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# A SCHLIEREN SYSTEM FOR PERFORATED WALL TYPE TRANSONIC WIND TUNNELS

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# FOREWORD

This report was prepared by Eugene Behun, project engineer, Instrumentation Section, Research Department, United Aircraft Corporation, East Hartford, Connecticut. This Research was performed under Air Force Contract No. AF18(600)-171, Supplemental Agreement No.S2(54-733), Task No.70128, Project No.1363, "Development of Flow Visualization Techniques for Application to Wind Tunnel Test Sections Having Perforated Walls". The research was under the direction of Mr. Elmer G. Johnson, Aeronautical Research Laboratory project engineer. Professor F.W. Sears of the Massachusetts Institute of Technology was consultant to the United Aircraft Corporation on this research contract.

## ABSTRACT

The development of a schlieren system for clear visualization of the flow in perforated wall type transonic wind tunnels is described. One of the perforated walls is diffusely backlighted such that the perforations act as a multiplicity of point light sources. It is shown that the visual interference due to the presence of the perforated walls can be reduced to an inconsequential amount by the proper design of the wind tunnel and schlieren. The system is sufficiently sensitive to be of definite utility as an instrument for flow visualization. The basic system can also be readily modified to a color schlieren. The capabilities of the system are demonstrated on a number of simulated wind tunnel test sections. Successful application of the schlieren is also made to two small operating transonic wind tunnels. Photo-chemically etched perforated glass, in conjunction with a conventional parallel-light schlieren, is also investigated as a replacement for perforated metal walls and holds some promise for two-dimensional testing in small wind tunnels.

## PUBLICATION REVIEW

This report has been reviewed and is approved.

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# A SCHLIEREN SYSTEM FOR PERFORATED WALL TYPE TRANSONIC WIND TUNNELS

## INTRODUCTION

Flow visualization requirements in wind tunnels operating at subsonic and supersonic speeds have been very adequately met by conventional schlieren and shadowgraph techniques. The test section side walls can accommodate large glass inserts or be made of a solid sheet of glass thus making possible the unrestricted observation of the flow in the test section. Testing at transonic speeds, however, has required considerable modification of the mechanical and aerodynamic design of the test section to eliminate troublesome shock reflections at the tunnel walls. Perforated tunnel walls, through which air is withdrawn, have effectively eliminated the shock reflections. These walls, which are commonly made of perforated metal with porosities (ratio of the open area to the entire wall area) of approximately 25%, have seriously restricted the amount of visual information obtainable with conventional schlieren. By using a parallel-light type single-pass schlieren under the ideal condition of perfectly matched perforations in both tunnel side walls, only 25% of the test section is visible so that detailed interpretation of the visible flow pattern is extremely difficult at best, and for the most part impossible.

It is apparent that (1) either the walls must be made transparent in order to utilize a conventional schlieren, or (2) an optically different flow visualization technique, that is not deleteriously affected by the presence of the metal walls, must be employed. The following two sections outline methods of achieving each of these alternatives.

# I DISCUSSION OF A MULTIPLE-SOURCE SCHLIEREN

In considering means by which observation of the complete flow disturbance pattern in the transonic test section might be achieved, Professor F. W. Sears of the Massachusetts Institute of Technology suggested the multiple-source schlieren system that constitutes the major portion of the investigation reported herein. The system is similar to sharp-focusing schlieren systems described in the literature (see Ref. 1 and 2 in the Bibliography).

A diffuse source of light is located exterior to one perforated wall of the test section (Fig. 1), the perforations in the wall acting as a multitude of "point" light sources for the schlieren. The light from this wall (the source plate) passes successively through the test section, the perforations in the wall opposite the source plate (near-wall), the field lens, and the cut-off plate onto the photographic film or viewing screen. The cut-off plate, which is placed in the image plane of the source plate, consists of a photographically produced negative replica of the source plate, i.e., a pattern of black dots on a transparent background. Complete coincidence of the image of the source plate and the negative replica on the cut-off plate ideally results in total blockage of the light so that no light reaches the viewing screen. A disturbance in the test section deviates the light rays passing through the disturbance so that a ray formerly blocked by the cut-off plate may now pass through the clear portion of the plate to reach the screen. The sensitivity of the schlieren is non-directional but may be made directional through the use of a cut-off plate having the opaque portions properly shaped.

The outstanding differences between the system described above and similar systems appearing in the literature is the presence of the perforated wall between the source plate and the field lens. This wall, which is required aerodynamically, serves no useful purpose in the schlieren system; in fact, it introduces a pattern that can, under certain conditions, seriously obscure the flow pattern.

In normal photography by either reflected or transmitted light, a perforated plate located in either of the principal planes of the lens would act as an iris and would not influence the character of the image, other than decreasing the illumination. However, in photography by transmitted light emanating from a number of discrete sources and being transmitted through a number of discrete apertures, the near-wall, irrespective of its position relative to the principal planes of the lens, is an obstacle to the attainment of uniform illumination of the image field. This can be seen by reference to Fig. 2 which is a simplified diagramatic representation of the various light rays passing through the test section that are collected by the field lens. Without any disturbance in the test section, the light pattern on the viewing screen is primarily a duplication of the light pattern of the plane in the test section that is optically conjugate to the location of the viewing screen. Inspection of Fig. 2 reveals that the light pattern is not uniform in any plane, and for identical perforation patterns in the test section walls, the least uniformly illuminated area is the test section centerline plane 0-0. The intensity

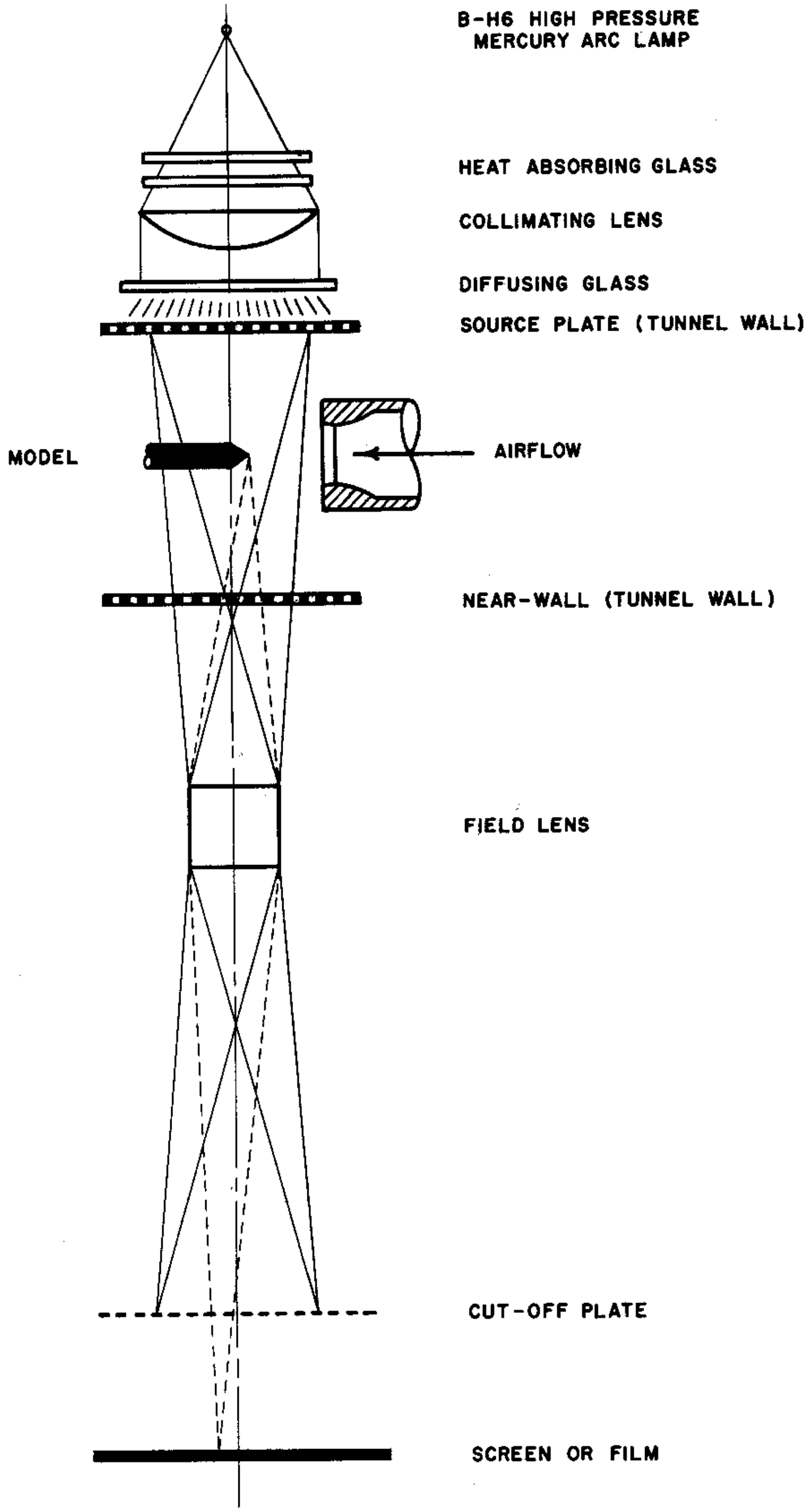


FIGURE I. MULTIPLE-SOURCE SCHLIEREN SCHEMATIC DIAGRAM

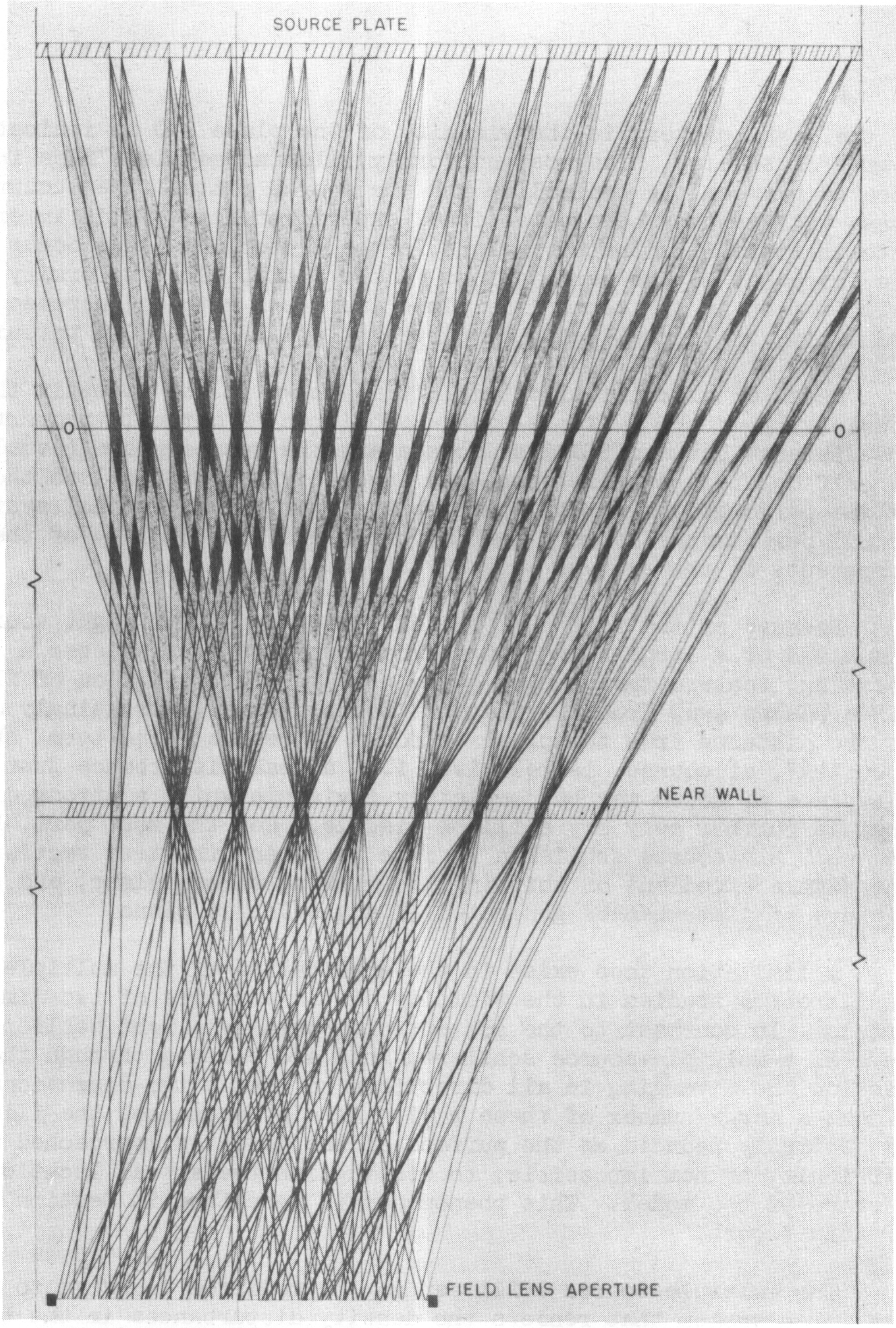


FIGURE 2. RAY DIAGRAM THROUGH PERFORATED WALL TEST SECTION

of the light pattern in the vicinity of the plane 0-0 is indicated by the degree of shading. The most uniformly illuminated plane lies in a region located between the centerline and the source plate. The occurrence of these patterns has been established experimentally. It is interesting to note that the illuminated regions in the centerline plane occur at twice the frequency of the perforations in the plate. The uniformity of the illumination in the centerline plane increases with an increase in porosity, the limit, of course, being complete uniformity with 100% porosity.

