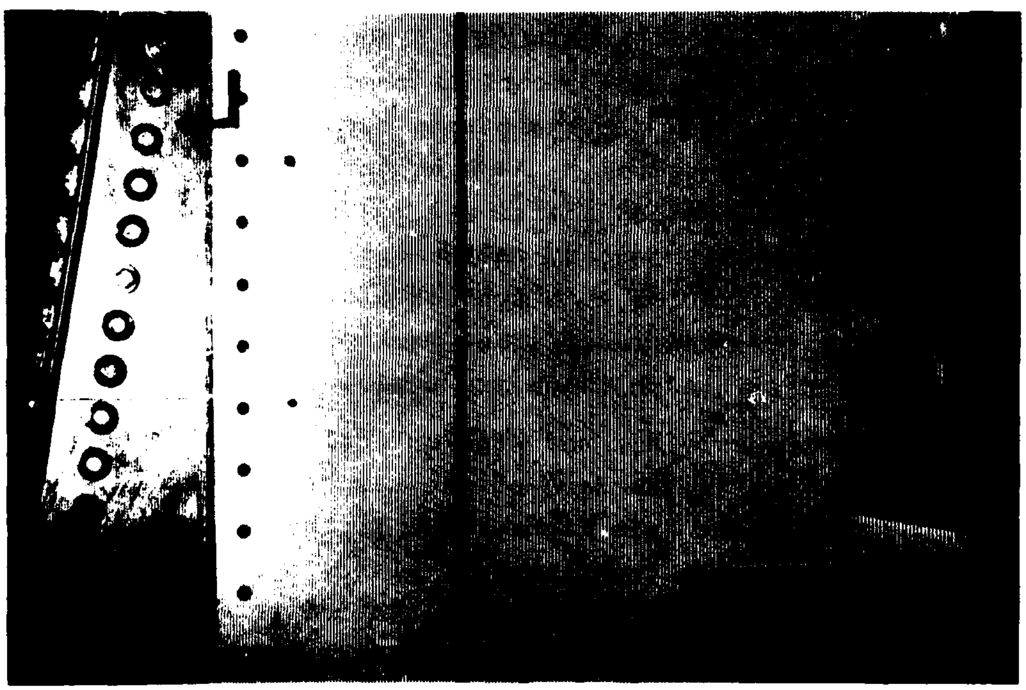


Figure 9. View of Target Surface Showing the Ronchi Ruling as it is Projected onto the Target.

aligned with the optical axis is selected according to the arbitrarily adopted convention shown in Figure 5, i.e., dark area on right side for optical system on the right and dark area on left side for optical system on the left. During this first phase of alignment, the Ronchi ruling and its mount are moved until the appropriate boundary and the center of the short black line between the interruptions do not change position when the entire head is rotated.

At the conclusion of this adjustment, the following measurements are taken: (1) distance from image to lens, (2) distance from image to Ronchi ruling, and (3) spacing of every tenth line in the image of the Ronchi ruling. These last measurements are used to determine the magnification of the assembled system and to assess the extent of distortion, if any, that is present in the image.

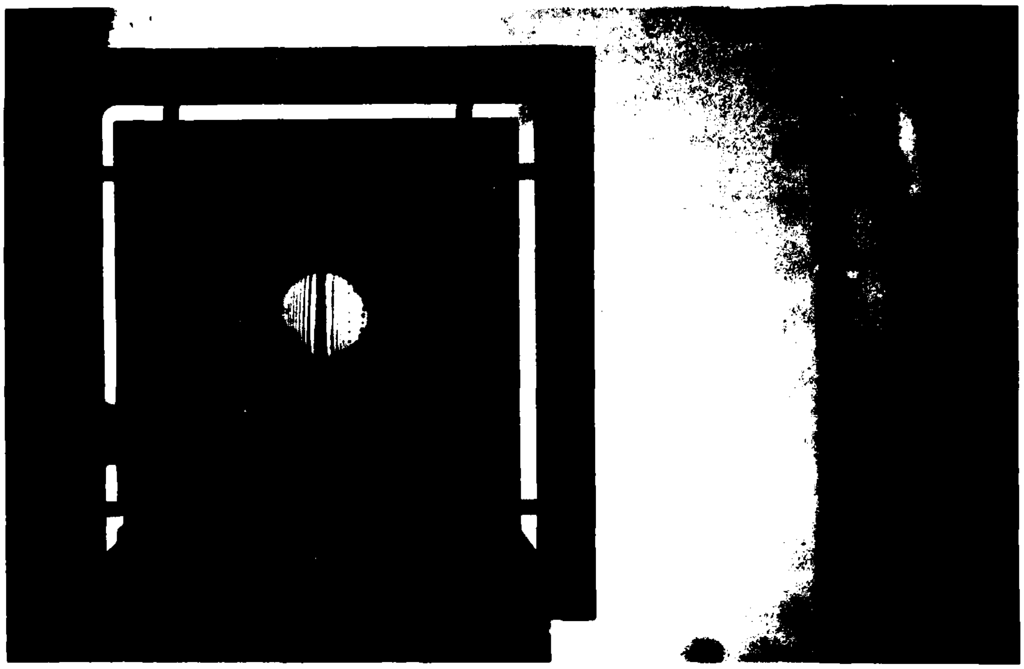
After both heads have undergone the procedures just described, they are mounted on the support beam at their appropriate distances from the target surface. (The dovetails, which align the optical axes of the heads at specified angles to the target surface, have been attached to the support beam using the surface plate and sine bars to assure minimal error in their orientation.) An examination of the images formed by both heads is made and additional adjustments are made in the base section of the head. Alignment of the device is complete when the optical axes of both systems are parallel to the surface plate (the reference plane mentioned earlier) and the individual lines in each image are normal to this reference plane.

