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Laser Alignment Method for Portable Schlieren System

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Astigmatism and coma are two optical aberrations that are common with Z-type schlieren systems. The effects of these two aberrations can be minimized by increasing the accuracy in the optical alignment of all optical components of the system. For portable schlieren systems, the alignment process can become a time-consuming task every time the system is relocated. A portable schlieren system utilizing alignment lasers and newly designed mirror mounts was developed. The system can be set up rapidly and accurately.

I. Introduction

SCHLIEREN optical systems deliver the ability to view phase objects that cannot normally be seen with the naked eye.[1] Schlieren systems utilizing the Toepler technique have become the standard for most systems. The schlieren images can be used qualitatively and quantitatively, especially nowadays with the advent of digital technology, lasers, high-speed imaging systems and the use of color schlieren for tracking density gradients.[2–16] Most common schlieren systems are built or set up for a particular configuration although some schlieren systems such as the IAB-451 and TE-19 Soviet-based systems are designed for production use and can be considered to be portable units.

Whatever system or setup configuration is used, it needs to be properly aligned. Depending on the complexity of the system, the alignment process can take anywhere from 8–10 minutes for an experienced hand or 10–15 min. for a novice user (Ref. 1, p. 179), although many assumptions are made in arriving at those times regarding the performance of individual components. For a schlieren system to be both portable and practical, a quick alignment process needs to be conceived.

Vasli'ev[17] describes the alignment process for a Soviet IAB-451 system and notes that the difficulty of the alignment process is the optical axis (Ref. 17, p. 153). He accomplished the optical alignment by utilizing an auto collimating eyepiece on one instrument and an illuminator with images of crosshairs on the two ends of the other instrument. By aligning the two crosshairs through the eyepiece, the optical axis of the instruments can be considered properly aligned.

With modern technology, a new alignment technique is proposed that can significantly reduce the time spent in the process as well as ensuring accuracy. This paper describes the alignment technique that includes newly-designed mirror mounts and the use of lasers to properly align the optical axis with respect to both mirrors and all the required optical components of a Z-type schlieren system.

II. Alignment Concept

The Z-type Schlieren system is a well known configuration that is both inexpensive and simple to set up. The Z-type configuration, however, has several major disadvantages. The most important is the off-axis alignment of the two mirrors. Off-axis alignment causes two well-known optical aberrations. The first is known as coma. Coma is produced by a light source that is off axis with respect to the mirror's optical axis. In a Z-type system, the concave mirrors are rotated to a known angle and thus the light source is incident on the mirror at an angle thereby producing a distinct comet-like image. For the Z-type configuration, coma is unfortunately unavoidable; however, it can be reduced by placing the mirrors on opposite sides of the optical axis. This placement gives this schlieren configuration its noticeable Z pattern. Each angle must be identically opposite in direction in order to reduce this aberration to a negligible level.

Astigmatism is the second aberration for Z-type systems. Astigmatism occurs when the sagittal plane (horizontal) from an off-axis light source come into focus at the sagittal focus (vertical line). At this point, the

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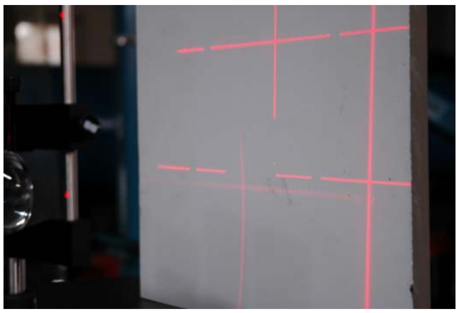
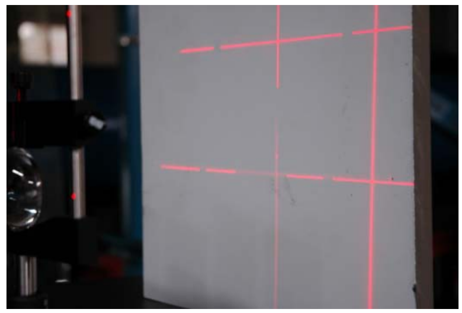
image is itself elliptical with respect to the vertical axis. The same is true for the tangential plane. The tangential plane comes into focus at the transverse focus (horizontal line) which is an elliptical image with respect to the horizontal axis. The sagittal and transverse planes come into focus at two different locations along the mirror's optical axis. The point where the image is circular is known as the point of least confusion. While the effects of astigmatism cannot be eliminated, it can be reduced by minimizing the offset angle of the mirrors. The alignment techniques are aimed at reducing coma and astigmatism rapidly.

