Color schlieren imaging with a two-path, double knife edge system

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Abstract: The traditional arrangement for visualizing optical phenomena with the schlieren technique is modified to include a Mach-Zehnder geometry. This allows for the implementation of two independent knife edges along two different beam paths, resulting in an enhanced combined image that is uniquely adjustable. Post-processed combined images are also generated by spatially separating the paths from each arm and then colorizing and combining the images into a single composite. In this way, bidirectional, color schlieren images have been produced using both white-light and monochromatic sources.

OCIS codes: (120.0120) Instrumentation, measurement, and metrology; (120.4640) Optical instruments; (220.4840) Testing.

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1. Introduction

The schlieren imaging technique is a well-known and time-tested method used to visualize optical inhomogeneities that are otherwise invisible to the naked eye [1,2]. In a common arrangement, a small light source is placed two focal lengths (2f) away from a curved mirror. The reflected light is brought to a focus slightly offset from the source, and the resulting image is captured electronically or on film. The optical disturbance under study is located in front of the curved mirror. Within the disturbance, gradients in the optical index of refraction result in small light ray deviations, which may very well be imperceptible in the final image. But by placing a knife edge in the focal plane, some of the optical paths will now be blocked, giving rise to a high-contrast image that is sensitive to optical phase variations [1]. Even though the original schlieren technique was pioneered by Toepler over 150 years ago, this scheme and its variations are still in common use. Recent examples include imaging of shock [3] and ablation [4] processes, supersonic jets [5], combustion [6,7], ball lightning [8], biomaterial transfer [9], large-scale processes [10] and explosives testing [11].

In the standard arrangement, a single knife edge is used and its orientation is selected such that the final image is optimized. For example, if light ray deviations along a horizontal direction are to be emphasized, then a vertical knife edge would be chosen. In this case, the system’s sensitivity to vertical deviations would be diminished. While more complex filters have been used to enhance the bidirectional sensitivity of a schlieren system [12–21], we present here an alternative approach whereby two independent knife edges can be used simultaneously. This allows for the generation of an image that is sensitive, for example, to optical deviations along both the vertical and horizontal directions. Indeed, the idea to capture two simultaneous views in a schlieren system is not new. Over 60 years ago, Barry and Edelman developed a clever technique to divide the light from a schlieren setup into two beams, one of which was rotated by 90° with respect to the other, resulting in two spatially separated images sensitive to orthogonal path deviations [22]. This arrangement is considerably more complex than what is presented here, it does not generate a single combined image, and it is much less flexible with regards to knife edge orientation and independent control of the beam paths. A different approach was taken more recently, utilizing two laser sources of different wavelengths to generate the two images [23]. While this technique has the flexibility of using two unique beam paths, it does not generate a single, composite image, and it relies on the use of two laser sources with distinct wavelengths. Other schemes have been developed that take two simultaneous schlieren views through a disturbance, but along perpendicular viewing directions [24,25].

The experimental approach presented here does not rely on a particular light source and can be assembled from ordinary, off-the-shelf optical components. The two paths are spatially distinct and can be manipulated with knife edges and filters independently. And while at least some versions of our arrangement can be mimicked with a single, multi-zone filter incorporated into an ordinary schlieren system, such a filter would have to be carefully

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manufactured and positioned, and once created, could not be modified. In our scheme, the "equivalent filter" can be constantly, smoothly and dynamically adjusted, and the effect on the final image can be immediately observed. It is also possible to generate two simultaneous, but spatially separated, images. These can then be individually colorized and combined with image processing software to generate a single composite image. Using this technique, we have created color images using monochromatic light. To our knowledge, this is the first time a monochromatic source has been used to create direction-indicating, color schlieren images.

2. Experimental arrangement

In order to generate two separate optical paths, a Mach-Zehnder optical geometry is used after the primary focus of a traditional schlieren system. A sketch of the experimental arrangement is shown in Fig. 1. A small source of white light is generated with a white LED and an 800-μm pinhole (PH), located 2f away from an astronomical-grade parabolic mirror (PM; 25-cm diameter, 114-cm focal length primary telescope mirror from e-Scopes). The region of interest (ROI) is located 12.5 cm in front of the mirror. The reflected light comes to an initial focus adjacent to the source and is re-focused with an achromatic focusing lens (AFL; 75-mm focal length) into the interferometer, made up of two flat mirrors (M1, M2) and two pellicle beam splitters (PBS1, PBS2). The position of the AFL along the beam propagation direction is adjusted until an even background is achieved in the schlieren images. In fact with no lens in place, schlieren images from our parabolic mirror suffer from very uneven backgrounds. The combined light is imaged with a digital camera (DSLR; Canon 60D, 180-mm lens). Within each arm of the interferometer, knife edges (KE1, KE2) are placed at each of the secondary foci and color filters (CF1, CF2) are placed in each path.

