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Seeing the invisible with schlieren imaging

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Abstract. Schlieren imaging is a method to visualize differences in refractive index as caused by pressure or temperature non-uniformities within a medium, or as caused by mixing of two fluids. It is an inexpensive, yet powerful and straightforward, tool for sensitive and high-resolution visualization of otherwise invisible phenomena. In this article, application of the method to liquid membranes, sonar pulses, and microscopic gas flows is used, to illustrate its usefulness and versatility for physics education and research.

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1. Introduction

The schlieren method is primarily a qualitative method to visualize differences in refractive index in transparent media. Historically, the method has been used for a wide range of applications, among others to study lens glass for defects (Hooke, 1600s [1]), telescope mirrors for quality (Foucault, 1800s [2]), and pressure waves around supersonic projectiles (Mach, 1800s [3]).

In order to set up a general schlieren apparatus, all that is required, is fairly collimated light passing through a test area, and a lens – the schlieren lens – focusing the collimated beam onto a *cut-off*, and simultaneously focusing an image of the disturbance onto a screen or imaging device (Toepler, 1800s [4]). The purpose of the cut-off is to control the contrast in the image. For many applications, a simple razor blade will serve very well as a cut-off [5]. In theory, the schlieren lens will focus the light into a single point, but, in practice, there will be a focused image of the light source, which can be obstructed to a varying degree by moving the cut-off.

A schematic of the basic setup, including a collimating lens, can be seen in Figure 1. To minimize aberrations, it is desirable to have the largest possible f -numbers for both the collimating lens and the schlieren lens, preferably $f/8$ or longer.

In general, the light source will be too large for adequate collimation, which will result in poor image quality and sensitivity [5]. To improve this, a condensing lens is often used to focus the light onto an aperture or slit, which will then emulate a pointlike (aperture), or extended pointlike (slit) light source. By using variable apertures or slits, the degree of collimation can be adjusted to the disturbance to be visualized.

With this set-up, light refracted by the disturbance (angle ε_y in Figure 1), will be displaced a distance Δa at the cut-off. If this distance is toward the razor blade, the light will be obstructed, leaving dark areas in the image. If the light is refracted away from the razor blade, it will pass unobstructed by it, resulting in brighter areas.

The cut-off needs to be adjustable with high precision to control the amount of background light, as this relates to the sensitivity and measuring range of the apparatus [5]. The cut-off can, in the case of the razor blade, be rotated around the optical axis of the set-up to visualize disturbances deflecting light in different directions.

As a complement to the microscope, which allows us to see minute objects, and the telescope, which enables us to see things at great distances, the schlieren apparatus is a general tool to visualize inhomogeneities in transparent media. Possible applications are entirely up to the user.

2. Experiments

In this article, a schlieren apparatus was designed using a 1 kW quartz-tungsten-halogen (QTH) lamp, a 300 mm, $f/5.9$ condensing lens to focus the light onto a variable slit at the focal point, followed by an identical lens for collimation. Beyond the disturbance (at twice its focal length), a 400 mm $f/7.9$ schlieren lens focused the beam onto a razor

Figure 1: Schematic of a simplified schlieren set-up.

blade cut-off, Figure 1, and into a digital camera, with a 50 mm, $f/1.8$ lens mounted on a bellows. At the maximum magnification, the lens and bellows combination magnified the image approximately 3.6 times, imaging an area of 4.5×7 mm.

These lenses were chosen for high resolution imaging of exhaust gas from microthrusters placed in a vacuum chamber. The thrusters were fabricated using microelectromechanical systems (MEMS) technology by etching a photolithographically defined pattern into 22×22 mm silicon chips, and bonding a flat lid onto them. The thruster nozzles measured $20 \mu\text{m}$ at the throat, and $350 \mu\text{m}$ at the exit. The microthrusters were studied extensively, at different inlet and ambient pressures, with different propellant gases, and with and without integrated heaters activated.

The set-up was also used to study interference patterns from a piezoelectric sonar in an aquarium. The sonar is approximately 2 mm wide and 50 mm long, operated at 666 kHz, and is intended for use in a miniature submersible [6].

The mixture of liquids was imaged by introducing ethanol into water by means of a syringe with a plastic needle.

