Zebra schlieren optics for leak detection

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A modification of schlieren optics was explored as a technique for industrial gas-leak detection. A high-contrast pattern on thin reflecting material was imaged with a zoom lens onto a negative of the same pattern as a method of eliminating the ordinary rays. The geometry of the industrial setting determines the useful spatial frequency of the pattern. © 1996 Optical Society of America

1. Introduction

Gas-leak detection is an important problem in industry. Local techniques such as mass spectroscopy with sniffers are labor intensive. Optical sensing is preferred. Those methods based on chemical specific identification by lasers may lack sufficient flexibility and may be precluded by cost and safety concerns. An ideal system would use incoherent light with inexpensive optics and should be able to image leaks over large areas together with reference objects.

A technique capable of imaging leaks of foreign gases in air is the classic schlieren method.[1] A common feature is the presence of optical elements on both sides of the test region. Because industrial gas-handling systems are not typically designed for the convenience of schlieren methods, there will be many enclosed and cluttered situations that preclude the placement of bulky optics on one side of the test region. There will also be situations in which the test region is large compared with the field of view of a usual schlieren setup. A prototype system that potentially circumvents these problems by using compact, off-the-shelf optics is described here.

We begin with a brief description of standard schlieren optics to establish the essential principles of operation. Then the method we call zebra schlieren is described. The setup procedure is provided, results given, and quantitative geometric considerations presented.

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2. Standard Schlieren

Figure 1 presents a schematic of a standard double-pass schlieren setup. Two optical systems are superimposed. The first is composed of a diffuse illuminator, a telescope mirror, and a Ronchi ruling ~black stripes on glass with a 50% duty cycle!. The diffuse illuminator ~a 5-V lamp below 1.5-mm Teflon! uniformly illuminates the lower half of the Ronchi ruling as shown. The Ronchi ruling is placed at the mirror's center of curvature ~twice the focal length! and symmetrically about the optical axis so that the illuminated half is below the axis. An inverted image of the illuminated part is formed above the axis with unity magnification and is superimposed on the unilluminated part. By moving the Ronchi ruling perpendicular to the optical axis ~vertically in Fig. 1!, we can make the dark parts of the image line up with the open stripes of the physical ruling. When this occurs, no light passes the ruling.

The schlieren effect is easiest to explain when this dark field exists. In these conditions, none of the light from the illuminated part of the ruling passes the upper part of the ruling. A phase object ~e.g., a gas leak! can deflect rays from the group that forms the image of the lower ruling on the upper one. These deviated rays may fall on an open part of the upper ruling and get through. The second optical system operates with these rays.

The second optical system consists of an imaging apparatus, such as the camera shown in Fig. 1. The camera images the test region in front of the mirror onto a CCD. Larger index gradients within the test region permit more light to reach the camera so that the intensity distribution in the recorded image maps out the disturbance itself. In practice, imperfect cancellation of undisturbed rays by the first optical system permits an image of the disturbance to be formed with intensity changes of both signs and conveniently permits an image of reference objects to be simultaneously recorded.

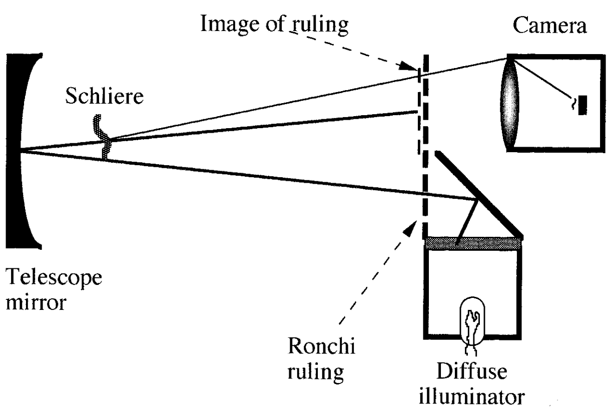

Fig. 1. Standard schlieren optics.

