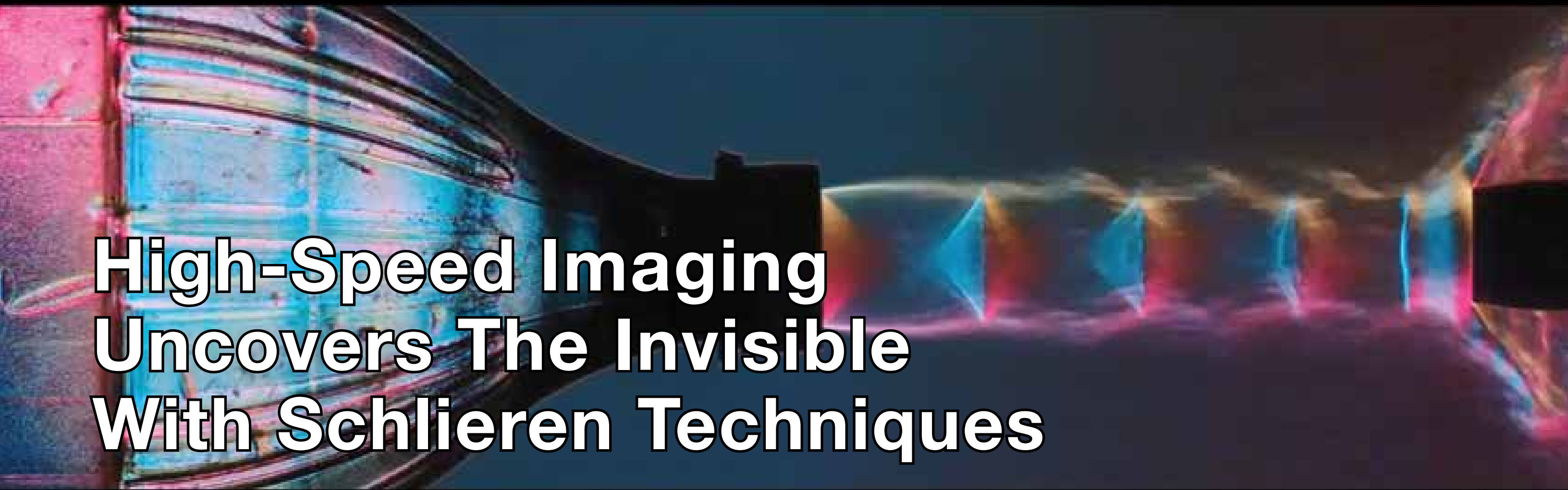


High-Speed Imaging Uncovers The Invisible With Schlieren Techniques

By Phil Taylor, field applications engineer, Vision Research

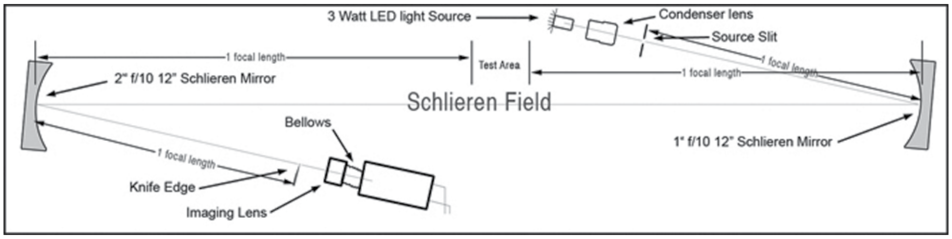
Scientists use schlieren imaging, a non-invasive testing method, to visualize density gradients within otherwise invisible flows. Schlieren imaging is a practical method of visualizing air movement around an airfoil in a wind tunnel or gas interactions within a combustion chamber. Over the past decade, significant improvements in the speed and sensitivity of cameras have greatly increased the quality of schlieren images and the speed at which images can be acquired. Although this advanced imaging technique can now deliver detailed images of highly dynamic processes, obtaining high-quality data requires choosing the best high-speed camera for the application and careful optimization of the optical setup.

CAPTURING CHANGES IN TRANSPARENT MEDIA

Schlieren imaging comes in many forms, all of which capture normally invisible density gradients, or "schliere," in transparent media such as air, water, and glass. Schlieren imaging is typically used for laboratory-based, in-depth studies while a related technique known as shadowgraphy is more commonly used for field studies because its simpler optical setup is easier to transport and less likely to get damaged.

