C.P. No. 167
(16,023)
A.R.C. Technical Report

MINISTRY OF SUPPLY

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CURRENT PAPERS

Schlieren Methods for Observing High-speed Flows

By

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LONDON: HER MAJESTY'S STATIONERY OFFICE
1954
Price 2s 6d net

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1st July, 1953

SUMMARY

This paper discusses the present state of knowledge concerning the use of schlieren and direct-shadow methods for the visualization of high-speed flow, the emphasis being on the use of the methods in wind tunnel experiments. The techniques for observing flows which are two-dimensional or which possess axial symmetry have reached an advanced stage of development, and are satisfactory for most investigations of this kind; recent progress is reviewed in Part I.

In contrast, comparatively little work has been done on the development of techniques for visualizing the flow round finite wings and wing-body combinations. Several methods which may be useful for the study of flows of this type are described briefly in Part II, but further work is necessary before the value of these methods can be assessed.

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1./

1. Introduction

The changes of air density which occur when air flows at high speed past a body are accompanied by changes of refractive index, and they may thus be observed or photographed by optical methods. Among these methods, the schlieren techniques are those most widely used in aeronautical work, and although their use has been largely confined to wind tunnels, successful records have also been obtained in flight. The methods have also been in use for many years to photograph the flow round projectiles fired along ballistic ranges.

Although the principle of the schlieren methods has been understood for nearly a century, many improvements have recently been made largely as a result of experience gained by using the methods to examine the flow in high-speed wind tunnels. The present paper reviews some of these developments and gives examples of the usefulness of the methods in aerodynamic experiments.

In theory[1,2] it is sometimes possible to use the schlieren techniques to measure the density gradients in the flow quantitatively, but there are usually severe practical difficulties[3] and in aerodynamics they are most commonly used to show the positions and shapes of regions of density gradient such as those occurring in shock and expansion waves, and in boundary layers and wakes. Used in this way the methods require only comparatively simple apparatus and are of great assistance in building up a physical understanding of the flow. They enable a relatively large field to be examined rapidly and without the introduction of the disturbances produced by exploring instruments, and when used in conjunction with high-speed photography are particularly valuable for studying unsteady flows. Quantitative measurements of the density in the field of flow can be made by means of an interferometer, but although comparatively simple instruments have recently been used successfully, the apparatus is more complicated and expensive than a schlieren system with a comparable field. Moreover since an interferometer record is a function of the density whereas a schlieren record is a function of the density gradient, there are certain flow phenomena which are more clearly seen by schlieren methods. Thus although the interferometer is of great value in certain types of investigation it should not be regarded as an alternative to the schlieren methods and it is frequently desirable to supplement the interferometer measurements by schlieren observations. Because of the difficulty of interpreting the photographs, the use of optical methods of exploration has been largely confined to flows which are either two-dimensional or possess axial symmetry. The importance of aspect ratio and planform at high speeds makes it highly desirable, however, to develop the methods so that they may be used to study more complicated types of flow. Several techniques which may be useful for this purpose are described; some of these have already given valuable results, but further work is necessary before the value of others can be assessed.

The present paper is confined to optical methods. Other methods such as the use of tufts or of an oil film[4,5] on the surface of the model, or the "vapour-screen"[6] and "tuft-grid"[7] techniques for observing the trailing vortex pattern behind the model are frequently of great value, and details are given in the references cited.

Part I/

Part I. General Considerations, and Methods for Two-dimensional Flow

2. The Principles of the Schlieren Methods

The best-known schlieren methods are the Toepler system[8] and the direct-shadow technique which is usually attributed to Dvorak[9]. The principle of the Toepler method is illustrated on the basis of geometrical optics in Fig.1 which shows diagrammatically a typical arrangement of the apparatus round the working section of a wind tunnel. A source of light (S) placed at the focus of a concave mirror (M_1) produces a parallel beam of light which passes across the flow to be examined. A second mirror (M_2) placed behind the flow gives an image of the source in its focal plane (K), and a camera lens (L) then forms an image of the plane of the flow on the screen or photographic plate Q. By placing a knife edge in the focal plane (K) a fraction of the image of the source is cut off so that only part of the light reaches the screen. If the density in the flow is uniform across planes normal to the direction of the light the screen darkens uniformly as the knife edge is moved across because the images of the source associated with light passing through individual regions of the flow field are coincident at K.

If, however, there is in the flow a density gradient normal to the direction of the light the beam is deflected towards the region of higher density because the light travels more slowly where the density is greater. The image of the source arising from the light which passes through this region of density gradient is thus displaced relative to the knife edge and the amount of light passing on to the screen changes. Thus the illumination on that part of the screen corresponding to the density gradient in the flow changes relative to that of the surrounding image.

Of the types of stop which may be used in the focal plane of the second mirror, a knife edge usually gives the most valuable results in aeronautical work. With a knife edge the system is sensitive only to deflections of the image of the source in a direction normal to the edge, and this should usually be set, therefore, perpendicular to the direction of the density gradient to be observed. For example, Figs. 2(a) and (b) are Toepler photographs of the flow round a double-wedge wing section moving at 1.6 times the speed of sound taken with the knife edge perpendicular to and parallel to the chord line respectively. The directions of the positive components of the density gradient perpendicular to the knife edge are shown by arrows, and since the image of the source will be deflected in these directions it follows that the image of any region of the flow where there is a component of the density gradient towards the opaque part of the edge will appear dark. Regions of the flow in which there is a component away from the opaque part of the edge will appear as highlights. Thus in Fig.2(a) the shock waves (through which the density increases) appear dark, and the expansion waves as highlights. In the boundary layer and wake the density gradient is almost entirely parallel to the knife edge and these features are, therefore, most clearly seen in Fig.2(b)*.

Direct-shadow observations may be made by using the light source and the first mirror shown in Fig.1 to produce a parallel beam of light and observing the flow on a screen or photographic plate held at Q' immediately behind the working section.

3. The Sensitivity and Working Range

The Toepler apparatus is sensitive to deflections of the light beam only over a certain range of deflection in which the image of the source remains partially cut off by the knife edge; if the image is deflected completely on to or away from the edge, further deflection produces no change of illumination on the viewing screen or photographic plate. If this working range is exceeded in parts of the field, detail is lost in the photograph because it is then impossible to distinguish[10] between density gradients in the flow stronger than those corresponding to the limits of the range.

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*Because of the effects of diffraction regions of sharp density gradient in a direction normal to the knife edge are in fact visible.

It is easy to show[10] that the sensitivity (defined as the rate of change of contrast in the final image with change of density gradient in the flow) of the apparatus is inversely proportional to the working range, so that when the apparatus is set up a compromise is necessary between the conflicting requirements of sensitivity and range. The only certain way of determining whether the range is exceeded is to make detailed observations of the displacement of the image of the source, but this is often impracticable in wind-tunnel experiments where it may be necessary to take in succession large numbers of photographs of flows in each of which the density gradients differ. In such cases it is usually found that the best procedure is to provide adequate range for the series of photographs and to accept the associated unnecessary loss of sensitivity in some of them.

The only convenient method for adjusting[10] the range and sensitivity of a Toepler apparatus is to change the height of the light source (i.e., the dimension perpendicular to the knife edge). This may be done within limits by using an optical system consisting of a condenser and slit, or by changing the physical dimensions of the source itself. A convenient method is to use a rectangular shaped source which can be rotated about the axis of the optical system so that the height of the source can be adjusted to any value between its length and its breadth.

In wind-tunnel work a large range is sometimes needed, and it is often difficult to provide a uniform source which is large enough to give this, especially if the source is required to be of very short duration for high-speed photography. Moreover, if the range is adjusted by changing the dimensions of the source, the position of the knife edge in an off-axis system of the type shown in Fig.1 also needs to be adjusted because of the astigmatism. To overcome these and other (see Section 4) drawbacks of the conventional Toepler method, a new apparatus[11] has been developed at the N.P.L. Here, instead of a knife edge in the focal plane of the second mirror, a filter is used. This is graded in one direction so that the amount of light which is transmitted changes as the image of the source is deflected. Since such a filter can be produced with any required dimensions there is no limit to the range which can be obtained by using a filter of suitable size; moreover, a "point" light source can be used thus minimizing the optical aberrations and increasing the depth of focus of the apparatus, as well as enabling direct-shadow photographs to be taken without having to change the source (see Section 6).

The filters used so far at the N.P.L. have been made by using a photographic enlarger to print from a neutral glass wedge onto a photographic plate; filters giving different ranges and sensitivities are produced by altering the enlargement in the printing process. Filters with any required characteristic could be produced by using a cam-driven shutter to control the photographic exposure, and this method is being investigated. In particular the use of a linearly-graded density in the filter is of interest as this would give an apparatus whose sensitivity was independent of the position of the source image relative to the filter, a feature of considerable value on wind tunnels where a considerable amount of vibration may occur.

4. The Sharpness of Schlieren Photographs

One of the advantages of the schlieren methods over other methods of flow exploration is the ease with which they may be used to examine unsteady phenomena. The flows to be examined generally contain regions of unsteadiness (e.g., the wake)[1] and it is, therefore, the practice at the N.P.L. to take the majority of still photographs with exposures of less than one microsecond. Time exposures are sometimes taken for comparison with the high-speed photographs when it is uncertain whether the flow is steady or not, or as a simple alternative to high-speed cinematography when it is required to estimate the amplitude of a periodic oscillation (e.g., the fore and aft oscillation of a shock wave along the surface of an aerofoil). Since a schlieren system integrates the density gradients over the span of the wind tunnel and conditions are never exactly uniform across the span (especially near the side walls) it might be expected that, as the exposure was reduced, a value would be reached beyond which further decrease would give no improvement in the sharpness of the photograph. Experience in testing at speeds between about $\frac{1}{2}$ and 2 times the speed of sound aerofoils completely spanning the working section has shown that this limit has not been reached when the exposure

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has been reduced to about 1/5 of a microsecond* which is the smallest value so far achieved at the N.P.L. when sufficient energy is used in the light source to give a satisfactory photograph.

If the exposure is short enough, the sharpness of the photograph depends mainly on the focussing and on the resolving power of the optical system and of the photographic emulsion. The apertures of the mirrors and the camera lens should, if possible, be large enough not to limit the resolution. For aerofoil models spanning or nearly spanning the working section it is frequently found that the appearance of the boundary layer and wake alter as the plane of focus is changed over a region in which, when the tunnel is not running, the image of the aerofoil model remains sharp. This effect arises because rays of light entering, from one side of the working section, the region of highest density gradient within the boundary layer may be refracted so much that they pass right out of the optical system, whilst the curvature of other rays is such that their apparent point of origin in the flow is displaced[13]. It is, therefore, found to be necessary to focus the apparatus with the tunnel running so that the image of the boundary layer is not unduly distorted. The practice of focussing on fine wires or electric-lamp filaments held in the centre of the tunnel before the experiment begins is unsatisfactory.

The use of a graded filter instead of a knife edge is found to give an improvement in the sharpness of the photographs in addition to overcoming difficulties associated with the working range of the apparatus (see Section 3). This feature is illustrated by comparing the image of the wake in Fig.3(a) which was taken using a knife edge with that in Fig.3(b) which was taken with the same exposure time using a graded filter in an otherwise identical optical system. The improvement obtained with the filter is associated with an amelioration of the effects of diffraction at the knife edge. The authors are unaware of any direct reference to this matter in the literature, but several workers in France[14,15] and America[16,17] have studied the diffraction effects associated with modifications of the imaging aperture by means of shaped screens or filters with graded transmission.

