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Digital focusing schlieren imaging

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ABSTRACT

Since its invention in the 19th century, schlieren imaging has been an essential method for studying many aerodynamic effects, particularly convection and shock waves, but the classical method using parabolic mirrors is extremely difficult to set up and very expensive for large fields of view. Focusing schlieren methods have made large- area schlieren more feasible but have tended to be difficult to align and set up, limiting their utility in many applications We recently developed an alternative approach which utilizes recent advances in digital display technology to produce simpler schlieren system that yields similar sensitivity with greater flexibility.

Keywords: schlieren photography, digital image processing, aerooptics

1. INTRODUCTION

Schlieren imaging was first applied by Toepler[1] over 150 years ago and has been an essential method for studying aerodynamic effects, including convection, shock waves, and turbulence. However, the classical method using parabolic mirrors is extremely difficult to set up and very expensive for large fields of view. Classical schlieren systems use light collimated by optics such as mirrors or lenses, which effectively limits the area under test to the size of the optics. An important improvement on the original concept was the matched-grid focusing schlieren system, originally described by R.A. Burton.[2] Burton's technique relies on the same edge filtering concept as classical schlieren, but instead of using collimated light, it images a background grid pattern onto a matched and offset opaque cutoff filter such that a multiplicity of knife edges is produced, while the target phase object is imaged in a different plane by the camera objective. When a distortion in or near the phase object plane tilts a ray, potential ray paths that had been dark can be illuminated or illuminated ray paths can be darkened (Figure 1).

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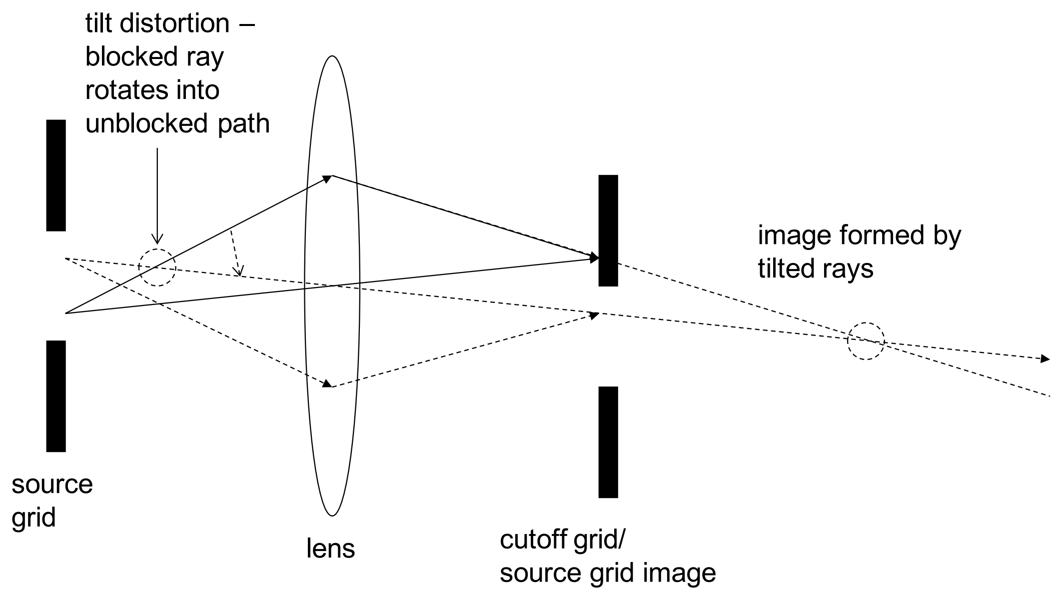

Figure 1. Diagram of focusing schlieren image formation.