The density gradient, or spatial variation in density over an area, of a medium such as air or gas is determined by environmental factors such as pressure or temperature. As rays of light hit the medium, variations in this density gradient cause the light to change direction in a way that can be imaged. The most common setup used for schlieren imaging is the z-type system. This setup includes two parabolic mirrors, a point light source, a camera, and a knife edge (Figure 1). It provides the highest level of image quality and can be quickly transformed to a shadowgraph

Figure 1: In a z-type schlieren imaging system, the first mirror (right) collimates the light rays onto to the second mirror (left), which in turn directs light to the camera. To the camera, the field of view is evenly illuminated and variations in the density gradient of the subject, between the two mirrors, will change the refractive index of the light and appear in the image. Adding a knife edge at the focal point of the second mirror uniformly blocks some of the light traveling to the camera. This creates a high-contrast image that makes the variations in the density gradient more visible. Components at the source and the cut-off can be altered to change various characteristics in the image, such as color.



system or hybrid shadowgraph/schlieren system.

Schlieren imaging can be used for examining aerodynamics, fluid mechanics, thermal exchange, and other processes. For example, Schlieren imaging can be used to examine a thermal plume from a candle (Figure 2), helium gas flow (Figure 3), and shockwave formations (Figure 4).

GETTING HIGH-QUALITY DATA

Because schlieren imaging captures extremely fast processes with an approach that requires a small light source, it's important to use high-speed cameras that are very sensitive. A high dynamic range is unnecessary though, as schlieren images are naturally high-contrast. Using a camera with tonal curves customization lets the user extract the best grey-level data and can be key for creating quality images. In addition, an option to turn the camera's fan off during imaging will keep heat emitted from the camera's sensor from entering the schlieren field and destroying the integrity of the data.

The optical setup used to acquire schlieren images is very sensitive to the slightest changes. For example, a few-micron change in the position of the knife edge or a few degrees change in ambient temperature could dramatically affect the brightness of the image, making the system less sensitive and ultimately diminishing the quality of any collected data. This sensitivity variability is what makes a schlieren system a bad scenario when comparing high-speed cameras. The simple act of switching cameras changes the setup enough to alter the resulting image. Because of this sensitivity it is also important to run a number of schlieren tests before determining if any modifications to the setup might be needed for a specific application.

Because consistency is key to schlieren testing the high-speed camera should be able to quickly store image data, allowing multiple tests to be performed in one lab session and reducing the occurrence of temperature changes, subject variation, or movement in the optical components. Data management solutions, such as flash memory or 10Gb ethernet, help to ensure data integrity by eliminating these variables.

VISUALIZING SHOCK MOTION ON AIRPLANE WINGS

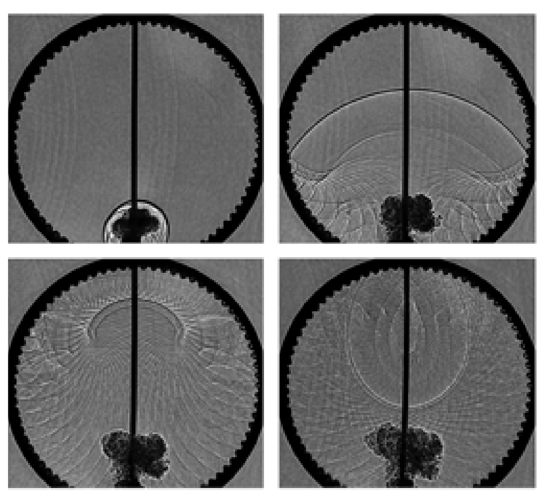
Variations of the traditional z-type system can be used to acquire specific types of information or study particular phenomena. For example, a special schlieren imaging system with a narrow depth of field proved ideal for studying a type of aircraft instability known as buffeting.[1] These structural vibrations intensify as an aircraft increases in speed or angle of attack affecting aerodynamic behavior and limiting the flight envelope.