Aligning the optical components to a common optical axis is achieved by using lasers which produce highly colliminated pencils of light.[18] If a light ray is to pass orthogonally through a lens to its plane, then the reflection and refraction angles are both zero. One can conclude that the light ray is aligned to the lens' optical axis. This concept is applied to aligning the optical components of the system.



(a) Off-axis.



(b) On-axis.

Figure 1. Aligning optical components using a pair of aiming lasers with crosshair tips.

An example of the alignment process is shown in Figure 1. Two laser diodes equipped with crosshair tips an mounted at the 12 and 3 o'clock positions of the mirror mount, looking from the back, are used for alignment. In Figure 1, a white board is place behind the condenser lens, just visible to the left, for clarity. Figure 1(a) shows that the condenser lens is placed such that its optical axis is close too but not parallel with the laser beams. As a result of the misalignment, the laser beams that were incident on the lens were refracted off axis as can be seen in the lower left part of the screen in Fig. 1(a). By moving the lens, the misaligned beams can be brought into alignment to yield a rectangular pattern as can be seen in Fig. 1(b). In Fig. 1(b), the lower left crosshair now represents the optical axis of the mirror. Once these crosshair patterns are visible, it is a matter of adjusting the lens to bring these crosshairs into alignment, both vertically and horizontally, which then aligns the lens with the lasers (or, equivalently, the mirror). All the optical components of the system, namely, the source slit, the knife edge, and the camera are aligned utilizing the intersection of the two laser beams.

III. Schlieren Optical Equipment

The system configuration follows that of a typical Z-type system. A 3 W white LED manufactured by Nasun capable of producing 150 lumens is used as the light source. The size of the LED is approximately 2 mm by 2 mm. The LED source overcomes many complications that occur with other light sources. For instance, xenon bulbs produce an arc between two electrodes that actually forms a distributed source. The LED is inexpensive and consumes less energy compared to most other light sources. The condenser lens is an Edmund Scientific NT43-593 with a diameter of 1.96 in. (50 mm) with an effective focal length (E.F.L) of 1.693 in. (43 mm). The source slit is a 1 mm high by 2 mm wide rectangle. The spherical mirrors are 6 in. diameter with an f# of 6. The remaining equipment include two Sentry Steel Rx type portable tables, a knife edge mounted on a vertically positioned traverse rail, a focusing lens, and a Nikon D70 camera. The custom tables by Sentry Steel were needed due to the specific height, mobility, and length requirement that are not normally found with conventional work tables.

To ensure quick and accurate alignment of the optical equipment, the alignment method is centralized around the mirror's optical axis. Newly-designed mirror mounts were manufactured in house, allowing the mirrors the ability to rotate about their vertical axes as well as provide locations to mount the alignment lasers, see Fig. 2. Two Egismos HA-3-635-5-C crosshair pattern lasers are seated inside the laser mounts at right angles with respect to each other. These laser mounts are shown in red in Fig. 2. The resulting placement and crosshair pattern ensure an accurate representation of the mirror's optical axis. The inner diameter of the mirror mount was machined to the design specifications of each individual mirror. A tolerance of 0.015 in. (0.38 mm) was added to allow the mirrors to seat into the mounts. The mounts rest on a rotating dial with an angle indicator.

IV. Alignment Process

The alignment begins with the placement of the optical components on their respective tables. Table 1 holds the first mirror, the LED source, the condenser lens and the source slit. Table 2 holds the second mirror, the knife edge, the focusing lens and the camera. The mirror mounts are placed on the table such that the zero degree mark is facing toward the other mirror. With the lasers representing the optical axis of the respective mirrors, the first mirror is aligned to the second mirror, see Figure 3. The accuracy of the alignment is determined by the placement of the vertical and horizontal laser beams. Since both mirror mounts are identical in design, the location of one laser module corresponds to the same location of the other laser module on the second mirror. Proper alignment ensures that the faces of both mirrors are parallel with to each other with respect to the vertical axis. This alignment process is repeated for aligning the second mirror to the first mirror.

