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Large-Field High-Brightness Focusing Schlieren System

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The analysis and performance of a large-field high-brightness focusing schlieren system is described. Techniques are described that allow the system to be used even through slightly distorting optical elements. The system can be used to examine complex two- and three-dimensional flows.

Nomenclature

A = clear aperture of focusing schlieren imaging lens
A_3 = effective diameter of focusing lens for conventional schlieren
a = light source image height above cutoff
b = distance between cutoff grid lines in focusing schlieren
DS = depth of sharp focus
DU = depth of unsharp focus
d = resolution limit due to diffraction from slit
d' = resolution limit due to diffraction from circular aperture
F = distance from cutoff to image in focusing schlieren
F' = distance from cutoff to image in conventional schlieren
f = focal length of focusing schlieren imaging lens
L = distance from source grid to imaging lens in focusing schlieren
L' = distance from mirror or lens to cutoff location
l = distance from object in flowfield to mirror or lens
l' = distance from mirror or lens to final image location
m = magnification of image in focusing schlieren, l'/l
m' = magnification of image in conventional schlieren
n = grid lines per millimeter at cutoff grid
n' = grid lines per millimeter at source grid
R = object distance divided by lens diameter, l/A
w = grid diffraction limited resolution of flow detail in focusing schlieren
w' = lens edge diffraction limited resolution of flow detail in conventional schlieren
Δa = change in a due to refraction
ε = angle change, normal to cutoff, for focusing schlieren
ε' = angle change, normal to cutoff, for conventional schlieren
ε_{min} = angle change resulting in 10% brightness change in focusing schlieren
ε'_{min} = angle change resulting in 10% brightness change in conventional schlieren
λ = wavelength of light
ϕ = pairs of lines involved in forming each point in focusing schlieren image

Introduction

THE three principal optical methods used to examine flow density variations—schlieren, shadowgraph, and interferometer—give information that is related to refraction of the light integrated along the optical path. Variations of these optical methods, which are capable of focusing in a fairly thin portion of the optical path, would greatly aid in the examination of complex flowfields. Focusing schlieren, which was first described over 40 years ago, is capable of producing images that can be examined in narrow planes normal to the optical axis. Two separate versions of focusing schlieren were developed. One version, by Kantrowitz and Trimpi,[1] required two well-corrected wide-angle lenses and was limited to a field of view smaller than the lens diameter. The second version, by Burton,[2] required only one lens and could cover a field of view larger than the lens diameter. A review paper on focusing schlieren techniques by Fish and Parnham[3] provided an analytical description of these systems. The paper also discussed the weaknesses and limitations of focusing schlieren. Two of the limitations that were described were the small size of the field of view compared with large conventional schlieren systems and the relative difficulty of setting up and adjusting these systems. This paper is quoted in many of the review articles of such systems.[4] A Master's thesis by Boedeker[5] was the first paper to describe the use of a Fresnel lens for higher brightness. His analysis anticipated some of the problems that had to be overcome to take full advantage of the technique. Unfortunately, the work was not disseminated and remained buried to the present time. A version of the Kantrowitz and Trimpi system was used by Buzzard[6] in 1968 to make three-dimensional schlieren pictures of flows using holography. Rotem et al.[7] examined a color focusing schlieren system in 1969. This system did not have a depth of focus small enough to be of much help in examining complex three-dimensional flowfields. Diffuse-illumination, double-exposure holographic interferometry has also been used for three-dimensional flow visualization,[8] but this approach requires a far more complex setup than versions of focusing schlieren that use holography.

These focusing optical systems all have significant limitations such as low brightness, small field of view, large depth of focus, or difficulty of use. The current paper describes a focusing schlieren system that eliminates some of these limitations and is far less complicated than the diffuse-illumination, double-exposure holographic interferometer. In addition, techniques are described that can be used to make focusing schlieren a particularly powerful and versatile tool to examine a wide range of flows.