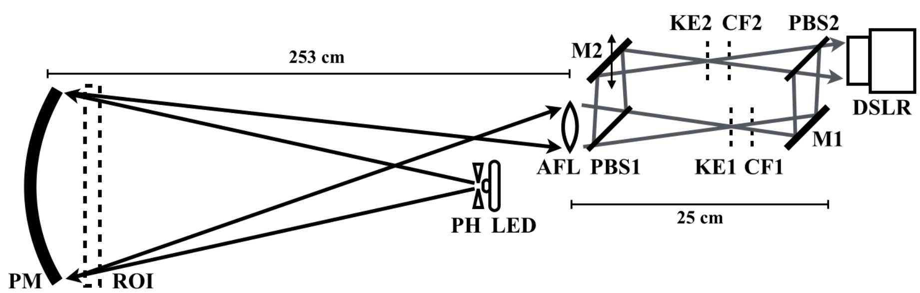

Fig. 1. The experimental arrangement of the two-path system, showing the light source (LED), region of interest (ROI), parabolic mirror (PM), and Mach-Zehnder setup, with the final image captured by the Canon 60D DSLR.

To align the system, a wire mesh screen (13-mm spacing, 0.9-mm wire thickness) is placed at the ROI. By tuning the mirrors and beam splitters, the images of the screen from both arms are overlapped and their size is matched by adjusting the position of M2 with a translation stage. When good overlap is achieved and the path lengths are matched, white-light fringes are observed, as shown in Fig. 2(a). Further fine tuning results in very broad fringes (Fig. 2(b)), indicating excellent position and pointing overlap. Inserting a green and a red filter in paths 1 and 2, respectively, yields a yellow image (Fig. 2(c)). By inserting a vertical knife edge in the focal plane of path 1, horizontal deviations appear as green in the final image. Likewise for a horizontal knife edge in path 2, which produces a red image of vertical deviations. This is shown quite dramatically in Fig. 2(d), where the diffracted light around the vertical wires is green and the light around the horizontal wires is red. For greatest effect, the knife edges are inserted far enough for the near complete obstruction of non-deviated light. Due to the 0.5° angular separation between the incident and reflected beams on the parabolic mirror, a slight double image, separated by 1.0 mm in the horizontal direction, is observed. This effect can be easily eliminated by using normal incidence on the PM and a

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beam splitter to redirect the reflected light, or by utilizing a "z-type" arrangement with two mirrors [1].

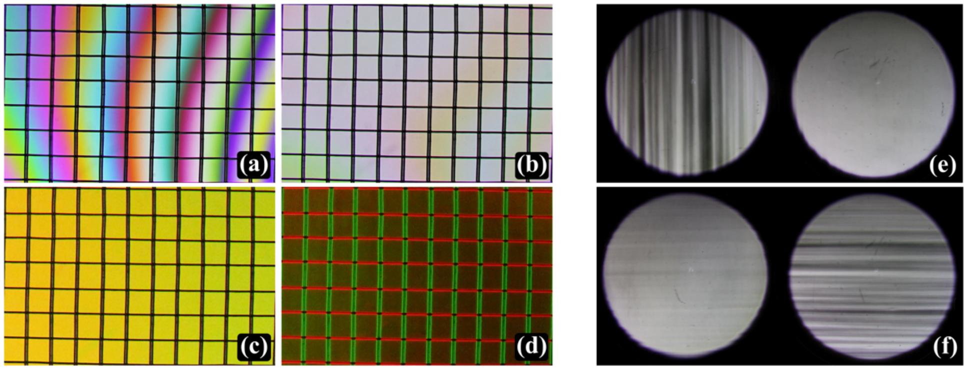

Fig. 2. A wire mesh screen is used to align the system: a) white-light fringes appear once the path lengths are matched, b) broad (nearly invisible) fringes form with fine tuning, c) adding green and red filters yields a yellow image, d) inserting knife edges gives color-indicating bidirectional sensitivity. By misaligning the system and removing the color filters, two views of a pane of glass are captured simultaneously: e) defects running vertically and f) horizontally. The left image corresponds to the path with the vertical knife edge, and the right image to the path with the horizontal knife edge.

