Flow visualization techniques, new developments and modernization of the existing Schlieren system in the Trisonic Wind Tunnel

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Abstract: *Schlieren flow visualization methods are an important part of high speed wind tunnel testing, being a fast and reliable method of graphically presenting complex dynamic phenomena that occur in high subsonic, transonic and supersonic regimes. Images can be processed and effects of configuration changes can be understood faster. Quantitative variations of the Schlieren method enable CFD simulations to use real data, resulting in greater precision and thus help improve efficiency of the re-design phase for the aerodynamic object. A modification of the classic Schlieren system is proposed, that would enable extraction of such data with minimal costs.*

Key Words: *Schlieren methods, optical flow visualization, fast background-oriented Schlieren, quantitative optical flow measurements*

1. SCHLIEREN METHOD TYPES

Schlieren methods are useful for a faster understanding of how the regions of different densities (hence pressures) are distributed in flows around aerodynamic objects and what their shapes are. For high-speed and thermal transfer problems these are important aspects that help understanding complex transient phenomena. To the present day, Schlieren methods are mostly used as qualitative methods, but lately the long-awaited quantitative procedures are emerging.

Schlieren apparatuses are arranged differently depending on the phenomena to be observed and local technical conditions (availability of light sources, etc), but all have the same basic principle: light from a collimated source (in some varieties, a coherent source such as a laser) passing through a flow having regions of different densities is refracted in accordance with the refraction index that is directly linked to density by (1), where n is the refracting index, n the normal to the flow median plane and z, x and y regular coordinates in space. Images are formed based on various filtering methods that select preferential directions to measure light path deviations from, and the filter threshold is implemented by a variety of means, such as quarter plates, knife edges, wavefront sensors or even zone plates.

$$
\begin{aligned}
\frac{\partial^2 x}{\partial z^2} &= \frac{1}{n}\frac{\partial n}{\partial x} \\
\frac{\partial^2 y}{\partial z^2} &= \frac{1}{n}\frac{\partial n}{\partial y}
\end{aligned}
\tag{1}
$$

The total angular deflections of rays passing through a density disturbance in a flow can be computed by integrating the above quantities over the working section of a length L across the flow, and considering that a ray of light leaving the working section will be deflected by $n\sin\varepsilon' = n_0 \sin\varepsilon$ yielding (2):

$$\varepsilon_x = \frac{1}{n_0}\int \frac{\partial n}{\partial x} dz = \frac{L}{n_0}\frac{\partial n}{\partial x}$$
$$\varepsilon_y = \frac{1}{n_0}\int \frac{\partial n}{\partial y} dz = \frac{L}{n_0}\frac{\partial n}{\partial y} \quad (2)$$

where n_o is the refracting index of air outside the flow/ working section and n the refractive index in the flow, ε and ε' being total ray displacements outside and inside the flow respectively [1].

By the type of focus, on object or on a specially designed high resolution at any magnification-background (such as fractal or wavelet noise patterns) we call the method classic or background oriented Schlieren.

The most common technique that offers only qualitative descriptions of flow fields is the Toepler method, that came to be known as classic Schlieren because its simplicity favored its implementation wherever such imaging was needed. Toepler method uses a partial obstruction of the image by the means of a “knife edge”. Displacements of light rays take place towards the higher refracting index in the flow, in accordance with (2), hence using a knife edge to partially block the image of the source filters out the smallest deviations. Large deviations of light rays that exceed the recording apparatus's sensor /view screen's limits such as the ones caused by strong shock waves embedded in high density gradients fail to be registered altogether so the careful study of the limits, sensitivity and range of the Schlieren apparatus is required and settings are to be made in accordance with the expected experimental output range. The classic Schlieren technique can be applied for all kinds of refractive indices. With proper setup and observing the sensitivity and range settings, even very weak density gradients cause reliably detectable refractive index changes, e.g. the convection of warm air over a human hand in a normal temperature room can be visualized.

