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SUMMARY

The substitution of grids for the usual knife edges in a Schlieren apparatus confers focussing properties on the system. Three possible systems are described and their optical limitations discussed. Achromatic lenses are used in place of mirrors because of the excessive off-axis aberrations of the mirrors. Some practical suggestions for the construction of the grid and the adjustment of the system are given.

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1 Introduction

The formation of images in a Schlieren system is largely limited by diffraction which, because of the narrowness of the beams, leads to diffuse images and spurious fringes at the edge of any discontinuity.

Further difficulties arise in practice through shortcomings in materials; the windows need to be completely free from inhomogeneities, mirrors have to reach an extremely high standard of workmanship and even the air itself has to be kept free from turbulence.

Work recently reported[1,2] has aimed at overcoming these limitations by the so-called focussing systems, which give improved definition in the image and allow optical components of lower quality. The published work, however, has not always been specific in outlining the optical conditions and the limitations of size, field etc. if these systems are to be successful.

The present note is intended to investigate these focussing systems with particular reference to their use in wind tunnels for measuring air densities.

2 The Basic Principles of the Focussing Systems

The basic optical layout of the conventional Schlieren system is shown in Fig.1 where the slit S is at the focus of the lens L_1 from which a parallel beam of light emerges. A second lens L_2 brings this beam to a focus and, at this position, the knife-edge K is arranged to cut off the image of the slit. No light then appears upon the screen I. Suppose now, at a position O in the parallel beam, there is a region of discontinuity (a Schliere) which deviates the incident light ray through a small angle ε, the ray OP becoming OP'. By the usual optical theory, all rays passing through O will, after refraction at the lens L_2, pass through the conjugate point I. The ray PI will no longer be cut off by the knife-edge, and the point I will appear bright upon the screen. The lens L_2 will have produced an image of the Schliere O upon the screen at I.

In order to investigate the quality of this optical image, we need to consider the exact illuminating conditions at the point O and the manner in which this light is presented to the projection lens L_2. Fig.2 represents these illuminating conditions. As the illuminating slit is at the focus of the first lens L_1, parallel light emerges corresponding to each point on the slit although beams from various points on the slit are not all parallel to each other. Any point O in the field will be illuminated by one ray from each point of the slit, in fact by a fan of rays making an angle θ where θ is the angle subtended at the lens by the slit. For small values of θ we have

$$\theta = \frac{d}{f_1} \qquad (1)$$

where d is the slit width
and f_1 is the focal length of the lens L_1.

Fig.3 now shows the same cone being focussed by the lens L_2 to form an image at I, the entire fan having been deflected sufficiently by the disturbance to prevent any cut off at the knife edge K. The maximum possible light is now going into the image I. Should the movement at the knife-edge be insufficient to clear the knife-edge completely, it can readily be seen that this provides an effective reduction in the slit width and the angle θ will be given by

$$\theta = \frac{d_2 f_1}{f_2 f_1} = \frac{d_2}{f_2} \qquad (2)$$

where d_2 is the width of the beam transmitted past the knife-edge
and f_2 is the focal length of the second lens.

In practice therefore the illuminating angle will be less than the value given by equation (1) and may vary with the deflection ε.

In conventional lens theory, the angle θ determines the relative aperture or f/no at which the lens L_2 is working, the approximate relation between them being, for small angles θ

$$f/no = \frac{1}{\theta} \qquad (3)$$

For a typical case, the slit width may be 0.020" and the focal length of the lens L_1 may be 120". The image is then being formed by a beam of angular extent $\frac{1}{2}$ minute of arc and at an aperture equal to f/6000. The result is that the lens will have an enormous depth of focus in the object space about O. The narrow angular beam causes diffraction effects to become prominent and the image, in the case when all the light passes the second knife edge, takes on the characteristics of the diffraction pattern of the illuminating slit. When the knife edge cuts off part of the light, the resultant illumination is a complicated function of the diffraction patterns of the slit and the knife edge.

Another method of considering the focussing problem is illustrated in Fig.4 where the light path, because of its extremely narrow angle, is considered to be merely a "light ray". The point O_1 deflects the ray by an amount ε_1 but before striking the lens L_2, the ray meets another disturbance O_2 which deflects it a further amount ε_2. On arrival at the lens the total deviation is $\varepsilon_1 + \varepsilon_2$ and the lens finds it impossible to distinguish these deflections as separate entities. The light patch at I will merely be a function of $\Sigma\varepsilon_1$ taken along the entire light path and the lens has no focussing action. Bad windows, poor lenses or mirrors, convection currents, local irregularities will all show up in the final picture. In addition to the alteration in intensity, the position of the image I of the Schliere O_1 will be affected by the presence of the disturbance O_2, the image shift depending on the term $\varepsilon_2 t$ (where t is the distance O_1O_2) and the magnification ratio between the image planes of O_1 and I. This image movement is likely to be small; a window with a local deviation of 1 minute of arc will move the image of a Schliere 10" from it and photographed at a 3 : 1 reduction only by 0.001".

We now consider an arrangement with two slits and two knife edges so arranged that the beams from both slits are cut off simultaneously. Fig.2 will apply again and the angle between the two beams will be given by equation (1) where d is now the distance between the two slits, which can be made much greater than the individual slit width. Fig.4 shows these two rays both being deflected an amount ε_1 at the Schliere O_1 and coming to a focus at the point I, the conjugate point to O_1. The final image of the Schliere is formed by the superposition of these two images. If a second small disturbance occurs at the point O_2 in the path of one beam only, this beam will be deflected while the other will be unchanged and will form the image I with the same intensity and at the same position. For a system with a large number of slits and corresponding knife-edges, i.e. for two complementary grids, there will be a large number of rays forming the image of the point O_1 and the presence of a small disturbance O_2 in one or two of the beams will be completely swamped by the larger number of undisturbed beams. The system now has a focussing action and the image from every slit will only coincide exactly in position and brightness for disturbances on the one plane O_1, conjugate to the image plane.

