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Comparative study of different Schlieren diffracting elements

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Abstract. This paper presents an analysis of diffraction effects taking place at different Schlieren diffracting elements. Two types of diffraction effects are prominent in the Schlieren schemes. One is diffraction of direct light (source image) at the Schlieren element, which limits the sensitivity and resolution of Schlieren systems. The second type is the diffraction of light deflected from the test object at the Schlieren-diffracting element. This second type of diffraction degrades the quality of Schlieren results. Experimental results showing the effect of diffraction of light deflected from the test object at a phase knife-edge, corner of a square phase aperture and an optical fiber tip as Schlieren diffracting elements have been presented and discussed.

Keywords. Schlieren techniques; diffraction; phase visualization.

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1. Introduction

Schlieren systems are among the oldest known techniques for making density gradients visible in transparent media. These techniques rely on the principle of light beam deflection during its passage through the test volume. The deflection of a single beam of light contains information about the spatial gradient of the refractive index integrated along the optical path. Robert Hooke was the first to demonstrate Schlieren effect before the Royal Society of London in 1672, where he showed in an experiment that besides the flame and some smoke of a candle there is a continual stream rising up from it, distinct from the air. However, Hooke's work was forgotten and Leon Foucault (1859) and August Toepler (1864) are generally regarded as the discoverers of this group of techniques. During the course of time a number of variations of the technique have been developed for specific and general purposes [1,2]. These techniques are widely used for performing various types of test studies on transparent objects such as depicting deviations in light beams induced by density, temperature or refractive index gradients in combustion research, laminar and turbulent fluid flow, shock and detonation waves, plasma diagnostics, acoustic studies and other steep refractive index gradients associated with heat and mass transfer, or pressure changes, but not confined to these. As an instrument, a Schlieren apparatus is suitable to measure the slope of index gradients and is sensitive to transverse refractive index gradients in the test section. The relative magnitude of index gradients is estimated by observing the shadow patterns generated in the image plane. The first area to become dark has the positive gradients, followed by the flat areas, and finally the negative gradients. It is known that diffraction is an integral part of the Schlieren image-formation process [1,2]. Following are the two main diffraction effects observed in Schlieren systems. One is diffraction of direct light (source image) at the Schlieren element, which limits the sensitivity and resolution of Schlieren systems. The second type is the diffraction of light deflected from the test object at the Schlieren-diffracting element. This second type of diffraction degrades the quality of Schlieren results. Apart from these diffraction effects, diffraction also takes place at object edges in the test area, creating halos in the image. Due to this type of diffraction dust particles, window flaws and object edges etc. become visible when the direct beam is blocked. These diffraction halos are not a very serious problem for Schlieren analysis because these just outline object edges with thin white lines/fringes and usually do not obscure the Schlieren image.

Gayhart and Prescost [3] reported the first Schlieren-based interferometric scheme and demonstrated that the diffraction of incident light at Schlieren element could effectively be used for quantitative measurements. Here, the Schlieren element is adjusted in such a manner that it reduces the width of the light–source image to several microns. The narrowing of source image diffracts incident beam, generating a fringe pattern that is used for quantitative analysis of phase objects. Here diffracted light serves as the reference beam and the geometrical beam, directly reaching the observation plane, serves as the test beam. Temple [4] presented a detailed theoretical and experimental analysis of the Schlieren diffraction interferometer using the Fourier optics approach and a number of researchers made further investigations on various aspects of the Schlieren diffraction interferometry [1,2,5–7]. Most of the researchers used the Fourier optics approach (which is based on the Huygens–Fresnel diffraction formula) to explain the Schlieren imaging process [1–7]. Conventionally, the focal plane filter, known as Schlieren stop or diffracting element modifies in one way or the other the spatial frequency spectrum, letting zero-order frequency undisturbed (either blocked or allowed to pass). It is well-known that the zero-order spatial frequency of the input plane information corresponds to the central disk of the airy pattern, known as airy disk that accommodates around 84% of the incident light. In conventional Schlieren diffraction interferometry, first explained by Temple [4] using Fourier optics approach, the airy disk has been blocked with Schlieren diffracting element and interference takes place between a strong object beam (light deflected/refracted from the test object) and the weak light diffracted from Schlieren element, serving as reference beam. This interference of a strong object beam with a weak reference beam generates low contrast interference fringes.