This arrangement can function in three different ways depending on how the matching grids are offset from each other. They can be exactly complementary, which gives a “dark field” (DF) mode; exactly overlapping, the “bright field” mode (BF); or somewhere in between, typically with a quarter-period (QP) offset. The DF mode allows for the highest sensitivity, since the contrast is always positive, but it does not distinguish the sign of the tilt distortion. BF mode has only negative contrast and is much like shadowgraphy in effect, but it is rarely of interest. The QP mode produces a true bipolar schlieren image.

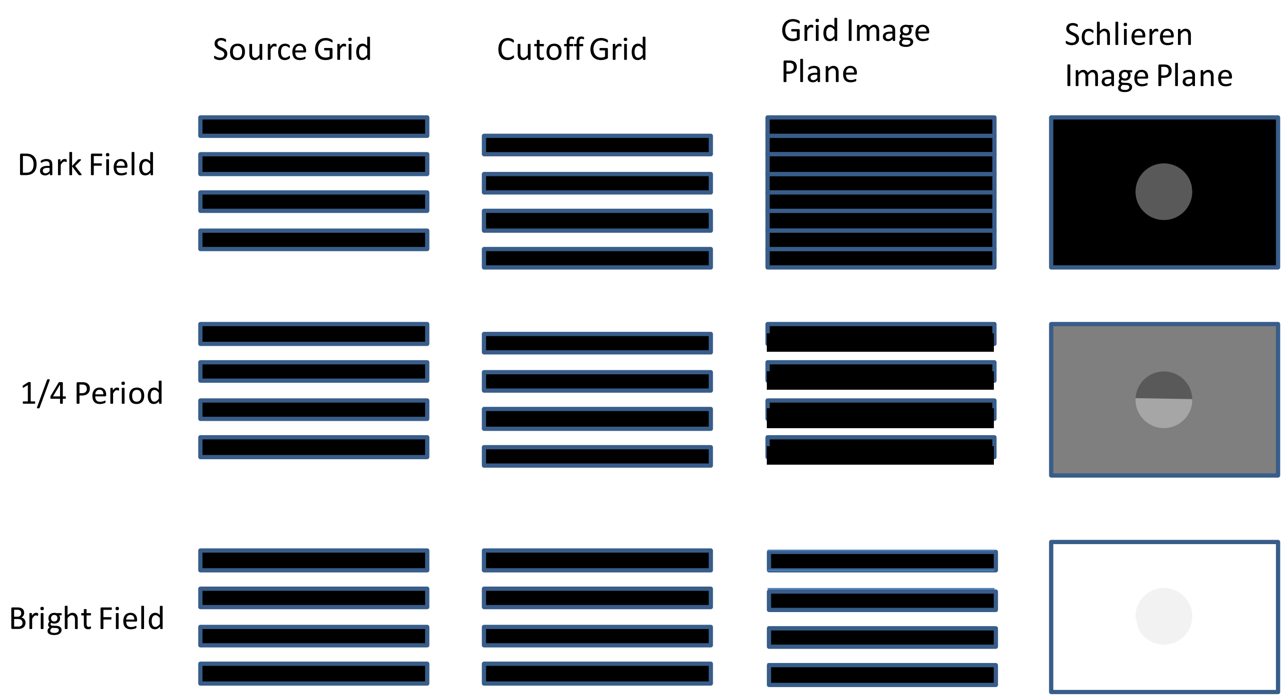

Figure 2. Effect of grid alignments for dark field (1/2 period shift), bipolar schlieren (1/4 period shift), and bright field (no shift) alignments.

A few other salient characteristics of focusing schlieren are that the sensitivity tends to improve as the grid frequency increases. This trend is limited by several factors. First, diffraction blurs out the lines as they become narrower, reducing the contrast. Second, narrow line widths can produce saturation of the signal with large distortions. And finally, higher frequency grids usually become increasingly difficult to build. In terms of applications, focusing schlieren allows larger areas and restriction of the sensitivity to a particular object distance, roughly corresponding to the system's depth of field. This latter property allows one to blur out schlieren effects from outside the area of interest, including both flow features and window effects.