An alternative point of view uses the concept of the f/no. With the same lens as previously considered, the single slit width of 0.020" may be replaced by a 12" grid containing 100 or more slits.

The angle θ subtended by the outer beams at the projection lens L_2 is now about 6°, equivalent to f/10 and at this relative aperture the depth of focus will be much reduced; small disturbances nearer or farther from the lens not being recorded. This is not exactly equivalent to the usual case of lens focussing as there is not necessarily any phase relationship between the various beams and they will therefore not interfere to form a diffraction image in all cases.

3 Optical Limitations of the Focussing System

The explanations given of the focussing action also help to bring out some of the limiting factors in this type of optical imagery.

As the final image is made up from overlapping images formed by different light rays, it is essential that these rays should all have the same deviation, but unless two-dimensional Schliere are being observed, so that otherwise the rays are in a uniform medium, this is not likely to happen. Each ray will pass through a different part of the three dimensional field, there will be small differences in the deviation of each ray and the images formed on the screen will have different brightnesses and positions. The final picture will not have the correct intensity and will be slightly blurred if these differences in deviation are small, while for Schliere of small diameter a multiple image may be formed. This effect is rather similar to the effect of optical aberrations upon the final image quality of a photograph.

A further difficulty arises from the fact that the beams striking the Schliere, do not do so all at the same angle, and will therefore be deviated by unequal amounts. Since the angle subtended by the beam is small, this difference is unlikely to be large unless the mean angle between the beam and the density gradient is large. This effect always exists however and must lead to an uncertain relationship between the density gradient and the intensity in the Schlieren image.

The use of the term "depth of focus" suggests that, outside a certain range, deviating objects will not show in the final picture. This is only partly true, depending largely upon the size of the disturbance. For a very small disturbance, well outside focus, only one beam may be affected and the loss to the final image may be small. But if the disturbance affects a large proportion of the total beams, it will be very noticeable in the final picture as an intensity difference and a very small shift in position. Should the disturbance cover completely the required Schliere then the deviations will be additive, the position of the image on the screen will be altered and the intensity of the image will correspond to the combined deviation and will, therefore, not be a true indication of the deviation of the Schliere in focus.

While it is true that the effect of an out of focus disturbance on the focussed Schliere is much reduced, the opposite is also true and an out of focus disturbance affects the image over a much larger area. In Fig.5 a disturbance O_2, not in focus, would in a single slit system merely affect an area AB equal to its own area in the plane of focus. Using a multi-slit system with an illuminating cone of angle θ an increased area A'B' will be affected by the disturbance even though the influence of the disturbance will be much reduced in the original area AB. The effect of the out of focus disturbance is spread out and weakened.

The focussing effect is in many ways very similar to that seen in normal pictorial photography where objects not in focus still appear in the final picture unless they are very small. They appear to be larger than when in focus, are very diffuse and when subtending a small angle at the camera, allow other objects to be seen through them. This is the appearance of out of focus disturbances in a Schlieren field and if these disturbances are large in area or possess large deflections they will always be apparent in the final picture although in a diffuse manner. In the Schlieren case moreover there may be an increase in illumination and a slight change of the position of a Schliere in the plane of focus, due to an out of focus disturbance.

In spite of these difficulties, in a great many cases information about a three-dimensional system can be obtained by taking a series of photographs through focus. The position of any Schliere can then be estimated by finding the plane of sharpest imagery. When sharp discontinuities are present, this can be done with an accuracy comparable to that of focussing in normal photography. In general, however, a change of focus will merely alter the intensity distribution in the image, there will be nothing definite to focus upon and the new intensity distribution will not be a reliable guide to the actual density gradients in the plane of focus.

4 Defects in Optical Components

In focussing systems it may be possible to reduce the quality required in the windows, mirrors etc. of the system. The wind tunnel is normally closed by windows of thick glass and the problem of obtaining glass of sufficient strength and homogeneity is very difficult to solve except at great expense and with great waste of glass in selection. Fig.6 shows a focussing system for a wind tunnel. Each Schliere O in the plane of focus is illuminated by a cone of angle θ given by equation (1), and this cone will intersect the window in a patch of size h given by

$$h = \ell\theta = \frac{\ell d}{f_1} = \frac{\ell}{f/no} \qquad (4)$$

where ℓ is the distance from the Schliere to the window
d is the size of the grid containing the slits
f_1 is the focal length of the first lens or mirror
f/no is the relative aperture of the illuminating beam.

For a beam of focal ratio f/10, the window patch size for a wind tunnel of total length 20" ($\ell \approx 10"$) will be about 1". The window will not affect the Schlieren images if any patch 1" in diameter contains a large proportion of undeviating glass. By far the most common defect of glass is the presence of ream (or veins) in the form of long threads or filaments which, in a single slit system, are registered directly upon the screen. They possess, however, only a small area and would disappear in many cases when a focussing system is used. Ordinary twin ground and polished plate glass, selected to be free from major defects, should be satisfactory for a system with the dimensions quoted.

The mirrors or lenses are illuminated by each point in the Schlieren field over an area instead of there being a point to point correspondence. The size of the illuminated patch will be governed by equation (4) where ℓ is now the distance from the plane of focus to the mirror. The mirror can then have local defects, polishing marks, small pits or narrow grinding zones without affecting the image, providing these never cover a high proportion of this illuminated area.

5 Focussing System No.1

This, the most simple system, consists of a single lens and is shown in Fig.7. Here L is the lens, AB the grid, CD the focussing plane containing the Schliere, EF the plane of the complementary or knife-edge grid upon which the lens forms an image of the primary grid. The plane GH, conjugate to the Schliere plane CD, contains the screen or photographic film upon which the image is recorded.