Recently, it has been shown that the boundary diffraction wave as suggested by Young, has indeed its physical existence [8] and this boundary diffraction wave serves as an inbuilt reference beam in the Schlieren diffraction interferometry [9–11]. Here it has been shown for the case of a solid knife-edge [9], mirror-edge [10] and a phase knife-edge [11] that the first diffraction fringe (due to the diffraction of incident light from the Schlieren element) near the geometrical shadow could be broadened such that it covers the whole field of view. At this position Schlieren element diffracts light from the airy disk, giving a much stronger boundary diffraction wave as reference beam and hence enhancing the contrast of Schlieren interferogram. In the present paper, experimental investigations have been presented in Schlieren diffraction interferometry using different Schlieren diffracting elements for the study of phase objects. The effect of diffraction of the test object deflected light from various Schlieren elements on the Schlieren results have been discussed.

2. Theory and experimental details

According to Maggi–Rubinowicz boundary diffraction wave theory, the diffracted field at the observation plane is given by [12]

$$U(P_1) = U^{\mathrm{g}}(P_1) + U^{\mathrm{d}}(P_1), \tag{1}$$

where

$$U^{\mathrm{g}}(P_1) = \begin{cases} \frac{\exp(jkR)}{R}, & \text{when } P_1 \text{ is in the direct beam} \\ 0, & \text{when } P_1 \text{ is in the geometrical shadow} \end{cases} \tag{2}$$

and

$$U^{\mathrm{d}}(P_1) = \frac{1}{4\pi} \int_{\Sigma} \frac{\exp[jk(r+s)]}{rs} \frac{\cos(n,s)}{[1+\cos(s,r)]} \sin(r,dl)\mathrm{d}l, \tag{3}$$

where R is the distance from source to the point of observation, $P_{1;}$ s is the distance between a typical point A on the knife-edge and P_1, Σ denotes the boundary of the illuminated part of K, dl is an infinitesimal element situated on Σ and n is unit vector outward normal to the plane of the Schlieren diffracting aperture. Here U^{g} propagates according to the laws of geometrical optics and is known as the geometrical wave while U^{d} is generated from every point of the illuminated boundary of the diffracting element and is called the boundary diffraction wave. This diffraction pattern could be manipulated by moving Schlieren diffracting element towards the focus such that a single diffraction fringe covers the whole field of view. This situation is known as an infinite fringe-mode condition where the intensity distribution in the observation plane will be [9]

$$I = |U^{(\mathrm{g})}|^2 + |U^{(\mathrm{d})}|^2 + 2U^{(\mathrm{g})}U^{(\mathrm{d})}\cos(\phi). \tag{4}$$

It becomes obvious from eq. (4) that the intensity distribution of the interference pattern, in infinite fringe-mode, depends only on the phase variation (ϕ) introduced

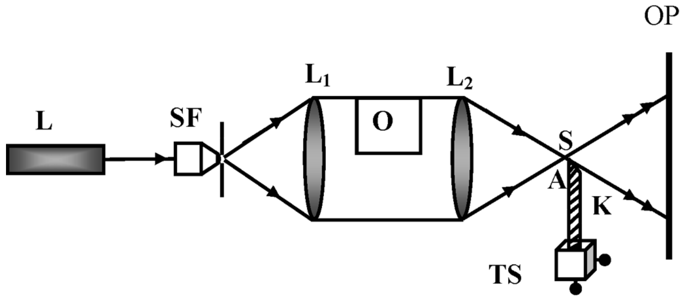

Figure 1. Schematic experimental setup of Schlieren diffraction interferometer.

by the phase object (O) into the test region between lenses L_1 and L_2. This shows that the described system behaves as a two-beam interferometer where interference takes place between an aberrated wavefront (test beam) and a reference wavefront (boundary diffraction wave).