In this connection it is of interest to compare the images of a pin hole placed in the object plane (i.e., the working section of the wind tunnel) obtained with schlieren systems using a knife edge and a graded filter with the image when neither is present. Fig.4(a) shows the extension of the image in a direction perpendicular to the knife edge which would be expected for this type of aperture[18], and Fig.4(b) shows that the effect of the graded filter on the distribution of light in the image is comparatively small.

5. Schlieren Methods giving Images in Colour

Simple modifications to either the Toepler apparatus or the graded-filter apparatus enable a multi-coloured image to be obtained in which each hue corresponds to a particular density gradient in the flow pattern. One method[19] is to place a prism in front of a source of white light located at the focus of the first mirror (M_1) in Fig.1. A spectrum is thus produced at the focal plane of the second mirror and the colour of the image on the screen can be adjusted by moving a slit (parallel to the bands of the spectrum) across the spectrum. When a density gradient is present part of the spectrum is displaced and light of a different colour passes through the slit.

An alternative method analogous to that employed in the graded-filter apparatus is to use a point light source and to place a colour transparency of a pure spectrum in the focal plane of the second mirror. This method is simpler than that described above, and has the further advantage that the effects of diffraction at the slit are avoided.

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*The exposure times quoted in this paper have been determined by means of a photo multiplier, and give the time interval over which the brightness exceeds 1/10 of the maximum.

Since the eye is more sensitive to changes of hue than to changes of illumination, the colour methods are more sensitive than the conventional methods, but because of the difficulties of processing and reproducing colour photographs they are seldom used in routine work except when visual observations alone are required.

6. Direct-shadow Methods

If in Fig.1 the density gradient normal to the light beam is non-uniform, adjacent rays will be deflected by different amounts and will converge or diverge on leaving the flow. An image may then be formed directly as a shadow on a screen or photographic plate held behind the working section at Q'. To obtain a sharp image the dimensions of the light source should be small.

Making certain assumptions it may be shown that the changes of illumination in the image are approximately proportional to the rate of change of density gradient normal to the light beam. For this reason the method is sometimes superior to the Toepler method (in which the change of illumination is roughly proportional to the density gradient) for observing certain flow phenomena, and it is, therefore, the practice at the N.P.L. to photograph nearly all flows by both methods. In addition to being valuable for visualizing shock waves*, the direct-shadow method is useful for observing other regions where the density gradient changes rapidly such as boundary layers and wakes. For example, it has been found[23] that the method can be used to determine whether the flow in the boundary layer on a two-dimensional aerofoil is laminar or turbulent, and to indicate the position along the surface at which transition from laminar to turbulent flow takes place. Fig.5 shows the rear of an aerofoil at zero incidence held in an airstream moving at 0.7 times the speed of sound. For the case shown in the upper photograph observations by a technique depending on the evaporation of a volatile oil from the surface showed that transition was at about 0.73 of the chord behind the leading edge. The direct-shadow image of the laminar boundary layer ahead of this region is seen to include a white line running parallel to, but separated from, the surface of the aerofoil. This line bends towards the surface close to the transition region. The boundary layer was made turbulent from close to the leading edge before the lower photograph was taken, and the image of the boundary layer then consists of a white line touching the surface.

The reason for this difference between the images of laminar and turbulent boundary layers may be explained by reference to Fig.6. The density profile+ for a laminar layer drawn at the left hand side of the diagram is seen to contain two sharp changes of slope. At a small distance from the surface the density gradient increases rapidly thus causing adjacent light rays to diverge as sketched in the centre of the diagram and producing a region of low illumination (I) close to the shadow of the aerofoil surface as shown on the right hand side. Near the outer edge of the boundary layer the density gradient falls thus causing the rays of light to converge and producing a region of illumination (the white line in the photographs) greater than that (I_0) in the image of the undisturbed flow at some distance from the shadow of the aerofoil. The density profile for a turbulent boundary layer shown in the lower half of Fig.6 contains only a single region in which the density gradient changes rapidly. Thus at a small distance from the surface the density gradient falls very sharply; this causes the light rays to converge and produces a region of high illumination much closer to the surface than for a laminar layer.

7. Light Sources

It has been pointed out in Section 3 that the range and sensitivity of a Toepler apparatus depend on the dimensions of the light source. In general, the source should be small because if it is magnified by a condenser arrangement the amount of light passing through the system is increased, but if it is reduced there is a loss of light which may be particularly unwelcome if short exposures are required.

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*In certain cases it is possible to derive the strength of a shock wave from a direct-shadow record (see Refs. 20, 21 and 22).

+In the diagram the ratio of the local air density ρ to the density ρ_0 in the undisturbed stream is plotted against the ratio of the distance y from the surface of the aerofoil to the thickness δ of the boundary layer.

For continuous observations, or for cinematography within the speed range of the Kodak or Fastax high-speed cameras, tungsten-filament projector lamps or high-pressure mercury vapour lamps are used. The latter are, of course, much brighter but this advantage is partially offset by their comparatively high cost and the harsh colour of their light. In applications where flash exposures are required in addition to continuous observations there are two commercially available lamps[24,25] which can be run continuously or flashed. Although both are satisfactory for much schlieren work, the flash duration is unfortunately too long for some purposes.

If exposures below about one microsecond are required, it is necessary to use a spark discharge[26,27,28]. At the N.P.L. most photographs are taken using sparks in air resulting from the discharge of low-inductance condensers of capacity varying from 0.01 to 0.1 μF. charged to between 5 and 30 KV. The discharge through the spark gap is oscillatory[29], the amplitude and period of the oscillation depending on the reactance of the discharge circuit. The oscillation is heavily damped by the dissipation of energy in the spark gap and the circuit. If the lowest possible duration of the current is required, the inductance of the condenser and circuit must be minimized.

The light output does not vary as rapidly as the current passing through the gap, and if the energy used is large the light may persist for a short time at a high level unmodulated[30] by the oscillations of the current. Thus if an effective duration of less than one microsecond is required, it is necessary to limit the energy discharged to less than about 5 Joules as well as keeping the inductance small. The design of the gap itself has a considerable effect on the light output; if the spark channel is constrained the light output is greater[29] but more prolonged than if it is unconstrained. In practice a gap which is at least partially constrained is essential if the shape and position of the source need to be fixed.

The electrodes of the spark gap vaporize to some extent during each discharge, and the material from which they are made thus influences[29,30,31] the colour, intensity and duration of the light output. Unfortunately, metals such as magnesium and cadmium which give the greatest intensity also give long duration because the light does not decay so rapidly as with relatively non-volatile metals such as tungsten and steel. For this reason, and because of their relatively long life, steel electrodes are commonly used at the N.P.L.

Typical spark gaps used at the N.P.L. are sketched in Fig.7. The design shown in Fig.7(a) utilizes the discharge up a Pyrex tube and produces a "point" source of about $1\frac{1}{2}$ mm effective diameter suitable for use with the graded-filter apparatus or for direct-shadow photography. The gap shown in Fig.7(b) consists of two flat electrodes clamped between glass plates and gives a source about 7 mm by $1\frac{1}{2}$ mm; it is usually mounted so that it can be rotated about the axis of the optical system thus enabling the dimension perpendicular to the knife edge to be adjusted to any value between the length and breadth of the source image. In America extensive use has been made of the so-called Libessart gap[32] which is similar in principle to that sketched in Fig.7(a) but has a much narrower tube made of soap stone.

By careful arrangement of the spark gap and condenser the inductance of the discharge circuit can be minimized. The concentric arrangement shown in Fig.8 is used at the N.P.L. to achieve this objective, and has the additional advantage that the high-voltage electrode is enclosed in the outer shell which can be earthed for safety. Special condensers[29] with paper dielectrics are available in a variety of low-inductance forms, and it is thus usually possible to select a condenser to give the most compact arrangement when connected to a particular spark gap. Recently successful experiments have been made at the N.P.L. with a condenser made in the form of a tube from a ceramic of high dielectric constant (about 3000), which was presented to us by The Plessey Co. Ltd of Towcester. The dimensions of the condenser, and the inductance of the discharge circuit, can be made very small, and very short exposures are achieved.

High-speed cinematograph pictures are usually taken at the N.P.L. by using a continuous light source and a standard Kodak or Fastax high-speed camera. Cameras giving much higher frame speeds have been developed for special

applications

applications of schlieren photography such as recording combustion phenomena in internal combustion engines (see, for example, Refs. 26, 33, 34). In applications where the exposure of each frame needs to be shorter than that obtainable with standard high-speed cameras, a drum camera has been developed[35] to work with sparks discharged at a single unconstrained air gap. This gives up to 2000 frames per sec each with an exposure of less than one microsecond.

In most wind-tunnel experiments it is unnecessary to control the instant at which the spark fires precisely, but in some cases, such as when it is required to photograph the flow past an oscillating aerofoil[36] or in shock-tube[37] or ballistic-range[38,39] work, accurate control is essential. Trigger circuits which may be used to do this are described in Refs. 27, 28 and 32. The signal which is used to trigger the spark may be obtained in many ways depending on the nature of the experiment which is in progress. One method depends on the use of an auxiliary schlieren apparatus. When the aerodynamic disturbance to be photographed enters the field of this apparatus a signal is produced by a photocell located in the image plane, and this signal is passed through a delay circuit and used to trigger the spark gap of the main schlieren apparatus. This method has been widely used in shock-tube experiments, and also in a self-stroboscoping schlieren apparatus[40] designed to photograph quasi-periodic aerodynamic phenomena in a wind tunnel.

8. Photographic Emulsions for Spark Photography

It is the experience of many workers[26,32,41] that the characteristics of photographic emulsions as determined for ordinary exposure times are not a reliable guide to their merits when used with spark light sources for recording the low-contrast images[26,42] obtained with schlieren and shadowgraph systems. At the N.P.L. it is found that the best results are obtained by using fast non-colour-sensitive emulsions. The negatives are developed to maximum contrast thus obtaining the highest effective speed from the material.

There is a tendency to underexpose rather than to overexpose the negative because it is found to be desirable to use a rather large image ($\frac{1}{2}$ plate), and because the duration of the exposure is shortest if the energy discharged in the gap is minimized. If the exposure is increased, for example, by reducing the size of the image, the superiority of the non-colour-sensitive emulsions becomes less marked. The light output of the spark sources described above is concentrated[29], however, mainly in the region 3000 to 5500 Angstrom units so that there is little to be gained by using orthochromatic or panchromatic emulsions in any case. Morever, if these emulsions are avoided it is possible to use bright safe lights round the working section of the wind tunnel; this is an important practical advantage as other observations are usually taken whilst the photography is in progress.

The inherently low contrast of the subject is enhanced by printing the negatives on hard grades of paper so that the full available range of tones can be used to show the different levels of illumination in the schlieren image.