With the notation shown in the diagram, we can derive quite simply the following relationships. The maximum diameter h of the Schliere observable is

$$h = \frac{d\ell}{L} + \frac{D(L-\ell)}{L} \qquad (5)$$

In this system, then, a sizeable field $d\left(\frac{\ell}{L}\right)$ can be obtained with a lens of zero aperture D. Using the full field given by equation (5) the extreme points suffer from considerable vignetting and the focussing effect is accordingly much reduced. The largest field that can be used without vignetting is given by

$$h = \frac{\ell d}{L} - \frac{D(L-\ell)}{L} \qquad (6a)$$

if the Schliere is nearer the grid and a large grid is used or by

$$h = \frac{D(L-\ell)}{L} - \frac{\ell d}{L} \qquad (6b)$$

if the Schliere is near the lens and a large lens is used. The effect of vignetting is to make the light intensity less in the outer parts of the field. As this upsets completely the relationship between light intensity and deflection, and may lead to the masking of Schliere in the outer parts of the field, vignetting is a bad fault in these systems. It should be investigated in the undisturbed field and only the central unvignetted area used in subsequent work.

The total illuminating cone is given for small angles by the smaller value of the two expressions

$$\theta = \frac{d}{\ell} \qquad (7a)$$

or

$$\theta = \frac{D}{L-\ell} \qquad (7b)$$

These are for corresponding conditions to those of equations (6a) and (6b) above.

The size of the complementary grid must be

$$d' = d\left(\frac{L'}{L}\right) \qquad (8)$$

The size of the image on the screen is

$$h' = h\left(\frac{\ell'}{\ell}\right) \qquad (9)$$

This image size can always be made more convenient by the use of an auxiliary lens between the complementary grid and the screen.

The necessary focussing conditions are

$$\frac{1}{F} = \frac{1}{L} + \frac{1}{L'} = \frac{1}{\ell} + \frac{1}{\ell'} \qquad (10)$$

In this equation all the terms are regarded as positive in Fig.7.

The image movement $\Delta s'$ at the knife-edge for a deviation ε at the plane O_1 is given by

$$\Delta s' = \varepsilon \frac{(L-\ell)L'}{L} \qquad (11)$$

The total deviation to bring the image from zero to maximum intensity is given by

$$\varepsilon_{max} = \frac{s}{(L-\ell)} \qquad (12)$$

where s is the width of the individual slits in the primary grid.

The black spaces in the primary grid should be large enough to prevent interference between the individual beams at large deflections. The thickness of the black spaces is given by

$$t = E(L-\ell) \qquad (13)$$

where E is the maximum deflection possible in the Schlieren system.

Equations (5) to (13) suffice to design or to calculate the performance of this type of system. As an example we take a system with a 3 : 1 reduction of the grid and a rendering of the Schlieren field at 1 : 1 magnification. From an application of equations (8), (9) and (10) the dimensions become $L = 4F$, $\ell = 2F$ and if the illuminating cone is to work at F/10, $D = {}^{2F}/10$ or $= {}^{F}/5$. The lens should have a minimum aperture of f/5. If the system is to work with a 20" wind tunnel, the Schliere being approximately central, then L must be above 20" i.e. 4F = 20" or F = 5" and D = 1". The system can use a 5" f/5 lens.

For practical reasons, the largest grid would appear to be about 12" square i.e. d = 12". Application of equations (5) and (6) gives

$$h = \frac{12 \times 2}{4} + \frac{1 \times 2}{4} = 6\tfrac{1}{2}" \qquad \text{if vignetting is permitted}$$

$$\text{or} \quad h = 6" - \tfrac{1}{2}" = 5\tfrac{1}{2}" \qquad \text{if no vignetting is permitted.}$$

The complementary grid at 3 : 1 reduction will be 4" square and at this size the width of the line obtainable with sufficient definition is about 0.003" equivalent to 0.009" slit width in the primary grid. With this slit width and the grid-Schlieren separation of 10", the total deviation from zero to maximum intensity will be $\frac{0.009}{10} = 3$ minutes of arc. With the system set to mean intensity a range of $\pm 1\frac{1}{2}$ minutes of deviation can be measured.

This calculated system is relatively insensitive, at mean setting a 10% change in brightness being given by a 9 sec deviation. The field cover is high for the diameter of the lens, an unvignetted field of $5\frac{1}{2}$" being given with a lens of only 1" diameter. It has therefore been called a wide-field system. To achieve this wide field, however, requires the use of large grids with fine slits and these are not easy to make and set up.

The lens requirement should be easily met, the system calculated requiring a 5" lens at f/5 covering a field angle of 30° total. The main disadvantage of the method is that the principle rays are inclined at an angle to the axis of the wind tunnel, and that therefore, unless the Schliere are approximately two-dimensional, the intensities recorded upon the screen will not be truly representative of the density gradients of the Schliere in focus.

6 Focussing System No.2

The previous system requires a large diameter grid unlike the usual system which requires large diameter lenses. A modification to the first system makes use of a large grid produced optically. The arrangement is shown in Fig.8 in which an image of the real grid S is formed by a lens L_1 at a position S'. A condensing or field lens L_2 must be used to form an image of the lens L_1 upon the third projection lens L_3 to ensure an adequate illuminating beam. The function of this third lens is similar to that of the lens in the first focussing system, namely to produce an image of the grid S' upon a complementary grid S" and an image of the Schliere O upon a screen at I. The equations of the previous section govern the performance of this part of the system. A completely symmetrical arrangement can be used with a supplementary lens, if required, between the complementary grid and the screen.

This system may be more simple in use, as it will be easier to make a large field lens L_2 than a large grid, particularly as the lens need not have great accuracy of figure. The main disadvantage of this system is its length for it will be at least twice as long as the previous system, and if the lens L_2 is to have a reasonable focal length may be more than twice as long. It also suffers from the same difficulty as the previous system if the Schliere are not all in one plane, for the principal rays are inclined to the axis.

7 Focussing System No.3

This is the counterpart of the common parallel beam Schlieren system, with grids replacing the slit and knife-edge. The system is shown in Fig.9, in which the grid S is placed at the focus of the lens L_2, so that a parallel beam passes through the wind tunnel to the projection lens L_2. At the focus of this lens, an image of the primary grid is formed upon the complementary grid S'. An image of the Schliere O is formed upon the screen at I.