The experimental arrangement of the Schlieren diffraction interferometer is schematically shown in figure 1. The system consists of a light source (laser), two diffraction-limited lenses and a diffracting element. A point source is created with a spatial filter assembly (SF) from a 35 mW He–Ne laser (wavelength = 633 nm, manufactured by Coherent Inc.). The diverging laser beam is collimated by a 100-mm diameter, f/4 good quality lens, L_1 (Tropel, Model 280, Laser Collimator). The shear plate interferometric technique was applied to ensure the optical quality of the collimated beam. Another lens, L_2 (with same specifications as L_1) focuses the collimated beam to generate the source image. Here Ronchi ruling technique was used for the optical correction of light for astigmatism and coma, which would otherwise be introduced by the off-axis arrangement. This focused light upon divergence illuminates the Schlieren-diffracting element, K mounted on a precisely controllable translation stage, TS. By providing fine movement to K, the distance between Schlieren element and the source (focus) is reduced so that the finite fringe-mode diffraction pattern ultimately converts to an infinite fringe-mode pattern. The object O to be studied is inserted in the test region L_1L_2. In infinite fringe-mode condition the system captures the region that is within the first bright or dark fringe and is used for the optical test purposes. The results presented in this paper have been captured using a Canon S-50 Power Shot digital camera (1024 $\times$ 768 pixels) in white balance settings.

3. Comparative studies of different Schlieren diffracting elements

It is well-known that the use of wire or phase knife-edge as diffracting element in the Schlieren diffraction interferometer has the advantage over the solid knife-edge, in that it provides more information about phase variations. This is due to the fact that the solid knife-edge blocks half of the phase information in the focal plane. Additionally, phase knife-edge has an advantage over a wire as Schlieren element in providing fuller information as it does not block any light even as those

Table 1. Comparison of information content retrievable with different Schlieren diffracting elements.

Schlieren diffracting element	Left	Right	Up	Down
Solid knife-edge	Yes	Blocked	No	No
Phase knife-edge	Yes	Yes	No	No
Wire	Yes	Yes	No	No
Corner of a square phase aperture	Yes	No	Yes	No
Optical fiber tip	Yes	Yes	Yes	No
Small disk	Yes	Yes	Yes	Yes

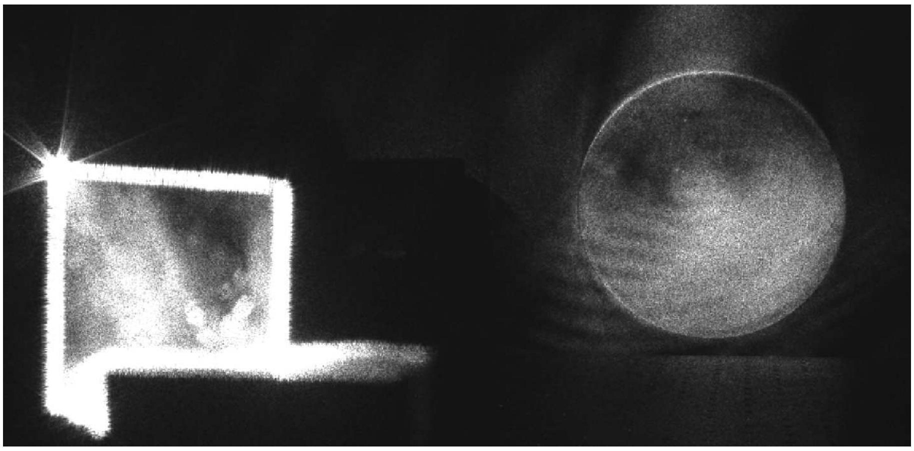

Figure 2. Square phase aperture with its corner illuminated with a focused laser beam (left) and corresponding infinite mode diffraction pattern (right).