Part II/

Part II. Methods for Three-dimensional Flow

Many of the features described in Part I apply no matter what type of flow is to be observed, and it is now necessary to consider the special arrangements which may be necessary if three-dimensional flows are to be visualized. If a three-dimensional flow is examined with a parallel beam of light, the image lacks depth and it is difficult to determine the positions along the beam of the flow phenomena which are present. The strongest deflections of the light occur[13] when the rays are tangential, or nearly so, to the shock and expansion waves. Thus the image resulting from a system using parallel light will give the impression of superimposed cross sections of the flow, the cross sections being taken normal to the beam at the points where the rays are tangential to the shock and expansion waves. Moreover, in a complicated flow the light rays may follow tortuous paths and the deflections at exit from the working section may not be a true indication of the strengths of the disturbances. These are only incidental difficulties, however, and in simple cases the use of a conventional schlieren system to observe a three-dimensional flow is satisfactory. For example, no difficulty usually arises for flows possessing axial symmetry since the image is essentially a cross section of the flow at the median plane from which (together with the traces of the interaction of the shock waves with the glass walls of the tunnel) the complete flow pattern can be deduced. If the flow is nearly axially symmetric useful results can usually be obtained by rotating the model about the longitudinal wind axis so that, in effect, a series of photographs is obtained from a number of directions perpendicular to this axis.

In many cases, however, the conditions are more complicated and it is then necessary to assign positions along the beam of light to the various flow phenomena. Several techniques have been devised to enable this to be done, and these are described briefly below. It should be emphasized that most of these techniques are in a very early stage of development, and that much more work is necessary before their value can be assessed.

9. The Stereoscopic Method

The stereoscopic method was developed[43] by Lyot and Françon for examining discs of glass, and has been used subsequently in France[44] and America[45] for observing combustion and aerodynamic phenomena. The apparatus (Fig.9) consists of either a single parallel beam of light used to photograph the flow in the working section from two different directions*, or two inclined beams used to take photographs from two directions simultaneously. The photographs are viewed with a stereoscope. An example[43] of a stereoscopic pair of photographs showing faults in a glass disc is reproduced in Fig.10.

10. The Rangefinder Method

The rangefinder method was developed[46] at the R.A.E. by Lamplough who used it for photographing the shock waves close to the wing of an aeroplane flying at high speed. The apparatus is sketched in Fig.11 and consists of a conventional parallel-beam arrangement with the addition of a glass wedge close to the collimating lens. The light beam is set up along the span of the wing, and the position of a shock wave along the beam is estimated by observing the relative displacement of the part of the image associated with light which has passed through the wedge. The type of record obtained is shown in the example reproduced in Fig.12. The displacement of the image is proportional to the distance from the shock wave to the plane in the object space conjugate to the viewing screen or photographic film, and is in opposite directions for shock waves lying on opposite sides of the conjugate plane.

In the apparatus used by Lamplough no knife edge was used in the focal plane of the second lens. This arrangement appears to be entirely satisfactory for observing shock waves, but if it is required to visualize the boundary layer as well it may be desirable to use a knife edge as sketched in Fig.11. If a knife edge is used it must be set parallel to the displacement produced by the rangefinder

wedge/

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*In Fig.9(a) the set-up is for the examination of a glass disc. It is then simpler to rotate the disc (from position I to position II) relative to the beam of light than it is to move the beam itself.

wedge. Although phenomena producing deflections perpendicular to the edge may thus be visualized, it will thus be impossible to determine their position along the light beam.

If the shock waves are highly curved, it may be necessary to incline the light beam in the manner described in Section 12 until it is approximately tangential to the element of the shock which is to be visualized. By taking photographs for a range of inclinations of the beam it may then be possible to obtain the position (and possibly also the slope) of a number of elements of the shock and hence to deduce its shape.

11. The Sharp-focus Method

The sharp-focus method was developed[47] on a small scale by Kantrowitz and has been the subject of considerable interest; in its present form it suffers from a number of disadvantages which have been discussed[48] by Fish and Parnham. The method (Fig.13) depends on the fact that any point in the object is illuminated by rays of light within a solid angle α equal to that subtended at the first lens or mirror by the extended source. The depth of focus depends on the angle β and the diameter of the acceptable circle of confusion in the image; the angle β is determined by the angle α and the image size. Thus, for a given ratio of the diameter of the circle of confusion to the image size, the depth of focus is approximately inversely proportional to the angle α. Hence a short depth of focus may be obtained by using a large source of light. The objection that the sensitivity as a schlieren system of the apparatus will be low when the source is large is overcome by using an array of small slit sources and a corresponding array of knife edges as a cut-off.

Examples of the type of record are shown in Fig.14 which is reproduced from Ref.47 and shows photographs of a shock wave in a nozzle with dimensions 2 in. by $2\frac{1}{2}$ in., the upstream Mach number being about 1.3. Fig.14(i) was taken with a conventional apparatus and Fig.14(ii) with the sharp-focus apparatus focussed on the middle of the tunnel. The comparison shows that the conditions in the middle of the tunnel differ from those near the walls.

When the sensitivity is moderately high the image quality suffers from the effects of diffraction at the multiple knife edges, and the situation is aggravated by the fact that the object plane in sharp focus is shown on a background of the out-of-focus object planes.

12. Shock-wave Plotting Methods

The shock-wave plotting method was developed[46] by Lamplough and has been used to record shock-wave patterns in flight and in the wind tunnel. The apparatus used in the wind-tunnel observations is sketched in Fig.15; the apparatus used in flight operates on the same principle. It involves the use of a parallel beam of light which may be rotated about an axis normal to the plane of the wing which will be taken as horizontal in the following discussion. The light passing through a horizontal slice of the working section is received on a film through a narrow horizontal slit. As the beam is rotated about the vertical axis the film is moved in a vertical direction, the slit remaining at rest. At any point in the rotation of the beam where the light rays are tangential to the shock front in the narrow slice of the flow field under observation a dark band is recorded on the film. From this record it is possible to deduce the shape of the shock front in the part of the flow examined. An example[49] showing the result obtained when the shock contour is reconstructed from the original record by means of a specially designed "reduction box" is reproduced in Fig.16. This shows the shock contour a little above the surface of a wing with 50 deg sweepback.

By moving the slit in front of the film to successive positions across the field of flow the entire field can be scanned, a frame of film being obtained for each slice explored.

The criticism has been made that when the method is used on a wind tunnel, the windows in the side walls need to be very long in order to allow the beam of light to be passed obliquely across the flow. The objection is not,

however/

however, confined to this particular method of visualization since most optical methods require that the light beam can be rotated until it is approximately parallel to the shock front which is to be observed.

13. Techniques for Half Models

If the wall or reflection plate from which a half model is supported is transparent, a beam of light can be passed across the tunnel and any of the schlieren methods described above can be used. Alternatively limited observations can be made through a small window located in the reflection plate; for example, the flow near the tip of a highly swept wing has been observed through a window located at the rear of the reflection plate.

In most cases, however, the wall or reflection plate is opaque, as the apparatus behind it will obstruct the beam of light. It may then be possible to use the reflection plate as an optical mirror and, using the schlieren methods described above, visualize the flow by reflecting the light back across the tunnel.

A simpler method for obtaining less detailed information is to project the image of shock waves and other flow phenomena onto the prepared surface of the reflection plate in the manner sketched in Fig.17. This technique is, of course, equally applicable to wing-body combinations (the image of the flow near the wing being projected onto the surface of the body) where the size of the body would prevent observations of the flow near the wing surface by the usual schlieren methods.

An alternative method which may be useful in special cases is to project the image of the shock wave onto the surface of the wing as shown in Fig.17.

References

No.	Author(s)	Title, etc.
1	H. Schardin	Das Toeplersche Schlieren Verfahren. V.D.I. Forschungsheft No.367 v.5 (1934).
	See also	"Die Schlierenverfahren und ihre anwendungen. Ergebnisse der exakten Naturwissenschaften v.10 (1941).
2	F. J. Weyl	Analytical methods in optical examination of supersonic flow. NAVORD. Rep. 211-45 (1945).
3	G. S. Speak and D. J. Walters	Optical considerations and limitations of the Schlieren process. R. & M. 2859 - January, 1950.
4	J. Black	A note on the vortex patterns in the boundary layer flow of a swept-back wing. J. R. Ae. S. v.56, p.279, April, 1952.
5	R. Hills	Use of wind tunnel model data in aerodynamic design. J. R. Ae. S. January, 1951. p.1.
6	H. J. Allen and E. W. Perkins	A study of effects of viscosity on flow over slender inclined bodies of revolution. N.A.C.A. Report 1048. (1951).

No.	Author(s)	Title, etc.
7	J. D. Bird and D. R. Riley	Some experiments on visualization of flow fields behind low aspect ratio wings by means of a tuft grid. N.A.C.A. T.N. 2674.
8	A. Toepler	Beobachtungen nach einer neuen optischen Methode. Poggendorfs Ann. d. Phys. u. Chem. V.127, p.556 (1866); see also V.128, p.126 (1866), V.131, p.33 and p.180 (1867), and V.134, p.194 (1868).
9	V. Dvorak	Uber eine neue einfache art der schlieren beobachtung. Wiedemann's Ann. d. Phys. u. Chem. .9, p.502 (1880).
10	D. W. Holder and R. J. North	The Toepler schlieren apparatus. R. & M.2780. April, 1950.
11	R. J. North	Schlieren systems using graded filters. A.R.C. 15,099 - 1st August, 1952.
12	D. W. Holder	Note on the wakes behind bodies moving at high Mach number. A.R.C. 14,720 - 11th March, 1952.
13	W. A. Mair	The sensitivity and range required in a Toepler schlieren apparatus for photography of supersonic flow. The Aeronautical Quarterly, Vol.IV. August, 1952.
14	P. Jacquinot	Quelques recherches sur les raies faibles dans les spectres optiques. Proc. Phys. Soc.372B, Vol.63, part 12, December, 1950.
	See also	
	B. Dossier, P. Boughon and P. Jacquinot	Apodisation des raies spectrales au moyen d'écrans absorbants. Journal des Recherches du Centre National de la Recherche Scientifique, no.11, 1950.
15	M. Françon	Etude de la lumière diffractée par les defouts d'homogénéité dans les instruments d'optique. Revue d'Optique, V.27, p.595 (1948).
16	R. K. Luneberg	Mathematical theory of optics. Brown University (1944).
17	H. Osterberg and J. E. Wilkins	The resolving power of a coated objective. Journal of Optical Society of America, 39, p.553-557, 1949.
18	Charles F. Meyer	The diffraction of light, X-rays, and material particles. University of Chicago Press, 1934.
19	D. W. Holder and R. J. North	A schlieren apparatus giving an image in colour. Nature, Vol.169, p.466. March 15, 1952.