When properly aligned, the optical axes of both systems will intersect at the surface of the target and form a dark fringe at that point (see Figure 5). If the target surface is flat and normal to the reference plane, this fringe will appear as a dark band that is normal to the reference plane since the point of intersection, i.e., the center of the fringe, is tangent to the target at that point.

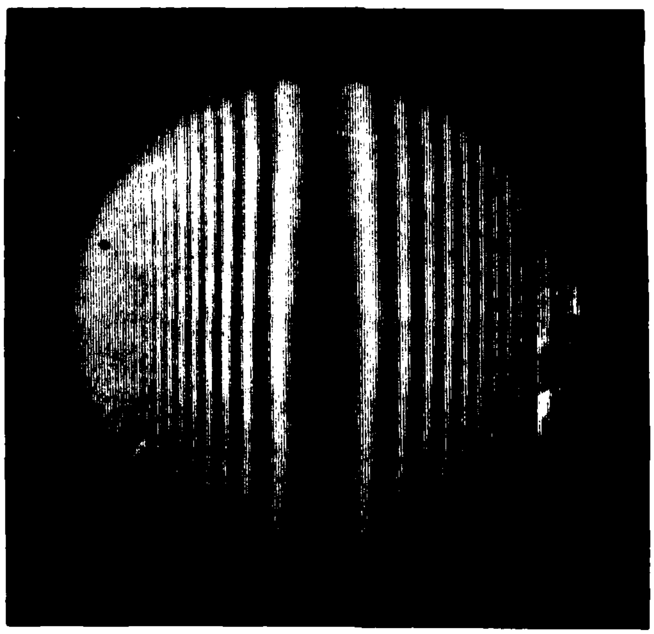
A view of a moiré pattern formed by a properly aligned moiré device is shown in Figure 10(A). In this view, which would be seen by an observer standing a short distance behind the viewing head, the relative size of the moiré pattern on the viewing head Ronchi ruling is shown. Also shown is a very blurred image of the target surface shown previously in Figure 9. This same moiré pattern as seen through the lens of a camera, is shown in Figure 10(B). Some "distortion" of the fringe pattern shown in the figure results for two reasons. First, the optical systems are not conjugates. This results in the formation of an assymetric system of fringes, as evidenced by the dark band being much heavier on the right side of the image. Second, the target surface is a piece of rolled aluminum plate and has some curvature. This results in a further distortion of the pattern. In the system used to produce the moiré patterns shown in Figure 10, the projection system was located on the left side of the device and the viewing system was on the right side. This condition is the reverse of that shown in Figure 5.

SECTION IV
INTERPRETATION AND ANALYSIS OF MOIRÉ PATTERNS

Since the moiré device described in this report is used to analyze the dynamic response of surfaces, the moiré patterns that are produced experience continual and rapid change. Use of a high-speed framing camera permits these transient fringe patterns to be "recorded" at various intervals of time during the event. Interpretation of the fringe patterns formed at these intervals of time is accomplished using enlarged prints of selected frames taken from these high speed films. During processing, care is taken to insure that all prints are made at the same magnification and that the enlarged image is not distorted in any way.



(A)



(B)

Figure 10. View of Moiré Pattern Formed at Ronchi Ruling in Viewing Head. (A) Pattern as seen by an observer standing some distance behind the head. (B) Pattern as seen through lens of camera.

Data Reduction Procedures. Data taken from these individual prints is normally processed with use of a computer-assisted data reduction technique (Reference 10). During processing, measurements taken from the film are corrected for the variation in film magnification which occurs as a result of the oblique viewing of the target surface. Image magnification, in these films, is determined with the use of fiducial marks applied to the target surface and measurements of the location of these marks in the prints of several frames of film exposed immediately before response of the target surface begins. In succeeding frames, measured values which have been corrected for film magnification errors are used to determine the position of the measured point in the three-dimensional coordinate system shown in the lower right corner of Figure 11.