The introduction of a finite grid of size d, illuminates the Schliere with a cone of angle θ given, for small values of θ, by

$$\theta = \frac{d}{F} = \frac{1}{f/no} \tag{13}$$

where F is the focal length of the two lenses
f/no is the relative aperture at which the illuminating beam works.

The diagram shows that Schliere in the plane O will not all be illuminated by this full cone of light, that vignetting will occur and that the total diameter of the field without vignetting will be given by

$$h = D - \ell\theta = D - \frac{\ell d}{F} \tag{14}$$

where ℓ is the distance of the Schliere from either lens if placed centrally or is the longer of the distances L_1O, L_2O if unevenly spaced. The field is therefore restricted compared with the usual single slit system in which a field equal to the lens diameter D is obtained. The size of the Schlieren field upon the screen I is given by

$$h' = h\frac{\ell'}{\ell} \tag{15}$$

and ℓ' and ℓ are connected by the equation

$$\frac{1}{F} = \frac{1}{\ell'} + \frac{1}{\ell} \tag{16}$$

with both distances being regarded as positive in the diagram.

The change in ray position $\Delta s'$ at the complementary grid for a deviation ε is given by

$$\Delta s' = \varepsilon F \tag{17}$$

and so is independent of the separation of the two lenses and the Schliere position. The maximum measurable deflection from zero to maximum intensity is then given by

$$\varepsilon_{max} = \frac{s}{F} \tag{18}$$

where s is the width of the individual slits in the grid.

These equations (13) to (18) allow the complete system to be designed or the performance of a given system to be calculated.

As a numerical example we will assume two 36" f/6 lenses are used for the lenses L_1 and L_2. For an illuminating cone working at f/10 the grid size from equation (13) is $d = 3.6"$. From equation (16), in order to have a real image of the Schliere O formed upon a screen, ℓ would need to be larger than F i.e. 36" becomes the least value for ℓ. Under such circumstances we find

$$h = \frac{36}{6.3} - \frac{36}{10} = 5.7" - 3.6" = 2.1".$$

The field without vignetting is much reduced and would be reduced to zero if with this arrangement the lenses had been separated by 144" to produce a 1 : 1 image of the Schliere upon the screen at I. However the use of an auxiliary lens placed beyond the knife-edge allows the two lenses to be brought closer together, and we therefore take the case of Fig.9 with the lenses separated by 20" and an auxiliary-lens placed at L_3 to focus the Schlieren image.

The unvignetted diameter then becomes

$$h = 5.7'' - 1'' = 4.7''.$$

By application of equation (16) to L_2 and L_3 successively, the necessary focal length of the lens L_3 can be found. For slit widths of 0.005" in the primary grid, the maximum deviation becomes (equation 18) equal to 28 seconds of arc or at a mean intensity setting ± 14 seconds of arc. The 10% illumination change in sensitivity is then $1\frac{1}{2}$ secs of arc. The system may be made less sensitive by having wider slits on the grid.

This system has greater sensitivity than focussing system No.1, has rather less field and requires three large lenses and two small grids. Compared with the usual non-focussing type, it achieves its focussing action at the expense of a reduced field and the necessity for an auxiliary lens.

8 Application to Mirror Systems

A common wind tunnel Schlieren system uses concave mirrors in place of a lens, the system being shown in Fig.10. The slit and knife-edge are not on the axis of the concave mirrors but are offset to prevent interference with the main parallel beam. They are offset by equal angles on opposite sides of the axis, the coma errors introduced by the two mirrors are then equal and opposite, the final image at the knife-edge being coma-free but suffering from astigmatism which does not cancel.

A typical system uses mirrors 10" in diameter, working at f/10 or f/15, with a mirror separation of 120". This may be converted into a focussing system by the substitution of grids for the slit and knife-edge. The size of the grids required for a given illuminating angle can be found from equation (13). For a focal length of 120" and a diameter of 10", an illuminating cone of f/10 requires a 12" grid and with the mirror separation of 120" and the Schliere mid-way between the mirrors, this gives an unvignetted field of only 4".

As the Schliere is within the focus of the second mirror an auxiliary lens must be used to focus the Schliere upon the final screen and this lens must have a diameter as large as the second grid, in this case of 12" or over in diameter.

These figures admittedly refer to an f/10 system, this being a purely arbitrary choice. Using an illuminating cone of f/20 corresponding values become 6" for the grid and auxiliary lens diameters and the unvignetted field becomes 7". These values are more acceptable in many respects but the focussing effect will be much reduced by this change. The illuminated patch size on the window of a wind tunnel 20" in length will be only $\frac{1}{2}$", or for a 5" wind tunnel only $\frac{1}{8}$". As disturbances have to be small compared with this patch size, it is clear that there will be very little focussing effect in the 5" tunnel although some advantage might be obtained in the 20" tunnel.

Another difficulty in using a conventional mirror system becomes apparent in Fig.11. The optical path is halved by using an auxiliary plane mirror to fold up the light path and thus allow the main mirrors to be brought closer together. When a grid is used, the necessary diameter of the plane mirror is increased, from 5" to 8" for an f/20 system or to 11" for an f/10 system. The off axis angle will have to be increased considerably to prevent the interference of this much enlarged mirror with the main beam. This increase in angle brings increased astigmatism in the image, this astigmatism growing rapidly with angle. It is also apparent that all the slits do not subtend the same angle with the axis and for those at one edge of the grid an extra 3° angle is necessary for an f/10 system. The increased astigmatism present in some of the slit images will effectively reduce the focussing action of the system and cause a general loss of definition, this being accentuated by the loss due to the increase of the overall angle with the axis and consequent astigmatism.

The sensitivity of the mirror system should not be affected by the substitution of the grid providing the slit dimensions have been correctly chosen. It seems unlikely, however, that the full benefit of a focussing system can be obtained with the usual concave mirrors owing to the large f/no's and because of the necessity of forming images of good quality at large angles off-axis. Mirrors are known to be poorly corrected for off-axis aberrations and, from this point of view, the use of well corrected flat-field lenses of much shorter focal length seems to be necessary if the full advantage of the focussing system is to be obtained.