Based on geometrical optics, it is shown in the Appendix that the sensitivity of the multiple-source schlieren is directly proportional to the distance between the disturbance and the source plate (usually equal to half the test section span) and inversely proportional to the diameter of the perforations in the source plate. As in any optical system, the actual performance is very much a function of the quality of the optical components in the system.

Because of the fact that the effective schlieren light source is comprised of a large number of sources, the system possesses a "sharp-focusing" feature that can be quite useful. The rendition of flow disturbances away from the plane of focus becomes increasingly diffuse as the distance from the plane of focus increases. The term "sharp-focusing", of course, is relative, i.e. a weak disturbance just outside the plane of focus may be completely invisible while a strong disturbance that is further away may still be visible. For the most part, however, the multiple-source schlieren is able to "scan" the test section span by the simple expedient of shifting the viewing screen plane, and gives a picture of disturbances generated in any selected plane.

A limitation does exist in the application of the multiple-source schlieren to studies in the vicinity of the surfaces of two-dimensional models. In contrast to the conventional parallel-light schlieren, the rays in a multiple-source schlieren that are passing through the test section are diverging in all directions so that a two-dimensional model blocks a large number of these rays. As a consequence, the illumination is seriously reduced as the surface of the model is approached making it difficult, if not impossible, to distinguish the actual location of the surface of the model. This phenomenon is described in Section IV, page 9 of this report.

The multiple-source schlieren may be modified somewhat to produce a schlieren system that renders the density disturbances in the test section in various colors, each color corresponding to a particular value of the density gradient in the test section. The components of this color multiple-source schlieren are identical to the black and white version except for the substitution of a spectrum color transparency for each of the opaque areas in the cut-off plate, the areas between these spectra now being black instead of transparent. The new cut-off plate is again positioned in the image plane of the source plate. However, the undeviated rays traversing the test section are no longer blocked but pass through a particular part of each of the spectrum transparencies and produce a specific color for the background illumination, e.g. green. Deviation of the light rays in passing through a density disturbance in the test section will result in a shift of these rays with respect to the spectra transparency. If the density gradient vector has a component in the direction of the spectra spread, the deviated rays will now pass through a different color in the transparency than the undeviated rays. As a result, the density disturbance is reproduced on the viewing screen in a color different from the background, e.g. red. A density gradient of the opposite sense results in a shift of the rays in the opposite direction and the reproduction of the disturbance on the screen is of a hue towards the blue end of the spectrum.

## II DISCUSSION OF PERFORATED GLASS WALLS

Consideration has been given to the replacement of the perforated metal side walls with perforated glass so that a conventional parallel-light schlieren may be utilized for visualization of the flow. Fabricating the perforated glass by conventional drilling techniques was considered impractical due to the large number of closely spaced holes. The Corning Glass Works, however, has recently made available a technique whereby glass may be perforated by a controlled etching process (Ref. 3). A special photosensitive glass is exposed to a light pattern of the desired perforation configuration. The glass is then heat-treated and etched. Because of the much higher susceptibility of the photographically exposed portions of the glass to etching as compared to the unexposed portions, the perforation is completed with only a nominal amount of etching of the photographically unexposed glass. Optical polishing of the glass must be performed after the etching process to provide a clear surface, to remove any distortion due to the earlier heat-treatment of the glass, and to obtain optically parallel surfaces.

Two factors limit the usefulness of perforated glass at the present time:

1. The structural weakness of glass compared to metal is perhaps the most serious limitation. The Corning Glass Works is limited to the production of photosensitive glass blanks having maximum dimensions of approximately 17 x 20 x $\frac{1}{4}$ in. Inasmuch as the process has only recently been made available commercially, the manufacturing limitation on plate thickness may be removed in the future. The Optron Company of Dayton, Ohio, may also have a solution to the problem of providing thicknesses in excess of $\frac{1}{4}$ in. by means of a glass fusion process. Individual sheets of glass are stacked together to the desired overall thickness, held in compression, and brought up to a moderate temperature in an oven for an extended period of time. The bonding process, however, may not be necessary for increasing the structural strength of

the relatively thin glass under some conditions of application. A metal supporting grid backing the glass may be adequate, provided the moderate light blockage afforded by the structure does not prove objectionable.

2. Constant diameter perforations throughout their depth are relatively difficult to obtain. The photosensitive glass blank is normally exposed to a positive transparency of the perforation pattern in a well collimated light beam so that the glass is exposed to the perforation pattern through the entire thickness of the plate. Since the unexposed glass is also etched to some extent, the perforations in the glass become tapered when the glass is etched from one side only, or "hour-glass" shaped if the etching is allowed to proceed from both sides of the glass blank. Current practice at Corning results in a minimum taper of approximately 0.085 in. per in. (in contrast to 0.020 in. per in. as reported in Ref. 3). The projected area of the taper normal to the schlieren light path is the effective blockage to the light passing through the wall since the light within this region is completely scattered by the etched surface. For example, with a minimum perforation diameter of 0.0625 in., a porosity of 25% and a $\frac{1}{4}$ in. plate thickness etched from both sides, the effective light blockage amounts to approximately 20%. Although this figure represents a considerable improvement in the 75% blockage afforded by an opaque wall of the same porosity, the blockage may, under certain circumstances, be quite disturbing.

   Within limits, truly cylindrical holes can be etched by having the exposed volume of the glass in the shape of a cone and etching from the side having the smaller perforation diameter. The multiplicity of holes poses no particular problem in obtaining a conical shape to each exposed region in the plate. The positive transparency of the perforation pattern is placed in contact with the photosensitive glass blank. The assembly is then exposed to a beam of parallel light inclined with respect to the normal from the glass surface by an amount equal to the etching taper. During the exposure, the assembly is rotated about the normal. It should be noted that the size of the perforations in the positive transparency must be reduced from the desired pore diameter by an amount proportional to the etching taper and the glass thickness.

The limitation on structural strength of the perforated glass makes its application to test sections of small size more suitable. The perforated glass walls in conjunction with a conventional schlieren may serve in place of the multiple-source schlieren for investigations into the boundary layer on two-dimensional models.

## III TEST EQUIPMENT

Presented in Fig. 1 is a schematic representation of the multiple-source schlieren as arranged on the optical bench. The light source is a B-H6 high pressure mercury arc lamp rated at 900 watts. Two sheets of heat absorbing glass are required to reduce the intensity of the long wave length radiation that would endanger the adjacent condensing lens. The condensing lens is not absolutely necessary for the operation of the system but it was found to give more uniform illumination of the field. A sheet of ground glass serves to scatter the light prior to its passage through the perforated tunnel wall which acts as the source plate for the schlieren system proper. All the test work has been conducted with source plates 0.020, 0.060, and 0.125 in. thick and perforation diameters equal to the plate thickness. The porosity of all the plates was approximately 23%. The perforations were oriented in a staggered pattern such that each perforation is equidistant from the neighboring perforation. This particular pattern has been found to have more suitable aerodynamic characteristics compared to a large number of other patterns tested at this laboratory. The perforation geometry of the near-wall in tunnel installations is commonly identical to the source plate but in the bench tests it was also varied somewhat as will be described subsequently. All wall surfaces were chemically blackened to reduce reflections.

A mock-up of a 17 x 17 in. test section was also provided for testing on the optical bench. In order to illuminate adequately the considerably larger side wall area as compared to the early 6 x 6 in. test section, a light source consisting of 27-100 watt incandescent lamps and a ground glass panel was provided.

A variety of available lenses were utilized as field lenses of the schlieren system:

1. Eastman Kodak Anastigmat, 13½ in. focal length, f/3.5
2. Eastman Aero Ektar, 7 in. focal length, f/2.5
3. Eastman Aero Ektar, 12 in. focal length, f/2.5
4. Zeis Tessar, 150 mm. focal length, f/4.5
5. Dallmeyer Rapid Rectilinear, 22½ in. focal length, f/4
6. Perkin-Elmer Enlarger Lens, 6 in. focal length, f/4.

The cut-off plates were made by exposing Kodalith Ortho glass plates in a variety of ways which will be fully described in a subsequent section. The extremely high contrast emulsion assured practically opaque spots with high transmission in the intervening spaces. Measurements made on a sample plate indicated optical densities of 4.5 and 0.14 (transmissions of 0.003 and 72.5%) for the exposed and unexposed areas respectively. A 4 x 5 in. camera back with focal plane shutter provided the means of photographically recording the schlieren patterns.

A flow disturbance was provided in the test section by air flow impinging on a 54 deg. cone. The air at a total pressure of 38 psig. issued from a simple convergent conical-divergent nozzle having an exit diameter of 0.72 in., and an exit Mach number of 1.4 (based on one-dimensional isentropic flow). The test section was completely sealed except for the wall porosity so that all the air issuing from the nozzle was discharged to atmosphere through the porous walls. The pressure drop across the walls was approximately equal to 1 in. of mercury corresponding to the pressure drop existing in the actual transonic test section currently in operation at United Aircraft's Research Laboratory. The weak shock pattern existing in the vicinity of the perforation in an actual transonic installation was not simulated in this mock-up.

The arrangement of the components of the multiple-source schlieren when applied to an actual operating 6 x 6 in. transonic test section was essentially identical to the arrangement on the optical bench. One wall of the plenum tank surrounding the test section was located between the light source and the diffusing ground glass, and the other between the near-wall and the field lens. Ordinary glass windows in the plenum tank walls are provided along the light path.

## IV TEST PROCEDURE AND DISCUSSION OF RESULTS

### Multiple-Source Schlieren

#### Optical Bench Tests - Three-Dimensional

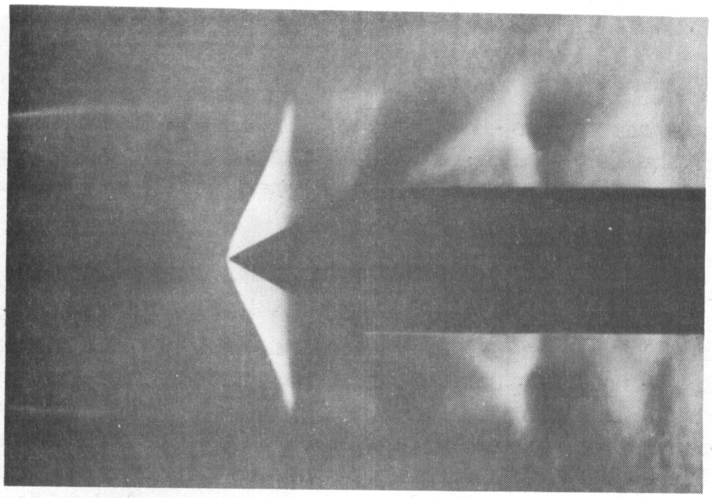
The initial series of tests of the multiple-source schlieren on the optical bench utilized a pair of 0.060 in. thick metal walls with a separation of 6 in., each having 0.060 in. diameter perforations equilaterally spaced on approximately 0.125 in. centers. The resulting wall porosity was approximately 23%. Two Eastman Kodak Anastigmat $13\frac{1}{2}$ in. f/3.5 aerial camera lenses were used as the field lenses. Since these lenses were designed for minimum aberrations with an object plane at infinity and the film located at the focal point, the two lenses were placed face to face with the source and cut-off plates located at the focal planes of the first and second lens respectively. This location also simplified the process of producing a cut-off plate since the source plate and its image are equal in size so that the cut-off plate could be produced by contact printing of the source plate on a photographic plate. Use of a cut-off plate produced in this manner revealed that the high intensity disturbances in the test section were rendered quite visible but the schlieren system was seriously lacking in sensitivity. It was observed that a great deal of light was being transmitted through the clear areas of the cut-off plate which resulted in a relatively high level of background illumination indicating that complete cut-off was not achieved. Some amount of scattered light is to be expected in the system due to the reflections occurring at the numerous air-glass interfaces in the field lenses. Low reflection coating of the lens elements, however, did not sufficiently reduce the amount of scattered light in the system to significantly improve the sensitivity.