Characteristics of Focusing Schlieren

Figure 1 shows the present focusing schlieren system. The basic design is similar to the version described by Burton,[2] with the main differences being the substitution of a Fresnel field lens for the diffuser and the use of a small but extended light source. The Fresnel lens concentrates the light source at the imaging lens location. This results in an image over 100 times brighter than the diffuser version. The source grid can be either closely spaced small points or thin lines that fill the source area. For the current paper, only thin parallel-line grids are considered, but the results would be similar for other types of grids. The source grid has to be about twice the size of the test area since it is about twice as far from the lens. The cutoff grid is a photographic negative image of the source grid. Orientation of the grid (horizontal or vertical) depends on the desired direction of sensitivity.

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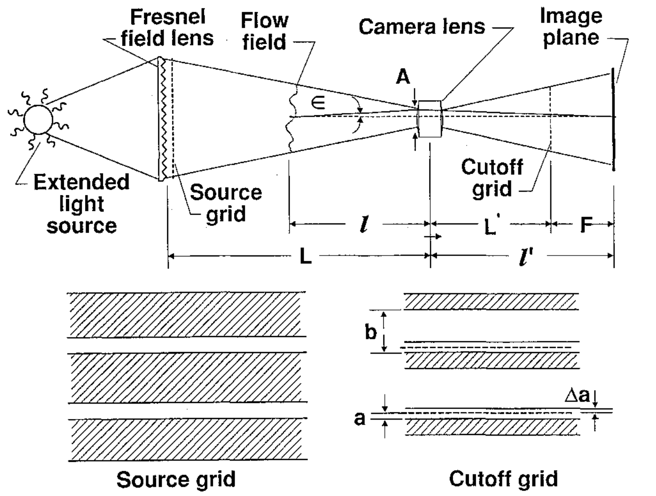


Fig. 1 High-brightness large-field focusing schlieren system.

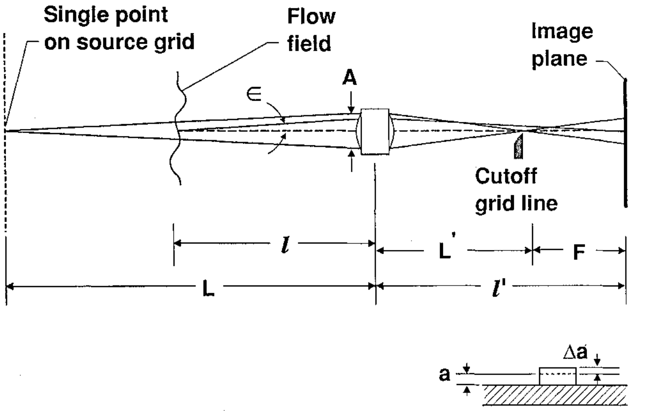


Fig. 2 Single source point in focusing schlieren system.

If we examine the light from one point at the source, we have the optical system shown in Fig. 2. If several closely spaced source points are used to show a feature in the flowfield, the feature shows up in several overlapping images, with overlapping flow features if we are in focus and nonoverlapping features if we are not in focus. Different positions in the flowfield can be brought into focus by moving the image plane location. As the source array is made larger, the field of view also gets larger, with different parts of the source array (grid) being used to examine different parts of the flowfield.

An examination of the optical properties of focusing schlieren and comparison with conventional schlieren demonstrate the capabilities and limitations of this technique.

Sensitivity

Figure 3 shows the basic layout of a conventional schlieren system[9] with a lens-type system shown for simplicity. A light source with image height $2a$ is imaged on a knife edge so that half of the image is cut off by the knife edge. Refraction caused by density variations in the test region bends the corresponding portion of the collimated light beam and moves a portion of the image of the source relative to the undeflected image. Movement normal to the knife edge results in a change in the brightness at the corresponding location in the image of the test region. If we use the criterion that the smallest change in brightness that can be detected is 10%, the sensitivity of the system is

$$\varepsilon'_{min} = 0.1(a/L')\ \text{rad}$$

which can be rewritten as

$$\varepsilon'_{min} = 20{,}626(a/L')\ \text{arcsec} \qquad (1)$$

The sensitivity for the focusing schlieren system shown in Fig. 1 is defined in a similar fashion as the conventional schlieren. Because of the optical arrangement used, the sensitivity of the focusing schlieren is[3]

$$\varepsilon_{min} = 20{,}626aL/[L'(L-l)]\ \text{arcsec} \qquad (2)$$

The value of L' is generally much smaller in focusing schlieren systems than in conventional schlieren. The added term $[L/(L-l)]$ also tends to make focusing schlieren systems less sensitive. These two effects result in the need for very small values of a to obtain high sensitivity in focusing schlieren systems, and this may be a limitation for some lenses.