The surface structure of soap bubbles and films was studied to see the topography changes as the bubble aged. The studies of soap films allowed for simultaneous conventional photography by a second camera placed next to the cut-off, to compare iridescence from the soap film with the surface structure. For appropriate illumination, the soap films were suspended above a light table [7].

3. Results

Initially, high refractive index disturbances, such as butane from a gas lighter passing through a 27 gauge hypodermic needle, were used to verify and tune the set-up, Figure 2.

Through the tests of the microthrusters under different operating circumstances, the functionality of the thrusters could be verified, and the exhaust was seen to be supersonic in vacuum. In Figure 3, the thruster chip is to the left, exhausting a supersonic jet of

Figure 2: Schlieren image of butane from a lighter, passed through a 27 gauge (i.e. 0.21-mm inner diameter) hypodermic needle (lower left corner). Field of view is 20×15 mm.

Figure 3: Schlieren image of a microthruster exhaust in vacuum. Cut-off is perpendicular to jet. (Exhaust nozzle is in line with, but hidden under, a clamping device). Field of view is 7×4.5 mm.

xenon horizontally in the frame. The pressure disk pattern is clearly visible closest to the nozzle, and fades as the plume extends outwards. These results were the same regardless of the gas used, but the visibility of the exhaust was related to the difference in refractive index of the gas from the thruster, and the surrounding medium.

The visualization of pressure waves from the piezoelectric sonar was straightforward, but the image quality deteriorated slightly, as a number of new glass surfaces were introduced by the aquarium, as well as particles in the water along the entire length of the beam through the aquarium. The results were still very useful, and validated simulations of the sonar in the same surroundings. Figure 4 shows a schlieren image of the sonar (top left in the frame) and a complex interference pattern.

Studies were also conducted on the mixing of liquids. Figure 5 shows a plastic needle (left) discharging ethanol into water.

Figure 4: Schlieren image of standing waves from a sonar (top left) in an aquarium. Field of view is 25×16 mm.

Figure 5: Schlieren image of ethanol in water. Field of view is 20×14 mm.

The study of soap bubbles and soap films provided an excellent opportunity to compare conventional results with schlieren images. The beautiful colors of a soap bubble are due to the extremely thin film reflecting light which then interferes with the internal reflections. This phenomenon is known as iridescence, and the color is governed by the thickness of the soap film. Figure 6 shows a vertically hanging planar soap film photographed simultaneously with conventional digital imaging equipment, and with the schlieren apparatus. The similarities between the patterns in the images are striking. Figure 6 (a) shows the topography of the film, and hence the cause of the different colors in Figure 6 (b). The softer color gradient from top to bottom in Figure 6 (b) is perpendicular to the cut-off and does not show up in the schlieren image.

The topography of a soap bubble is easily made visible using schlieren photography, Figure 7, but the result is harder to interpret, as the light is refracted by both the near and far surfaces of the bubble.

(a)

(b)

Figure 6: Soap film on a wire ring. (a) Schlieren image. (b) Photograph with conventional equipment. Field of view is 25×16 mm.

Figure 7: Schlieren image of a small soap bubble on a straw. Field of view is 25×16 mm.

4. Discussion

In this article, the schlieren apparatus was designed with a specific purpose in mind. A more general system could be set up using mirrors rather than lenses [8], allowing a

larger viewing area, and a common slide projector may be modified for use as a light source to reduce cost. Ideally, the disturbance should be placed in the focal points of both the collimating and schlieren lenses, and these should have the same focal length, but very good results can still be obtained without this optimization.

As demonstrated, even this relatively small set-up can be used for a wide variety of applications. The camera could easily be replaced with a high-speed camera, or be triggered by computers or electronics for exotic high-speed captures [9]. The system demonstrates the fundamentals of refraction (both in the lenses of the system, and the disturbances), and is a useful tool for studying otherwise invisible phenomena. In the case of the gas flows and pressure waves in water, this is especially true. In the case of the soap films, the schlieren apparatus provides a very good illustration of the correlation between refraction and surface structure.

The schlieren method is primarily a qualitative tool, making deductions about actual thickness, refractive index, geometry, temperature, etc. difficult. However, there is still very valuable information to be found simply by the visualizations themselves.

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