A major portion of the difficulty was finally attributed to the fact that the diameters of the opaque areas in the cut-off plate were slightly smaller than the perforations in the source plate. Although the contact printing process used to produce the cut-off plate accurately reproduced the spacing of the perforations, the perforation diameters were reproduced slightly undersize. The difficulty was finally resolved by a modified contact printing process. A point source of light was directed at the source plate which was suspended a few thousandths of an inch above a photographically sensitized glass plate. During the exposure the source plate was given a small controlled circular movement, the diameter of the path traced determining the increase in size of the opaque area on the photographic plate. Use of a cut-off plate made with the opaque areas slightly larger than the images of the illuminated areas in the source plate resulted in a marked increase in the sensitivity of the system.

Contrary to expectations (see Appendix) no increase in sensitivity was noted by reducing the perforation diameter from 0.060 to 0.020 in. For this experiment both a pair of 13½ in. f/3.5 lenses and a Zeiss Tessar 150 mm. (6 in.) f/4.5 lens were used. Production of the cut-off plate followed the same procedure as outlined above to insure completeness of cut-off. The probable reason for the departure from theory was revealed in subsequent tests (p. 8) wherein the sensitivity of the system was found to be extremely dependent on the quality of the field lens. As a result, a decrease in the perforation diameter below a certain value, depending on the degree of correction in the lens, may not yield any increase in sensitivity.

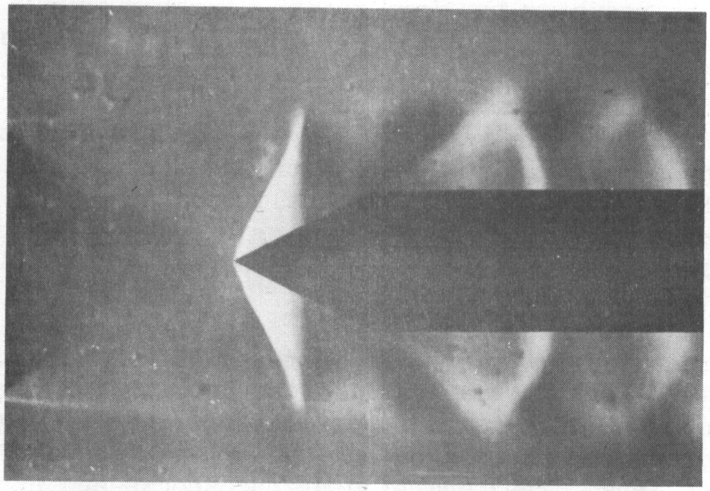
As predicted by theory, an increase in sensitivity was very evident when the test section span was increased to 17 in., again using the walls having the 0.060 in. diameter perforations. Unity magnification was maintained between the source and cut-off plates with a single 13½ in. f/3.5 field lens. The rendition of the shocks and expansion waves about the conical model was comparable to that obtained with a conventional parallel-light type schlieren (without test section side walls) utilizing the same 13½ in. f/3.5 lenses as collimators and a 0.060 in. diameter light source. The photographs taken under these two conditions are shown in Fig. 3.

A series of tests were conducted on the 17 x 17 in. test section at source plate to cut-off plate magnifications of ½ and ¼ rather than the value of unity as previously used. This was done in order to test the schlieren under conditions which might more nearly represent the requirements of an actual installation. An Eastman Kodak Aero Ektar 12 in. f/2.5 lens was used as the field lens and walls having perforation diameters of 0.060 and 0.125 in. were included. Since the direct contact printing process to produce the required cut-off plates is only possible



(a.) MULTIPLE – SOURCE SCHLIEREN PHOTOGRAPH

TUNNEL SPAN = 17 INCHES
PERFORATION DIAMETER = 0.060 INCHES
WALL POROSITY = 22%
BACKGROUND PATTERN VISIBILITY FACTOR = 0.08



(b.) CONVENTIONAL SCHLIEREN PHOTOGRAPH – NO TEST SECTION WALLS

LIGHT SOURCE DIAMETER = 0.060 INCHES
SCHLIEREN LENS FOCAL LENGTH = 13.5 INCHES

JET MACH NUMBER ≈ 1.4
STAGNATION PRESSURE = 53 PSIA
MODEL DIAMETER = 0.38 INCHES

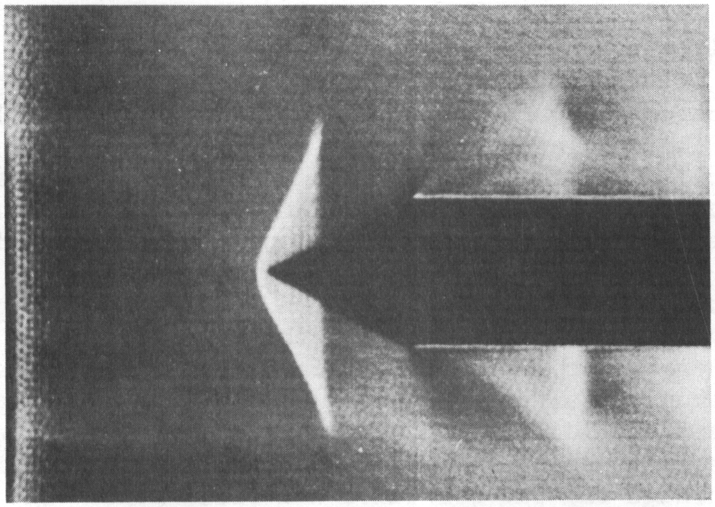
FIGURE 3. REPRESENTATIVE MULTIPLE—SOURCE SCHLIEREN AND CONVENTIONAL SCHLIEREN PHOTOGRAPHS

for a source plate to cut-off plate magnification of unity, the cut-off plate was made by exposing the photographically sensitized plate to the image of the source plate in the actual schlieren system. The apparent sensitivity of the schlieren system was definitely superior for the installation utilizing the 0.060 in. diameter perforations as compared to the installation having the 0.125 in. diameter perforations. This fact supports the theoretical prediction developed in the Appendix.

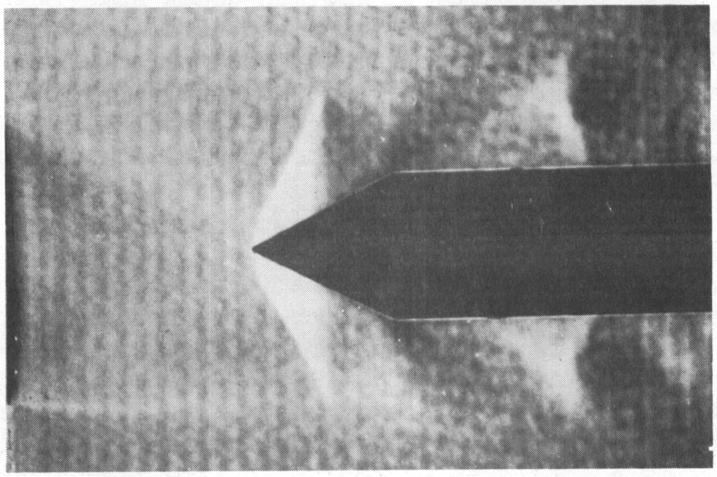
The effect of the lens aberrations on the sensitivity of the schlieren system was very dramatically evident in the tests performed with the Eastman Kodak Aero Ektar 12 in. f/2.5 lens. The cut-off plate was positioned for maximum cut-off as evidenced by the uniform darkening of the image of the test section centerline plane to a minimum illumination level. The completeness of cut-off was determined by looking at the source plate through the cut-off plate and field lens. The central portion of the field lens was observed to be uniformly dark but a very bright band of light existed at the periphery of the lens. The periphery of the lens was apparently not focusing the light received from the source plate in the same location as was the central portion of the lens. The lens was then masked by an opaque shield placed over the periphery of the front element of the lens. The rendition of the density disturbances about the conical model in a supersonic air jet was thereby immensely improved. The image produced by an Eastman Kodak Anastigmat $13\frac{1}{2}$ in. f/3.5 lens used in the earlier tests was inspected as above and found to have no specific zone that was contributing to the undesirable general illumination but rather that the entire lens aperture appeared illuminated. It is apparent that the field lens must be highly corrected for the particular object distance involved to be useful for application to a schlieren system requiring high sensitivity.

A Perkin-Elmer 6 in. f/4 enlarger lens was obtained on loan from WADC near the end of the contract period. The lens is highly corrected for conjugate distances of 18 and 9 in. which makes it quite suitable for application to a tunnel having a span of 6 in. As described under "Wind Tunnel Tests", p. 15, this lens was utilized in one application of the multiple-source schlieren system to an actual transonic test section. A limited study of its performance on the optical bench was also carried out. Shown in Fig. 4a is a schlieren photograph of the flow about the conical model in a free jet located between walls having perforation diameters of 0.020 in. and a porosity of approximately 23%. The span of the section is equal to 6 in. The rendition of the expansion regions and the weaker shocks is noticeably improved as compared to Fig. 4b which is a schlieren photograph taken with walls having perforation diameters of 0.060 in. and with the two $13\frac{1}{2}$ in. f/3.5 Eastman Kodak Anastigmat lenses as field lenses. It is felt that the difference in sensitivity noted in the tests is due to the difference in perforation diameter alone. The quality of cut-off in the system utilizing the pair of $13\frac{1}{2}$ in. f/3.5 lenses is quite good inasmuch as the lenses are being used for the conjugate planes for which they were designed.

An indication of the sensitivity of the multiple-source schlieren was obtained by introducing glass reference wedges into the test section to



(a.) PERFORATION DIAMETER = 0.020 INCHES
BACKGROUND PATTERN VISIBILITY FACTOR = 0.14



(b.) PERFORATION DIAMETER = 0.060 INCHES
BACKGROUND PATTERN VISIBILITY FACTOR = 0.11

JET MACH NUMBER ≈ 1.4
STAGNATION PRESSURE = 53 PSIA
MODEL DIAMETER = 0.38 INCHES
TUNNEL SPAN = 6 INCHES

FIGURE 4. EFFECT OF PERFORATION DIAMETER ON SCHLIEREN SENSITIVITY

produce a known deviation of the light rays. The most sensitive system tested (test section span of 17 in. and perforation diameters of 0.060 in.) was able to indicate the presence of a disturbance that results in the deviation of a light ray by $\frac{1}{2}$ minute of arc. According to the calculations made from material contained in a report by W. A. Mair (Ref. 4), a schlieren system sensitive to disturbances of this order is adequate for most flow visualization work. The deviation of $\frac{1}{2}$ minute of arc produces a considerable change in illumination at the film plane in most conventional schlierens, but, as Mr. Mair points out, most conventional schlierens are more sensitive than is usually necessary. Consequently, severe disturbances in the test section "overload" the system, i.e., the image of the light source formed through such a disturbance is either completely blocked by or completely misses the knife edge. Thus, the comparative severity of the disturbances can no longer be judged by the change in illumination at the film plane.