Characteristic data collected with the standard schlieren apparatus of Fig. 1 are presented in Fig. 2. This image was recorded with an Elmo CCD television camera and the Macintosh-based NuVision image-processing system by Perceptics. In Fig. 2 the disturbance is caused by a squirt from canned air of the type used to dust electronic components. The gas is 1,1,1,2-tetrafluoroethane and has a refractive-index that is different from air. Intensity changes map out an image of the turbulent flow of gas from the nozzle, located just above and in front of the telescope mirror ~diameter, 0.4 m; radius of curvature, 3.6 m!. None of the disturbance recorded here is visible to the naked eye. With this system, heat waves from warm body parts and even air-conditioning currents are easily observed. However, this standard schlieren system is unsuited for leak detection in industrial settings because the telescope mirror's bulk may preclude its placement in a cluttered environment and its diameter may be too small to cover a significant area.

3. Zebra Schlieren

The following modified schlieren method is intended to eliminate the difficulty caused by the bulkiness of the mirror in situations with limited space. It can also be scaled to cover large areas without significant increase in cost. Figure 3 presents a schematic of our experimental zebra schlieren apparatus. The name zebra comes from the striped pattern that is substituted for the mirror in Fig. 1. Stripes made from black construction paper are placed in front of reflecting cloth ~3M Corporation!. The cloth is illuminated with a projector. The zoom lens superimposes an image of the stripes on a Ronchi ruling, and the subsequent theory of operation is similar to that of the standard schlieren.

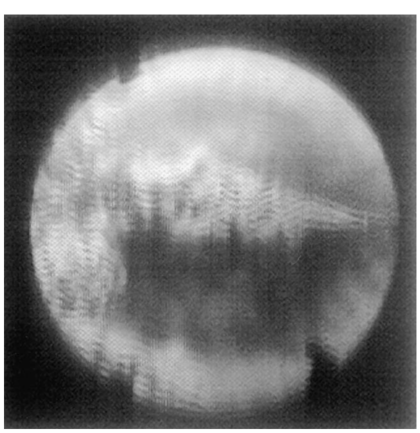

Fig. 2. Test results of standard schlieren. An inert gas duster is sprayed from the right, and turbulence from the expanding jet is observed. Before the spray a dark field exists with bright bands at the mirror edges from spherical aberration.

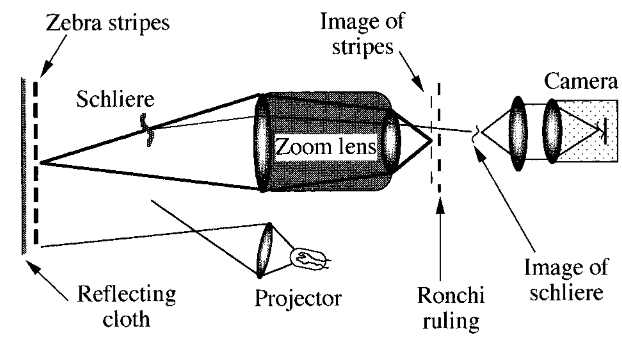

Fig. 3. Zebra schlieren optics. An illuminated high-contrast stripe pattern is precisely imaged onto its negative ~Ronchi ruling!. Ordinary rays are blocked, and deviated rays form an image of the disturbance farther back. This image is viewed with the CCD camera.

Figure 4 shows our optical setup and the illuminated stripe pattern. The stripes are 6 mm wide and cut out of black poster board. The stripe pattern is located ; 2 m from the optics. The projector ~foreground! consists of a 5-V lens-end light bulb and a 50-mm focal-length plano–convex lens. The zoom lens has a focal length of 20–100 mm, the Ronchi ruling has 40 cyclesycm, and the lens behind the Ronchi ruling is plano–convex with a 50-mm focal length. The camera is not shown in Fig. 4.

Initial alignment is done with the Ronchi ruling removed from the setup. First, the focus of the zoom lens is set to infinity to move the focal plane for the nearby zebra stripes back as far as possible. This allows more room for placement of the Ronchi ruling. A simple lens of short focal length is adjusted so that the image formed by the zoom lens is separated from the simple lens by its focal length. Rays leaving this lens are then parallel. The camera is focused at infinity to form an image on the CCD from these parallel rays. This arrangement allows translation of the camera along the optical axis without losing focus. In particular, the camera can be placed directly behind the simple lens so that the object of interest fills its field of view. At this point a sharp image of the zebra stripes appears on the TV monitor.