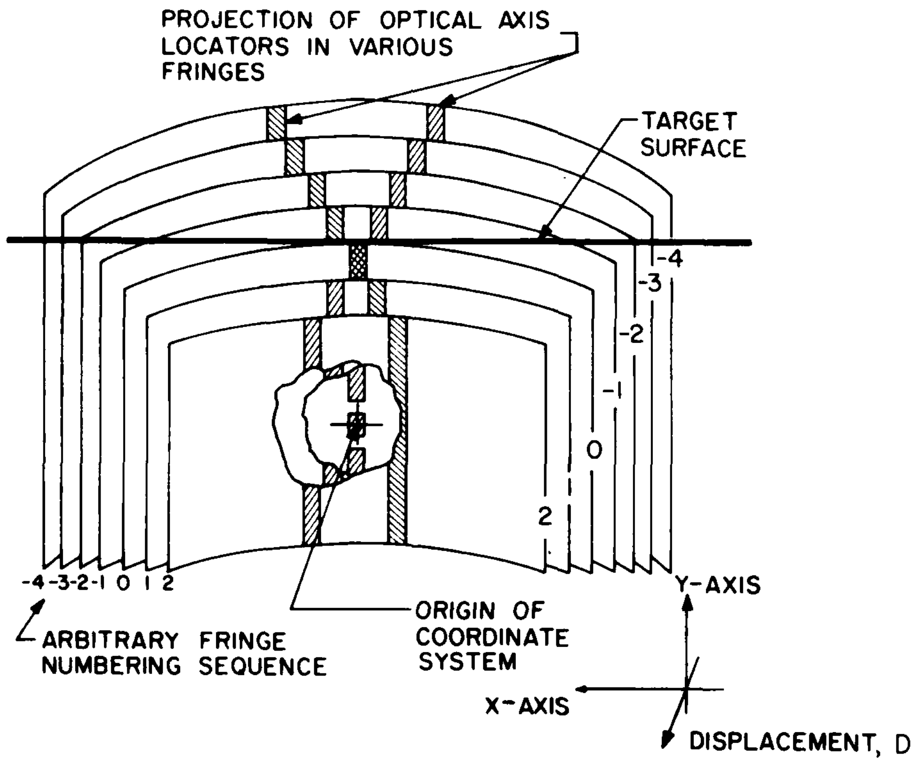


Figure 11. Arbitrary System of Identifying Fringes and Coordinate System Used in Analysis of Fringe Patterns. In this figure, the reference plane is parallel to the X-D plane. Note the position of locator lines in each fringe.

Figure 11 shows the arbitrary system for numbering the fringes produced by the device. As shown in this figure, the heavy locator lines described in Section III intersect at the target surface. The dark fringe formed there (and the entire dark surface which curves away from the target surface) has arbitrarily been identified as fringe zero. Careful study of the way in which the locator lines are "projected" in the system of fringes facilitates identification of fringe zero in the prints from the high speed films. Dark surfaces which form in front of fringe zero (toward the viewer) have been assigned positive numbers and surfaces formed behind this surface have been assigned negative numbers.

As discussed earlier, the fringe patterns are composed of light and dark bands and the transition from a light band to a dark band, or vice versa, is gradual. If an observer were to travel through the system of fringes shown in Figure 11, he would pass through a series of light and dark regions. The relative intensity of his position at any point in his traverse would lie somewhere on the curve shown in Figure 12. In actual

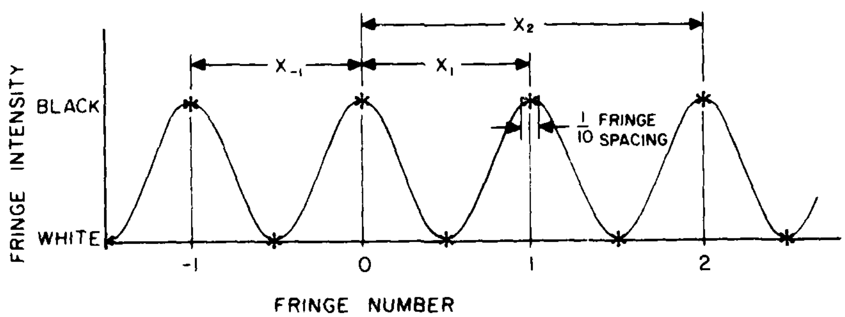


Figure 12. Relative Intensity of Fringes as Seen by an Observer Passing Through the System Shown in Figure 11.

practice, those positions where fringe intensity is "whitest" or where fringe intensity is "blackest" are most easily identified. These points have been marked with an asterisk in Figure 12. It is also possible to identify points of "equal grayness", i.e., points midway between the blackest and the whitest portion of the pattern.

The data reduction techniques and conventions which have been adopted for use with the moiré device arbitrarily established the darkest portion of a dark band as the point of measurement. The user's ability to accurately determine and measure the location of this point determines, to a large degree, the accuracy with which the user can determine the location of that point in the moiré coordinate system. Typically, this accuracy is one-tenth of the nominal spacing between the dark surfaces for measurements taken from the photographs. Nominal dark surface spacings used for various devices which have been constructed were 2.5 and 5 mm. Further degradation of measurement accuracy occurs when the distance between successive dark fringes on the target surface (or in the photographs) is less than four times the distance between lines in the projected ruling image.

The system of fringe surfaces that is generated by the moiré device is unique for the system parameters which are measured during alignment of the device. Consequently, the location of each surface can be determined in terms of the moiré coordinate system shown in Figure 11. The computer program which processes the moiré fringe data uses various geometrical relationships associated with the measured system parameters to generate, in moiré coordinates, the locations of all fringes observed in the patterns produced by the device. Since care is taken during alignment of the device to insure that the fringe surfaces are not skewed, the loci of all points in a fringe at a specific value of X will be a line that is normal to the reference plane. As a result, the displacement of a point in a fringe can be determined for any value of Y merely by specifying the number of the fringe and the appropriate value of X. Normally, measurements of X are made for constant values of Y, since deflected shapes along particular sections (Y = constant) are the desired final product.

The data analysis program generates a table of X and D coordinates for each fringe number that will appear in subsequent treatment of the data by systematically computing the coordinates of the intersections of all appropriate boundaries (or rays) shown in the illustration given in Figure 5. Using the convention given in Figure 5 for denoting the viewing and the projection system (subscripts V and P, respectively, in later relationships) individual boundaries or rays for both systems shown in that figure are numbered according to the following convention: (1) the optical axis is numbered zero, (2) rays emanating in a clockwise direction from ray zero are numberd positively, and (3) rays emanating in a counter-clockwise direction from ray zero are numbered negatively. The fringe in which a particular intersection lies can be determined using the appropriate ray numbers and the following relationship:

$$\text{Fringe Number} = \text{Ray Number}_V - \text{Ray Number}_P$$

The equation of each ray in the moiré system can be determined, in slope-intercept form, using the system parametric constants for Ronchi ruling pitch, system magnification, etc. X and D coordinates of the point of intersection of any two rays can be determined using the following relationships for each pair of rays

$$X = \frac{\text{Intercept}_P - \text{Intercept}_V}{\text{Slope}_V - \text{Slope}_P}$$

$$D = X(\text{Slope}_V) + \text{Intercept}_V$$

The out-of-plane displacement of any point on a surface is determined by entering the table using the appropriate fringe number as an index and interpolating between those tabulated values of X and associated values of D which bound the "measured" value of X. This "measured" value is, in reality, a measured value that was taken from the photograph and corrected for film magnification.