deflected from weak optical-inhomogeneities. However, it may be noted that use of solid knife-edge, phase knife-edge or a wire as Schlieren diffracting element provides information about transverse phase variations only. The two-dimensional information may be obtained if the Schlieren diffracting element also has two dimensions [5] i.e. either two crossed-wires, one oriented in horizontal direction and the other has its orientation in vertical direction or a small square phase aperture. However, we used the corner of a square phase aperture as Schlieren diffracting element to obtain two-dimensional phase information. Figure 2 shows the corner of a square phase aperture (thin glass slide) illuminated with a focused laser beam in the left portion and corresponding infinite fringe-mode diffraction pattern in the right portion. The experimental test results on an optical glass plate obtained with this type of Schlieren diffracting element are shown in figure 3. These results show that the use of corner of a square phase aperture as Schlieren diffracting element could provide two-dimensional information of the test object but the diffraction of light deflected from test object at the Schlieren diffracting element noticeably affects the test results. This problem remains in almost all the Schlieren diffracting elements and the test results showing the effect of diffraction of test object deflected light

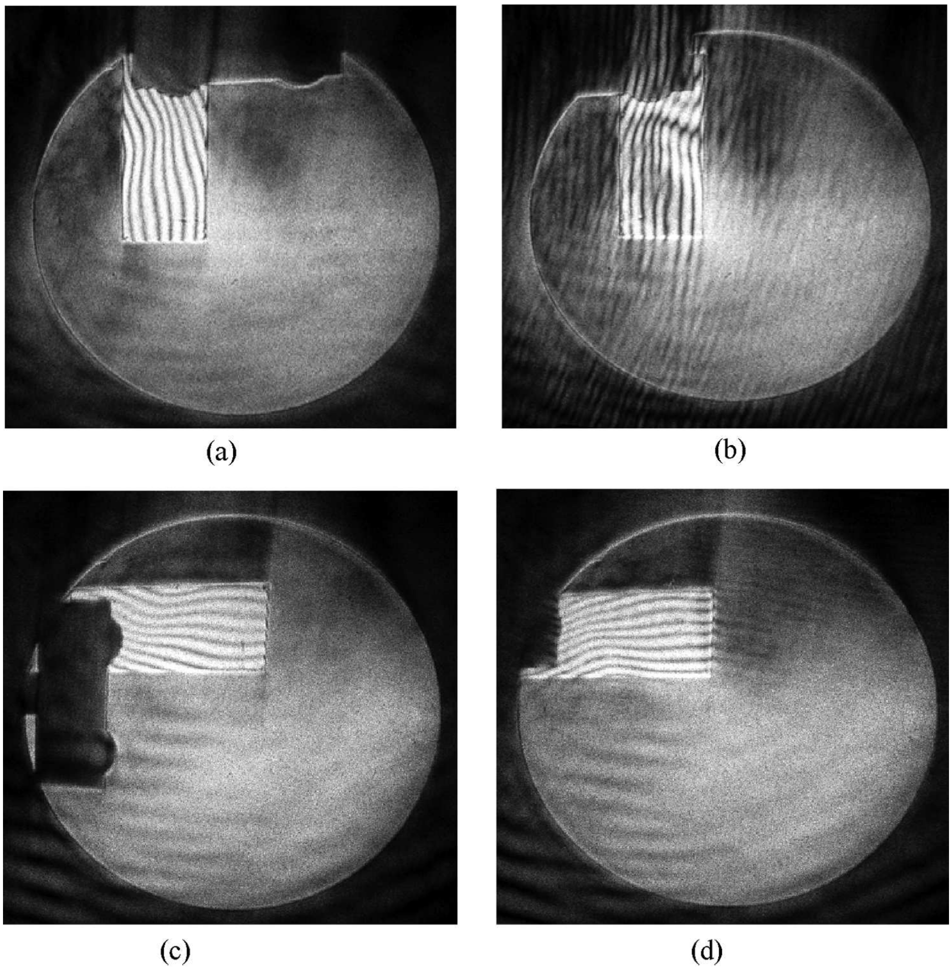

Figure 3. Test results of an optical glass plate with corner of a square phase aperture as Schlieren diffracting element.