9 Practical Details

It is not easy to suggest the best values for all the variables of these systems, and it may well be that the Schlieren user will require a number of systems having different sensitivities and field diameters, these being the main variables. For fields of 4-5 inches diameter with a 10% sensitivity of 2-3 secs deviation, the system of section 7 using 36" f/6.3 lenses should give good results. Shorter focal lengths could be used with a loss of field and sensitivity.

The two main lenses could be photographic lenses or even doublet lenses could be used as they have to handle a total angular field of only 6°. They should be well corrected for spherical aberration, coma and chromatic aberration if the illumination in the Schlieren field is to be uniform, free from colour, and the full focussing effect is to be obtained. The auxiliary lens required cannot be the usual single lens as the image-forming light is no longer confined to a single ray but has a cone working at around f/10 in the object space and according to the final image size may work at even smaller aperture ratios in the image space. The spherical aberration present in a single lens may then be sufficient to destroy the definition in the Schlieren image. For an image size of 4" in the 36" system, the auxiliary lens has an aperture of $3\frac{1}{2}$", a focal length of 18" and has to cover an image 5" in diameter. A flat field photographic lens is necessary here.

The primary and complementary grids are required to match each other with great accuracy, and the optical system should form an image of the primary grid with the highest possible definition. The complementary grid may well be made by photography through the system using a photographic plate in the position at which the primary grid is focussed. The photographic plate, after processing, becomes the complementary grid and has to be replaced in the same position. Auxiliary marks should be placed on the edges of the primary grid, so that the plate after processing can be replaced and re-aligned with the optical image of the primary grid. This method of making the complementary grid has the advantage that any distortion in the lens system will be compensated and even though the slit image may be curved slightly, the complementary grid will still match it. If the complementary grid is made by contract printing from the primary grid, this matching will not occur in the presence of lens distortions and intensity errors will arise.

It should also be noted that it is essential for the complementary grid to be replaced in the correct plane with great care. If this is not done, the image of the primary grid will not be in focus on the complementary grid and intensity differences will be blurred over. In addition the scale of the image will be wrong, it will not be possible to have all the slits cutting off together, the intensity due to each slit will be different, the focussing effect will be reduced and the relationship between intensity and air density gradient may vary over the field. It will therefore be necessary to pay more attention to the correct focussing and alignment of the complementary grid when setting up the apparatus, than is usual in the case of a single knife-edge.

As the grid system requires the optical components to give an image over an extended field with a finite aperture, lenses are more appropriate than mirrors. They have however appreciable chromatic aberration and it may be necessary to work with monochromatic light perhaps from a sodium lamp or green mercury light filtered from a high pressure mercury lamp. Unless approximately monochromatic light is used the image formed on the complementary grid may have diffuse coloured edges and the visual Schlieren field will have coloured patches.

Illumination of the primary grid may present a problem as the area to be illuminated is large (up to 12" square) and each slit in the grid must illuminate the whole of the unvignetted field. A condensing lens of large diameter can be used if the source has a large enough area to illuminate the entire field, a condition not found in the compact source type of high pressure mercury lamp. The compact source lamp is so desirable for its nearly monochromatic, highly intense light output that it will largely be used for focussing systems with an opal glass diffuser close to the grid. This method of illuminating loses a great deal of light in the opal glass and the final image brightness of the Schliere upon the screen may be lower than the brightness normally met in single slit systems.

10 Conclusions

(1) The focussing effect depends upon the increased illuminating angle obtained when grids are substituted for the usual knife-edges.

(2) The effect upon the final image plane of an out-of-focus Schliere depends largely upon the amount of deviation caused by the Schliere and its area.

(3) Areas with large deviations will always be recorded in the final image even though much out of focus.

(4) The location of discontinuities can be found from their plane of best focus.

(5) The intensity distribution in the plane in focus is not a reliable guide to the density gradients in that plane.

(6) Focussing systems have by normal wind tunnel standards a small working field.

(7) For parallel beam systems the unvignetted field is considerably less than the mirror or lens diameter although the grids can be small in size.

(8) For inclined beam systems the field can be larger than the lens diameter although very large grids may be required and these are difficult to make and illuminate.

(9) The inclined beam systems are at a disadvantage with three-dimensional Schliere.

(10) Mirror systems are not as well suited as lens systems because of the large off-axis aberrations likely to be introduced. Present wind tunnel mirrors cannot effectively be adapted to focussing systems.

(11) These focussing systems require very great care in setting up and adjustment.

(12) There are likely to be more sources of intensity errors in a focussing system and quantitative work is not likely to be accurate.

(13) The focussing systems are not suitable for general wind tunnel work because of their small fields but may be of use as special tools for investigating problems in three dimensions.

(14) The use of lower quality windows and optical components is possible in focussing systems.

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2	Kantrowitz, A., and Trimpi, R.L.	A sharp-focussing Schlieren system. Journal of Aeronautical Sciences, 17 (1950) 5 (May) pp. 311-314.

Wt.2078.CP54.K3. Printed in Great Britain.

FIG. 1.2.3 & 4

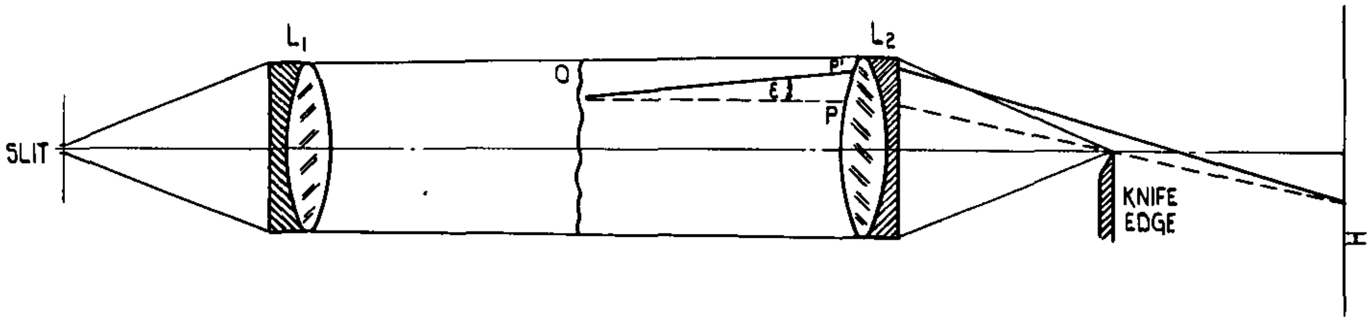

FIG. 1 CONVENTIONAL SCHLIEREN SYSTEM.