Background-oriented Schlieren methods are used in conjunction with image processing hardware. A pattern of wavelet noise is used as background because it has very high local contrast at all magnifications and thus it helps identify fine details in flows, at any magnification. The pattern is illuminated and imaged in absence of the flow; then flow is started having the illuminated pattern as background and high speed high resolution images are recorded. The technique does not use any form of knife-edge or filtering, being based on cross-correlations between the two sets of images, the undistorted background in absence of the flow and the distorted, through the flow background. The resolution of this method is linked to the camera and background pattern resolution, details being identified by a point-to point correspondence method. No advanced optical system is needed but a high speed good resolution camera is essential to this type of method [2].

A compound method uses a laser as a light source and he phenomena of self-interference between deflected and undeflected rays. The principle of the method is the classic Toepler theory but in addition to that, the fact that the collimated light used as source is coherent, being a laser, adds interferometry data over the recorded image. A modest quality laser diode can be used because the mirrors in a classic Schlieren setup correct the small phase aberrations, improving coherence length, and a typical setup has a short working section, of 2 to 3 meters maximum.

Rainbow Schlieren uses a specially designed “bull's eye” target instead of a knife edge, having an opaque center (it may be round or square). Graded filters are also an option whenever the working section is larger, as they give a better sharpness overall because diffraction is not abruptly cut off nowhere in the image plane.

Another variant of Schlieren uses a zone plate as both an image forming and knife edge element. Zone plates are alternating regions of opaque and transparent material arranged in a concentric fashion, so as to form a lens. The main advantage of zone plates is the fact that, same as rainbow Schlieren, present a “knife edge” light blocker evenly around the center of the image. Contrast and sensitivity are uniform in a zone plate system.

Of course, the same optical effects can be obtained with suitable lenses, but they are prohibitively priced and hard to manufacture at the focal lengths and diameters required for a large Schlieren system. The setup remains popular with smaller, lower resolution and portable Schlieren systems dedicated to small scale work.

2. SYNTHETIC SCHLIEREN AND ITS ADVANTAGES

A synthetic Schlieren system is simpler and considerably cheaper, but it still needs a good and reasonably fast camera, a goods quality lens and a good quality/resolution background noise print. As the flow is illuminated, noise patterns in the image appear distorted by shifting along the x and y coordinates by the amounts described by (2). Due to the nature of such setup, the synthetic Schlieren system is sensitive to vibration that could cause background pattern shifting without the contribution of the optical effects of the refracting index change due to variances in pressure in flows, thus a second “zeroing” setup is to be provided, for motion analysis and subtraction of total displacements from the imaged flow with vibration “noise” added. The method works remarkably well and it is very simple to extrapolate it to study truly 3D flows using multiple background panel plates and cameras arranged at various angles around the flow (if possible) and then integrating the displacement vectors to compute the image of the flow with all its separate density regions. A very vast palette of post-processing software and tools allow for sectioning the flow field or importing its geometry in 3D FEM /CFD solvers.

A recent development of the method allows for Schlieren imaging inside the tunnel, using a camera that “sees” the model and a pattern printed on it; the background should also be covered with pseudo-random wavelet noise that will form the reference image.

Light sources in background-oriented synthetic Schlieren can be of any type, but for an accurate imaging of phenomena in transonic and supersonic regimes, the speed of flashes should be sufficiently short to capture relevant detail, and the energy per pulse is to be sufficient to correctly impress the sensor. Today most cameras have a good sensitivity to light, with noise-free images taken as high as ISO 3200, while a few exceptional ones reach ISO values of 12500 or more. This translates in requirements for a flash lamp capable of 2-3 microsecond pulses having energies as high as 50 Ws.