No.	Author(s)	Title, etc.
20	H. Lewy	On the relation between the velocity of a shock-wave and the width of the light gap it leaves on the photographic plate. APG. BRL. Report No.373. (1943).
21	P. C. Keenan	Shadowgraph determination of shock-wave strength. BuOrd. Explosives Research Report No.11. (1943).
22	W. F. Hilton	The photography of airscrew sound waves. Proc. Roy. Soc. A. V.169, p.174. (1938).
23	H. H. Pearcey	The indication of boundary-layer transition on aerofoils in the N.P.L. 20 in. × 8 in. high speed tunnel. C.P.10. (1950).
24	R. H. J. Brown	Flash cinematography. Phot. Journal, Vol.92B, 1952, p.130.
25	-	Technical Literature. British Thomson Houston Co. Ltd., Rugby.
26	W. D. Chesterman	The photographic study of rapid events. Clarendon Press (1951).
27	H. Schardin and E. Fünfer	The basis of spark photography. Z. angew. Phys. V.4, p.185, and p.224 (1952).
28	P. Fayelle and P. Naslin	Photographie instantée et cinematographie ultra-rapide. Memorial de L'artillerie Français V.22, p.657 (1948).
29	W. G. Standring and J. S. T. Looms	The electrical and luminous characteristics of short air sparks suitable for high speed photography. Proc. Phys. Soc. B. Vol.65, p.108, (1952).
30	W. G. Standring and J. S. T. Looms	Light output from a spark point source. Nature, Vol.165, p.358. March 4, 1950.
31	J. B. Higham and J. M. Meek	Voltage gradients in long gaseous spark channels. Proc. Phys. Soc. 369B, Vol.63, part 9. (1950).
32	Ben S. Melton, Rochelle Prescott and Everett L. Gayhart	A working manual for spark shadowgraph photography. Applied Physics Laboratory, The Johns Hopkins' University. Bumblebee Report No.90. (1948).
33	G. A. Jones	High-speed photography. Chapman and Hall, London, 1952.
34	K. Shaftan	Progress in photographic instrumentation in 1950. J.S.M.P.T.E., Vol.57, p.443, November, 1951.
35	D. W. Holder, R. J. North, W. G. Standring and J. S. T. Looms	A high-speed camera for the photography of shock-wave oscillations in a wind tunnel. R. & M. 2901. August, 1949.
36	A. Chinneck, D. W. Holder and C. J. Berry	Observations of the flow round a two-dimensional aerofoil oscillating in a high-speed airstream. A.R.C. 15,141 - F.M.1779 - O.1006. 23rd August, 1952.

37/

No.	Author(s)	Title, etc.
37	D. W. Holder	A note on shock tubes. C.P.110. (1953).
38	A. C. Charters	Ballistic spark photography. NAVORD Report 74-46, p.35, (1946).
39	G. A. Hankins and W. F. Cope	The flow of gases at sonic and supersonic speeds. Proc. I. Mech. E., V.155, p.401, (1946).
40	L. F. Lawrence S. F. Schmidt and F. W. Looschen	Self-synchronizing stroboscopic schlieren system for the study of unsteady airflows. N.A.C.A. T.N. 2509.
41	See discussion on the following paper:-	
	L. Tupper	Reciprocity-law failure. J.S.M.P.T.E., V.60, p.20, (1953).
42	H. Jerome Schafer	Physical optic analysis of image quality in schlieren photography. Journal of Soc. of Motion Picture Engineers Vol.53, p.524. November, 1949.
43	B. Lyot and M. Françon	Observation des défaut de poli et homogénéité au stéréoscope par la methode du contraste de phase. Revue d'Optique, .27, No.7, p.397 (1948).
44	C. Veret	La strioscopie stéréoscopique. La Recherche Aeronautique No.29, (1952).
45	J. H. Hett	A high-speed stereoscopic schlieren system. J.S.M.P.E., V.56, p.214, (1951).
46	F. E. Lamplough	Shock-wave shadow photography in tunnel and in flight. Aircraft Engineering, April, 1951.
47	A. Kantrowitz and R. L. Trimpi	A sharp-focussing schlieren system. J. Ae. Sc., V.17, p.311 (1950).
48	R. W. Fish and K. Parnham	Focussing schlieren systems. R.A.E. Technical Note No. I.A.P.999. C.P.54. November, 1950.
49	A. O. Ormerod	Note on the use of the three-dimensional shock-wave recorder for studying interference in a supersonic tunnel. R. & M. 2798. December, 1950.

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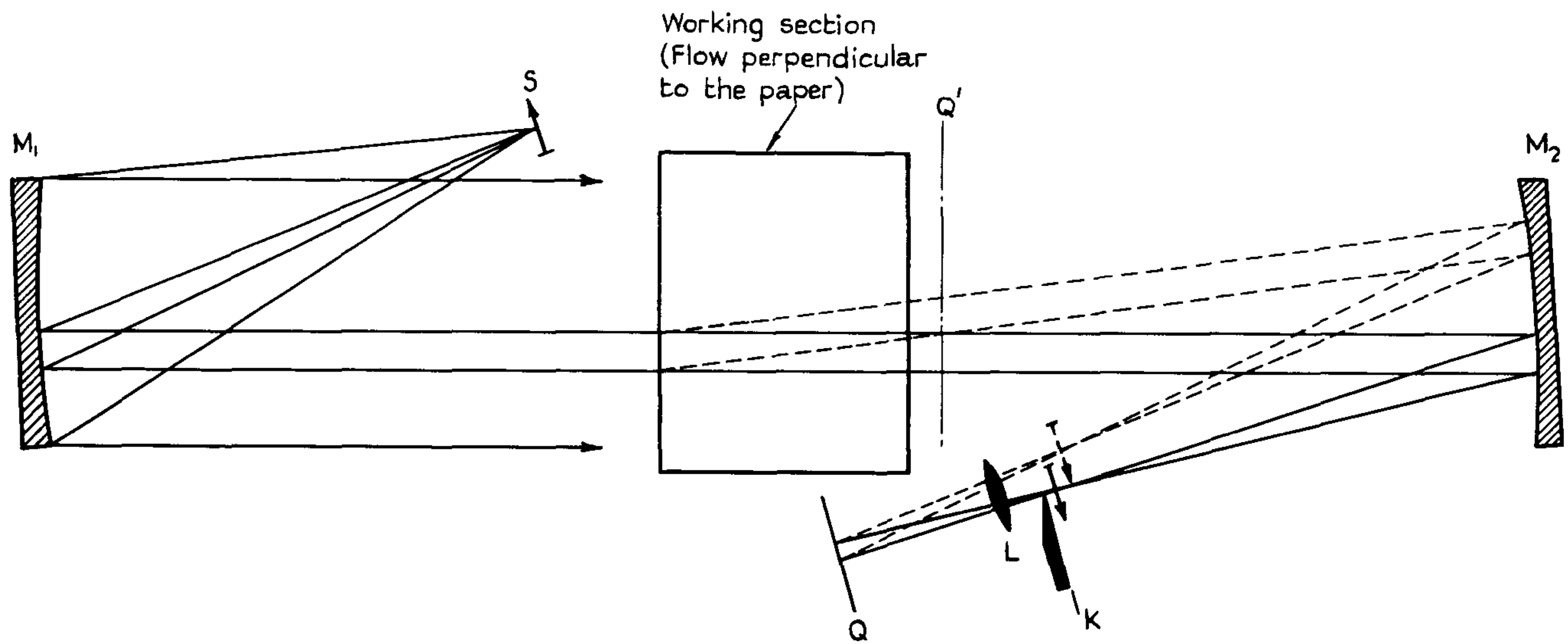
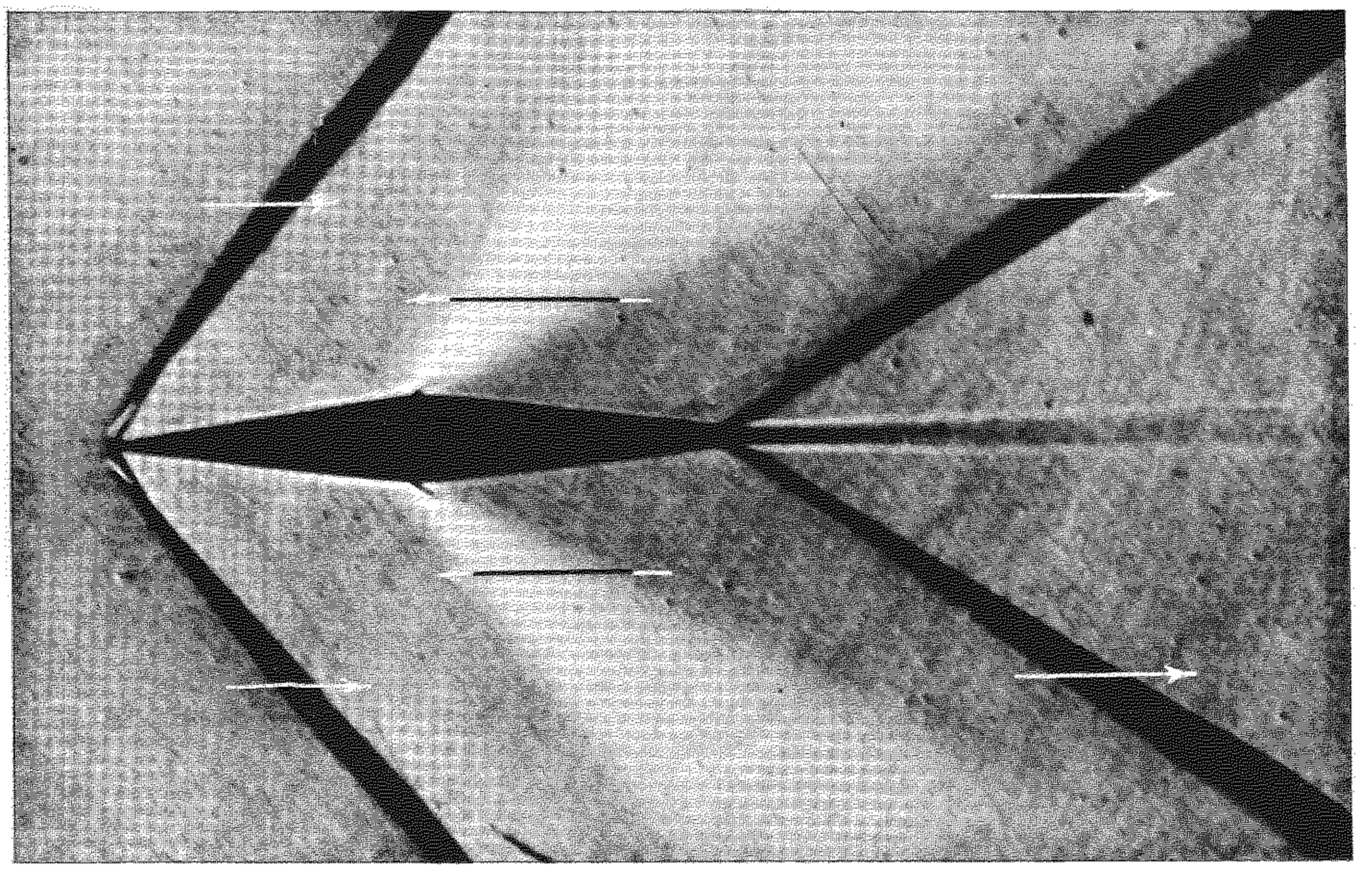