The front of the zoom lens is now blocked, and the Ronchi ruling is inserted at the location of the stripe image behind the zoom lens. A sharp image of the Ronchi ruling now appears on the TV screen. The zoom is unblocked so that the stripe image is superimposed on the Ronchi ruling. Moiré fringes are

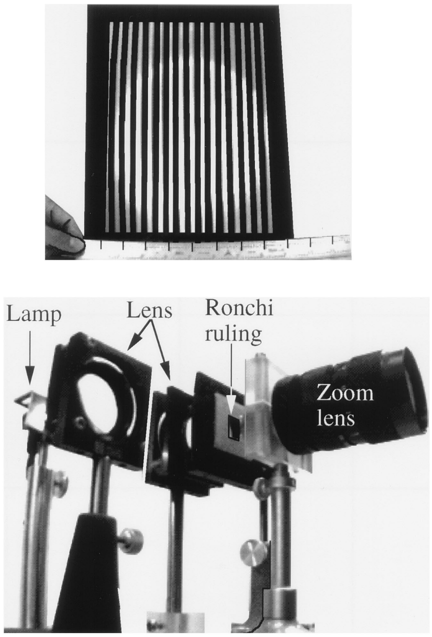

Fig. 4. Zebra schlieren optics and the illuminated zebra pattern. This setup is based on Fig. 3. The projector, consisting of a lamp and a lens, is in the foreground. The imaging system is in the background with the camera removed.

seen on the TV monitor if the image of the stripes has a different scale than the Ronchi ruling. The Ronchi ruling is the correct distance from the zoom when the moiré bands have their maximum contrast. The Ronchi ruling has the correct orientation when the moiré bands are parallel with the direction of the stripes. By adjusting the zoom the scale of the stripe image can be matched with the scale of the Ronchi ruling. As this condition is approached, the separation of the moiré bands and their width increases until a single dark or light moiré band fills the view. During this procedure the focus of the zoom lens is continually adjusted to maintain maximum contrast of the moiré bands. The Ronchi ruling can now be translated perpendicular to the optical axis to achieve the desired level of extinction for the ordinary rays. This translation is sensitive and is best done with a micrometer stage.

All the above steps are performed with the simple lens placed so that the camera images the stripes and Ronchi ruling simultaneously. If a disturbance is placed close to the zebra stripes, it will also be in focus with respect to the camera. However, we find that zebra schlieren is insensitive to disturbances close to the stripes. The sensitivity is highest for disturbances near the entrance aperture of the zoom lens. For such positions the simple lens must be moved back so that the image of the disturbance formed by the zoom is at the focal point of the simple lens.

Figure 5 presents data taken with the zebra schlieren setup. A jet from the inert gas duster is located just in front of the zoom. The zebra stripes and Ronchi ruling are out of focus and therefore invisible. Similar results were obtained with He gas.

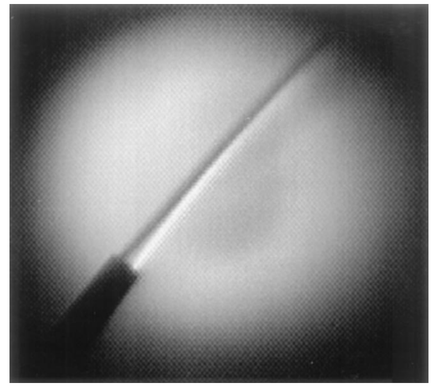

Fig. 5. Test results of zebra schlieren. An inert-gas-duster nozzle is placed just in front of the zoom lens.

The effect disappears if the Ronchi ruling is removed. This first zebra schlieren implementation is less sensitive than the standard schlieren, where the turbulent plume of gas can be observed far downstream, as shown in Fig. 2. Heat waves from warm body parts are not observed. We can improve the present crude setup significantly by fitting the critical optical elements with micrometer stages. Although the absolute sensitivity limit for zebra schlieren has yet to be determined, the method always works best for test regions well removed from the stripes, as explained below.