Detailed quantitative analysis of the fringe patterns begins with a series of measurements which relate the position of each fringe in the pattern to the locator line in the viewing head Ronchi ruling. This line is used since it provides a reference which is fixed in all photographs and is independent of motions which could occur in references attached to the target. Raw data, consisting of fringe numbers and measured values of X, are entered into the computer program and processed as described in the preceding paragraph. Since the locator line of the viewing head is, in reality, the optical axis of this head and not the D-axis, which would have been used if a means of identifying it were available, a correction is required to compensate for the considerable errors which result as the displacement of the surface enters those regions where the divergence of the D axis and viewing head optical axis becomes significant. The required corrections are made using an iterating subroutine in the main program.

Deflected shapes along specific sections of the target can be reconstructed by plotting the various values of X and D ultimately yielded by the data reduction program. A series of these deflected profiles obtained from a number of frames from a high-speed film sequence can be used to construct a time-history of the deflection of various points along that section. Profiles can be generated for several sections in each frame and used to describe the shape of a deflected surface.

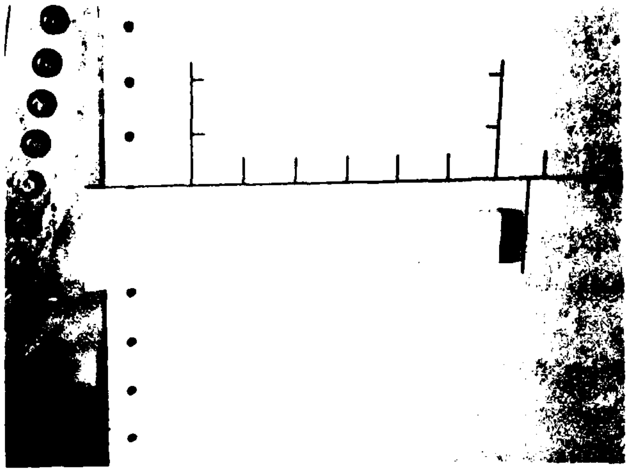
In some applications, the time-history of deflection at a specific point or points may be desired. In those cases, the user need only observe the number of changes from light band to dark band to light band, etc., that occurs as the surface displaces. Since the spacing of fringes is unique for each device, the number of changes can be related directly to an overall deflection using information contained in the table of fringe coordinates.

Verification of System Design and Data Reduction Procedures. It is possible to evaluate the combined effects of all design considerations, alignment procedures, photographic processes, and data reduction and analysis techniques in a single step by simply placing an object of known shape and dimension in front of the moiré device, obtaining a photograph of the resultant fringe pattern, and reducing the fringe data to a series of X and D coordinates. These X and D coordinates can be used to reconstruct the shape of the object. A simple comparison of the reconstructed shape and the true shape permits the user to establish a level of credibility in the techniques and procedures.

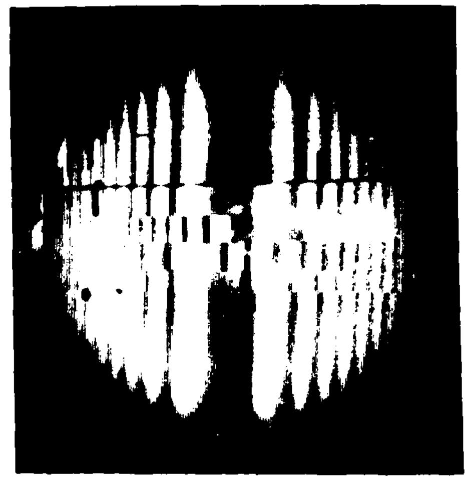
The results of a test using a calibration wedge are presented in Figure 13. The calibration wedge was machined from a block of aluminum to provide two surfaces of known configuration and dimension. A sheet of 1/16-inch-thick aluminum was bonded to the back of the wedge as shown in Figure 13(A) and the assembly was attached to a target surface. As seen in Figure 13(A), the wedge and target have been painted white to improve the quality of the image focused on the viewing system Ronchi ruling. Also shown in Figure 13(A) are the fiducial marks used to determine film magnification.

A photograph of the moiré pattern produced by the wedge and associated surfaces is shown in Figure 13(B). The reconstructed shape of the wedge and target surface is shown in Figure 13(C). The curvature of the back panel and wedge shown in Figure 13(C) are real. In the case of the back panel, the curvature results from the rolling process used to form the stock. In the case of the wedge, a light cut was made on nominally 3/4-inch-thick stock. The 0.744 inch dimension shown is that of the finish machined plate and paint. The approximately 0.025 inch bow in the wedge surface and the 3/4-inch thick surface was produced when strains in the rolled metal bar stock were relieved during machining. Bowing occurred when the machined stock was released from the clamps which held it during the machining operation.