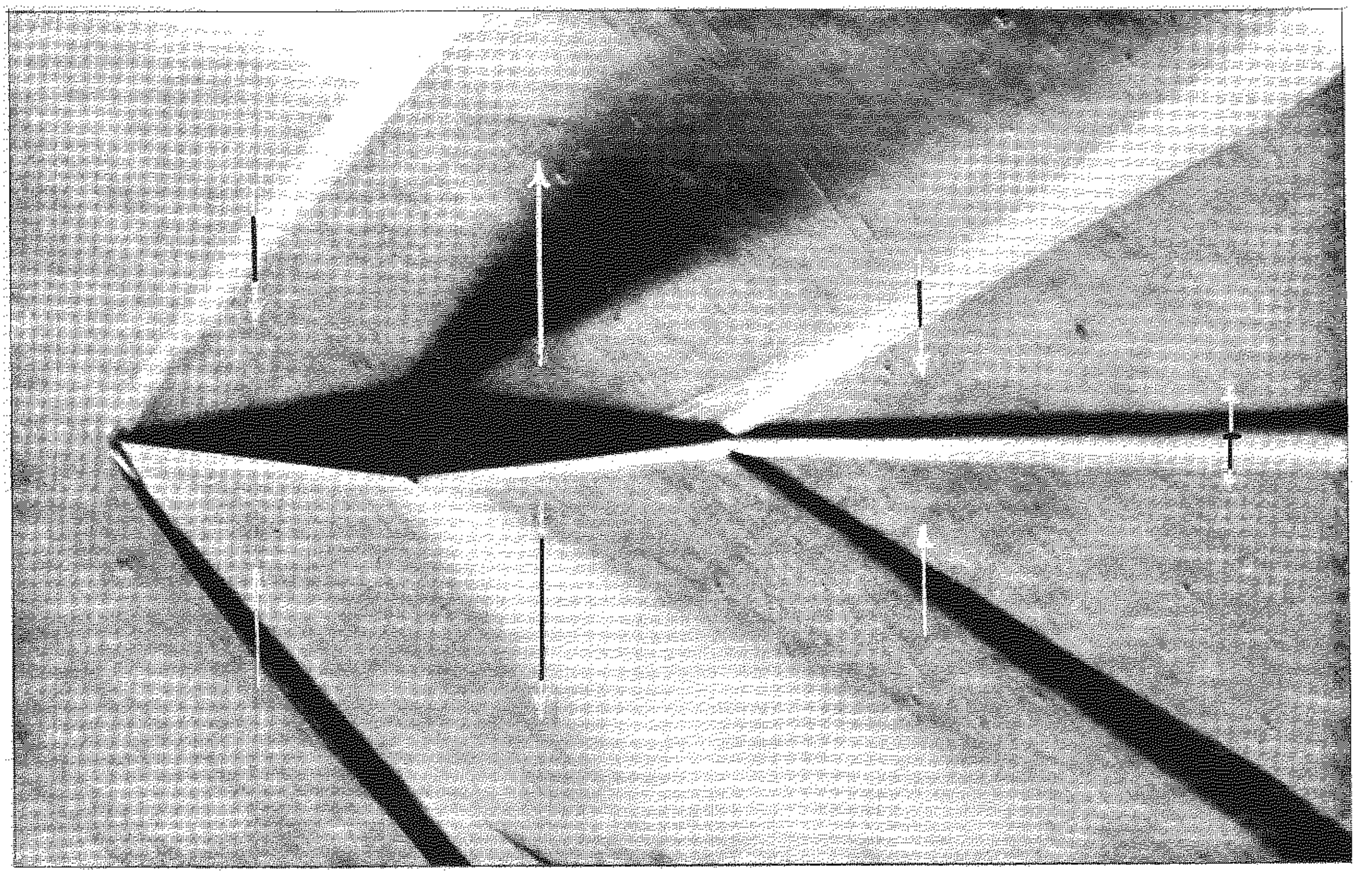
FIG. 1.

Sketch of a Toepler Schlieren Apparatus.
(Undisturbed rays shown full, disturbed rays shown dotted.

FIG. 2.



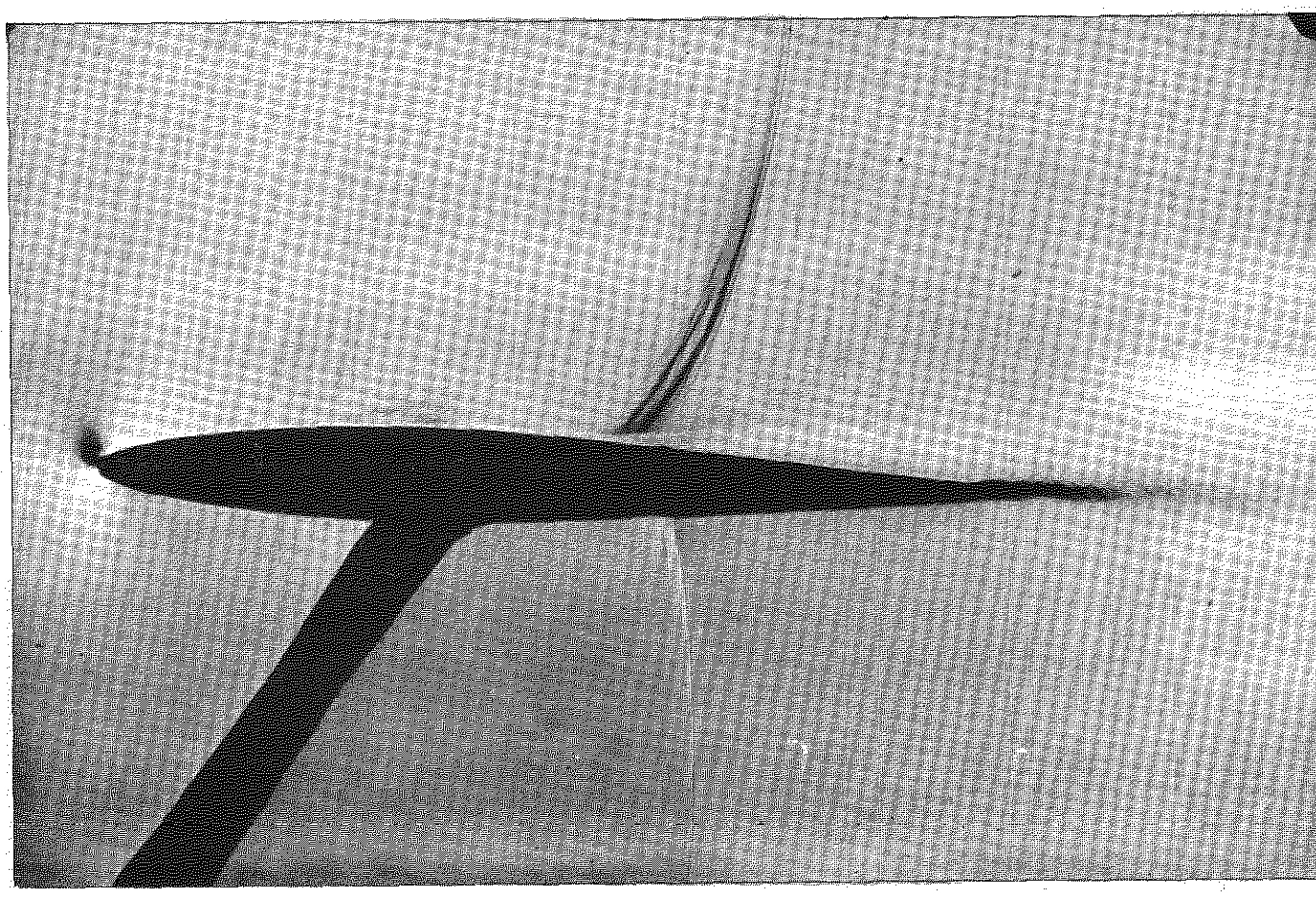
(a) Knife edge perpendicular to chord



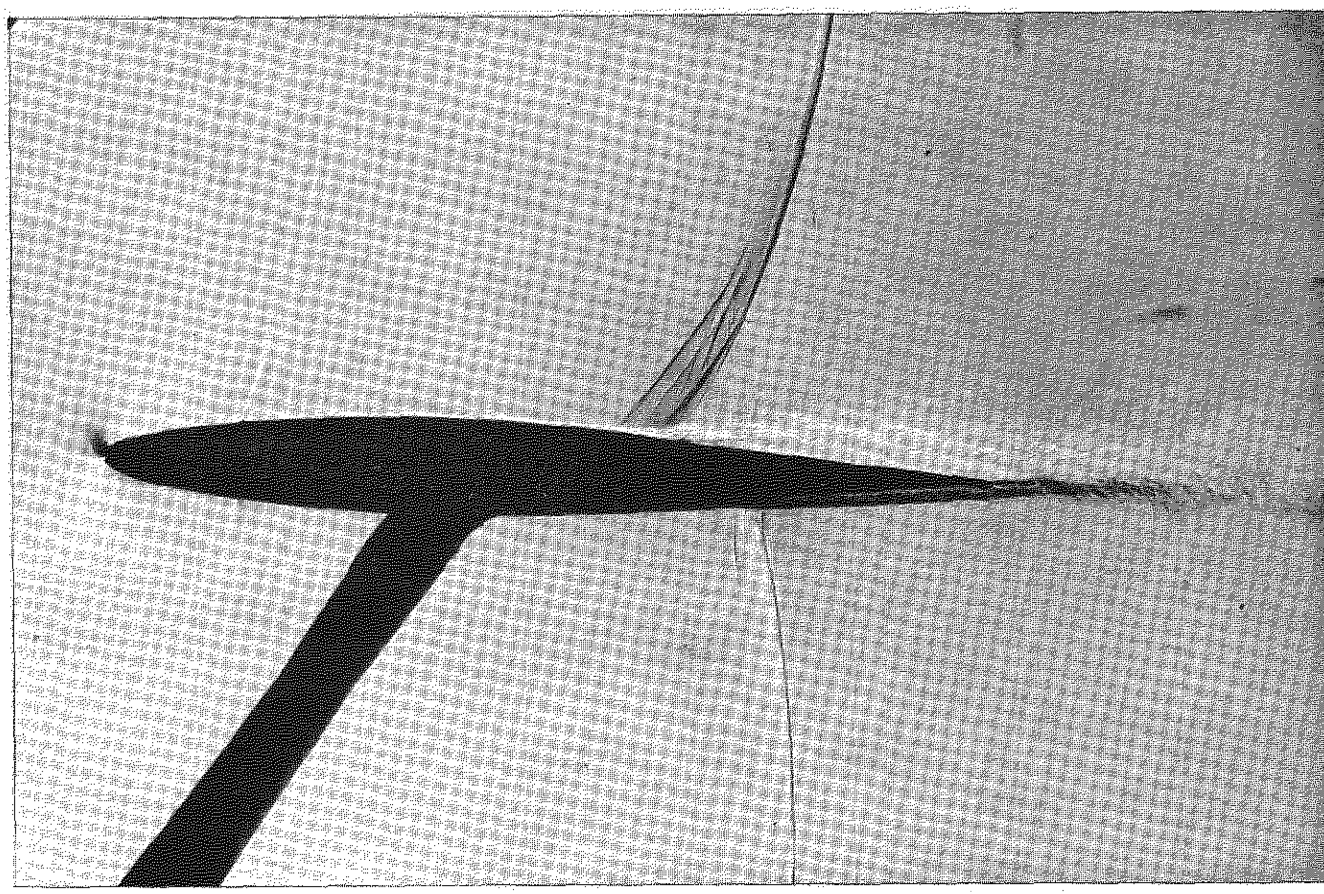
(b) Knife edge parallel to chord

FIG.2. TOEPLER SCHLIEREN PHOTOGRAPHS OF THE FLOW ROUND A DOUBLE WEDGE AT $M=1\cdot6$, $\alpha=0^{\circ}$

FIG. 3.