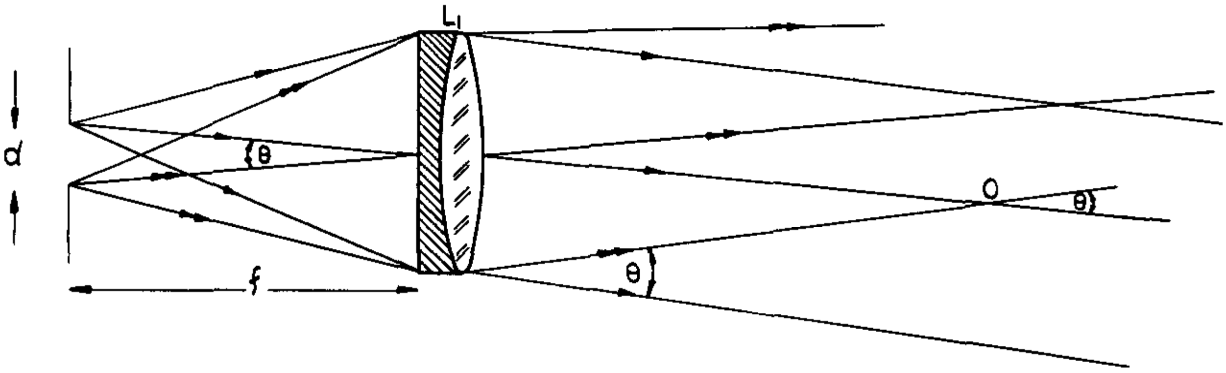

FIG. 2 THE ILLUMINATING CONE.

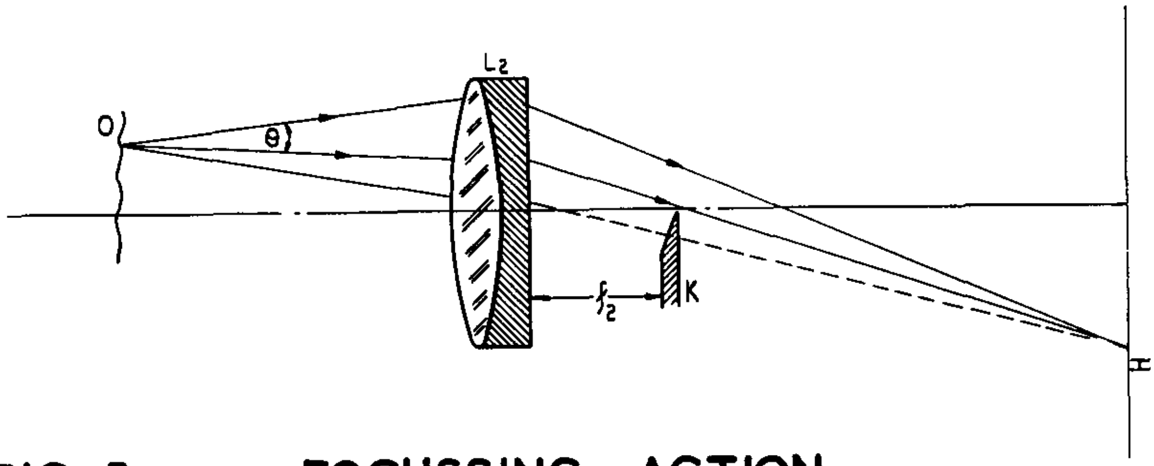

FIG. 3 FOCUSSING ACTION.

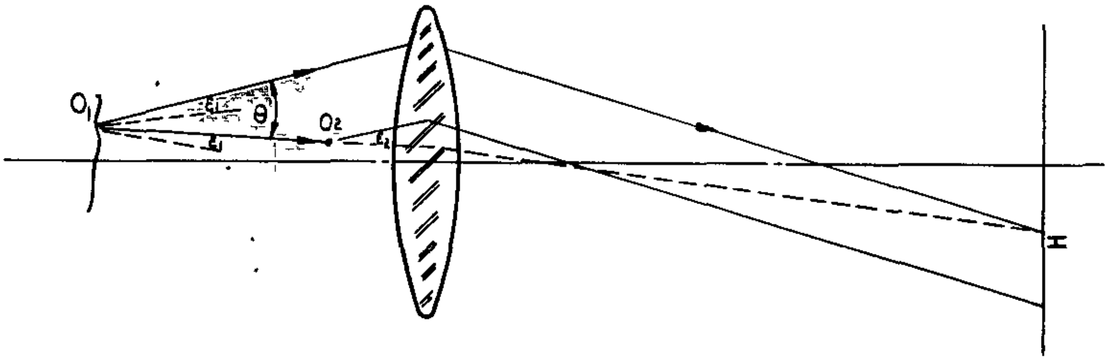

FIG. 4 EFFECT OF AN OUT - OF - FOCUS DISTURBANCE.