Resolution

The imaging resolution of features in the flowfield is limited either by the nondiffraction limited imaging quality of the optical elements or by diffraction effects.[9,10] For the following discussion we only consider the diffraction effects. In a conventional schlieren, diffraction from the perimeter of the focusing lens (lens 3 of Fig. 3) is usually the cause of the limitation. Only the portion of the lens above the knife edge is used for imaging. The resolution at the image (assuming, as an approximation, a circular aperture with diameter A_3) is

$$d' = 1.22F'\lambda/A_3$$

and this corresponds to a resolution of features in the test section of

$$w' = 1.22(l'-L')\lambda/(m'A_3) \qquad (3)$$

For focusing schlieren, the cutoff grid diffraction effect is the greatest limit to image sharpness. The resolution limit due to a slit was defined in Ref. 10 as $d=2F\lambda/b$, where

$$F = (l'-L')$$

We thus obtain

$$d = 2(l'-L')\lambda/b$$

and if the change in size from the test section to the image is included, the resolution of features in the test section is:

$$w = 2(l'-L')\lambda/mb \qquad (4)$$

Depth of Focus

Since a major feature of a focusing schlieren is the ability to examine two-dimensional slices of a flow, the effective thickness of this slice has to be defined. Two options for the definition of the

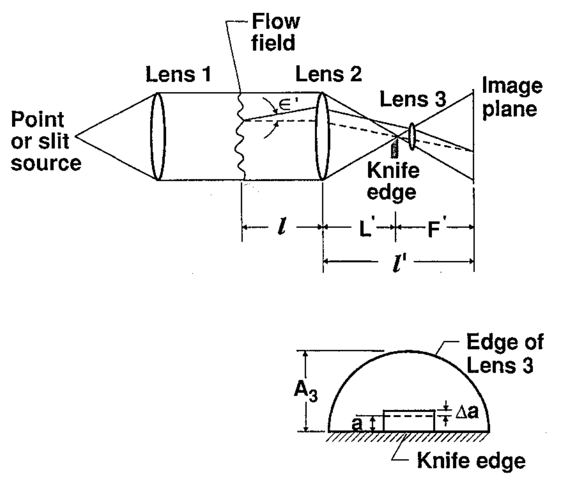


Fig. 3 Conventional schlieren system.

Table 1 Focusing schlieren examples: f=600, A=100, ϵ_{min}=4 arcsec, ϕ=5, λ=5×10^{-4}, image size=230[a]

l	L	l'	L'	R	n	m	a	b	w	DS	DU	Field of view	Lines of resolution
914	1,372	1,829	1,097	9	0.25	2.00	0.071	3.91	0.09	1.7	35.6	115	1,223
1,524	2,540	1,016	803	15	0.47	0.67	0.064	2.01	0.16	4.8	61.0	345	2,156
3,658	7,315	732	665	36	1.09	0.20	0.064	0.79	0.43	30.5	147.0	1,150	2,662
12,395	24,790	640	625	122	3.94	0.05	0.061	0.13	2.43	584.0	508.4	4,600	1,893

[a]All Dimensions in millimeters.

effective thickness are 1) the depth at which the loss of resolution due to being out of focus exceeds the resolution of the optical system and film and 2) the depth at which the loss of resolution due to being out of focus exceeds some selected flow-related value, such as the smaller details required in the object field. The depth of focus of any schlieren system is related to the maximum angle between different rays of light going through each point in the object field. For conventional schlieren, this is the angle that the source image makes in the test section and is so small that the focus essentially extends through the entire region between lenses or mirrors. For focusing schlieren, the imaging lens aperture is the source of the maximum angle, and objects go out of focus in a fairly short distance. For focusing schlieren, we use the first option mentioned earlier to define a "sharp focus depth":

$$DS=2Rw \tag{5}$$

where the factor of 2 includes both sides of the focal plane. We use the second option mentioned earlier to define an "unsharp focus depth." Since a considerable amount of unsharpness is needed for flow details to be effectively blended, a choice of 2 mm was used in this paper. For this case the depth of unsharp focus is defined as

$$DU=4R \text{ mm} \tag{6}$$

It should be noted that 2 mm is an arbitrary choice (found to be a reasonable choice for several flows examined by the author), and other choices may be better for some flows.