Various improvements to focusing schlieren have appeared in the literature since Burton's publication (viz. Settles' review[3]). One of the most important was the projection focusing schlieren system developed by Weinstein, which produces the background grid by projection through a grid and optical system identical to the cutoff grid imaging system.[4] The projection approach is particularly useful for schlieren of very large areas, and the technique was investigated in detail in a 2006 thesis by Goulding.[5]

The main difficulty with focusing schlieren lies in the fact that the cutoff grid and the background grid must be precisely matched to get good sensitivity. This makes the system very sensitive to misalignment and aberrations in the optical system, though the projection focusing schlieren approach can avoid this by using identical matched optics. Focusing schlieren systems have had some success in obtaining large area schlieren, but the matched grids are still often expensive and difficult to produce, and even with the projection approach, system alignment is delicate and the optical mounting systems required to perform and maintain the alignment are still relatively expensive and bulky. To address these drawbacks, the authors have developed an alternative approach in which digital modulators replace one or both of the cutoff grids and computer software performs the grid generation and system alignment. This approach results in inexpensive large-area schlieren systems and novel configurations which would be prohibitively difficult to realize with a fully analog focusing schlieren system.

2. DIGITAL FOCUSING SCHLIEREN

The key innovations in the new technology are (1) an optomechanically simplified schlieren receiver apparatus and (2) the software calibration procedure which allows this simplified schlieren apparatus to employ conventional display devices such as computer monitors, televisions, and digital projectors to provide the background grid pattern. One of the grid patterns is produced on a computer-controlled digital device, which allows it to be precisely matched to a fixed "analog" grid through a software-based calibration process. The computer first uses the camera to measure the relative position of the digital device based on its response to commands and from this develops a mathematical transformation connecting the digital device coordinates to the camera coordinates. The outline of the analog grid filter can then be measured, and using the coordinate transformation, a complementary grid can be produced with the digital device. If the camera is focused to a plane between the digital grid and the analog grid, a high quality schlieren image of phase gradients in or near that plane is produced, just as with analog focusing schlieren methods. The computer obviates the need for most of the mechanical alignment of the optical systems, since the digital grid image can be shifted or adjusted arbitrarily by a computer controlling the display system (with accuracy limited by the display resolution). This software-controlled alignment process often makes the device much less expensive to manufacture, easier to set up, and easier to maintain. Because the software can correct some for optical aberrations via the calibration process, it also has some of the same advantages as a system using identical projection and imaging lenses.

Digital focusing schlieren, like the analog version, can be used with either projection or backlighting, though the available technology creates particular opportunities for each type. The backlit-display device (Fig. 3) is one of the easiest to implement; it operates in a single pass mode, where the rays pass through the flow once before being detected. One of the simplest configurations is to use a digital display device such as a computer monitor or digital television to generate the background grid. In this case, the cutoff grid can be mounted with the camera and the lens system (an assembly we call the "sTube"), producing a focusing schlieren system of remarkable compactness and simplicity (Fig. 4), though it is generally limited to millisecond exposures or longer. For higher-speed applications, more specialized light sources can be projected through a transparent LCD display.