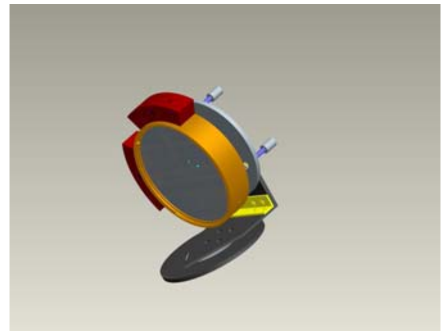


Figure 2. Pro-Engineer Wildfire drawing of the customized mirror mounts.

(a) Off alignment. **(b) Aligned with respect to the other mirror.**
Figure 3. Mirror axis alignment (a) off alignment and (b) aligned with respect to the other mirror.

Once the two mirrors are aligned with respect to each other, the next step is to align their associated optical components by the same method used to align the mirrors. Due to the dimensions of the mounting components for the optical equipment, the minimal offset angle is of the Z-configuration is set to 10 deg. The mirrors are then rotated half the offset angle according to the law of reflection. Figure shows the accuracy of the alignment method. The horizontal alignment laser verifies the location of the focal point upon the knife. The distance between the two mirrors was approximately 25 ft (7.6 m). The size and shape of the focal point at the knife edge was compared to thosee of the source slit to determine the effectiveness of the alignment method in reducing the effects of optical aberrations. Typical alignment setup times ranged from 2 to 5 min.

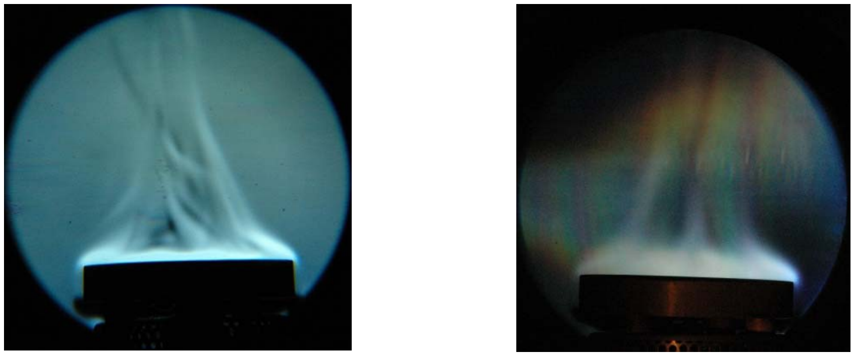
V. Results

Conventional techniques of aligning optical components involve using a white sheet of paper or card to follow the beam profile and make the appropriate adjustments where needed.[1] This is satisfactory depending on the configuration of the system and the type of mirror mounts used. Stability and accuracy may be difficult to achieve. In many cases vibrations may cause the mirrors to move and result in misalignment.

Figure 4. Focal point (the bright point) at the knife edge revealing accuracy optical axis alignment with lasers.

Only preliminary results are available at this moment. Qualitative improvements can be clearly seen by comparing two images under similar conditions. Three sets of images are used for qualitative comparison. Each set below was taken by the same Nikon D70 camera and same optical equipment with the exception of the different mirror mounts. The first qualitative comparison is the flow from a hot plate set to a temperature of 400 ^{o}F. Figure (a) shows results of a hot plate utilizing the custom designed mirror mounts with an knife edge cutoff of 50%. Figure (b) show the hot plate with an 80% cutoff utilizing

Edmund Scientific NT36-483 large angle mirror mounts. Aberrations are noticeable by the discoloration of the image as well as the uneven distribution of light. These aberrations admittedly may be removed through painstaking adjustments of the optics.