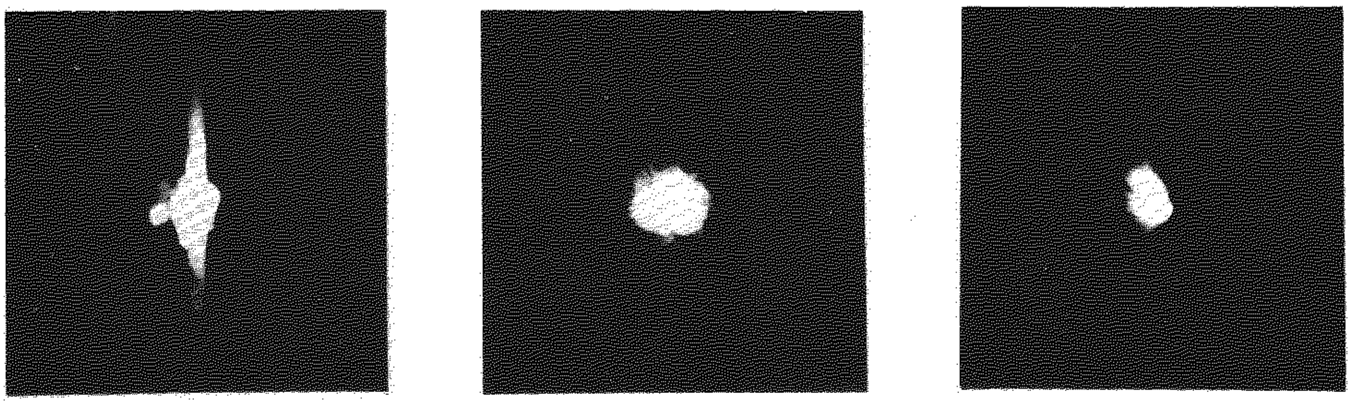


(a) Knife edge system



(b) Graded filter system

FIG. 3. SCHLIEREN PHOTOGRAPHS OF THE FLOW ROUND A 10 % THICK AEROFOIL AT $M = 0{\cdot}83$, $\alpha = 2^\circ$.

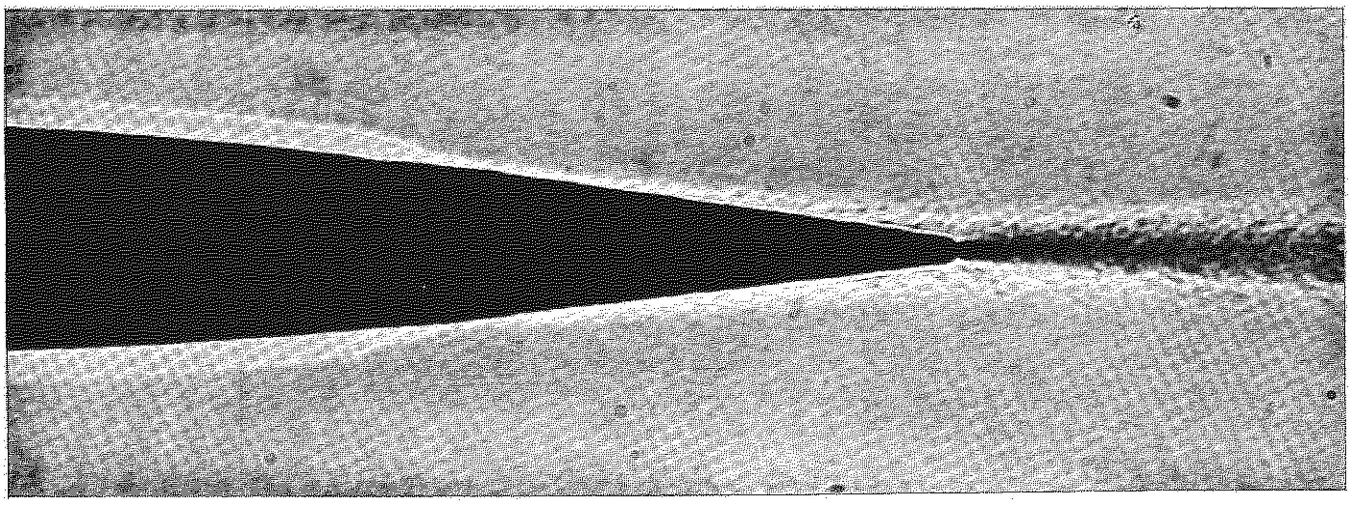


(a) Horizontal knife edge

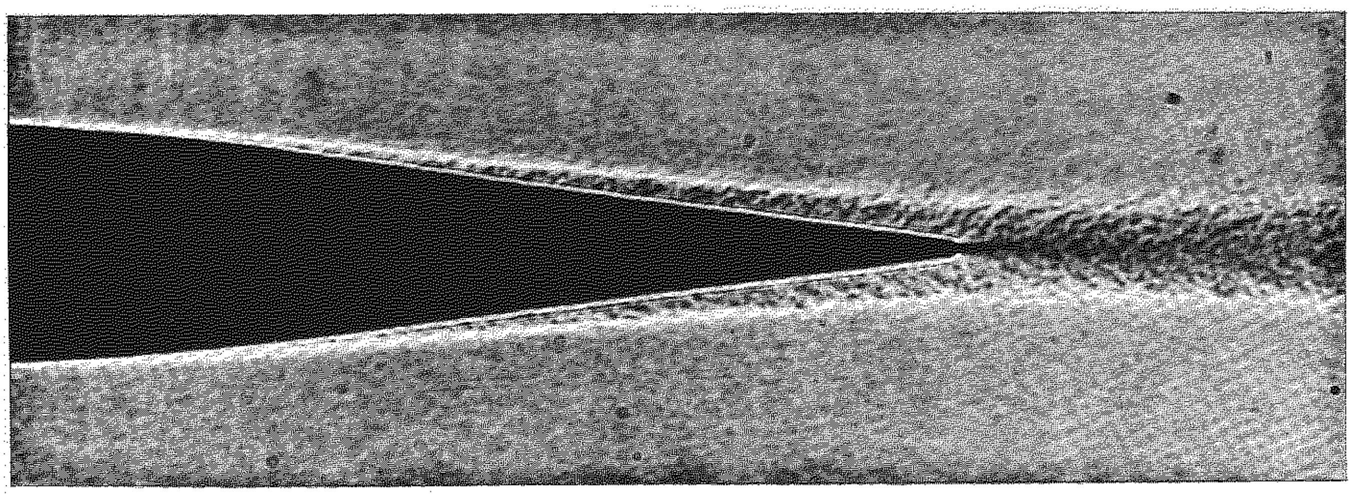
(b) Graded filter

(c) No knife edge or filter

FIG. 4 IMAGES OF A PIN HOLE WITH VARIOUS SCHLIEREN SYSTEMS



(a) Transition at 0·73 chord



(b) Transition near nose

FIG. 5. DIRECT SHADOW PHOTOGRAPHS OF THE REAR HALF OF AN AEROFOIL SHOWING THE STATE OF THE BOUNDARY LAYER

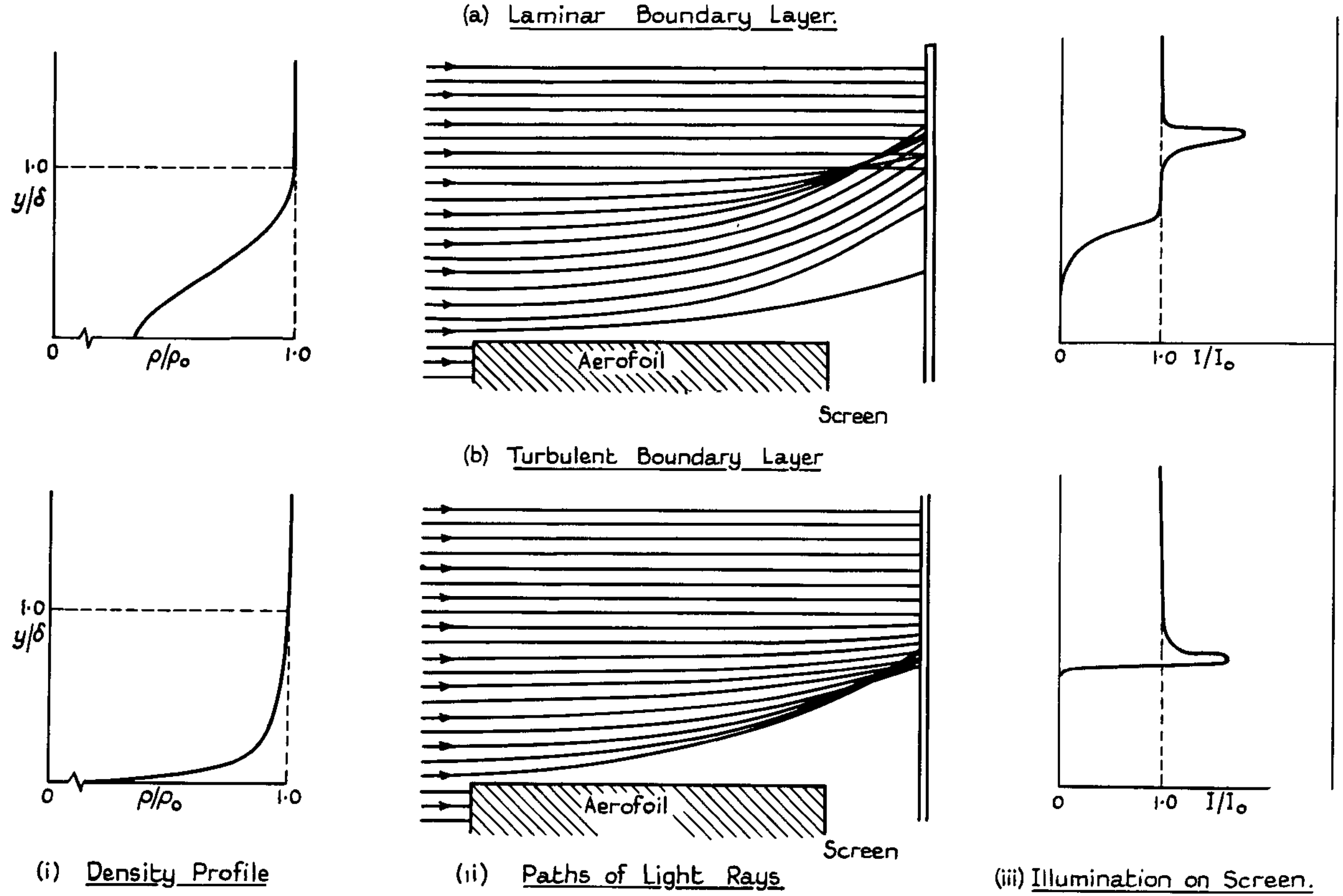
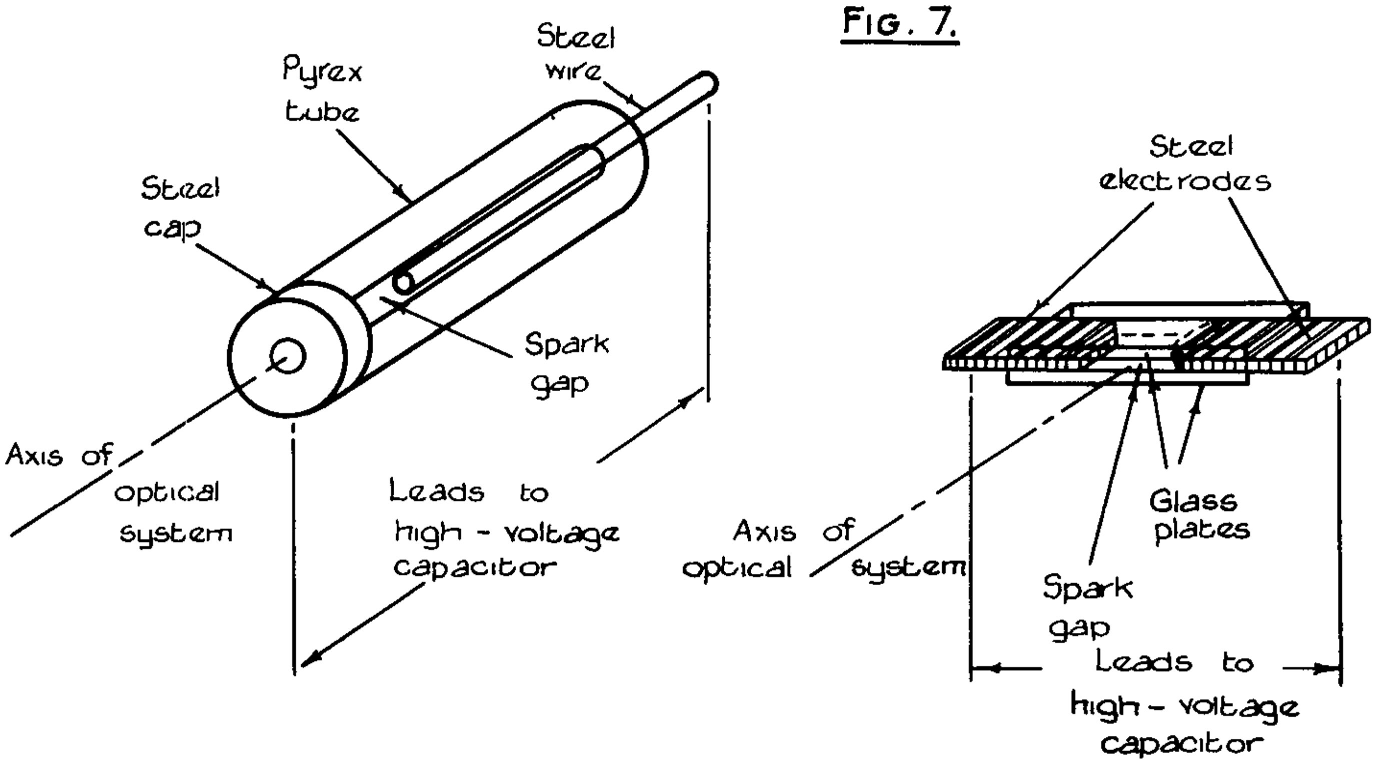