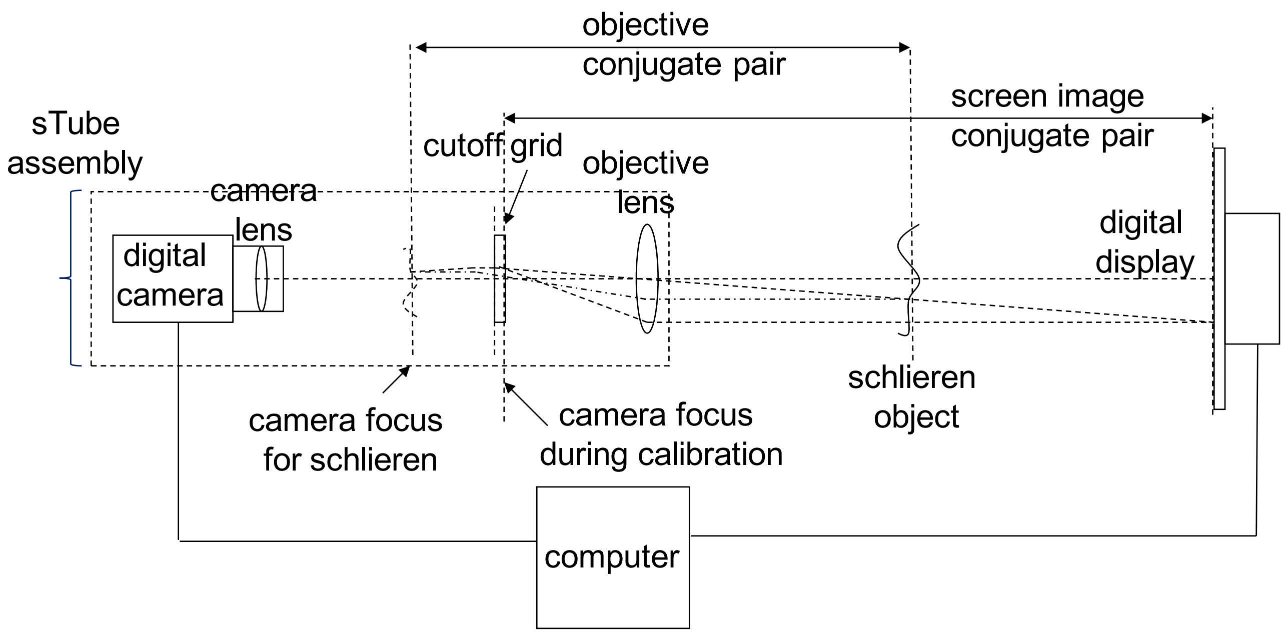

Figure 3. Backlit digital display based digital focusing schlieren system.

Figure 4. Cutoff filter mounted with receiving optics for use with a digital display.

The projection device (Fig. 5) can operate either in a single pass or double pass configuration. The single pass mode of operation has advantages in schlieren applications when the object is viewed through a window where stray reflections from the window surface can overwhelm the image. The double-pass projector approach can yield higher sensitivity because a given distortion can be passed twice by the same ray, doubling the deviation (assuming the grid offset is around half a period). Commercial digital projection systems can be used here as well, though the receiving optics are more complicated in the double pass mode by the need for a beam splitter. With conventional digital projectors, the application speed is again limited, but high speed projection systems can be realized using a digital modulator such as liquid-crystal on silicon (LCoS) modulator. Digital micromirror modulators can be used in principal, but they usually have a reset cycle which can interfere with the application timing.