Field of View

The maximum possible size for the field of view examined is the imaging lens format (allowed image size) divided by the magnification m. For a given allowable format, the greater the distance from the flowfield to the lens, the larger the allowable field. The actual field examined is generally smaller than this and is determined by the Fresnel lens and source grid size used.

The Fresnel lens and source grid have to be about two times the desired flowfield diameter, since they are about twice as far from the imaging lens. Fortunately, Fresnel lenses up to about 1 m in diameter are easily available (and inexpensive), and these would allow about a 0.5-m field of view. By using an array of Fresnel lenses, with separate light sources for each lens, even larger flowfields can be examined. By using front-lighted reflective grids (which may just be painted stripes) for sources, very large fields of view can be obtained, but this approach requires more source light intensity than systems with Fresnel field lenses.

Cutoff Grid

If cutoff grid lines are too widely spaced, only a small number of points are used to form each image, and the out-of-focus grid lines show up as distinct unsharp images. As we decrease the cutoff grid line spacing or increase the distance from the cutoff grid to the image, the image is formed from a progressively larger number of pairs of cutoff grid lines. The number of pairs of lines blended is

$$\phi=An(l'-L')/(2l') \tag{7}$$

and the author has observed that $\phi>5$ is needed to give a reasonably uniform exposure, with the best results obtained for $\phi>8$.

Design of Focusing Schlieren Systems

A variety of practical considerations limit the type of focusing schlieren system that can be easily made. Lenses with long focal lengths, large apertures, large angular fields of view, and high resolution are difficult to obtain or very expensive. By selecting some of the desired characteristics of a system, we restrict others. We need to decide what is needed most—high sensitivity, high resolution, large field of view, or small depth of focus—and what values of these are acceptable.

Lens and Grid Selection

Using Eqs. (2), (4), (6), and (7), the lens and grid needed to obtain the required performance can be determined. Many types of lenses can be used for focusing schlieren: aerial camera lenses, enlarger lenses, copier lenses, overhead projection lenses, and large format camera lenses. The lens selected has to form a sharp enough image of the grid to obtain the desired sensitivity. If we require two line pairs of resolution to adequately define a, we require a lens with $>2/a$ line pairs of resolution: The requirement for high sensitivity tends to make a small, whereas the need to keep $\phi>5$ tends to make b large. These result in the need for unequal dark and light line widths in the source and cutoff grids.

Several focusing schlieren systems, using a 600-mm focal length camera lens with 100-mm aperture (aerial camera lens), are used to show how tradeoffs can be made by varying the design. Table 1 shows how the same lens can be used with different spacing to vary the size of the field of view, the depth of focus, and the image resolution. The lens selected had a resolution of 30 line pairs/mm, resulting in a minimum value of a=0.064 mm. This would allow a minimum value of ϵ_{min}=4 arcsec. For all cases in Table 1, the sensitivity was fixed at ϵ_{min}=4 arcsec to allow comparison of other parameters. The examples in the table have a field of view varying from just over 0.1 to nearly 5 m. As the field of view is increased, the resolution drops, and the depth of focus increases. The total number of lines of resolution only varied slightly for the cases shown and were about the same as would be obtained for conventional schlieren systems.

Adjustment Requirements

The light source in a focusing schlieren system has to be an extended source that, when reimaged by the Fresnel lens, fills the imaging lens. For a continuous light, frosted light bulbs or reflector lights of 75 W or higher work well. Short duration exposures are obtained with lasers, air gap sparks, or flash lamps. Lens and diffusers may be needed to extend some sources and uniformly illuminate the field of view. Final adjustment of the light source location has to be made to obtain the most uniform brightness possible at the final image. The source grid should be located far enough beyond the Fresnel lens (typically 5–10 cm) to avoid showing the effect of Fresnel lens ridge lines on the image of the grid. A support assembly using plastic sheets (or glass) may be needed to hold these components flat. A box can be made to hold the light source and the Fresnel lens and source grid assemblies, as well as to block stray light.