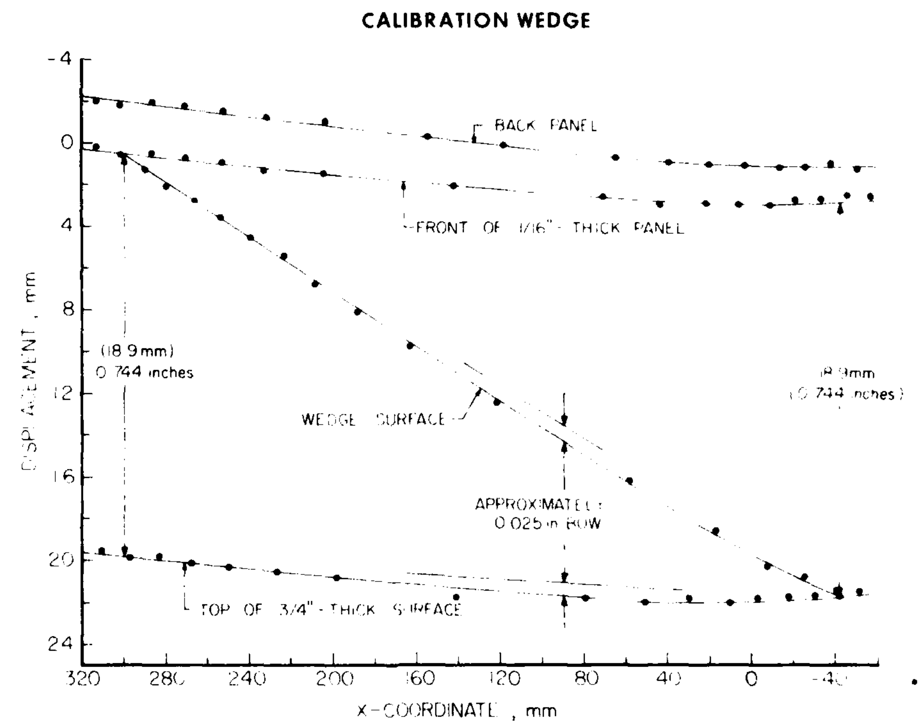
The results of the test demonstrate that the combined effects of all errors were within the one-tenth of a fringe spacing limit mentioned earlier. Nominal spacing of fringes in the device



(A)



(B)



(C)

Figure 13. Test Used to Verify Results of Measurements and Analytical Techniques Employed with Moiré Device. (A) View of calibration wedge and several surfaces of known height. (B) Moiré pattern formed by wedge. (C) Graphical results of test. Note that there is a 10 to 1 amplification of the displacement scale with respect to the x-coordinate scale.

used for this test was 2.5 mm. Accuracy of measurements was, therefore, 0.25 mm or approximately equivalent to the size of the plotted symbols used in Figure 13(C).

SECTION V
APPLICATIONS OF MOIRÉ DEVICE

Several moiré devices have been constructed and used to successfully determine the out-of-plane displacements of rapidly moving surfaces. Selected frames of high speed films showing moiré fringe patterns produced during the response of a simulated fuel tank panel[a] to the impact of a high velocity fragment are shown in Figure 14 (field of view is approximately 30 cm by 50 cm). The patterns shown were formed just before and approximately 1, 2, 3, 5, and 8 msec after impact. Analysis of the fringe patterns was performed for a single section through the point of impact although there are sufficient data to analyze the motion of the entire surface. Partial results of the analysis for a section along the horizontal fiducial line shown in Figure 14 are presented in Figure 15. As shown in this figure, some forward motion (up) of the water filled tank occurred during the response of the panel. Times shown on this figure are the approximate times after impact which correspond to each of the deflected shapes. A total deflection of approximately 43 mm was observed during a time span of 7.5 msec. Initial shape of the surface being examined is not of significant importance. The surface shown in Figures 14 and 15 was essentially a flat plate.

A moiré device was used to determine the out-of-plane displacement of F-16 aircraft transparencies subjected to birdstrike testing at Arnold Engineering Development Center, Tennessee. Initial shape of the transparency in the region of

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[a]Work performed under Air Force Contract F33615-77-C-2082.