FIG. 6.

Diagram Illustrating the Formation of Direct-Shadow Images of Laminar and Turbulent Boundary Layers.

FIGS 7 & 8.

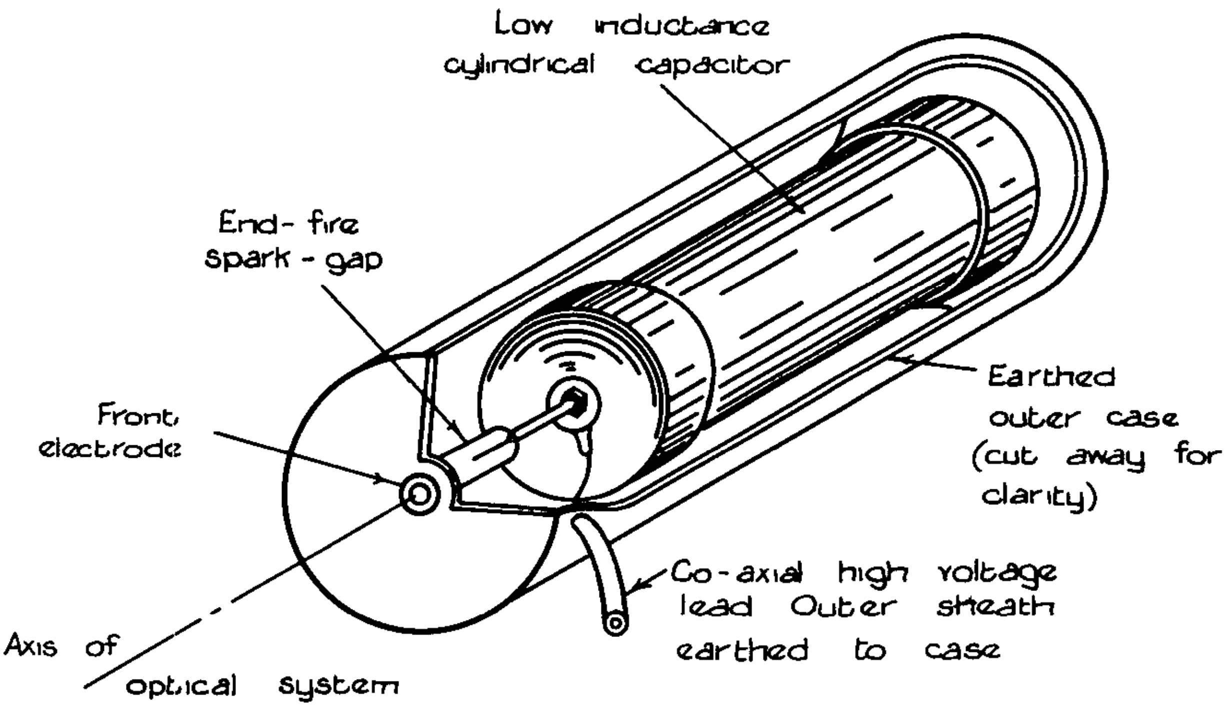
FIG. 7.



(a) End - fire gap (b) Bar gap

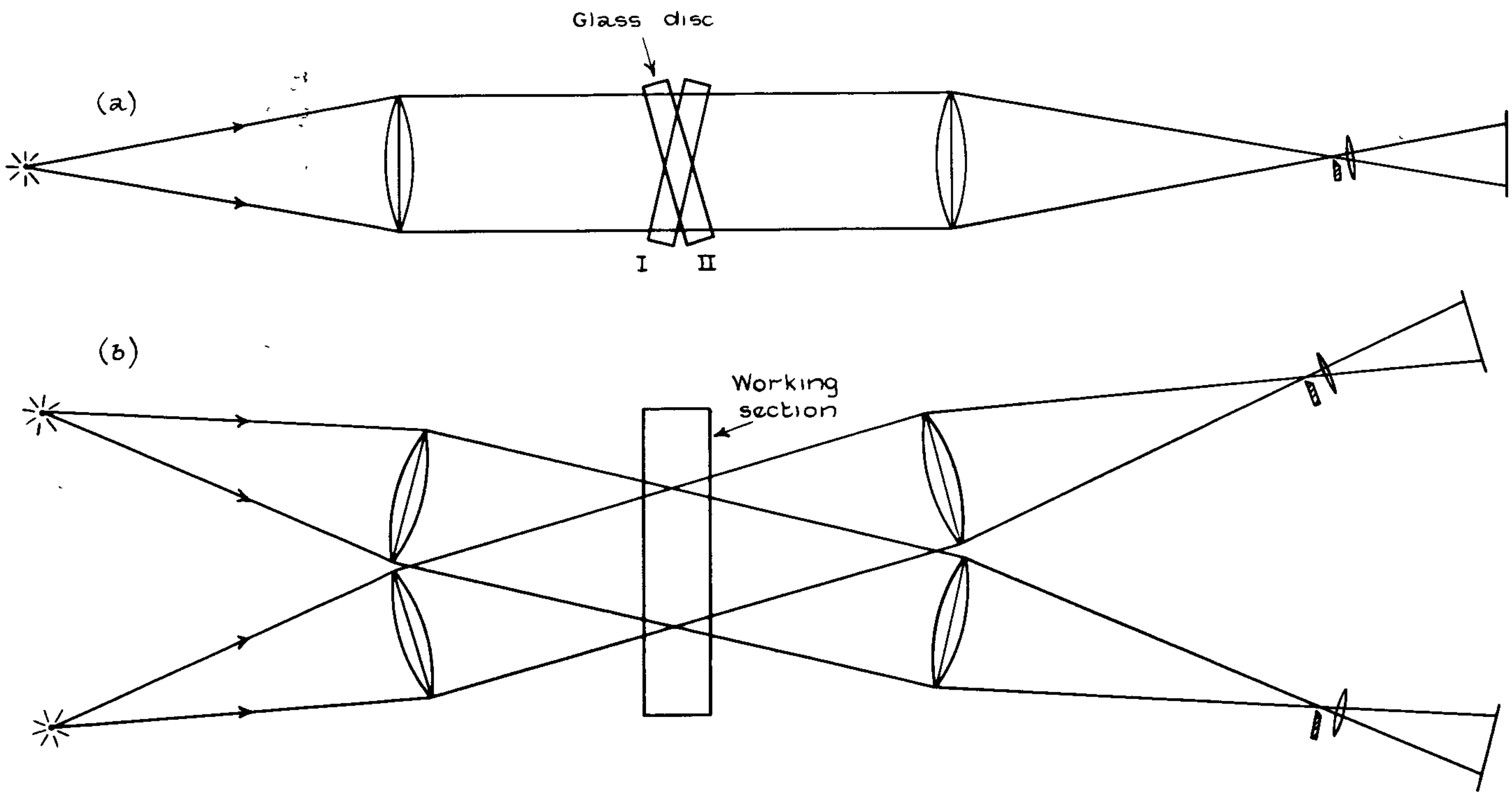
Sketches of Spark Gaps used at the N.P.L.

FIG. 8.