### Optical Bench Tests - Two-Dimensional

Tests were conducted to determine the suitability of the multiple-source schlieren for observation of the flow near the surface of a two-dimensional body. As explained on p. 2, so many of the diverging rays passing through the test section are blocked by a two-dimensional body extending across the span of the tunnel that the illumination in the vicinity of the body is seriously diminished. Consequently, the delineation of the surface is extremely poor. Observations in the immediate vicinity of the top or bottom walls of the test section would also be similarly hampered. To demonstrate the phenomenon, a partition was placed in the 17 x 17 in. test section extending between the source plate and the near-wall and located on the optical axis. With the walls having the 0.125 in. diameter perforations and the 12 in. f/2.5 lens positioned for a source plate to cut-off plate magnification of $\frac{1}{2}$, the illumination was not noticeably reduced up to a region approximately 3/16 in. from the surface of the partition. As the surface is further approached, the illumination is rapidly reduced and the visibility of the background pattern is markedly increased making it difficult to distinguish the actual surface. Although schlieren observations of the boundary layer on two-dimensional surfaces may therefore be impossible, observations of shock reflection at the tunnel wall are possible in that the actual surfaces of the wall need not be seen.

### Background Pattern Tests

It was observed in the very first tests of the multiple-source schlieren that a background pattern was present and that this pattern, under certain operating conditions, could seriously interfere with the observation of the flow disturbances in the test section. Complete elimination of the pattern is not considered possible for the reasons given on p. 1, but minimization of the visibility of the pattern is of great importance for maximum readability of the schlieren pictures. It was also noted on p. 1 that the character and visibility of the pattern changes for planes other than the centerline plane, the pattern being extremely severe in close proximity to either of the side walls. Inasmuch as most schlieren observation is concerned with disturbances generated in the test section centerline plane, all detailed work on the background pattern visibility has dealt with the centerline plane.

The background pattern existing for identically oriented source plate and near-wall as illustrated in Fig. 2 was considerably reduced by a 90 deg. coplaner rotation of one of the walls with respect to the other. Actually the same results may be achieved by a rotation of 30 deg. or 30 deg. plus any multiple of 60 deg. because of the equilateral spacing of the perforations in the plates. This rotational misalignment alters the light distribution pattern in the test section centerline plane because the light rays passing through various combinations of the perforations in the two walls no longer cross at common points in the test section centerline plane. Further reduction in the visibility of the background pattern was attempted by substituting for the near-wall other walls having perforation shapes such as rectangles, squares, and slots arranged in staggered, unstaggered, and herringbone patterns respectively. No material reduction in the visibility of the background pattern was noted although the structure of the pattern was modified. A small reduction in the visibility of the pattern was found when the circular perforation size and spacing in the near-wall was proportionately changed from that in the source plate. It is significant to note that complete uniformity of illumination in the test section centerline plane does not exist even with the removal of the near-wall. This plane is effectively illuminated by a series of overlapping circles. The area of each of the circles is determined by the intersection of the object plane with cones having their bases equal to the lens aperture and their apexes located at each of the perforations in the source plate. Through the use of square perforations in the source plate, a square aperture of proper size in the field lens and no near-wall, a high degree of uniformity of the illumination of the plane conjugate to the test section centerline plane is possible, but the introduction of the near-wall re-establishes the background pattern.

As a final attempt to reduce the background pattern visibility, a near-wall of 25% porosity containing perforations having a random distribution and random diameters between 1/32 and 1/8 in. was fabricated. This plate, in combination with a source plate having equilaterally spaced 0.060 in. diameter perforations, actually caused an increase in the visibility of the background pattern. Two patterns were now visible: (1) a regular pattern due to the presence of the uniformly perforated source plate and (2) a large scale random pattern due to the presence of the near-wall. The former pattern is quite pronounced and of finer texture than the slightly visible pattern produced by the source plate in the absence of the near-wall. No definite conclusions have been reached concerning the reason for the appearance of the former pattern.

Inasmuch as the background pattern appearing at the film plane is a duplication of the illumination received by the field lens from the test section centerline plane, the pattern should be independent of the focal length of the field lens. This fact was experimentally verified in the 17 x 17 in. test section successively utilizing the 12 in. f/2.5 lens and the 22 in. f/4 lens as the field lens. The diameter of these lenses are essentially identical and they were placed at equal distances from the source plate.

The efforts of the program were then directed toward the development of an equation relating the principal variables in the optical system with the visibility of the background pattern. Some of these variables were immediately fixed in order to concentrate the investigation on the variables of prime interest at this time. Walls having equilaterally spaced circular perforations and porosities of approximately 25% were adopted as most representative of current transonic tunnels. It had been previously established that a 90 deg. coplaner rotation of one of the walls with respect to the other produced a minimum background pattern visibility so that this orientation was maintained throughout the tests. As described above, the test section centerline plane is illuminated by a large number of overlapping circular areas. It was intuitively felt that the background pattern visibility would become lessened as the overlapping of these circular areas was increased. This overlapping obviously becomes greater as the lens diameter is increased and as the lens is moved closer to the test section. Furthermore, for a given porosity, there will be a larger number of such circular areas as the perforation diameter is decreased. Since all this light must pass through the near-wall, small perforations are again favorable in that the light is interrupted by a finer screen structure and hence tends to reduce the background visibility. The above considerations were initially set up in the following equation:

$$V = \left(\frac{d}{D}\right)\left(\frac{P}{w}\right) \qquad (1)$$

where

$V$ = background pattern visibility factor

$d$ = perforation diameter

$D$ = field lens diameter

$P$ = distance from source plate to field lens

$w$ = test section span

Tests were performed to determine the validity of eq. 1 with respect to variations in the value of the individual components of the bracketed terms while the value of the bracketed terms themselves remained fixed. The geometry and visibility of the background pattern was found to be unchanged, for a fixed perforation and field lens diameter, with a twofold variation in P and w. The comparison was made at equal magnifications of the test section centerline plane. It must be remembered that since the actual visual interference of the pattern varies as does the size of the structure of the pattern compared to the size of the model in the test section (or the spatial extent of the disturbance to be resolved), the visibility factor does not in itself specify the degree of visual interference until the pattern is compared to the size of the model under test. However, it is important to note that the utility of specifying the background pattern by this method lies in the fact that the type of pattern may be predicted for guidance in the selection of a suitable optical system. The visual interference of this pattern may then be estimated by comparison of the size of the model to a standard reference photograph of such a pattern.

For a fixed value of P and w, a threefold variation in the perforation and lens diameter was then made, keeping their ratio fixed. The visibility and structure of the pattern was once again found to be identical. The comparison was made, however, on the basis of a test section centerline plane magnification inversely proportional to the perforation diameter. An estimate of the actual visual interference must again be made by reference to the relative size of the pattern and the model under test.

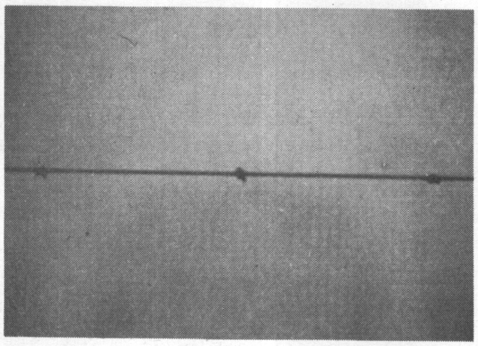
When the values of the individual bracketed terms in eq. 1 were varied inversely, i.e., the product of the two bracketed terms were held constant, the visibility of the pattern was found to change markedly. Through a large number of trial and error tests, it appears that the visibility of the pattern is quite adequately described, in the range of interest of the variables, by the equation:

$$V = \left(\frac{d}{D}\right)^{.71}\left(\frac{P}{w}\right). \qquad (2)$$

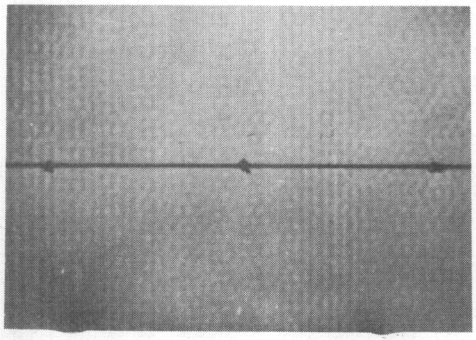
All the tests were performed with a 7 in. f/2.5 field lens since accurate control of the lens aperture was possible through the adjustment of a self-contained iris diaphragm.

At a fixed value of the visibility factor, the coarse structure of the pattern increases in size with a decrease in the value of the factor (P/w), however, the size of the finer structure remains fixed. What is considered most significant is that the contrast among the various elements in the pattern remains essentially unchanged.

Presented in Figs. 5a through 5d are reference photographs for visibility factors of 0.1, 0.2, 0.3, and 0.4 with a number of photographs in each group illustrating the change in the major structure of the pattern with a change in the factor (P/w). Reference marks are located on each photograph corresponding to separations of one inch in the test section centerline plane. All the photographs shown were taken with walls having perforation diameters of 0.060 in. It is apparent in Fig. 5d that eq. 2 has reached a limitation in its usefulness. The contrast among the



$\frac{P}{W} = 1.10$

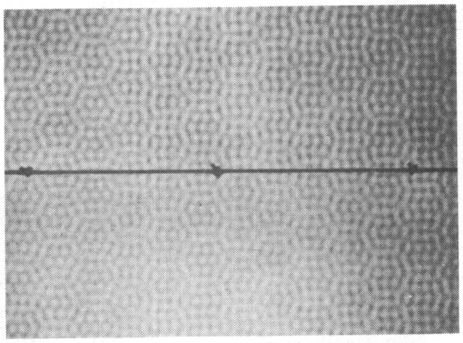


$\frac{P}{W} = 1.50$

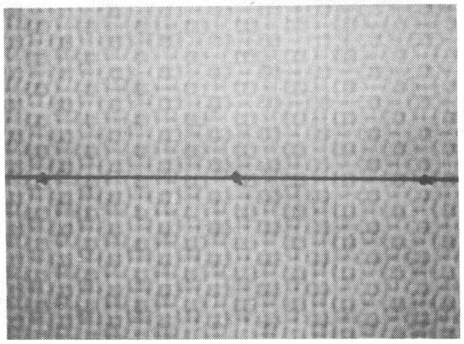
FIGURE 5a. BACKGROUND PATTERN REFERENCE PHOTOGRAPHS

PERFORATION DIAMETER = 0.060 INCHES

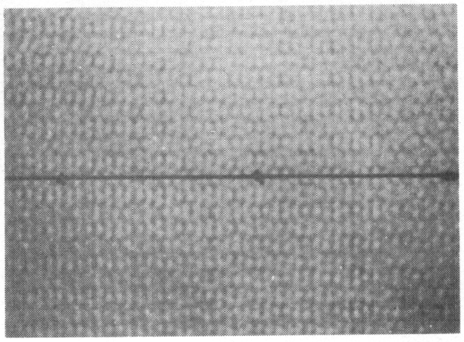
VISIBILITY FACTOR = 0.1



$\frac{P}{W} = 1.50$

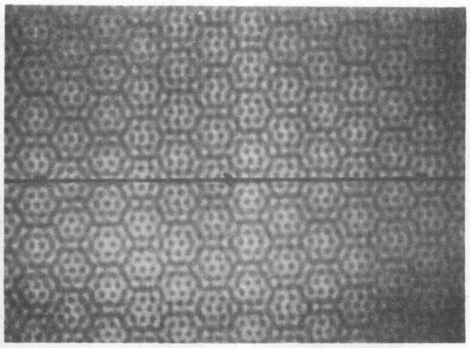


$\frac{P}{W} = 2.25$

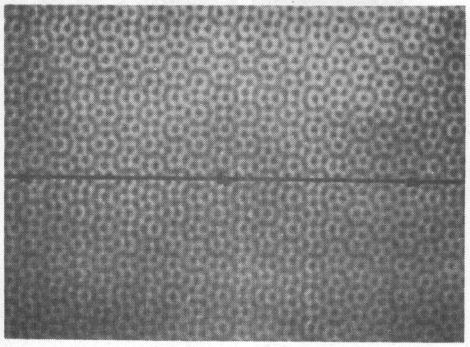


$\frac{P}{W} = 3.00$

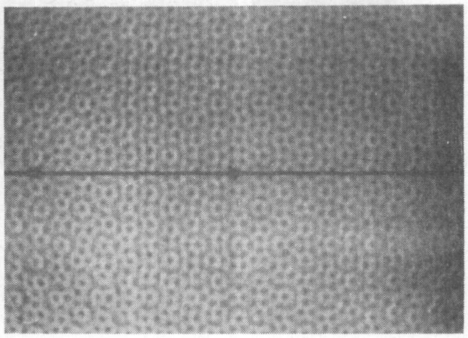
FIGURE 5b. BACKGROUND PATTERN REFERENCE PHOTOGRAPHS
PERFORATION DIAMETER = 0.060 INCHES
VISIBILITY FACTOR = 0.2