The remaining components, including the imaging lens, the cutoff grid, and the final image screen, should be mounted on a single rigid base. A two-axis positioner assembly is required at the cutoff location. Two plastic sheets held together with thumb screws (for quick release and reclamping) can be used to hold the cutoff grid. These positioners should allow small movements to be made in the grid focus and cutoff locations. The cutoff grid mount also requires a rotational adjustment. Although a precision tilt adjustment may be used, the author has found that hand rotation of the cutoff grid, combined with the quick release clamp, allows adequate control of tilt adjustment.

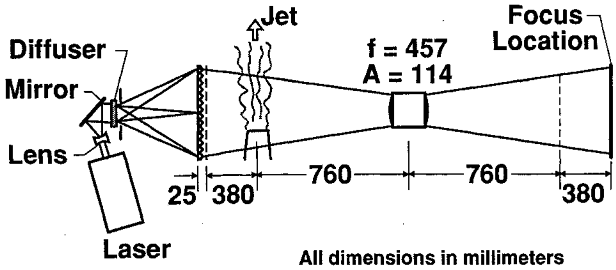


Fig. 4 Optical setup for crossed jets and Mach 2 jet.

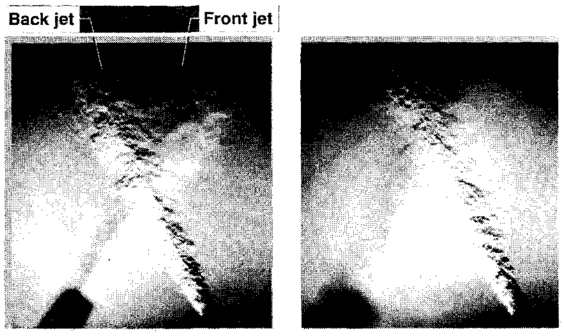


Fig. 5 Focusing schlieren of crossed jets, with one jet out of focus: a) 19-mm separation and b) 38-mm separation.

Each final image location corresponds to one particular depth location in the flowfield. To change the location being examined, the final image focus can be moved. This is usually a coarse adjustment and can be done with almost any type of positioner. If a position indicator is used to determine locations in the flowfield, a series of slices can be examined at known depths across the flow. It should be noted that the image magnification changes slightly with changes in image location, and the image location is not a linear function of source location.

Making and Using the Source and Cutoff Grid

Source grids can be made a variety of ways. One useful approach is to photographically enlarge small grids (which may be obtained commercially). If grids are made with equal clear and opaque line widths, two identical copies can be stacked, and by moving one relative to the other, one can obtain any desired open to closed ratio. One especially useful technique is to use photoplotters like the ones used to make printed circuits. A reference mark should be made on the source grid to help in alignment.

The first step in making a cutoff grid is to sharply focus the source grid image on a screen (sheet of tracing paper) placed at the cutoff grid location. In a darkened room, replace this focusing screen with a sheet of high-contrast film and expose it to make a negative image of the grid. The developed cutoff grid should be repositioned with the reference mark. Place a screen just behind the cutoff grid assembly for the following adjustments. If the cutoff grid is correctly positioned, then changes in the amount of cutoff result in a uniform brightness change over the entire image. The cutoff should be adjusted to give just about half of the maximum brightness. If the image does not darken uniformly with increased cutoff, then either the cutoff grid focal position is in error or the cutoff is rotated.

When the cutoff grid focus position is adjusted, broad lines appear on the image parallel to the grid lines. The thinner these lines are, the greater the focus error. The focus has to be adjusted so that the lines broaden until the image is nearly uniform. The cutoff should be adjusted to best show the variation. If the image is still not uniform, rotate the cutoff grid. Incorrect rotation results in bands or lines becoming visible perpendicular to the grid lines. Rotate the cutoff grid to obtain the most uniform brightness across the image in a similar manner as was used for the focus. Take care to retain alignment of the reference marks. By iterating these adjustments, a uniform image brightness should be found for all cutoff settings.

Applications of Focusing Schlieren

The following focusing schlieren systems were used to demonstrate specific capabilities of this technique. For all examples, the lens used had a 450-mm focal length with a 114-mm clear aperture.