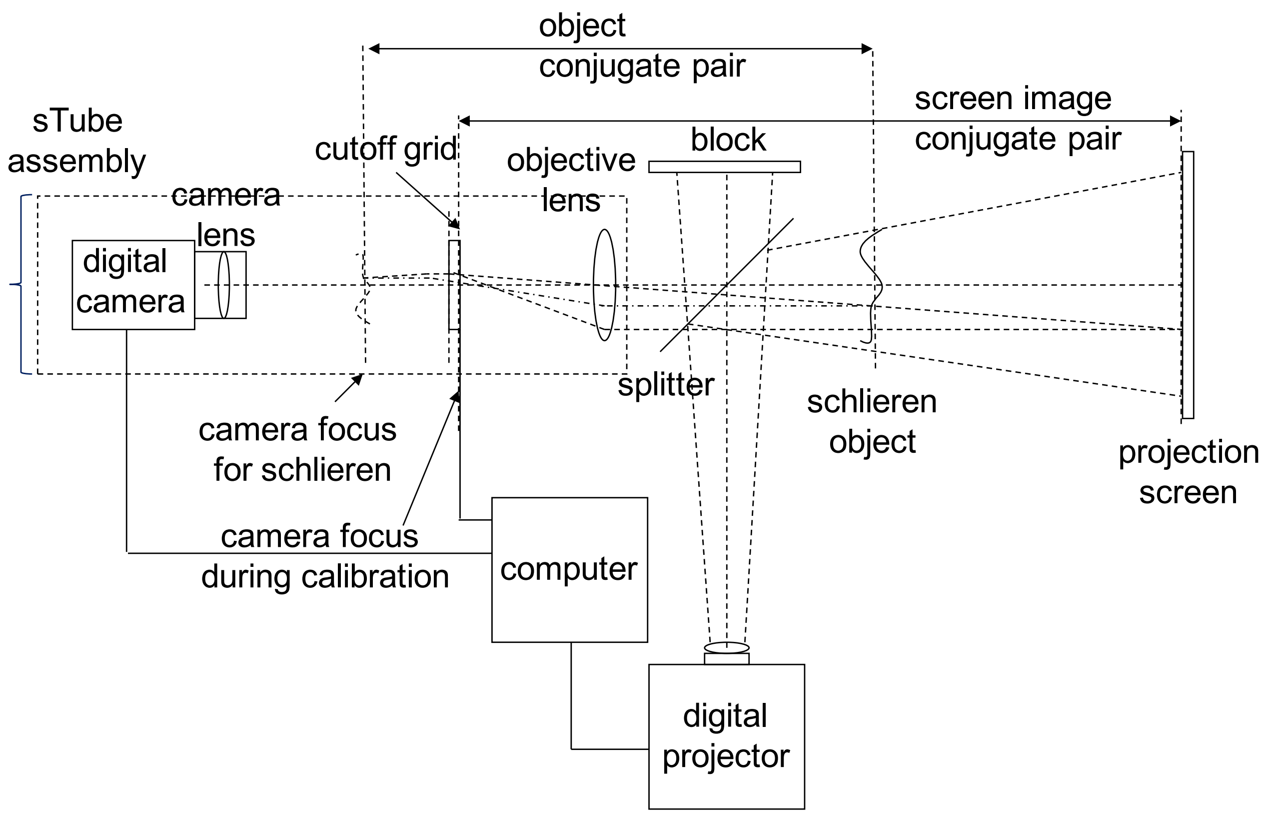

Figure 5. Digital projector based digital focusing schlieren system.

Because digital projection systems and computer display devices generally use the same interface protocols, the digital grid calibration software can be essentially identical in either case. The same schlieren receiver module can be used with most configurations as well, so that the basic apparatus can be fairly easily adapted to a large number of configurations.

Most commonly, the grid consists of an array of parallel transparent and opaque lines, such as a Ronchi ruling. The refractive index gradient that is perpendicular to the lines produces the strongest schlieren effect. However, other grid patterns may be used to tune the system for sensitivity to different gradient directions. For example, a cutoff grid of opaque squares could be used with projected lines to produce a coarser, less sensitive schlieren image but with the advantage that the direction of the projected lines could be switched in software to change the gradient direction sensitivity. In addition, radial grid patterns have been used to detect radial refractive index gradients. An electronically controlled transparency (such as a liquid crystal display) can be used for the cutoff grid as well. Having either a controllable cutoff or a controllable background grid image essentially offers the same capability, but having both components controllable allows a significant capability to adjust the schlieren directional sensitivity arbitrarily at the update speed of the control systems. Two-dimensional schlieren can thus be achieved by alternating between horizontal and vertical stripes, and sensitivity to particular features can be dynamically adjusted by selecting grid angles that have maximum contrast. The present DFS technology easily accommodates any applicable background grid pattern, making it extremely versatile and adaptable to a wide variety of applications with little added cost.