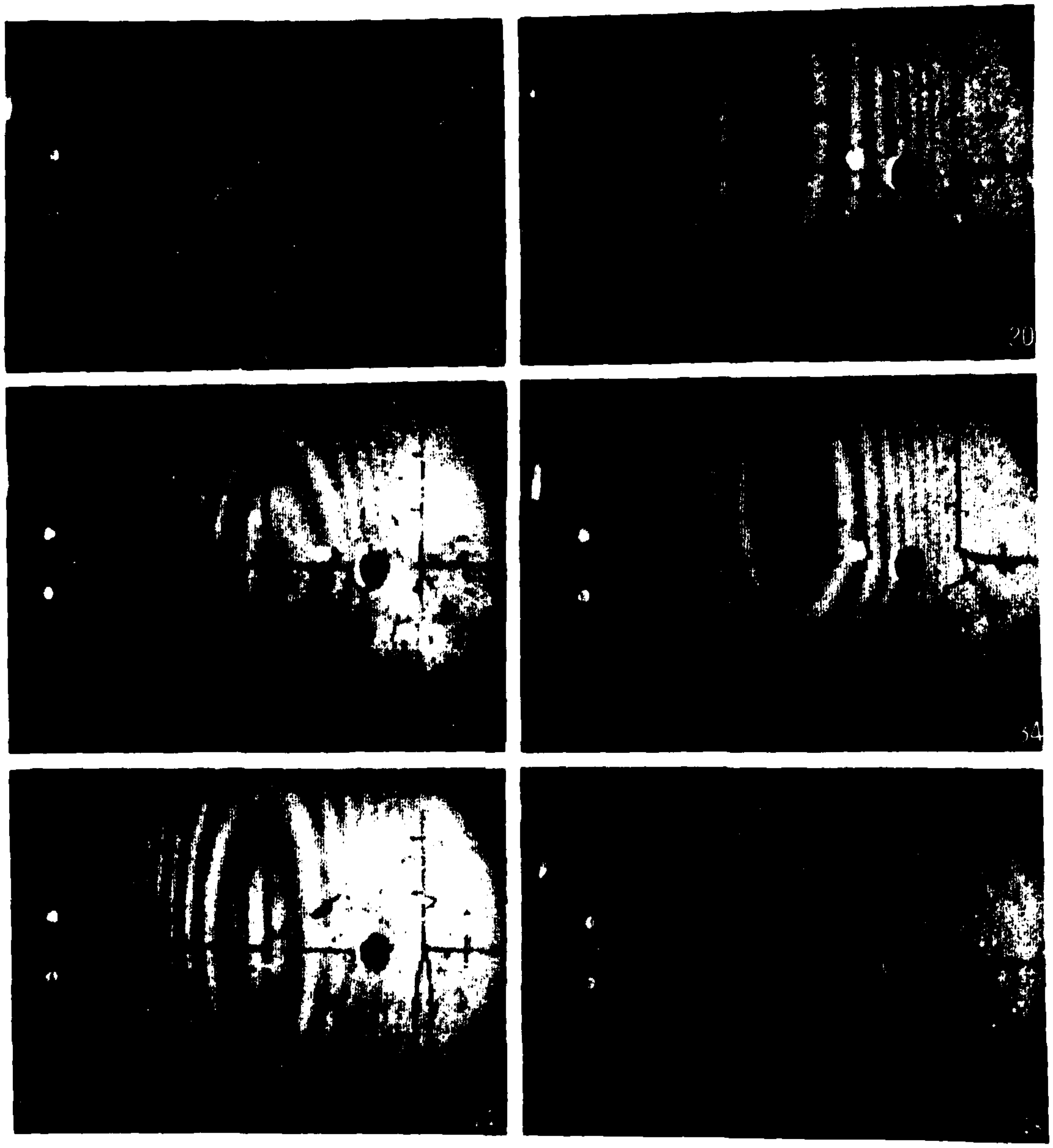

Figure 14. Selected Frames from a 16-mm Film Showing the Fringe Patterns Produced During the Response of a Simulated Fuel Tank Panel to the Impact of High-Speed Fragment. Target is a 6.4-mm (0.25-inch) thick aluminum plate which forms the side of a water-filled tank. Projectile was an 11.66 gm steel cube traveling at 1.63 km/sec (5400 fps). Framing rate was 6360 pictures per second. Numbers in lower right corner are frame numbers with respect to frame where impact occurs.

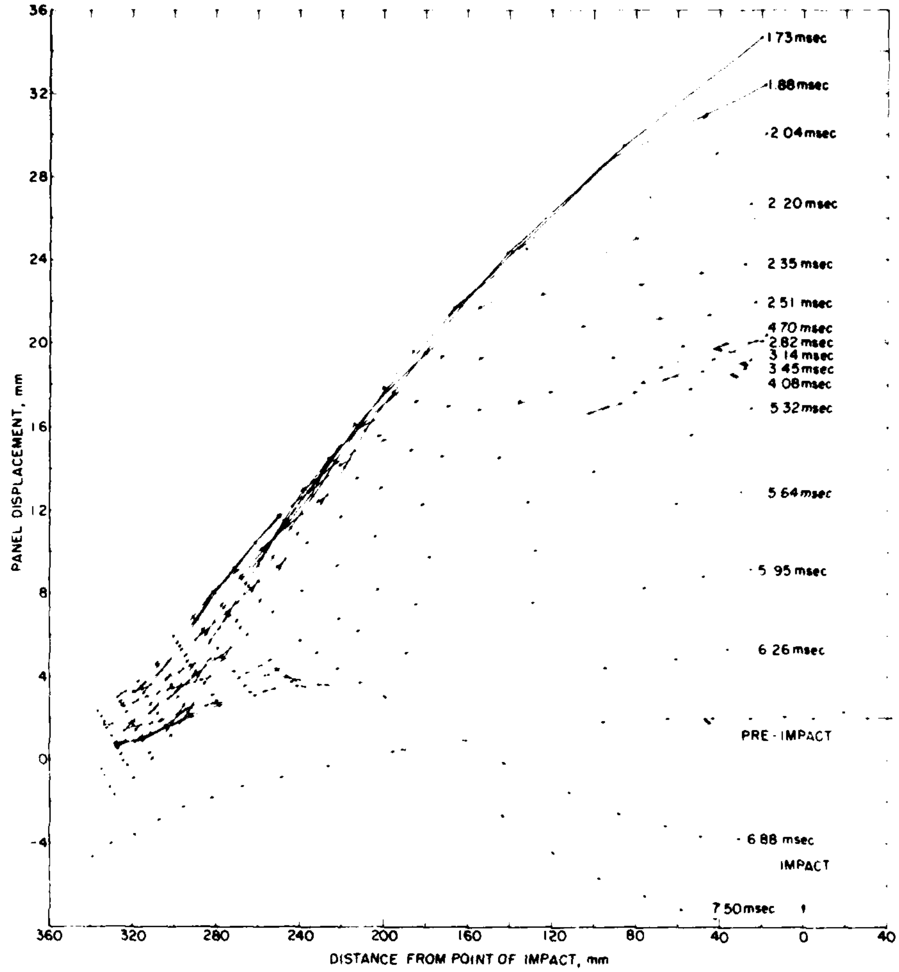

Figure 15. Deflected Shapes of the Panel Shown in Figure 14. Note that there is a 20 to 1 enhancement of displacement with respect to the X-coordinate. This figure shows the various shapes which the panel assumed during its response from the maximum outward (up) displacement to maximum inward (down) displacement.

interest may simply be described as concave with a radius of curvature of 40 cm. In the preceding examples, the reference plane of the moiré device was oriented parallel to the surface of the earth. Use of the moiré device for the transparency tests required the device to be rotated 90 degrees to permit examination of the interior surface of the transparency in a region approximately 40 cm by 50 cm centered above the pilot's head. A "screen" for projection of the Ronchi ruling onto the transparency was formed by brushing white paint onto a single layer of masking tape applied to the interior surface of the canopy.