from phase knife-edge and an optical fiber tip as Schlieren diffracting element are shown in figures 4 and 5 respectively. From the test results presented in figures 3 to 5, the effect of diffraction taking place at the Schlieren element of the light deflected due to an optical glass plate ($2'' \times 1''$) as test object in four directions (a) left (glass plate held in vertical position); (b) right (glass plate held in vertical position and rotated by an angle of 180° along its vertical axis from the normal position); (c) up (plate held in horizontal position) and (d) down (plate held in horizontal position and rotated by an angle of 180° along its vertical axis from the normal position), can be observed. These results are further summarized in table 1. Here 'Yes' denotes that the information becomes available without taking diffraction at the Schlieren element and 'No' denotes the test object deflected light which gets diffracted at the Schlieren element, distorting the results. A comparison

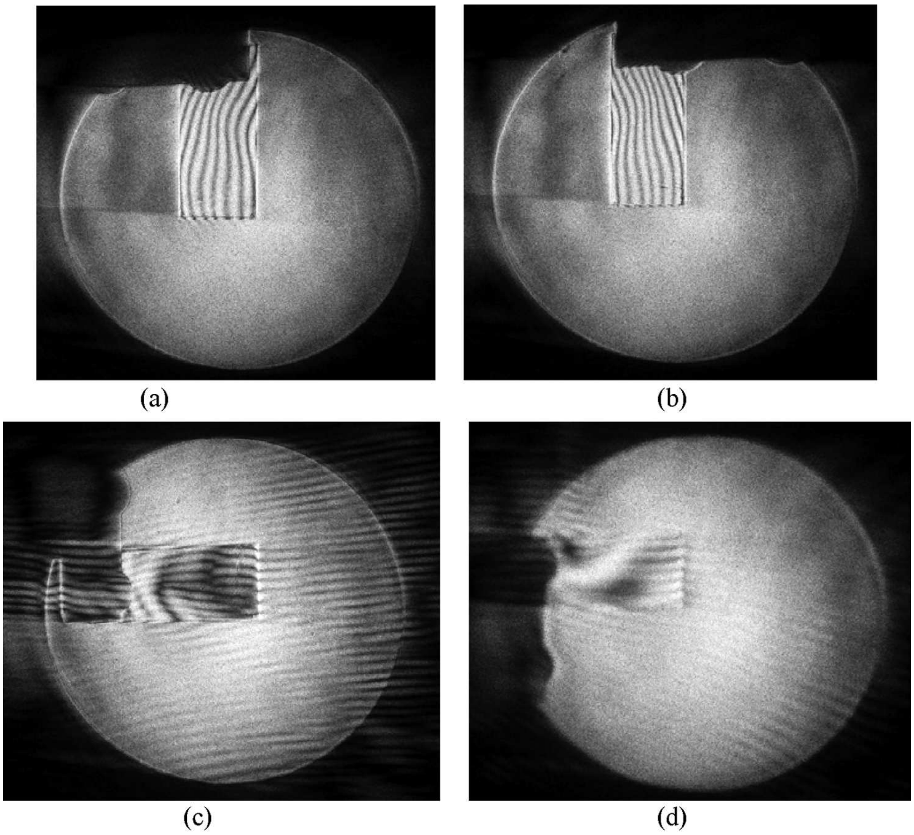

Figure 4. Test results of an optical glass plate with phase knife-edge as Schlieren diffracting element.

of information retrievable using various Schlieren diffracting elements shows that a properly fabricated tip of a thin optical fiber as Schlieren diffracting element could provide more information as compared to the solid knife-edge, wire, phase knife-edge or corner of a square phase aperture because in this case only the down-side deflected light gets diffracted from the Schlieren diffracting element.