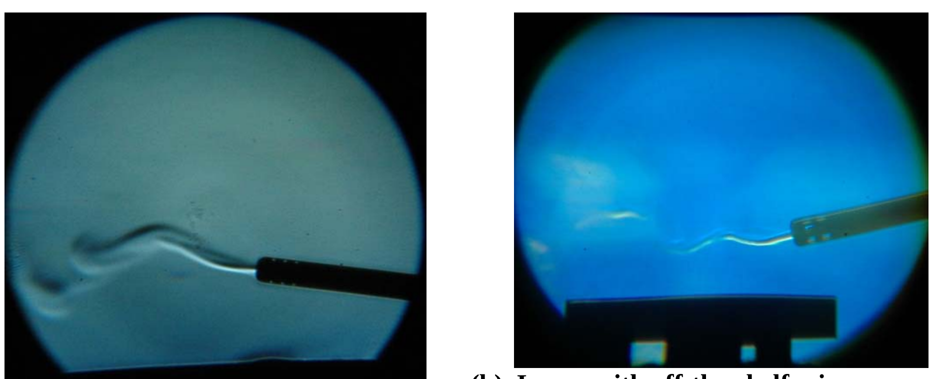
(a) Image with custom mirror mounts. **(b) Image with off-the-shelf mirror mounts.**
Figure 5. Schlieren image of flow from a hot plate at 400 ^{o}F.

A second qualitative comparison involves the use of isobutane gas from a lighter. Isobutane in a gaseous state has a density of 0.156 lb/ft^3 at 59 F and 1 atm. The refractive index of isobutane is 1.0019. The maximum refraction angle can be determined from[1]

$$\frac{n}{n_o} = \frac{1}{n_o} + \frac{\rho}{\rho_o}\left(\frac{n_0 - 1}{n_0}\right) \tag{1}$$

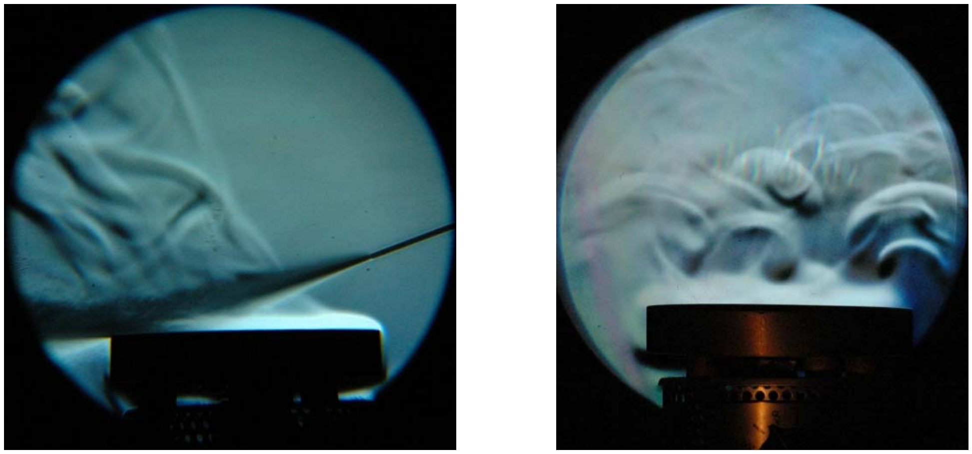
$$\varepsilon_{\max} = 2\left(\frac{n}{n_o} - 1\right) \tag{2}$$

The maximum refraction for isobutane is approximately 631 arcseconds, a very small angle. Figure compares the schlieren results of isobutane under similar conditions with the custom and off-the-shelf mounts at 50% cutoff. The astigmatism in Figure (b) is most noticeable around the edges of the plate and the edges of the butane lighter. Although some astigmatism is still present in Figure (a), improving the alignment of the mirrors and optical components results in a noticeable improvement in the quality of the schlieren image.



(a) Image with custom mirror mounts. **(b) Image with off-the-shelf mirror mounts.**
Figure 6. Comparison of flow from a butane gas lighter.

Figure compares the disturbed flow over a hot plate. The most noticeable difference is the accuracy of the alignment of both mirrors. Figure (b) shows a misalignment which is apparent by the double edge outline along the circumference of the circle. This supports the conclusion of the necessity of proper axis alignment of the mirrors and optical components in order to prevent or reduce optical aberrations and improved image quality.



(a) Image with custom mirror mounts. **(b) Image with off-the-shelf mirror mounts.**
Figure 7. Schlieren image of hot plate with an impinging cold jet from a can of lens cleaner.

VI. Conclusion

The Z-type configuration for schlieren visualization is common and well known. A portable schlieren system needs to have the ability to be set up in a short amount of time as well as have the ability to properly align all the optical components under any condition with good accuracy. The importance for maintaining proper alignment was demonstrated through reduction of coma and astigmatism using alignment lasers placed on mirror mounts. The lasers help to facilitate alignment.

VII. Acknowledgments

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