FIG. 5,6,7&8

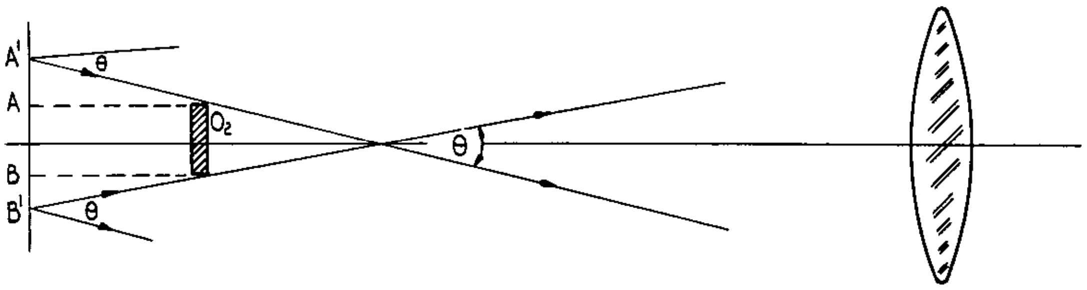

FIG. 5 AREA AFFECTED BY A DISTURBANCE

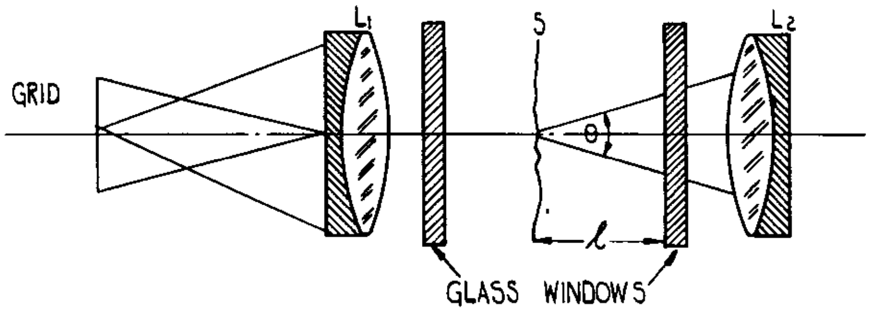

FIG. 6 WIND TUNNEL WINDOWS IN SCHLIEREN SYSTEM.