Such a system is described in [2] where a Photron Fastcam-X camera with a 60 mm Nikkor lens, a Xenon strobe light and a wavelet background noise pattern were used to detect unoxidized methane concentration and other combustion byproducts in a flame. A complete 3D reconstruction of the spatial flow field of the flame was carried out and a time-resolved synthetic Schlieren was computed.

Colored background Schlieren technique employing an illuminated background pattern having vertical and horizontal red and green stripes can be used in conjunction with a color camera to separate the two displacements on X and Y axes respectively. This method does not require the use of a knife edge, zone plate or phase knife of any kind. Because of he regularity of the pattern, a prior image of the no-flow condition is no longer required. Measurement of deviations

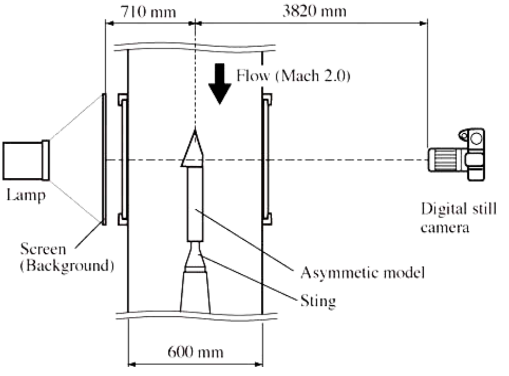

Fig. 1 The CGBOS setup used by Japanese scientists to image high speed (M=2) flows in a medium scale wind tunnel. The model has an asymmetry to explore 3D flow field reconstructions.

3. A COMBINED LASER SCHLIEREN-INTERFEROMETER SYSTEM

Using a laser source with a standard Schlieren setup will provide both Schlieren type images and interference patterns. The method is useful because once the classic Schlieren apparatus's sensitivity is exceeded, information on the highest deflections will appear as fringe interference over the Schlieren image. The width of the fringes or circular zones that appear as a result of exceeding Schlieren apparatus sensitivity code information about the density gradients, as given by (1). Moreover, using a scanning phase knife edge one can explore all the fine details in a flow. It has been shown in [4] that broadening of the first diffraction fringe, instead of conventionally modifying the spatial frequency spectrum, enhances the sensitivity of the Schlieren system. Using a phase knife edge in Schlieren interferometry as viewing diaphragm not only increases phase contrast but also keeps relevant phase information by allowing light from every direction of the test object to create interference patterns, making the method suitable even for the smallest disturbances, such as the density gradients caused by low subsonic flows.

Phase knives are very thin glass plates, exhibiting two clearly delimited regions of different refracting indexes, and rigorously parallel faces. Four region “phase knives” are actually called phase plates, and can be constructed in a variety of ways such as including superposing two phase knives at an angle, usually 90^0 and sealing the parallel faces with optical oil.

They are preferred for small and mixed (both very small but also large) optical gradients because of their extremely high dynamic range and ease of setup. The phase plates usually consist in one or several phase knives 99 to 200 microns thick, sandwiched between regular 6 mm glass plates. Their operating principle is amplifying interference patterns already present in the flow by selectively retarding the light rays that cross the two or four different refracting index areas. They can be used as lenses, on optical rails, in focused Schlieren systems instead of traditional zone plates or knife edges. The light source used in the optical flow imaging systems can be laser or incoherent light, and the imagers can be classic CCD cameras, granting a superior performance over the traditionally knife-edge equipped Schlieren apparatuses.

A multi-purpose system can easily be designed using the existing Schlieren mirrors, procuring a fast camera and improving the existing light source, supplementing it with a small-power laser on a moving optical rail to replace the classic source whenever Schlieren laser interferometry is required; zone plates or phase knives could form a complete Schlieren filter system with an automated exchange mechanism and a controlled displacement carriage for focusing purposes. Finding a suitable strobe light source and painting the inner tunnel walls with a high resolution BOS-appropriate pattern or even printing it on a transparent sheet to be fixed in the second Schlieren window and illuminated from behind would enable the use of this relatively simple and inexpensive technique.

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