$\frac{P}{W} = 1.5$



$\frac{P}{W} = 3.0$

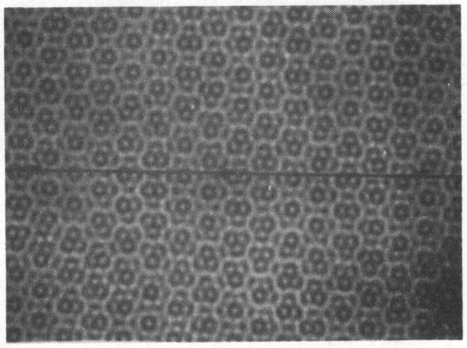


$\frac{P}{W} = 4.5$

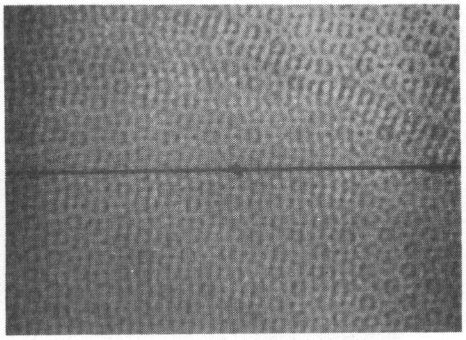
FIGURE 5c. BACKGROUND PATTERN REFERENCE PHOTOGRAPHS

PERFORATION DIAMETER = 0.060 INCHES

VISIBILITY FACTOR = 0.3



$\frac{P}{W} = 2.0$



$\frac{P}{W} = 4.0$

FIGURE 5d. BACKGROUND PATTERN REFERENCE PHOTOGRAPHS

PERFORATION DIAMETER = 0.060 INCHES

VISIBILITY FACTOR = 0.4

various elements of the pattern for P/w = 4.0 is noticeably less than the contrast appearing in the pattern for P/w = 2.0. Some caution must therefore be exercised in applying the equation in that it appears serviceable only for values of P/w less than about 3.0.

An estimate of the visual interference for any system may be made by comparing the reference photograph having a visibility factor equal to the value computed for the particular system with a superimposed silhouette of the model under test. The model should be drawn to a scale equal to the ratio of the perforation diameter used for the reference pictures (0.060 in.) to the perforation diameter utilized in the particular system.

Consideration of eq. 2 and the technique used to estimate the visual interference of the background pattern indicates the importance of utilizing the smallest perforation diameter aerodynamically and structurally practical. Not only is the visibility factor reduced by a reduction of the perforation diameter, but the scale of the pattern with respect to the model size is reduced resulting in a finer effective texture to the background pattern.

An item of some significance that was revealed during the tests was that, at certain uncorrelated values of lens aperture, the illumination of small areas in the background pattern is noticeably changed by very small changes in the lens aperture. In fact, an apparent inversion in the illumination level in these small areas as compared to the surrounding area, was noted as the size of the lens aperture passed through a particular value. The cause of this phenomenon was apparently resolved by some tests performed in the absence of the near-wall. All of the perforations in the source plate were blocked except for a few that were spaced several rows apart. The field lens aperture was reduced to a point where the illuminated areas in the film plane were distinctly separated circles. As the aperture of the field lens was increased, the area of the illuminated circles became progresively larger. No really pronounced change in appearance for each successive small incremental increase in lens aperture was noted up to the point where the illuminated areas became tangent. A slight additional increase in the lens aperture resulted in the overlapping of the adjacent illuminated areas so that these overlapping areas received twice their former illumination. The increase in contrast between these areas and the immediate surroundings was very apparent. Once the initial overlapping was accomplished, the structure of the pattern changed slowly as the lens aperture was further increased until the illuminated area corresponding to a particular perforation became tangent to that of the perforation beyond the adjacent perforation. The increase in illumination in the newly overlapping area also stood out clearly. In combination with the near-wall, the net result again appeared to be a sudden inversion in the illumination level of certain small areas in the pattern as compared to the general background illumination. The pattern was least visible at a very critical setting of the lens aperture between the settings encompassing the illumination inversion in the pattern.

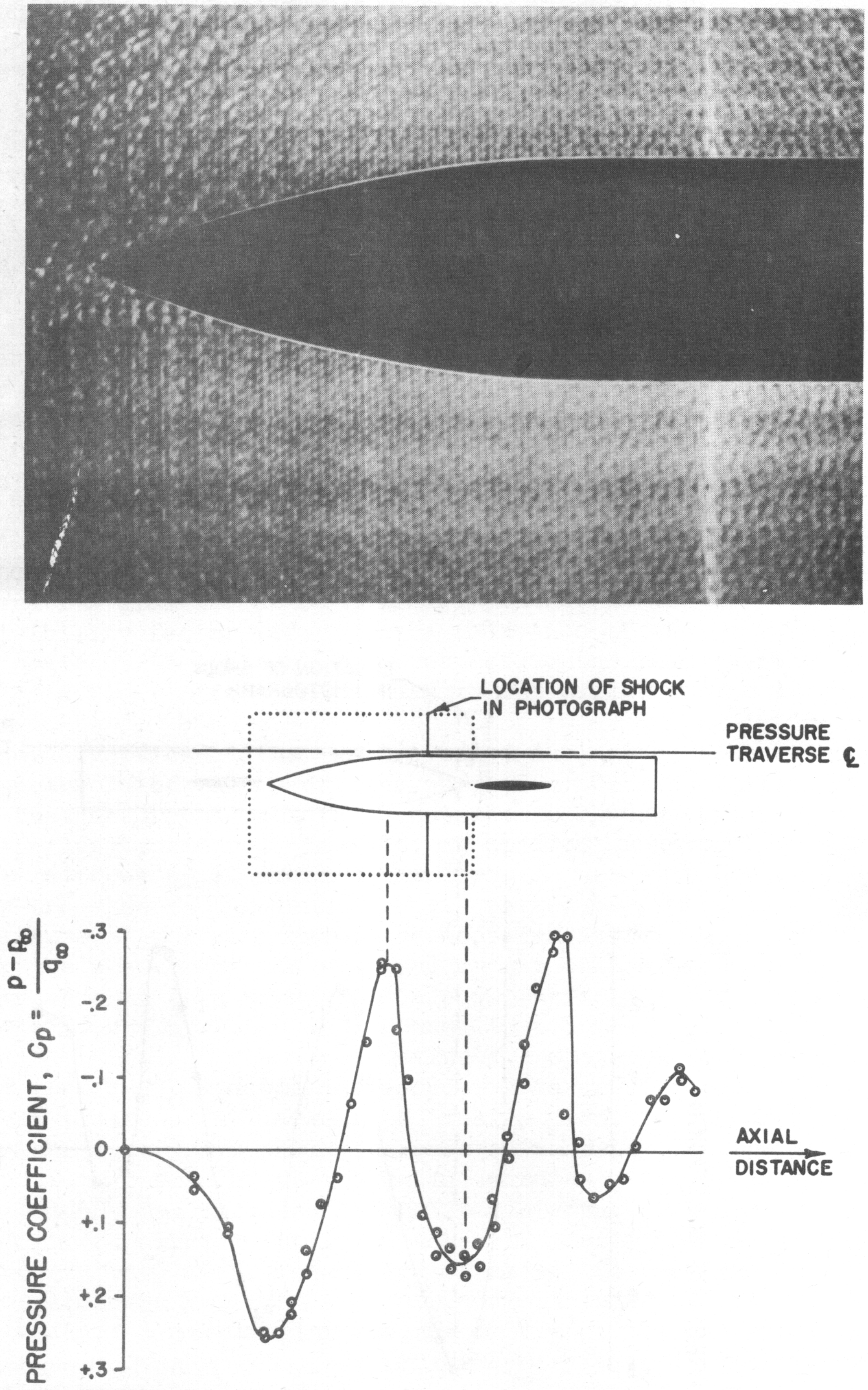
## Wind Tunnel Tests

The multiple-source schlieren was initially applied to an existing 6 x 6 in. transonic tunnel having perforated walls of approximately 23% porosity and perforation diameters of 0.060 in. The optical layout was essentially identical to that shown in Fig. 1. The mercury arc lamp housing was located outside the plenum tank enclosing the test section proper, the light being transmitted through a window to the ground glass diffusing screen located approximately two inches from the test section wall. The 12 in. f/2.5 field lens was also located outside the plenum tank with ordinary plate glass serving as a window in the plenum tank.

Some difficulty was encountered in the fabrication of a suitable cut-off plate for this installation. Of necessity, the cut-off plate had to be produced by exposing a photographic plate to the image of the source plate formed by the field lens in the schlieren system. It was found, however, that the size of the opaque areas in the cut-off plate was slightly smaller than the image of the perforations in the source plate so that complete cut-off of the light was not possible. This situation is similar to the condition reported in the tests performed on the optical bench. A satisfactory cut-off plate was finally made by utilizing the original plate to produce a positive transparency. This, in turn, was used to expose the final cut-off plate while the latter was given a small controlled circular movement thereby increasing the diameter of the opaque areas while maintaining their spacing.

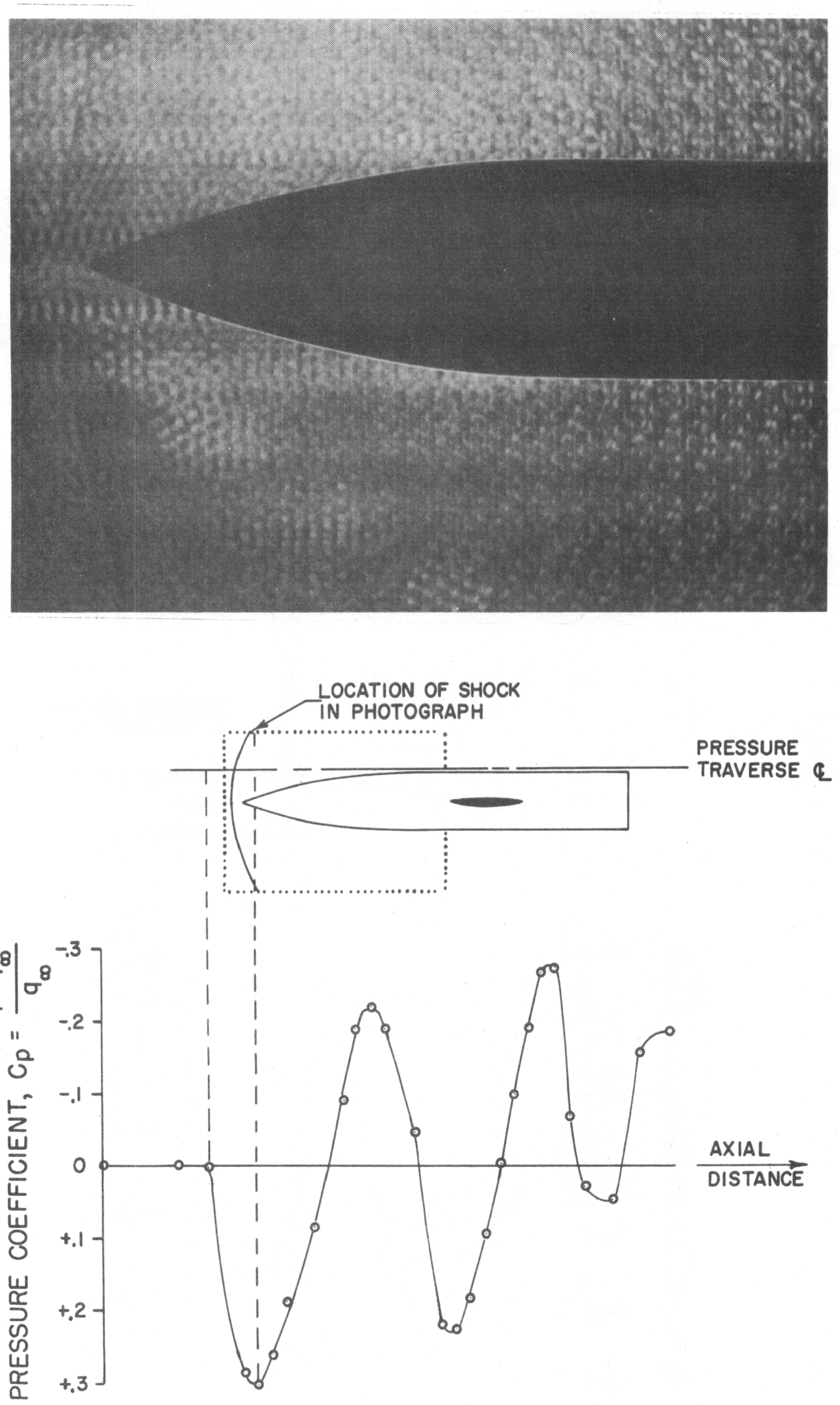
Photographs were taken of the flow about a cylindrical model having a 6 caliber ogive nose and an unswept biconvex wing. At a free stream Mach number of 1.0, static pressure surveys indicated that a shock wave existing on the body of the model and the bow wave due to the presence of the wing occurred in the same transverse plane. Shown in Fig. 6 is the schlieren picture of this flow condition. The shocks are clearly shown and occur in the position indicated by the static pressure survey.