4. Conclusions

In the present paper, experimental investigations on Schlieren diffraction interferometer using different Schlieren diffracting elements have been discussed. Various types of diffraction effects taking place in the Schlieren systems have been addressed and main emphasis is on the effect of diffraction of the light deflected from the test object at Schlieren-diffracting element. It is shown that use of a properly fabricated tip of a thin optical fiber as Schlieren diffracting element provides much more information as compared to the solid knife-edge, wire, phase knife-edge or corner

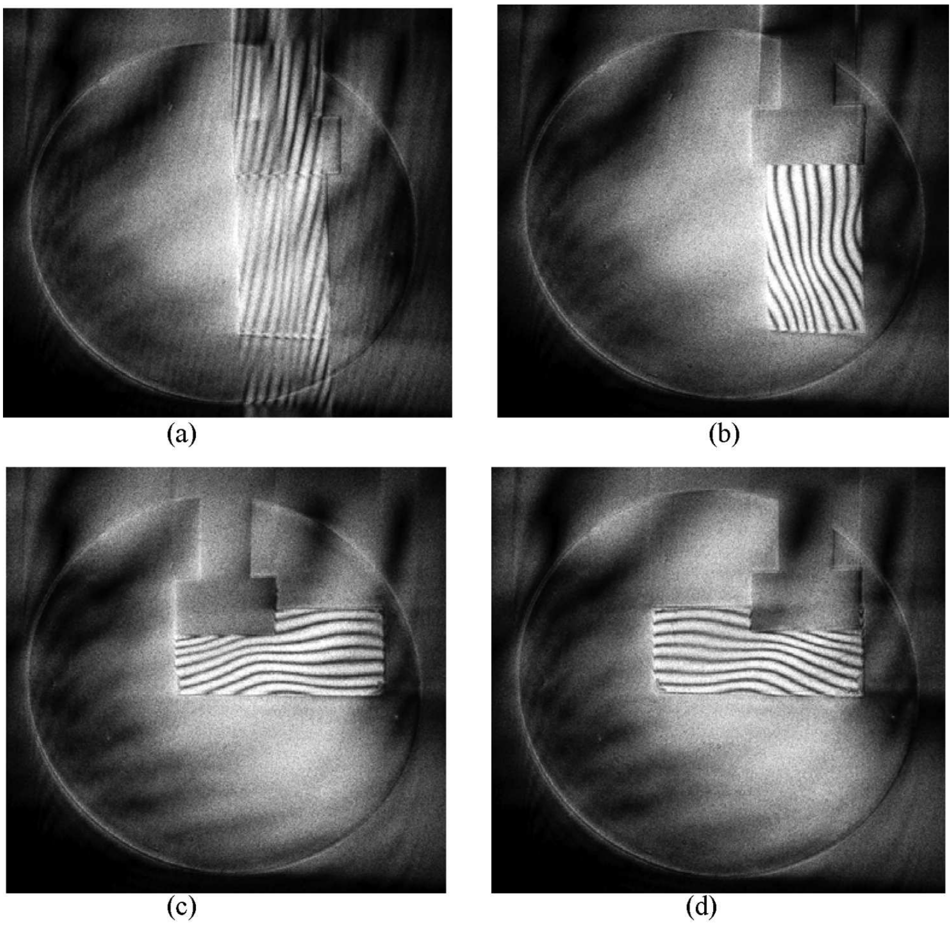

Figure 5. Test results of an optical glass plate with an optical fiber tip as Schlieren diffracting element.

of a square phase aperture because in this case only down-side deflected light gets diffracted from the Schlieren diffracting element. This diffraction of down-side deflected light in the case of an optical fiber tip as Schlieren diffracting element could also be avoided by using a small disk/aperture of dimensions less than the airy disk. In this case Schlieren diffraction interferometer becomes the well-known Smartt's point diffraction interferometer.

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