Figure 6 presents the pertinent geometric parameters for zebra schlieren. For a significant schlieren effect the disturbance must be large enough that deflected rays from a bright stripe appear to the camera to have originated from a neighboring dark stripe. Also the deflection must be sufficiently small that deflected rays are collected by the zoom lens. Both conditions imply a minimum distance x for the disturbance from the stripes for a given deflection ϕ. These are

$$x \geq w/\phi, \tag{1}$$

$$x \geq (L - R)/\phi. \tag{2}$$

To see how these conditions manifest themselves in practice, we take as an example an He leak into air. For simplicity we assume that the He forms bubbles in the shape of isosceles prisms. The formula for ray deviation is[2]

$$\phi = \theta - \alpha + \sin^{-1}[\sin \alpha (n^2 - \sin^2 \theta)^{1/2} - \sin \theta \cos \alpha], \tag{3}$$

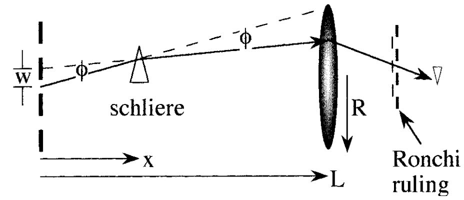

Fig. 6. Geometric considerations for zebra schlieren.

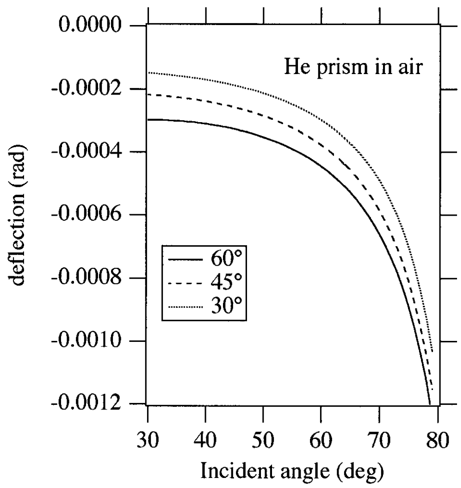

Fig. 7. Estimate of expected deviation from the He leak. The plot presents a ray deviation for a range of incident angles and prism angles that the majority of rays are likely to encounter.

where f is the deviation from the original ray direction, a is the prism angle, and u is the angle of incidence. The quantity *n* is the ratio of the index of refraction of He ~1.000036! to that of air ~1.000293!. The sign of the deflection ~negative! is opposite that for a glass prism in air.

In Fig. 7 we plot the deviation angle in radians for the range of incident angles and prism angles expected to be encountered by the majority of rays for random prism orientations. The deviation is 1 mrad at an 80° angle of incidence. Relatively few rays are expected to have larger angles of incidence, and their contribution to the effect is therefore small. Hence we take 1 mrad as the useful maximum deviation. This treatment ignores multiple deflections by multiple He bubbles.

Suppose the distance *x* between leak and stripes is 2 m, as in our experiment. For deviations of 1 mrad and optics of the order of 25-mm radius, condition ~2! is unimportant for distances *L* , 25 m, which typically hold in normal industrial settings. With *x* and f given as above, inequality ~1! gives as the condition on the stripe width for significant sensitivity *w* # 2 mm. Recall that a stripe width of 6 mm sufficed in our experiment with 1,1,1,2-tetrafluoroethane as the gas, so this method of estimation appears to give the right order of magnitude. For patterns with spatial frequencies much higher than one per millimeter, our studies with our prototype indicate a low value of the modulation transfer function[2] and a corresponding loss of contrast in the resulting stripe image produced at the Ronchi ruling. This potential limitation must be remembered when determining geometric parameters for a given situation.

4. Summary

A variation of schlieren optics with the potential for industrial remote leak detection has been described. To circumvent the use of a bulky and expensive mirror behind the test region and to allow inexpensive scaling to large fields of view, the method uses a high-contrast pattern behind the test region. The imaging optics in the prototype described are compact and inexpensive. The technique is most sensitive when the region of interest is well in front of the pattern. A simple quantitative method of determining relevant geometric parameters was presented by an illustrative example.

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1. For a collection of key papers see J. R. Meyer-Arendt, ed., *Selected Papers on Schlieren Optics*, SPIE Milestone Series, vol. MS61 ~The International Society for Optical Engineering, Bellingham, Wash., 1992!.
2. E. Hecht and A. Zajac, *Optics* ~Addison-Wesley, Reading, Mass., 1979!.