By intentionally misaligning the two paths through the interferometer and removing the color filters, it is possible to capture two spatially separated images simultaneously. In order to test this arrangement, a thin plate of glass from an ordinary picture frame is placed in the ROI as a source of "schliere." The glass has imperfections primarily along one direction, making it an ideal subject to test the double knife edge technique. In Fig. 2(e), the glass is placed such that the "ripples" in the glass run vertically, giving rise to horizontal beam deviations. The image from path 1 (vertical knife edge) is on the left, and the image from path 2 (horizontal knife edge) is on the right. In Fig. 2(f), the glass plane is rotated by 90°. As is seen convincingly in both images, path 1 is sensitive to horizontal light ray deviations, and path 2 is sensitive to vertical deviations.

3. Experimental results

A few popular sources of real-world schliere were used to generate images from our two-path scheme. In Fig. 3(a), the vertical laminar flow from a lighter's flame appears green before transitioning into red and green turbulent flow. The horizontal laminar flow from an aerosol duster appears red in Fig. 3(b), sending the green vertical flow from the flame into turbulence. In Fig. 3(c), a hot soldering iron gives rise to a gentle pattern. Indeed, similar images have been obtained from traditional schlieren arrangements with segmented color filters in place of the knife edge [12–21]. However, our approach does not rely on the physical assembly of such a filter, and the choice of colors can be changed quickly and easily. Also, the location of the vertical and horizontal filters can be individually optimized (e.g., to minimize the effects of astigmatism). Finally, more complex filter combinations, perhaps with gradient or phase filters, may be tested easily, with the effects on the resulting image immediately visible.

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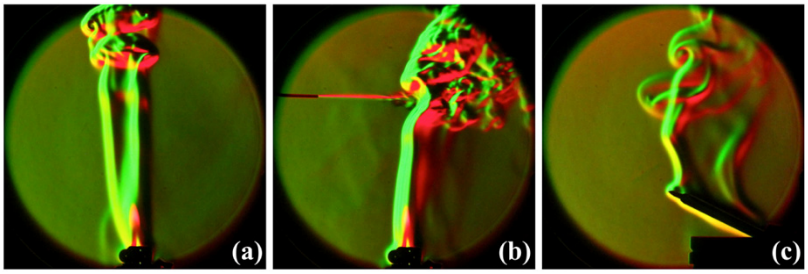

Fig. 3. Sample color schlieren images: a) flame from a lighter, b) flame and an aerosol duster, c) a hot soldering iron. Note the vertical green flow and horizontal red flow in (b).

By intentionally misaligning the two paths in the interferometer and removing the color filters, simultaneous but spatially separated images are captured. In Fig. 4, white-light images from (a) a flame, (b) a hot soldering iron, and (c) aerosol duster flow are shown. In each example, both images are captured on a single frame with the Canon 60D. The left image corresponds to path 1 (vertical knife edge) and the right image corresponds to path 2 (horizontal knife edge). Clearly, knife edge orientation has a dramatic effect on the features that are captured in the images. In order to generate a single, composite image, the two views are colorized and combined using Adobe Photoshop software, as shown in the right column of Fig. 4. With this technique, the separate views can be analyzed independently, or a synthesized single image can be created and optimized in “post production.”