As the free stream Mach number was increased, the shock system present at a Mach number of 1.0 moved downstream and out of the field of view. At a free stream Mach number of 1.1, the bow wave that had formed ahead of the nose of the model was in the field of view and is plainly seen in Fig. 7. The direction of cut-off was arbitrarily reversed in Fig. 7 as compared to Fig. 6 so that the shock now appears as a dark line against the background illumination. Once again the location of the shock in the photograph is within the region indicated by the static pressure survey. It should be pointed out that the formation and location of the shocks at Mach numbers near unity is sensitive to relatively small changes in Mach number and that the measured static pressure distributions may only differ in subtle ways. For example, the fore part of the pressure rise upstream of the wing as shown in Fig. 6 is quite steep while the rear part is relatively moderate. Since the static pressure tube used to obtain the survey has a boundary layer along its surface and since the pressure rise across a shock is transmitted upstream of the actual shock location through this boundary layer, it might be expected that the actual shock



STAGNATION PRESSURE = ATMOSPHERIC
TUNNEL SPAN = 6 INCHES
PERFORATION DIAMETER = 0.060 INCHES
WALL POROSITY = 23%
MODEL DIAMETER = 0.8 INCHES
BACKGROUND PATTERN VISIBILITY FACTOR = 0.27

FIGURE 6. MULTIPLE-SOURCE SCHLIEREN PHOTOGRAPH AND PRESSURE SURVEY - M = 1.0



STAGNATION PRESSURE = ATMOSPHERIC
TUNNEL SPAN = 6 INCHES
PERFORATION DIAMETER = 0.060 INCHES
WALL POROSITY = 23 %
MODEL DIAMETER = 0.8 INCHES
BACKGROUND PATTERN VISIBILITY FACTOR = 0.27

FIGURE 7. MULTIPLE-SOURCE SCHLIEREN PHOTOGRAPH AND PRESSURE SURVEY – M = 1.1

is located near the downstream side of the steep pressure rise. The expected location is verified by the schlieren photograph. In Fig. 7, the fore part of the pressure rise in the same region is no longer particularly steep, the gradient becoming more severe near the end of the pressure rise. The location of the shock may therefore be expected near the end of the pressure rise. This point is just outside the field of view of the schlieren picture so that pictorial evidence of the shock is not available, but it was observed during the testing that the shock disappeared from the field of view just before the Mach number of 1.1 was reached. It is apparent from the foregoing discussion that the schlieren system is superior to a pressure survey for critically locating the position of shocks.

The visibility factor of the background pattern in Figs. 6 and 7 is a rather high value of 0.27. Inasmuch as the test section was not designed with the schlieren in mind, the production of a schlieren photograph having a low background pattern visibility factor was not possible with the equipment available. For example, the full aperture of the 12 in. f/2.5 field lens could not be utilized in the tests because of the excessive aberrations in the lens periphery, the maximum acceptable aperture being approximately f/4.8. It was also noted that the granularity of the background pattern was considerably reduced at full cut-off, resulting in less visual interference. However, as the degree of cut-off was reduced, the character of the background pattern rapidly approached that of the reference pictures taken with no cut-off plate in the optical system. A variation in the visibility of the background pattern is apparent in each of the two figures due to the non-uniformity of cut-off in the particular installation. The somewhat non-uniform cut-off was also apparent without flow in the tunnel and was due primarily to the inability to align the field lens and cut-off plate properly with respect to the source plate because of the absence of suitable reference points. Alignment on the optical bench is considerably simpler and the uniformity of the cut-off is quite satisfactory. Proper design of the wind tunnel with respect to the schlieren system will considerably improve the uniformity of cut-off and the convenience of operation of the multiple-source schlieren.

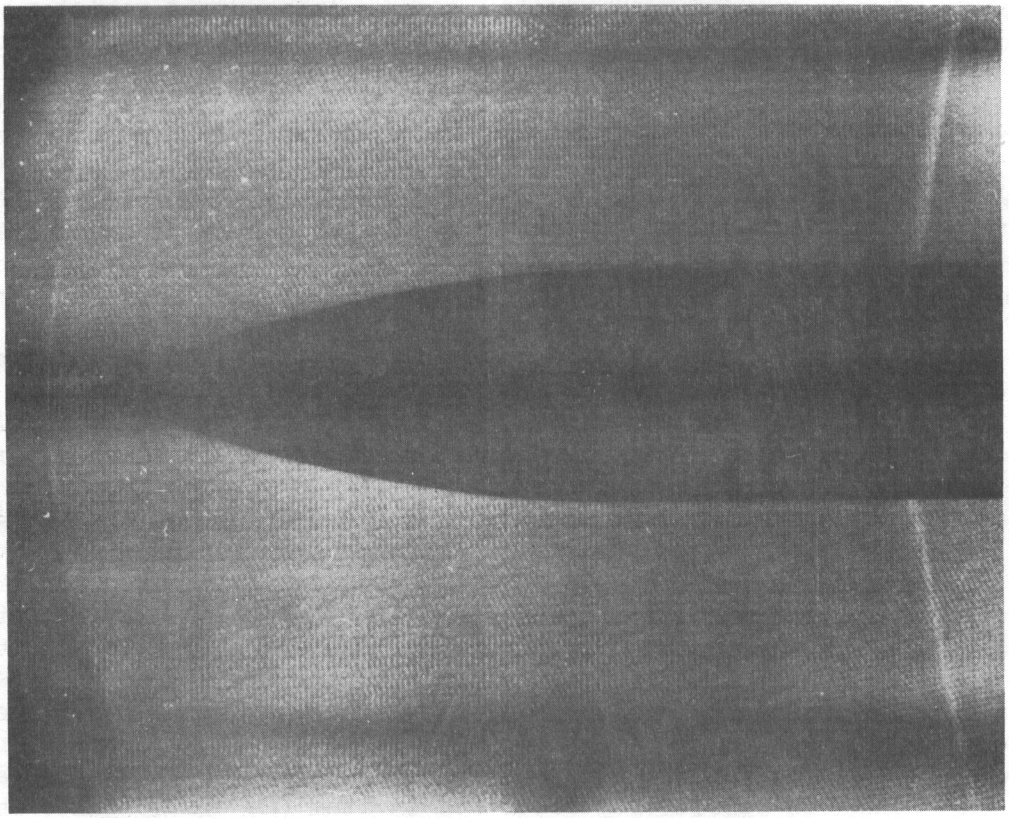
A noticeable increase in the visibility of the background pattern was observed in localized areas and was found to be caused primarily by the blocking of several rows of perforations in the source plate by the external side wall supporting structure. It was observed in tests on the optical bench that a reduction in the depth of the supporting structure reduced the severity and extent of the background pattern in these specific areas. The effective depth of the structure can be minimized by insertion of the ground glass diffusing screen into the open areas of the supporting structure so that the glass is in close proximity to the wall. Provision must be made, of course, for the removal of the air from the test section through the perforations. A staggered arrangement of overlapping strips of diffusing screen in each support structure opening may be a suitable solution.

Application of the multiple-source schlieren was also made to an outmoded 6 x $6\frac{1}{4}$ in. transonic test section. Since it was no longer in use for aerodynamic testing, a revision to the test section for optical reasons alone was possible, with only secondary concern with the effect on the aerodynamic performance of the section. The walls had a porosity of approximately 7% and perforation diameters of 0.060 in. The revision consisted of removing a section of both walls and replacing them with inserts having a porosity of approximately 23% and perforation diameters of 0.020 in. A Perkin-Elmer 6 in. f/4 enlarger lens was obtained on loan from WADC for use as the field lens in this specific test. As was mentioned earlier, this lens is extremely well corrected for conjugate distances of 18 and 9 in. These distances are ideally suited for application to the 6 in. tunnel span in that the lens may be conveniently located outside the plenum tank and the image size is convenient. Because of its high degree of correction, it was expected that the use of this lens in conjunction with the 0.020 in. diameter perforations in the tunnel walls would result in a schlieren system of notably higher sensitivity than the previous tunnel installation. A great deal of alignment difficulty was again encountered in the installation as previously cited. In this case, the alignment is substantially more critical than in the previous installation because the perforation diameter is decreased by a factor of three and the focal length of the lens is decreased by a factor of two. The cut-off achieved was far from uniform and the apparent sensitivity of the system was only equivalent to that obtained in the first tunnel installation.

Shown in Fig. 8 is a schlieren photograph taken at a Mach number of approximately 1.1 with the same ogive model used for the tests in the first tunnel installation. The field coverage was increased above that obtained in Figs. 6 and 7 so that both the bow wave ahead of the model and the bow wave upstream of the wings on the model were visible simultaneously. The background pattern visibility factor is equal to 0.14. The visual interference of the pattern is greatly reduced from that seen in Figs. 6 and 7 because of the reduction in the visibility factor and also the reduction in the ratio of the perforation diameter to the model size. The gradual variations in illumination apparent in Fig. 8 must not be interpreted as variations in the flow density but are due rather to the non-uniformity of cut-off. The change in illumination in the field is considerably more evident in the original negative of Fig. 8. The reproduction has been "dodged" in the photographic printing process to show both bow waves to best advantage. It should be stressed that the non-uniformity of cut-off does not result from the air flow through the test section, but is a result of the difficulty of alignment of the system with the equipment on hand. The previously described results of the tests with this system on the optical bench revealed that the sensitivity was increased as compared to the sensitivity obtained with 0.060 in. diameter perforations and a 6 inch test section span.