Crossed Jets

The optical setup used to investigate the flow from two crossed jets is shown in Fig. 4. The sensitivity was $\varepsilon_{min} = 16$ arcsec, and the depth of unsharp focus was $DU = 25$ mm . The field of view shown is about 75 mm square. A frequency doubled and Q-switched Nd-Yag laser was used to obtain a short (10 ns) pulse of green light. A relay optical system was used with a 70-mm camera to obtain photographs on ASA 400 film. The laser output was 5 mJ per shot and was more than adequate for this setup.

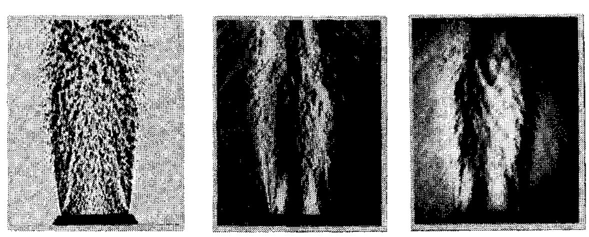
Jets of chlorodifluoromethane were injected into ambient air from 4.7 mm internal diameter (ID) tubes. The jets crossed near the middle of the field of view. The right jet was close to the plane of sharp focus, and the left jet was moved toward the imaging lens. The effects of different spacing are shown in Fig. 5. Fine detail is blended out when the jet is 19 mm out of focus, and medium-sized features blend out by 38 mm. Very large features may result in brightness variations that persist all of the way across a flowfield, but these features are clearly out of focus and thus can be effectively ignored.

Mach 2 Jet into Air

A small convergent-divergent nozzle injected unheated air into the atmosphere with an exit Mach number of 2. The exit ID was 25 mm, and the field of view examined was about 75 mm square. This nozzle is described in more detail in a paper by Cutler and Levey.[11] The same focusing schlieren setup was used for the Mach 2 jet as was used for the crossed jets (Fig. 4). A conventional schlieren with 1200-mm focal length mirrors was also used, with an air gap spark light source with a 1-mm effective diameter. The conventional schlieren had $\varepsilon'_{min} = 8$ arcsec, which is twice as sensitive as the focusing schlieren used. The conventional schlieren setup was also used with the cutoff removed and slightly defocused to obtain a shadowgraph system.

Photographs were made on a 70-mm camera with all three optical systems, for direct comparison, and the results are shown in Fig. 6. For the current examples the focusing schlieren picture was printed at high contrast and the conventional schlieren was printed at lower contrast to more closely match effective sensitivity.

Focusing schlieren shows the internal shock structure better than either shadowgraph or conventional schlieren. In addition, the lack of sharp turbulent structure in the central part of the flow (shown by the focusing schlieren) indicates that this part of the flow is not turbulent. Both the conventional schlieren and shadow-



a) b) c)

Fig. 6 Comparison of conventional techniques with focusing schlieren in Mach 2 jet: a) shadowgraph; b) conventional schlieren; and c) focusing schlieren.

graph are unable to separate detail in the front and back of the jet from the center of the jet, so that internal details of the flow are not clear.

Heater in Water

A similar focusing schlieren system was constructed to examine the flow in a rectangular water tank (300 mm in diameter). A low sensitivity of $\varepsilon_{min}=24$ arcsec was used to examine the very large density gradients encountered in heated water. The cutoff grid was made in place through the tank full of water. By making the grid in place, the system compensated for some of the distortion in the system (due to the walls of the tank). A 100 W frosted light bulb was used as the light source, and a Fresnel lens was used to relay the image onto a 100×125 mm format camera.

The flowfield shown in Fig. 7 was obtained from an immersion heater. The heater was initially held in place to establish a laminar thermal boundary layer, then slowly moved across the focal plane. Part of the boundary layer and some eddies shed from the heater movement are clearly seen.

Compensating for Optical Flaws

The light from a single point on the source grid in a focusing schlieren setup was shown in Fig. 2. The diameter of the light beam from this point to the imaging lens varies from the point source size to the lens diameter, depending on where in the optical path we examine it. Any optical element or flow induced refraction feature modifies this beam. We can group features of refracting elements into three categories: 1) features having at least one dimension (normal to the beam) much smaller than the local beam diameter, 2) features with at least one dimension (normal to the beam) not greatly different from the local beam diameter and the other dimension the same size or larger, and 3) very large features with both dimensions much larger than the local beam diameter.