The results of one birdstrike test are shown in Figure 16. In this figure, the reader can "see" the location of the dark

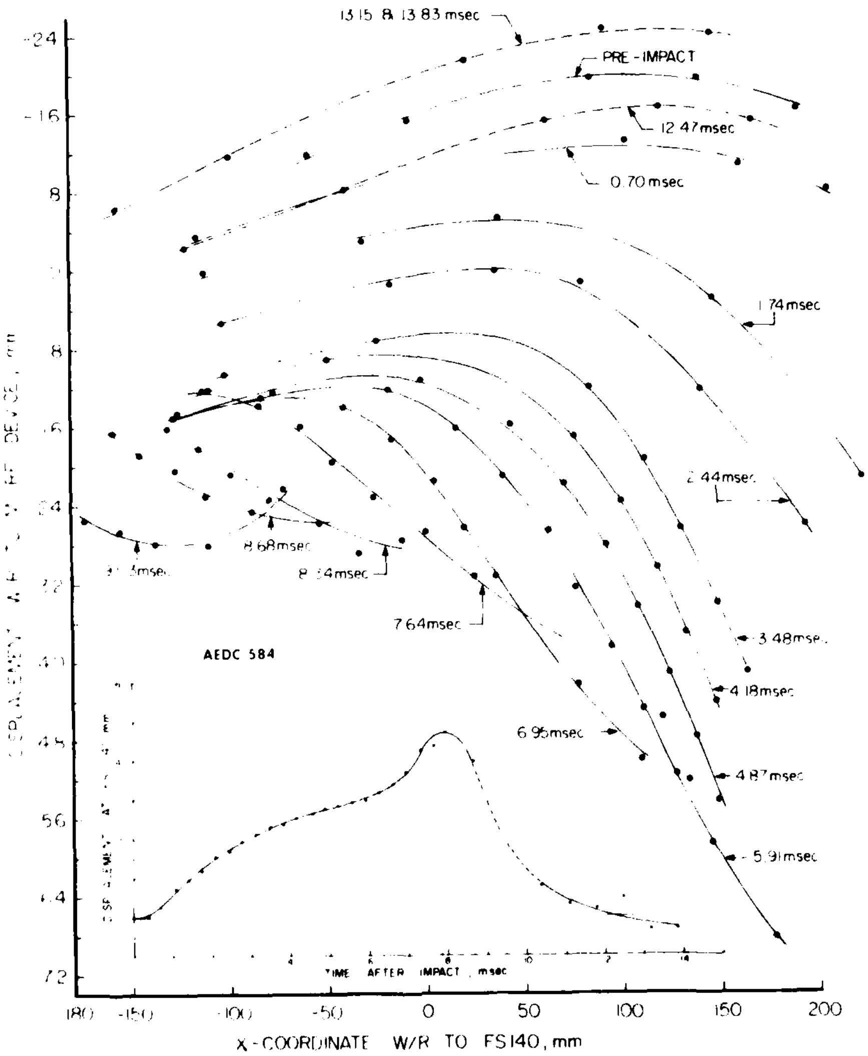

Figure 16. Response of a Section of an F-16 Transparency to a Birdstrike Test (AEDC-584). Of particular interest in this section along B.L. 0.0, is the inward displacement of the region above the pilot's head, F.S. 140.

surfaces formed by the device by mentally connecting sets of plotted points to form a family of downwardly curved lines. The time-history of the inward displacement of the transparency above the pilot's head is shown on the inset plot in the lower portion of this figure. Data used to generate this plot were obtained by merely recording the deflection of the transparency at fuselage station 140, relative to its initial position, for each of the profiles shown (and a number of profiles not shown).

In the results of a second birdstrike test presented in this report, the response of a portion of the transparency surface was analyzed. Individual profiles for seven equally-spaced transparency sections (parallel to and including the section used in Figure 16) were determined for a number of frames of film. The X-, Y-, and D-coordinates of each set of points in these profiles were fit to a surface using a cubic-spline approximation and the resulting surfaces drawn by a computer graphics unit. A sequence of surfaces generated from the profile data is shown in Figure 17. Views selected for presentation were chosen to show the shape of the deflected surface rather than the magnitude of the deflection at fuselage station 140. Data shown on the plot included in Figure 17 were obtained using the procedure described in the preceding paragraph.

In addition to the examples just presented, moiré devices have been used to determine deflected shapes of other panel-type and blade-type targets.

Light levels required to expose film and limits on framing rates of high speed cameras can restrict the application of the device because of poor exposures or motion blur of the images, respectively. Sharp changes in the profile of the deflected surface can also affect the usefulness of the device since the fringes tend to "pile-up" in those regions making individual fringes in the pattern indistinguishable. These limitations are pointed out only to acquaint the reader with possible areas of difficulty when considering the use of the device. To date, the device has performed satisfactorily in nearly every application in which it has been used.