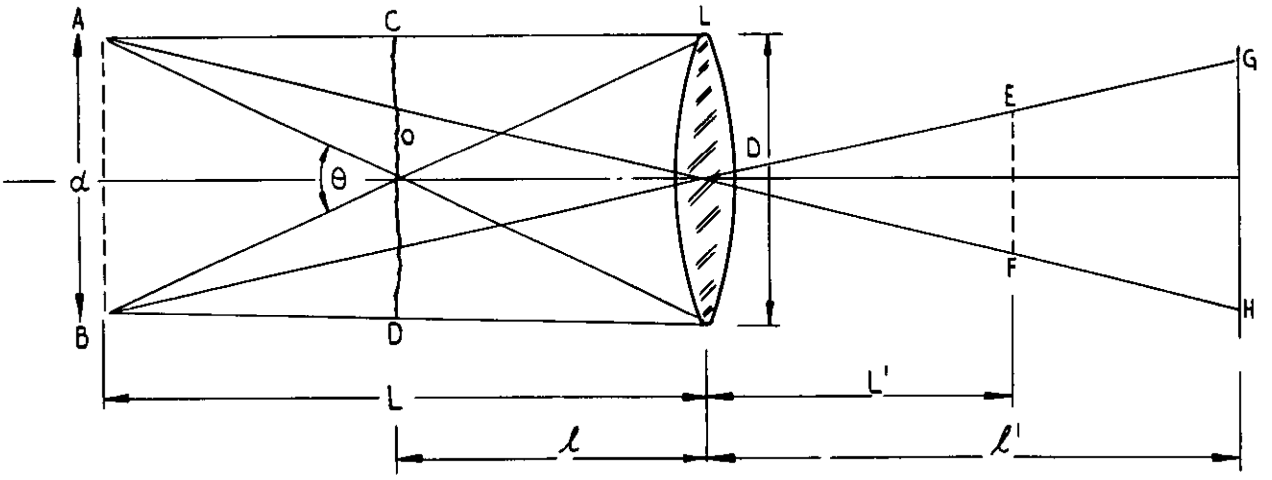

FIG. 7 SINGLE LENS FOCUSSING SYSTEM

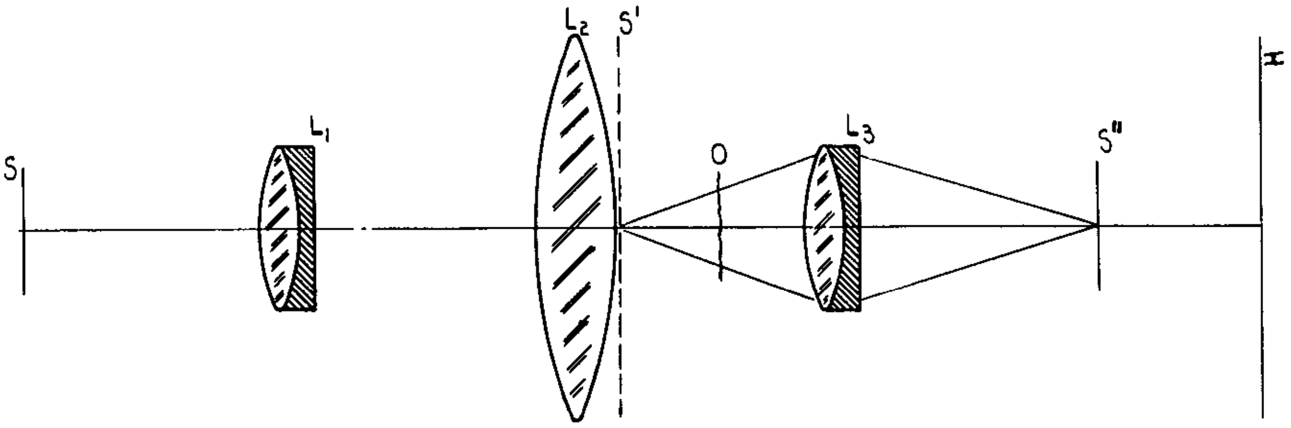

FIG. 8 SYSTEM USING OPTICAL ENLARGEMENT OF GRID

FIG. 9,10&11

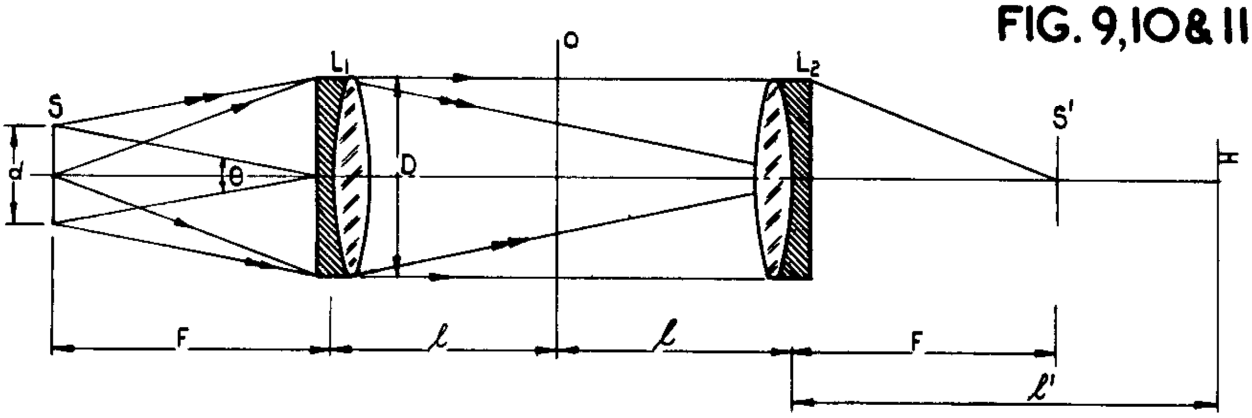

FIG.9 PARALLEL BEAM FOCUSSING SYSTEM.

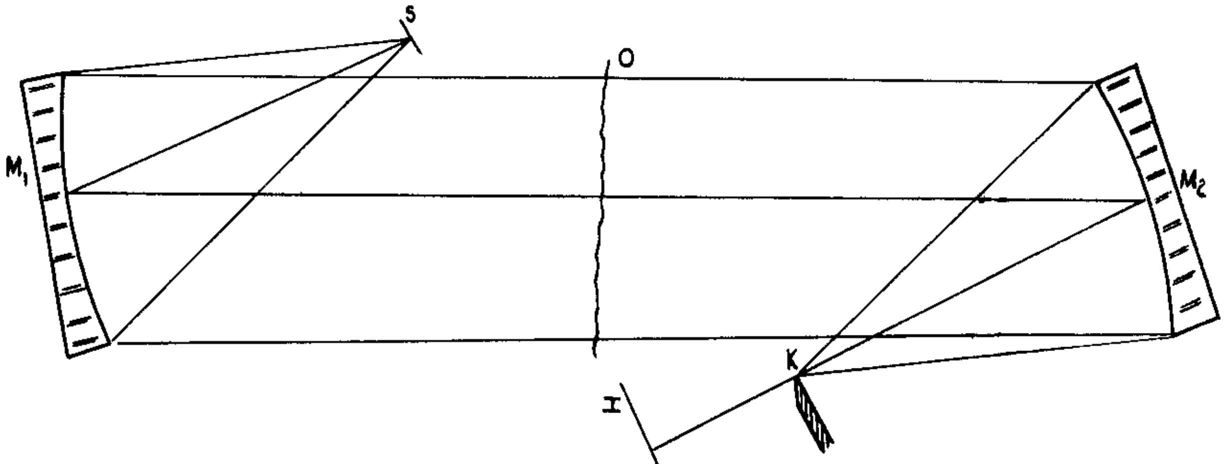

FIG.10 CONVENTIONAL MIRROR SCHLIEREN SYSTEM.

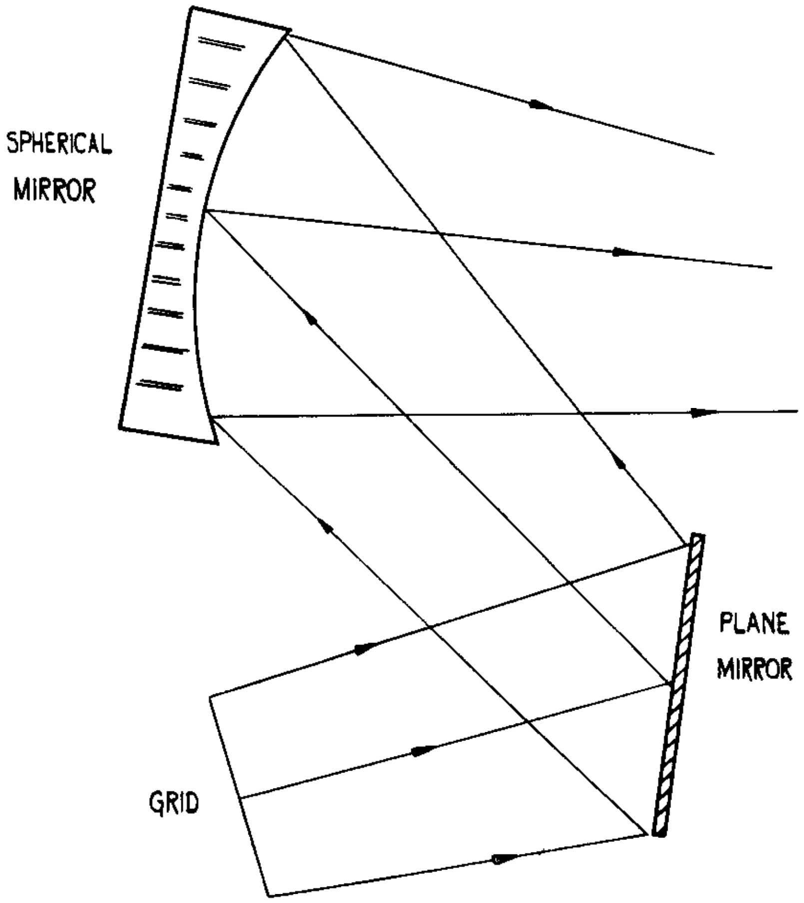

FIG. 11 FOCUSSING MIRROR SYSTEM.

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