### Color Schlieren

As described in Section I, the only change required in the black and white multiple-source schlieren to convert the system to a color schlieren is the substitution of a color transparency of a continuous spectrum for each of the opaque areas in the cut-off plate. As in the black and white



FREE STREAM MACH NUMBER = 1.1
STAGNATION PRESSURE = ATMOSPHERIC
TUNNEL SPAN = 6 INCHES
PERFORATION DIAMETER = 0.020 INCHES
WALL POROSITY = 23 %
MODEL DIAMETER = 0.8 INCHES
BACKGROUND PATTERN VISIBILITY FACTOR = 0.14

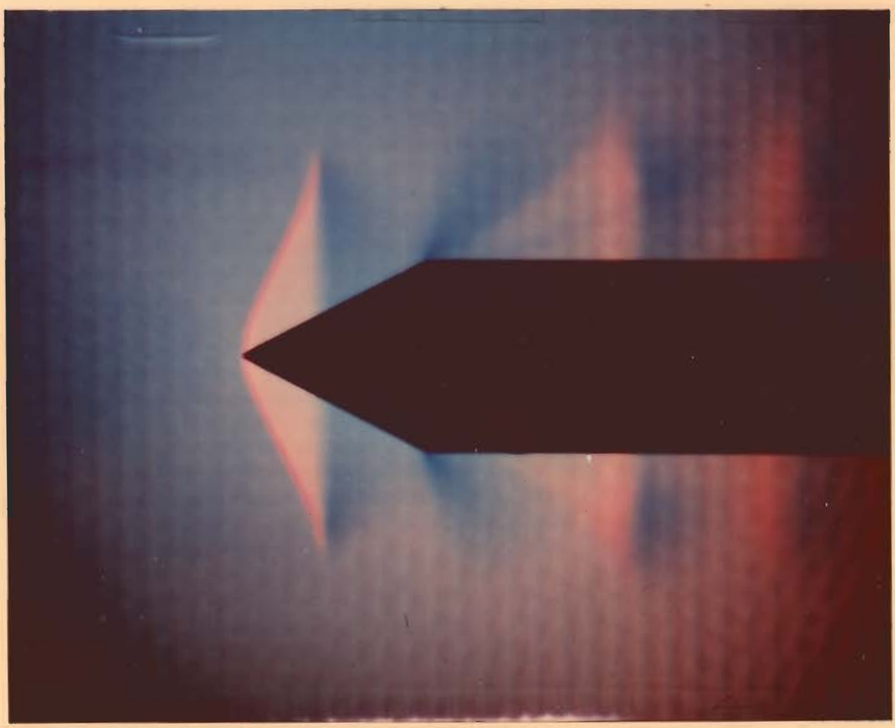
FIGURE 8. MULTIPLE-SOURCE SCHLIEREN PHOTOGRAPH

system, the spectrum transparencies must be in accurate register with the image of the perforations in the source plate of the schlieren. The schlieren arrangement consisting of perforation diameters of 0.060 in., walls separated by 17 in., and a single $13\frac{1}{2}$ in. f/3.5 lens was utilized for the tests. The image of the source plate was arranged to be equal in size to the source plate. The spectra transparency for the cut-off plate was then made external to the schlieren system proper. A well collimated light beam was directed through the source plate, a large water prism, and onto a sheet of Ektachrome film. By using the collimated beam and the actual source plate, the spacing of the individual spectra on the transparency is an accurate reproduction of the spacing of the perforations in the source plate. This statement is strictly true only for a particular wavelength in the spectrum, i.e., the wavelength for which the prism is set for minimum deviation. For all other wavelengths, the spectrum spacing in the direction of dispersion is slightly greater or less than the spacing for the aforementioned wavelength. The theoretical consequences of this distortion are (1) that the background illumination in the schlieren is of uniform color for only one wavelength, (2) the color change (i.e. sensitivity) produced by a given disturbance varies according to its position in the field of the schlieren, and (3) the light from any particular source that passes through the disturbance is rendered a slightly different color than the light from an adjacent source that passes through the same disturbance. The practical consequences are not particularly serious, however. The spectra transparency need only be used for one particular background color while the magnitude of the change in sensitivity described in item (2) can be quite small. Although the rendition of the disturbances is not spectrally pure, the dilution due to the cause indicated in item (3) is of relative unimportance.

Of real significance is the fact that the spectra are not generated from true point or line light sources. The spectra dispersion consequently could only be made of the order of two to three times the diameter of the finite sources. Thus, not only is the spectrum transparency not pure but it is also used to filter a light source of relatively large size. In addition, the color reproduction by the film is, of course, imperfect. These combined factors resulted in quite poor monochromatic rendition of a particular disturbance.

Shown in Fig. 9 is a color photograph, taken with the color multiple-source schlieren, of the flow disturbances about the conical model in a free jet. The orientation of the spectra is arranged to have a system sensitive to gradient components in the flow direction. Positive density gradients (shocks or gradual compressions) are rendered red, orange or yellow, and negative density gradients (expansion regions) are rendered blue, while the undisturbed regions are a blue-green. A reversal of this rendition is possible by the substitution of a spectra transparency having the dispersion in the opposite sense.

The color photograph may be compared to the equivalent black and white schlieren photograph shown in Fig. 3a. An approximately equivalent amount of information is shown in each photograph, but the color schlieren



JET MACH NUMBER ≈ 1.4
STAGNATION PRESSURE = 53 PSIA
MODEL DIAMETER = 0.38 INCHES
TUNNEL SPAN = 17 INCHES
PERFORATION DIAMETER = 0.060 INCHES
BACKGROUND PATTERN VISIBILITY FACTOR = 0.08

FIGURE 9. COLOR MULTIPLE-SOURCE SCHLIEREN PHOTOGRAPH

does so in a more vivid manner. In complicated flow phenomena, there is no doubt that a photograph produced in a color schlieren is much simpler to interpret because the human eye is capable of distinguishing and remembering colors more readily than shades of gray.

### Miscellaneous

An interesting additional feature in the use of the schlieren was demonstrated. Front lighting of the model provided excellent rendition of the configuration or texture of the model surface facing the field lens. This technique has been used in the past on conventional schlieren and has proved to be of some value in locating reference points or non-axisymmetric protuberances on the model that do not appear in silhouette. Presented in Fig. 10 is a multiple-source schlieren photograph taken of the flow about a 20 deg. cone in a free jet. The model is painted white with a dark stripe extending from the apex to the base of the model. Observations made with the front lighting revealed that its presence does not in any way detract from the rendition of the density disturbances.

## Perforated Glass Walls

Two samples of perforated glass measuring approximately $2\frac{1}{2}$ x 3 in. and 0.050 in. thick having equilaterally spaced perforations of 0.060 in. diameter and a porosity of approximately 23% were tested with a conventional parallel-light schlieren. The perforations are "hour-glass" shaped in transverse section because of the etching procedure described on p. 4. The transparency of the glass portion of the plates is quite high so that the light transmission through the glass and the perforations are sensibly equal. The presence of the perforated glass in the light path of the schlieren is not readily detected when the knife edge is removed from the system. With the introduction of the knife edge, however, it was observed that a considerable difference in illumination existed at the film plane between the glass area and the perforation area and that the illumination in the glass area was not uniform. This difference in illumination is due to the fact that the polished surfaces are not parallel nor sufficiently flat. Greater precision in the polishing of the surfaces was not possible because of the extreme thinness of the glass compared to its surface dimensions.

Shown in Fig. 11a is a conventional schlieren picture taken of the flow about a two-dimensional wedge airfoil in a transonic test section having solid glass side walls. The two samples of perforated glass are attached to the outside surfaces of the glass walls covering part of the field, and the perforations intentionally misaligned. Comparison of this figure with the conventional schlieren picture (Fig. 11b) taken of the same test section with two carefully aligned perforated brass plates shows that the principal shock wave and the model contour are much more clearly defined through the perforated glass plates, notwithstanding their relatively poor quality. The porosity, perforation diameter, and thickness of the brass plates were approximately equal to the values found in the perforated glass.

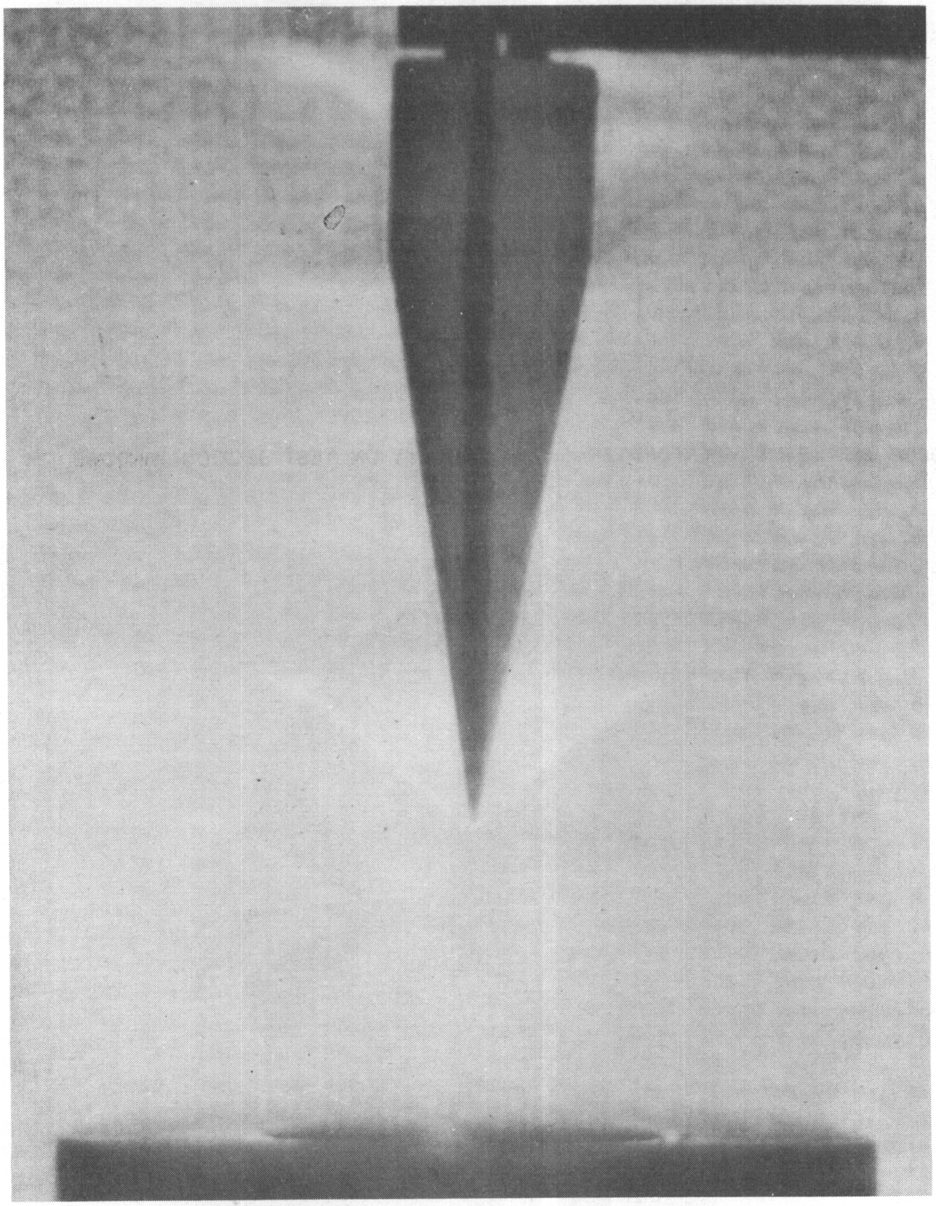
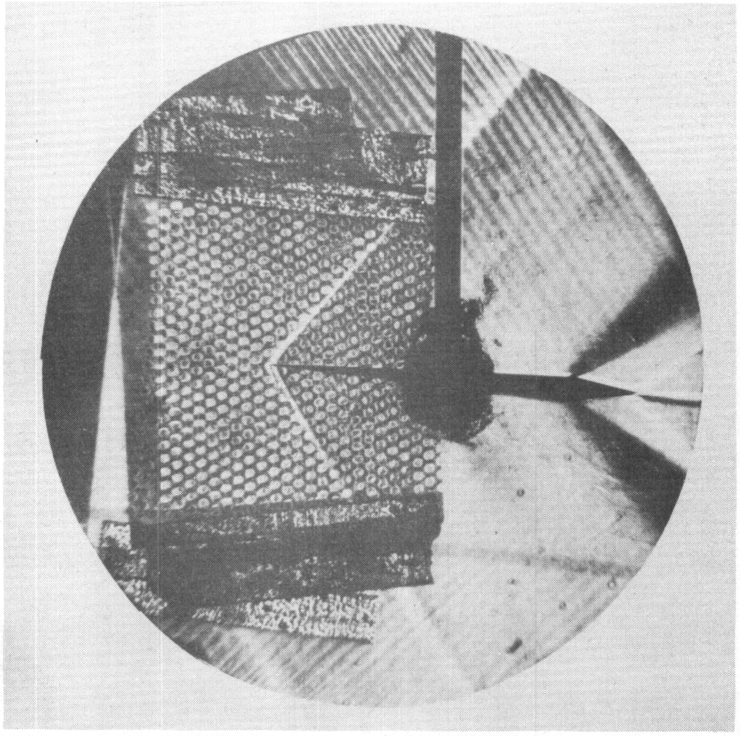
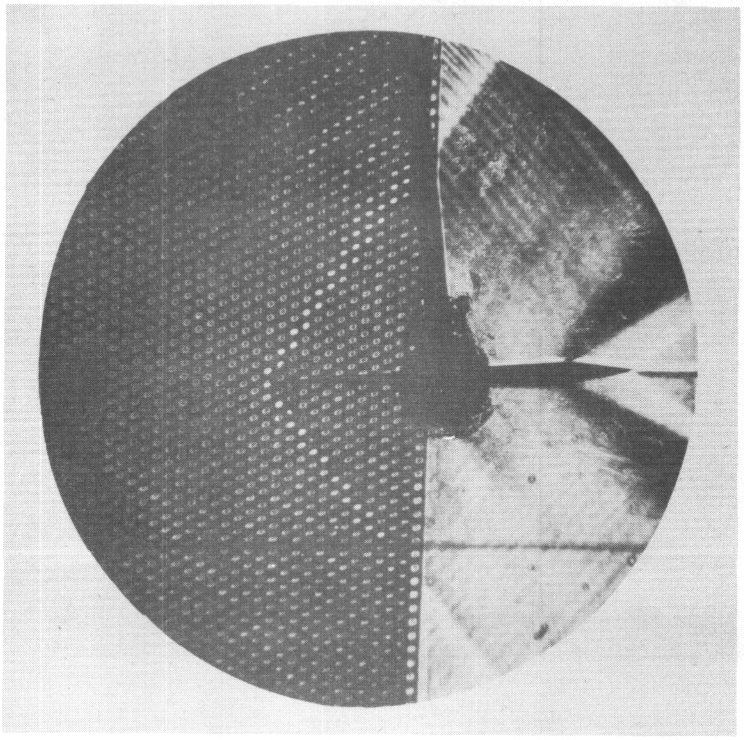