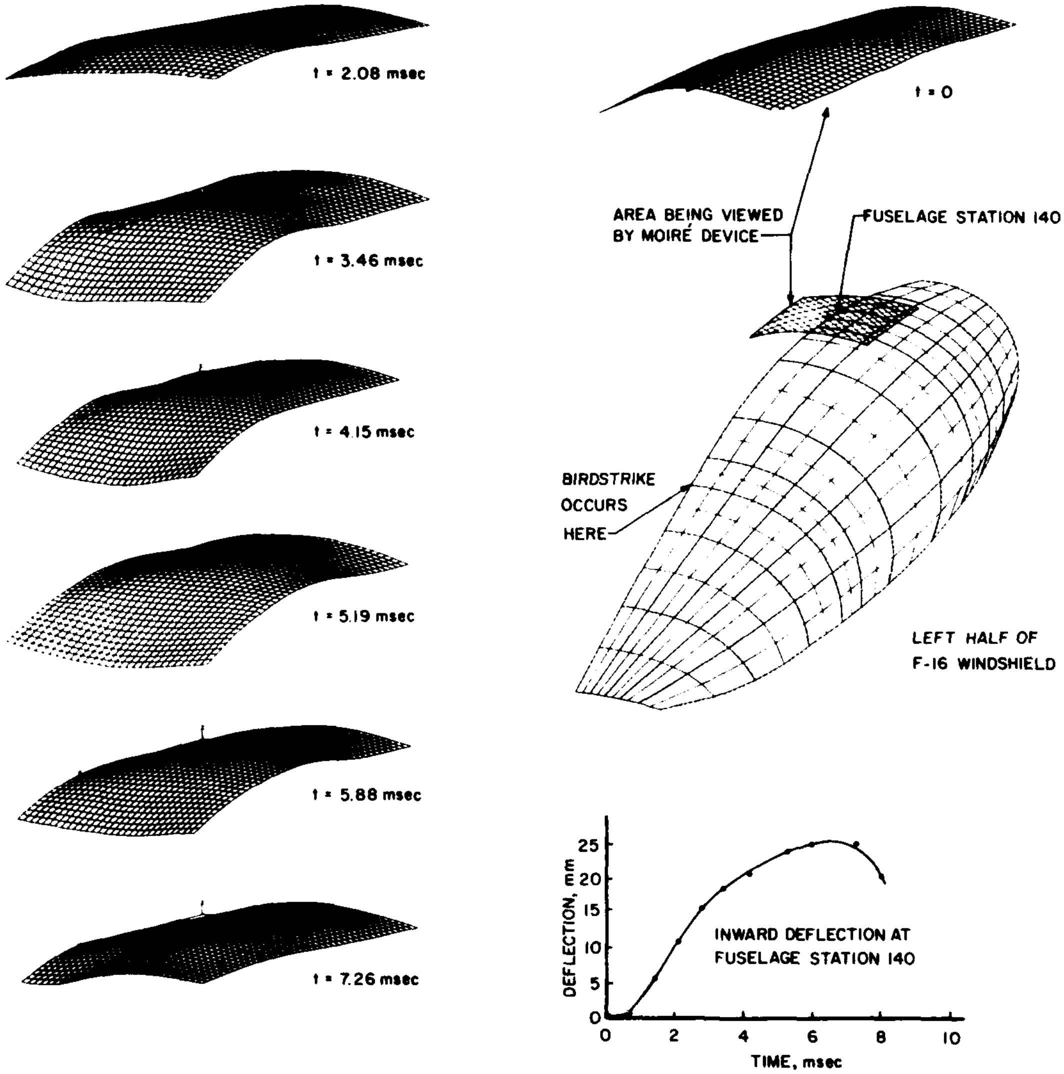

Figure 17. Response of a Portion of an F-16 Transparency to a Birdstrike Test (AEDC-585). Inward deflection of the region above the pilot's head was measured at B.L. 0.0 and F.S. 140.

Reduction of fringe patterns to deflected shapes is a time-consuming process, primarily because of the large quantities of data which can be taken from each frame of film of the transient pattern. The individual measurements which must be made, while somewhat tedious, are not difficult. Isolated errors resulting from improper measurements or misentry of data in the computer program are generally not subtle and become quite obvious when computer output is examined or the deflected shapes are reconstructed. Despite the drawbacks imposed by reduction of the fringe data, use of the moiré fringe technique to determine out-of-plane displacements of surfaces, in some cases, offers the only means of obtaining the required data.

Finally, successful use of the device usually required that the surface of the target be white to promote the formation of a good quality image at the viewing head Ronchi ruling. Any kind of reasonably white, non-glaring paint that can be safely applied to the target will fulfill this requirement.

SECTION VI
SUMMARY AND CONCLUSIONS

The moiré fringe device described in this report has been used successfully to accurately determine the out-of-plane motions of large surfaces experiencing a dynamic response to an impulsive load. The device will perform equally well in situations where response of the target is less dynamic. Use of the moiré device permits the motion of the target to be determined without physical contact between the target and the device.

Accuracy of measurement and the range of displacement to be measured are not independent since normal measurement tolerances are specified in terms of nominal fringe spacing--one-tenth of the fringe separation. Use of the device for measurement of large displacements generally requires that the dark fringes be widely spaced to avoid the tendency for fringes to "pile-up," with a resulting loss of ability to distinguish individual fringes. If total displacement is expected to be small, close fringe spacings can be used. However, as fringe spacing is reduced, the size of the area which has distinguishable fringes is also reduced. Following is a summary of typical performance characteristics of devices described in this report.

Nominal Fringe Spacing	Viewed Area	Range of Displacement	Measurement Accuracy
2.5 mm	1500 cm^2	60 mm	0.25 mm
5.0 mm	2000 cm^2	125 mm	0.5 mm

Although the target surfaces presented as examples in this report were planar or simply concave, use of the device is not restricted to these shapes. Practically any target shape is acceptable; however, targets with abrupt changes in profiles may limit resolution of fringes in the region of the nonconformity.

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