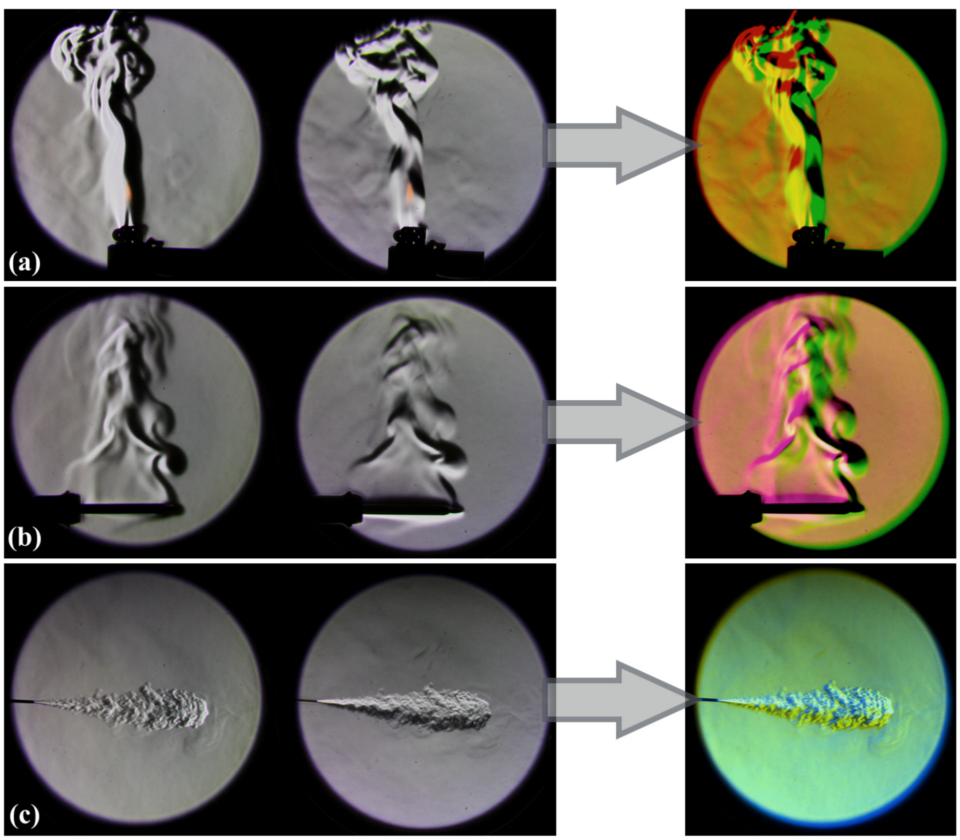

Fig. 4. Sample simultaneous two-view schlieren images and corresponding composite images using white light: a) flame from a lighter, b) a hot soldering iron, c) an aerosol duster.

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In order to test our scheme with alternate light sources, a green laser pointer (532 nm) and a red He-Ne laser (633 nm) were used instead of the white LED. In both cases, the expanded beam was brought to a focus at the same location as the LED pinhole, leaving the rest of the arrangement intact. Two examples of monochromatic, two-view images of the flame from a lighter are shown in Fig. 5, using (a) the green laser and (b) the red laser. The original images are converted to black and white, and then colorized and combined to create the synthesized images shown to the right. As expected, both sources yield excellent schlieren images. To our knowledge, these are the first examples of direction-indicating, color schlieren images generated with monochromatic sources.

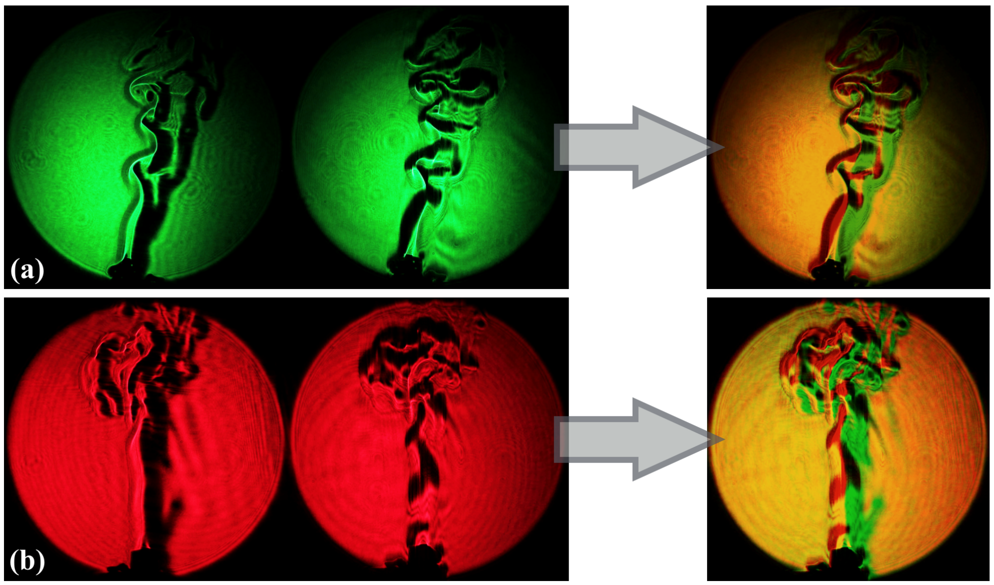

Fig. 5. Sample simultaneous two-view schlieren images and corresponding composite images of the flame from a lighter: a) using a green laser source and b) a red laser source.

4. Conclusions

We have demonstrated a novel schlieren imaging technique that allows for the use of two independent knife edges along two beam paths. Tests demonstrate that the system has excellent bidirectional sensitivity, and sample color images have been captured. The system has also been used to generate two simultaneous but spatially separated views, and synthesized composite images have been generated. Even when using monochromatic sources, synthesized bidirectional color images were created. This system should find utility in testing new filter combinations for direction-indicating schlieren, as well as for generating color images when using monochromatic sources (e.g., with ultrafast or pulsed-diode laser sources for high-speed schlieren imaging).

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