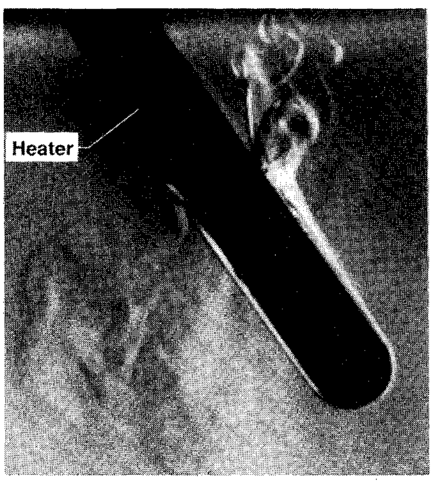


Fig. 7 Focusing schlieren of heater in water tank.

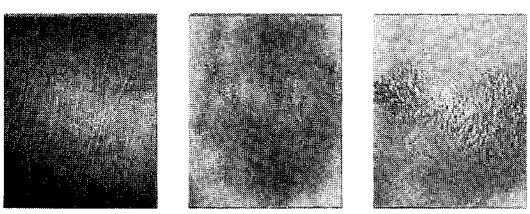


Fig. 8 Focusing schlieren through Pyrex window: a) window in focus; b) window 125 mm out of focus; and c) gas jet in focus window 125 mm out of focus.

Depending on which of the aforementioned categories a feature belongs in, the out-of-focus feature may be more or less noticeable and affect the image of in-focus detail in different ways.

The first category includes scratches, small bubbles, streaks due to optical nonuniformity, and surface irregularities in the windows. These, along with side wall boundary-layer or shock-wave details, out-of-focus turbulence, and the small-scale portions of thermal disturbances outside the tunnel, have little effect on the images of focused features. This is demonstrated in Fig. 8. A Pyrex window, with considerable internal optical flaws, was placed in a focusing schlieren system. The flaws in the glass, shown in Fig. 8a, are clearly seen when the schlieren system is sharply focused at the location of the window. As the plane of sharp focus is moved, the flaws blend out until they are not detectable, as shown in Fig. 8b. A chlorodifluoromethane jet (photographed with a 5-μs flash lamp source) is shown at the sharp focus location in Fig. 8c, to demonstrate that the image quality is still good even through the out-of-focus flawed window.

The second category of refracting elements is the most bothersome. Even if these features are badly out of focus, they cause a nonuniform brightness that persists across the full depth of focus. There are several ways to minimize the effect of these features. The techniques fall into two groups: 1) image subtraction, and 2) image enhancement.[12] The first of these takes advantage of the fact that badly out-of-focus features change only slowly with depth. The second uses the fact that out-of-focus details generally have lower spatial frequencies. There are some cases where one or both assumptions of these cases are violated, so care must be taken when using these techniques.

The third category of flaws is primarily caused by large-scale distortion in the optical windows. The principal effect is to cause a nearly constant distortion in both the image of the source grid and the final flow image. If the cutoff grid is made with the distorting optical elements in place, and if the flow pictures are made with the same optical elements in place, the distortion in the cutoff grid will be compensated for. Usually the small amount of distortion in the flowfield image is not nearly as significant as the grid error and can be tolerated. The photograph shown in Fig. 7 was made using this technique.

Concluding Remarks

An improved large-field focusing schlieren system has been developed. Equations have been derived to aid in the selection of components and to determine the performance of these systems. Techniques and requirements for the construction and use of these systems have been developed and demonstrated. Salient features of this approach are the following:

1) Use of a Fresnel field lens increases brightness of images over 100 times compared with the previous version of a large-field focusing schlieren system, making it more practical.

2) Systems can be made with a field of view up to at least 5 m.

3) The cost and overall complexity of large focusing schlieren systems are significantly lower than for conventional schlieren systems.

4) Poor quality windows and flow disturbances outside the flowfields do not degrade image quality nearly as much as in conventional schlieren systems.

5) Compensation can be made for source grid image distortion.

Acknowledgments

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