To investigate the shock motion that buffeting causes on an airplane wing, researchers needed to capture not just shock waves but also the propagation of pressure waves that help sustain the shock oscillation. A traditional schlieren setup wouldn't work well in this case because its sensitivity to the entire length of the light path causes the three-dimensionality of the air flow

Figure 2: Thermal plume. *Image courtesy of Phil Taylor.*

Figure 3: Helium gas flow. *Image courtesy of Gavan Mitchell and Phil Taylor.*

Figure 4: Shockwave formations. *Image courtesy of Phred Petersen.*



All images above were made in the RMIT University Schlieren System.

to blur the motion of the shock and pressure waves. To reduce the capture of unwanted three-dimensional flow structures, the researchers created a system with a narrower depth of field.

The experimental setup diffused continuous light to illuminate a source grid of multiple alternating dark bands and clear apertures that created a two-dimensional light source array. A Fresnel lens, a special lens with a large aperture and short focal length, was placed in front of the source grid to increase the light collection efficiency. A Phantom v710 CMOS camera with a large-aperture imaging lens captured the shock oscillation at 7,000 frames-per-second, recording 8,345 images in a single experiment with an exposure time of 20µs.

The researchers used this setup to visualize how buffets were affected by passive devices known as vortex generators that are often used to control shock buffets (Figure 5). They observed increased three-dimensionality in the flow around the airplane wing when vortex generators were installed, suggesting the narrow depth of field was key to accurately capturing the characteristics of the shock motion in these cases. The focused schlieren visualizations showed the shock buffet appeared at angles of attack greater than or equal to 5 degrees without vortex generators. However, when the vortex generators were installed, the shock oscillation caused by buffets disappeared, even for angles of attack of more than 6 degrees. The new findings provide insight into the physics of buffets and how they can be controlled to improve aircraft aerodynamics.

MAKING BACKGROUND-ORIENTED SCHLIEREN MEASUREMENTS IN A SUPERSONIC FLOW

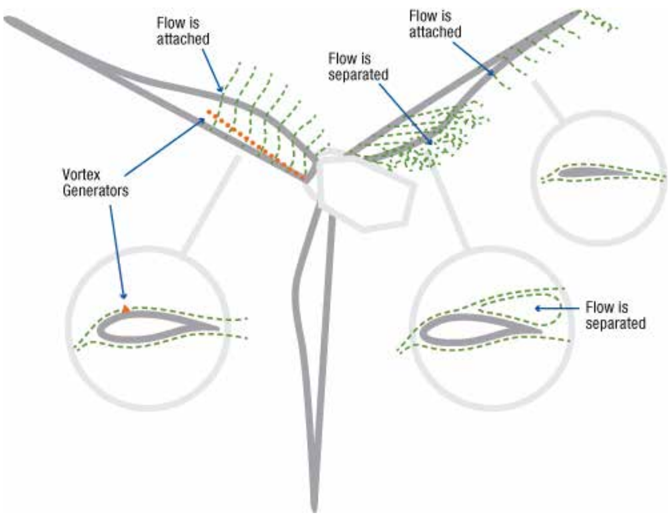
Although traditional schlieren imaging techniques can provide very detailed images, it isn't always easy to use those images for quantitative measurements. One of the newest variations on schlieren imaging, known as background-oriented schlieren (BOS) imaging, can fill this need. When new cinematography cameras with 4K resolution (4,096 x 2,160 pixels) came on the market, researchers tested one to see if it could be used with BOS to obtain precise quantitative density measurements with higher resolution than previously available.[2] These resolution requirements have since become available in scientific cameras.

Like traditional schlieren imaging, BOS images the bending of light rays that occurs with a change in density gradient. However, BOS uses a much simpler experimental setup, requiring just a background and a digital camera. Instead of using a knife edge to manipulate the sensitivity, BOS involves comparing images with slight, barely perceptible differences in refractions to a calibration image of the same exact scene before or after the striations are present.

For the experimental tests, the researchers used a high-speed Phantom Flex4K camera to acquire BOS measurement of interactions and dynamics produced by a jet exhausting in a cross flow. This type of flow field is often found in industrial settings such as a smokestack exhausting into the atmosphere as well as natural processes such as volcano eruptions. However, this flow scenario can be difficult to analyze because of the separate flows, rotational motions, turbulence, and supersonic shocks.