FIGURE 10. MULTIPLE-SOURCE SCHLIEREN PHOTOGRAPH — MODEL FRONT LIGHTED



(a.) 0.060 INCH THICK PERFORATED GLASS OVERLAY ON TEST SECTION WINDOWS



(b.) PERFORATED METAL OVERLAY ON TEST SECTION WINDOWS

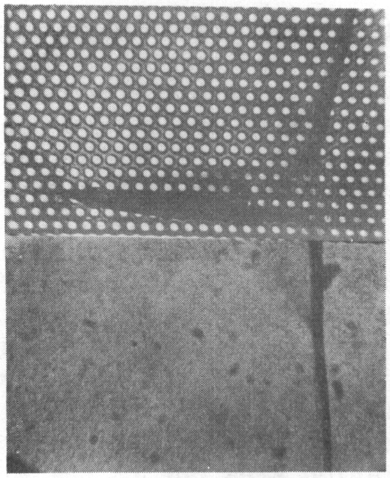
FIGURE 11. CONVENTIONAL SCHLIEREN PHOTOGRAPHS

Several other samples of perforated glass were obtained having the same perforation diameters and porosity as the first samples. The thickness of the plates, however, were nominally 0.2 in. and the perforations were kept quite cylindrical by means of the modified production technique described on p. 4. The increase in thickness made possible the successful optical polishing of the surfaces to accuracies commensurate with the sensitivity of the conventional schlieren. The thickness is also more representative of the value required in small wind tunnels for structural strength. The samples were immediately found unsuitable because of the relatively low light transmission of the glass. To the eye, the glass appeared quite milky. The sample was very readily visible in the schlieren with the knife edge removed. The optical polishing of the plates was quite satisfactory as was proved by the uniform darkening of the plate as the knife edge cut-off was increased. A pronounced contrast can still be noted between the glass area and the perforation area due to the glass absorption. Shown in Figs. 12a and 12b are conventional schlieren photographs of the flow about a subsonic airfoil in a two-dimensional transonic section having solid glass side walls. Two samples of the perforated glass were again attached to the outside surfaces of the glass walls covering part of the field. The perforations were aligned and misaligned in the two respective photographs. Fig. 12c is a photograph taken under identical conditions with the perforated glass replaced by two carefully aligned pieces of perforated metal. Although the shock wave and the model contour are somewhat more clearly defined through the perforated glass plates, the small gain in information is not particularly noteworthy.

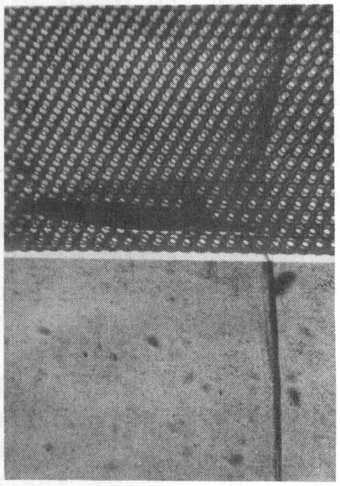
Inquiry was made of the Corning Glass Works concerning the cause of the milky appearance in the glass. They reported that their process normally produces perforated glass with glass areas of high transmission and feel that the processing of the particular samples was at fault.

## V SUMMARY AND CONCLUSIONS

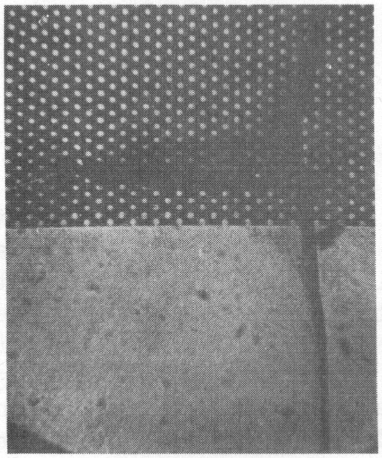
Investigations were made into methods of observing the flow field in a perforated wall type transonic wind tunnel. Two methods were evaluated experimentally and were found to be of definite utility. These methods are (1) the use of a multiple light source schlieren system whereby the perforations in one metal wall act as a series of light sources, and (2) the replacement of perforated metal walls with perforated glass in conjunction with a conventional parallel-light schlieren system. In connection with (1), a series of successful tests were completed on the optical bench and in operating transonic wind tunnels. An empirical equation was also developed relating the prime variables in the application of a multiple-source schlieren with respect to the visual interference resulting from the presence of the perforated metal walls. Experiments were performed with a modification to the basic multiple-source schlieren that converts the system to a color schlieren.



(a.) 0.2 INCH THICK PERFORATED GLASS OVERLAY ON TEST SECTION WINDOWS. PERFORATIONS ALIGNED.



(b.) 0.2 INCH THICK PERFORATED GLASS OVERLAY ON TEST SECTION WINDOWS. PERFORATIONS MISALIGNED.



(c.) PERFORATED METAL OVERLAY ON TEST SECTION WINDOWS. PERFORATIONS ALIGNED.

FIGURE 12. CONVENTIONAL SCHLIEREN PHOTOGRAPHS

The following conclusions were drawn from the experimental and analytical investigations of the multiple-source schlieren system:

1. The system is sufficiently sensitive to be of definite utility as an instrument for flow visualization in transonic wind tunnels.
2. Functioning of the system is quite satisfactory in actual application to operating transonic wind tunnels.
3. With the proper choice of variables in the test section and schlieren design, the visual interference due to the presence of the perforated metal walls may be reduced to such an extent as to be inconsequential.
4. The sensitivity of the multiple-source schlieren is proportional to the ratio of the test section span to the perforation diameter.
5. The sensitivity of the system is highly dependent on the quality of the optical components.
6. A color multiple-source schlieren is a practical system for flow visualization.
7. The empirical equation developed relating the prime variables influencing the visual interference resulting from the presence of the perforated metal walls is adequate for the major range of interest in the variables.
8. The system is somewhat limited for application to testing of two-dimensional bodies in that the surface of the body and the flow in close proximity to the surface is not well defined.

In addition the following conclusion was drawn from investigations into the use of perforated glass walls in conjunction with a conventional schlieren system:

9. Although final evaluation of the optical suitability of the perforated glass has not been completed, practical application of perforated glass to transonic test sections appears to be restricted to small tunnel sizes.

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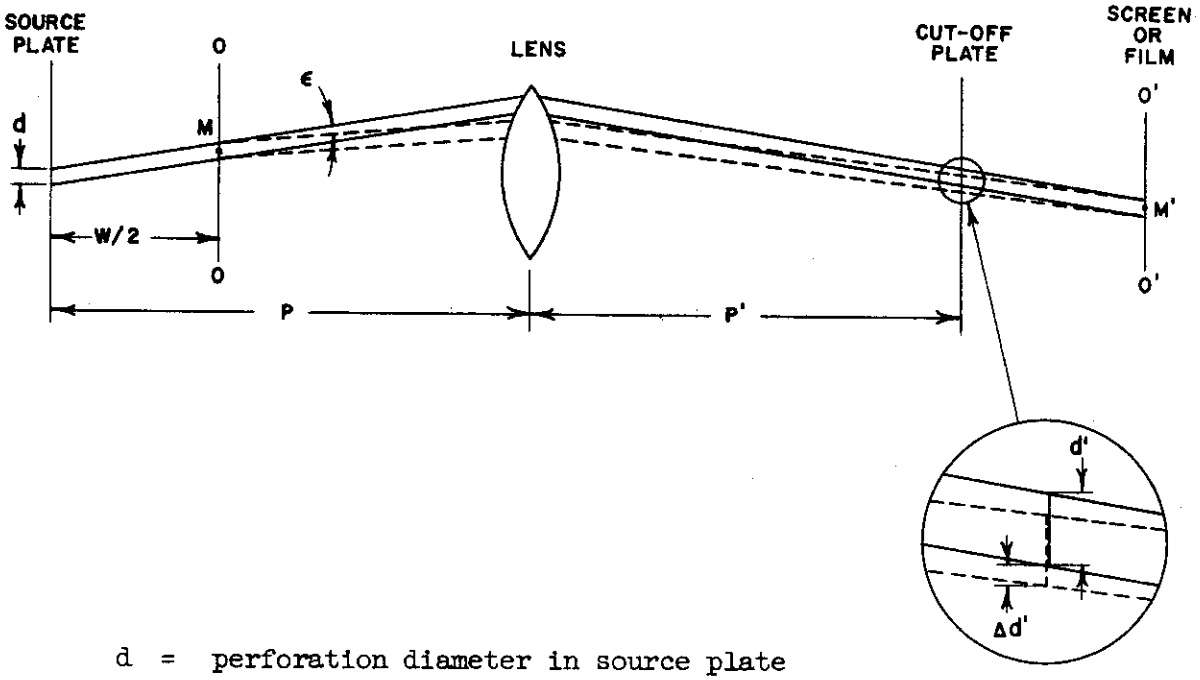
## APPENDIX

### Factors Affecting the Sensitivity of the Multiple-Source Schlieren



$d$ = perforation diameter in source plate

$P$ = distance from source plate to field lens

$M$ = location of disturbance in the test section

$w$ = test section span

$\epsilon$ = angular deflection of light ray by disturbance in the test section

Primed symbols are conjugate locations or distances of unprimed symbols.

Consider a pencil of rays from a single slit light source having a width d being refracted by a density disturbance through an angle $\epsilon$ at point M in the test section plane O-O. The position of the refracted ray is not altered on the film plane O'-O' due to the fact that this plane is conjugate to the object plane O-O, but the refracted ray has been shifted in the plane of the cut-off plate. The shift, $\Delta d'$, relative to the width of the image of the slit is a measure of the sensitivity of the system and is related to the other physical constants of the system by geometric optics. The relationship is simple to visualize if it is remembered that, after refraction by the disturbance, the position of the image of the source on the cut-off plate with respect to the image formed by the undisturbed ray is the same as the virtual object found by extending the deviated rays from plane 0-0 back to the plane of the source plate. Expressed algebraically, this relationship becomes

$$\frac{\Delta d'}{d'} = \frac{\Delta d}{d} = \epsilon \, \frac{w/2}{d} .$$

The sensitivity, therefore, is only a function of the distance of the disturbance from the source plate and the light source slit width.

Since the manifestation of the system sensitivity occurs in the change in illumination at the screen, the derivation holds strictly only for a slit source. The increase in illumination, in this case, is proportional to the displacement. For a circular light source, the derivation for image displacement is the same but the increase in screen illumination is no longer a linear function.