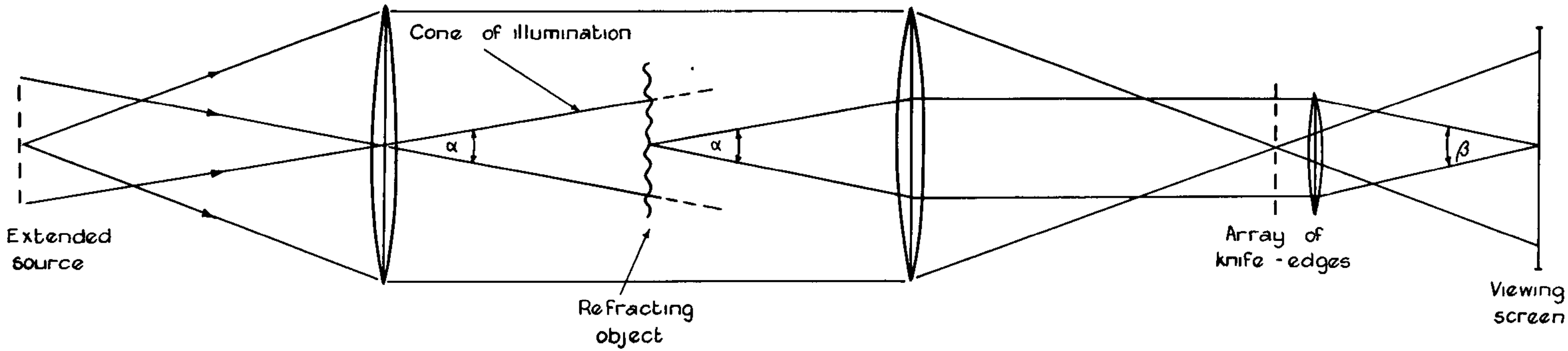


Concentric Arrangement of Capacitor and Spark Gap

FIG. 9

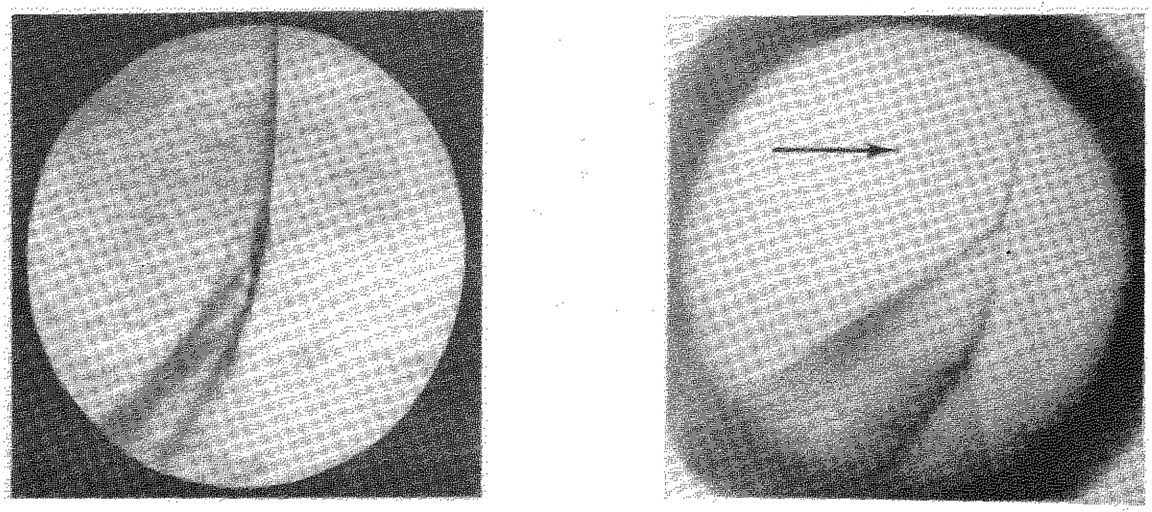


The stereoscopic schlieren apparatus



The sharp-focus Schlieren apparatus

FIG. 13.



(i) Conventional apparatus

(ii) Sharp-focus apparatus focussed on the middle of the tunnel.

FIG. 14. COMPARISON OF PHOTOGRAPHS TAKEN WITH A CONVENTIONAL AND A SHARP-FOCUS SCHLIEREN SYSTEM

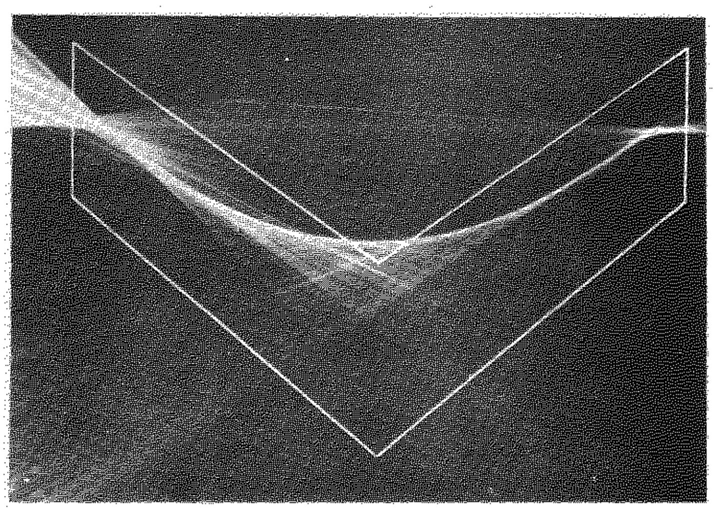
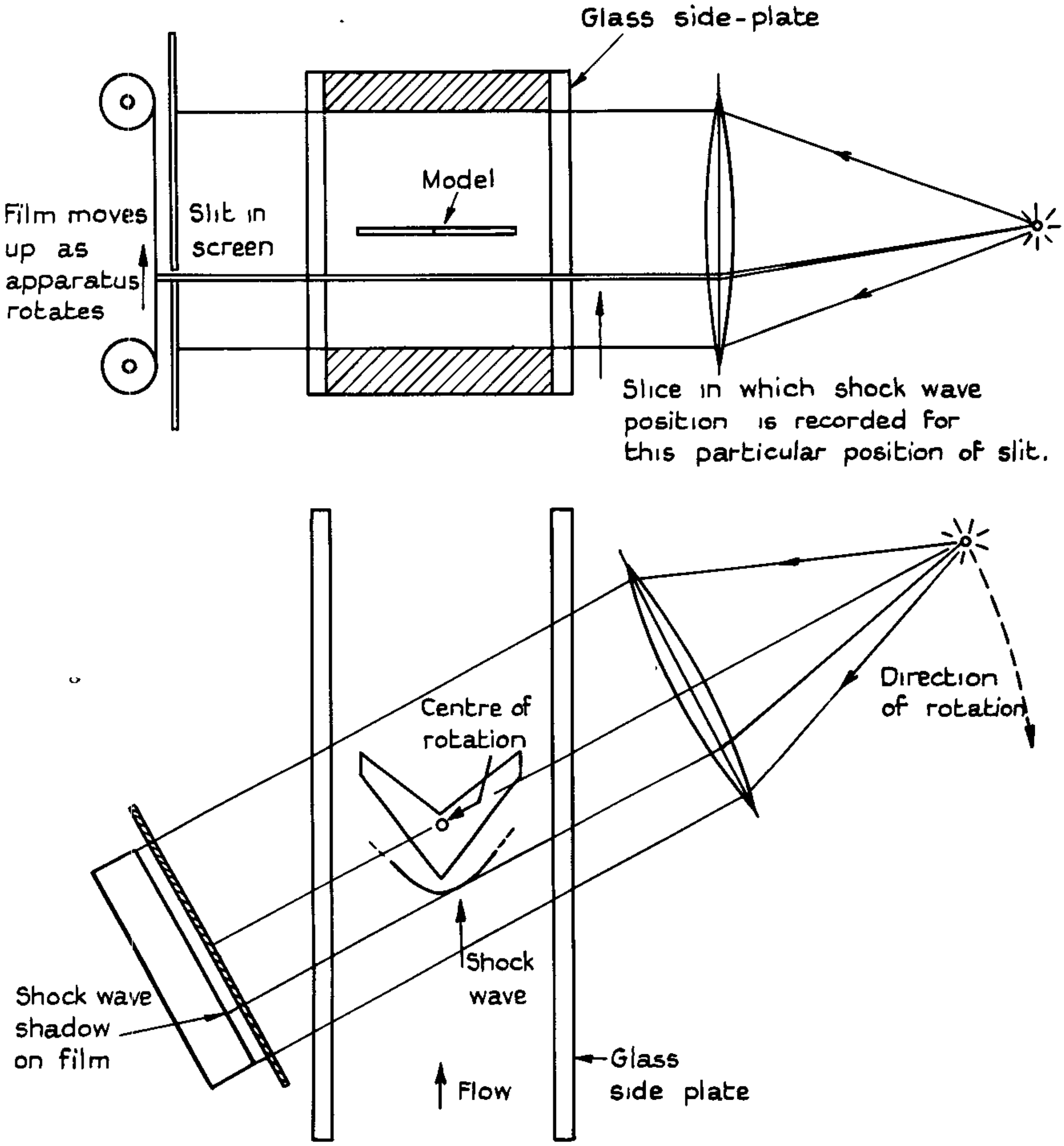


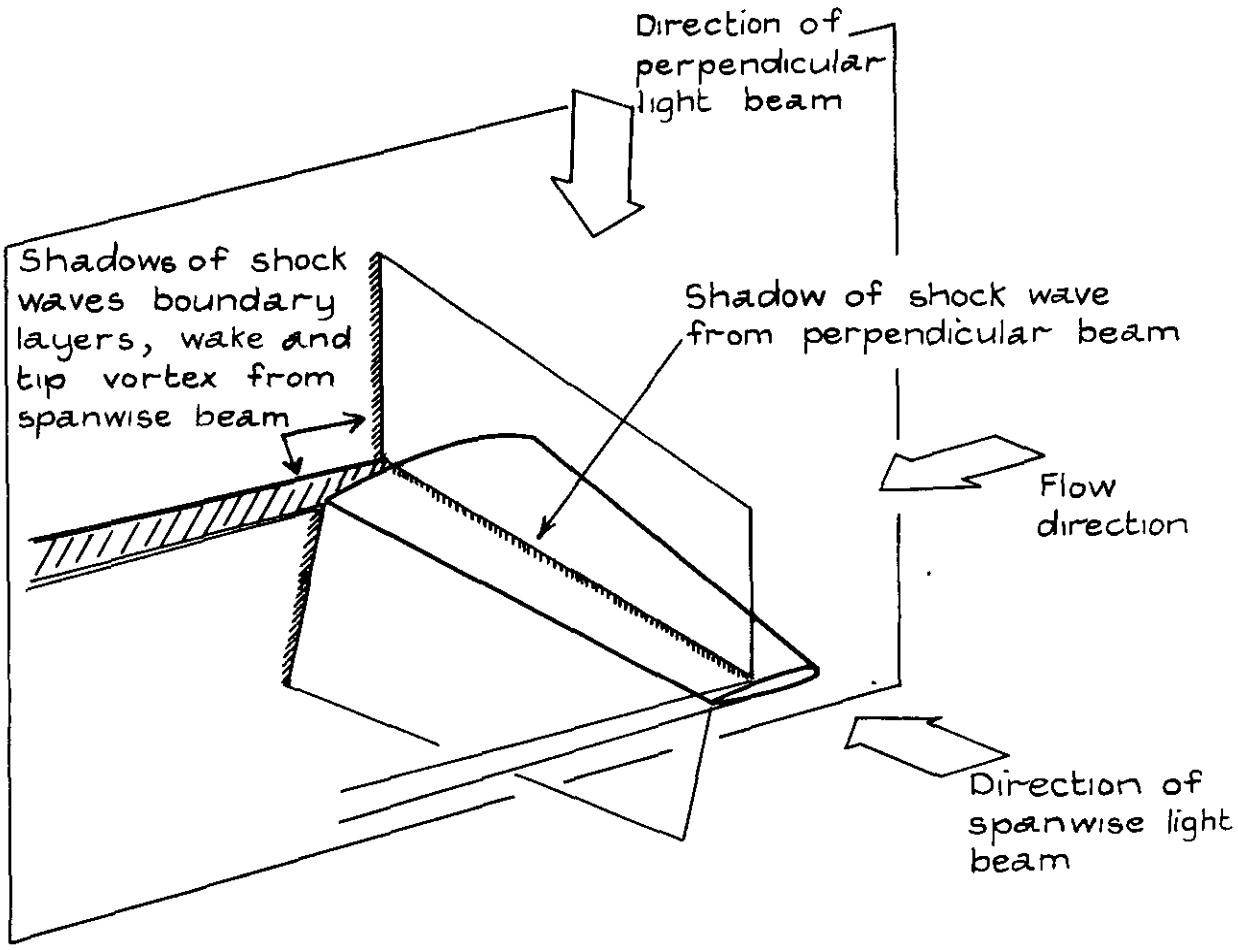
FIG. 16. RECONSTRUCTION OF THE CONTOUR OF A SHOCK WAVE ON A SWEPT BACK WING FROM RECORDS OBTAINED WITH LAMPLOUGH'S SHOCK-WAVE PLOTTING APPARATUS

FIG. 15.



The shock - wave plotting method as used on a wind tunnel.

FIG. 17.



Possible methods for use with a reflection plate.

C.P. No. 167
(16,023)

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