With the wind tunnel running, the researchers opened a valve and then attempted to capture the growth of the interaction field with the camera capturing the images at 1,000 frames per second at a resolution of 4,096 by 2,160 pixels. They captured a reference image in the free-stream condition before the valve was opened. The background was illuminated with a 640nm laser with a pulse duration of 50ns. The experiments showed that a high-speed 4K camera can be used

Figure 5: Schlieren imaging can be used to study how vortex generators affect a type of aircraft instability known as buffeting.
By Robert Bergqvist CC BY-SA 3.0 via Wikimedia Commons.



to quantitatively measure the growth of the interaction field produced by a jet exhausting in a cross flow, a flow scenario that scientists study to better understand a variety of natural and industrial processes (Figure 6).

Schlieren imaging advancements have brought researchers new data gathering techniques. The ever-increasing need for more detailed and accurate data is satisfied by choosing the correct technique and pairing that with the appropriate high-speed camera. Optimizing setup and execution aids in high-quality images and data collection.

References

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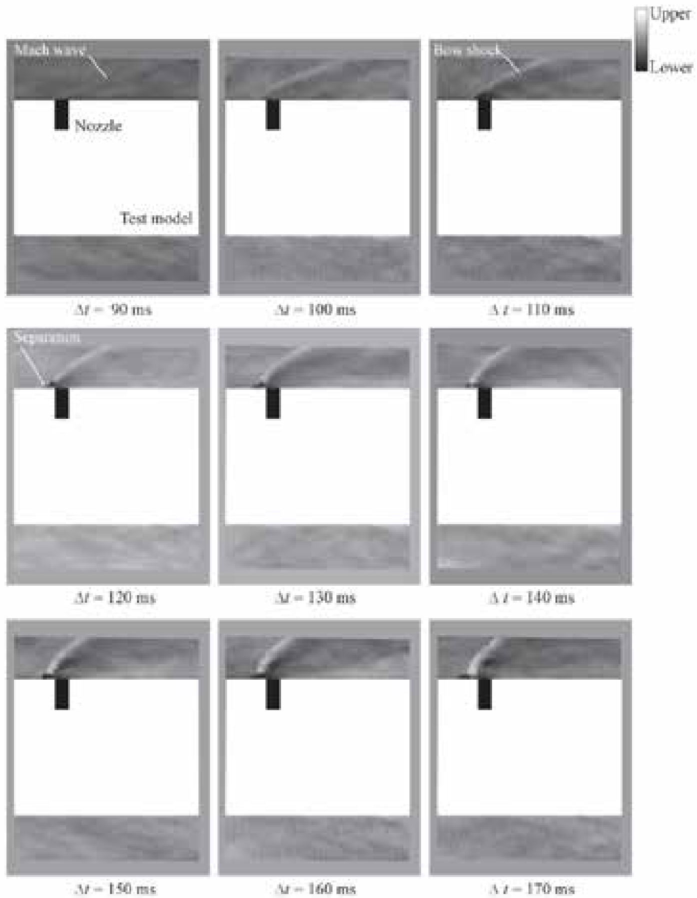
2. M. Ota, K. Kurihara, H. Arimoto, et al. "Background Oriented Schlieren (BOS) measurement in supersonic flow with 4K high-speed camera," Proc. SPIE 10328, Selected Papers from the 31st International Congress on High-Speed Imaging and Photonics, 103281E (February 20, 2017); doi:10.1117/12.2271019; http://dx.doi.org/10.1117/12.2271019

Cover image courtesy of Phred Petersen and Phil Taylor, captured on Phantom v2511.

Figure 6: As the lateral jet opened, a weak Mach wave (a pressure wave traveling at the speed of sound) was generated from the exit of the nozzle. Ten seconds later a weak shock wave was seen upstream of the jet flow and then the interaction field developed and the separation shock was observed. Finally, the bow shock (a curved, stationary shock wave found in a supersonic flow passing a finite body) became stronger and the interaction field continuously developed. *Reprinted from Proceedings of SPIE with permission.*



ABOUT VISION RESEARCH

Vision Research designs and manufactures digital high-speed cameras that can be used for a variety of schlieren imaging techniques. Vision Research is a business unit of the Materials Analysis Division of AMETEK Inc.

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