The digital grid calibration procedure can take many possible forms. The goal is to map the edges of the cutoff filter as they project into the screen plane and to brighten pixels corresponding to the occluded parts of the cutoff filter and to darken pixels which correspond to the transparent parts of the cutoff filter. The easiest form of this procedure is to simply take an image of the focused cutoff grid with the background fully illuminated. We must then also find the transformation connecting the camera coordinate space to the digital modulator coordinate space.

Calibration of the coordinate transform can also be done several ways, most conveniently by displaying images with the modulator, detecting then, and then analyzing their positions. Much of this process is facilitated with image processing libraries such as OpenCV. The main complication is that the cutoff grid occludes part of the view, so some conventional calibration targets such as checkerboards tend not to work well. We generally use circle images, since circle detection algorithms can be relatively immune to being "chopped up" by the cutoff grid. It is possible to simplify this procedure by temporarily removing the cutoff grid, but since this is inconvenient, we have developed fairly robust grid-in procedures.

Because the display resolution is inherently granular, the uniformity of the schlieren image can also be somewhat improved if intermediate pixel intensity values are used to compensate for partially occluded display pixels, though this can be accomplished in post processing as well.

This procedure results in a complementary grid which has its intensities balanced with the point spread function of the optical system and variations in display response so that the schlieren background is smooth and even when imaged through the display system. Note that the grid lines on the extreme edge are distorted, due to aberrations in the optical system.

Alternatively, a threshold can be used to determine whether to set pixels at the maximum or minimum value, and inhomogeneities due to partially occluded pixels can be removed by background subtraction after each schlieren image is acquired (Fig 6). This approach can give better sensitivity (schlieren contrast) for display devices in which the physical intensity difference between the 0 and 1 logical intensity levels is larger than for other intensity increments, which is a feature sometimes designed into display systems for better viewing contrast.

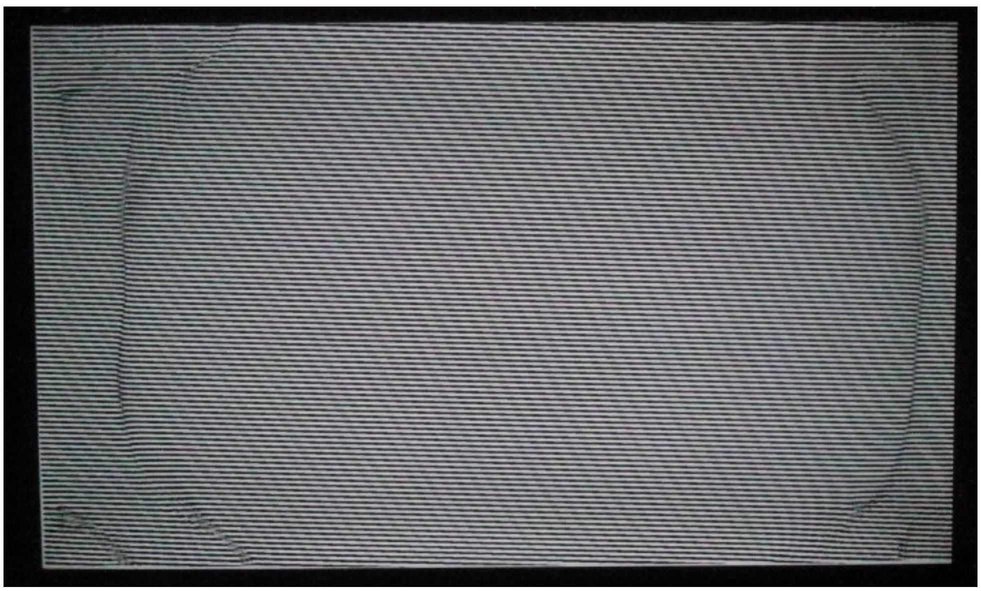

Figure 6. Complementary grid for an LCD television through a Ronchi ruling. Note distortions due to aberration near the edges.

This procedure works best when the grid plane well focused, in which case we change camera the focus between calibration and schlieren operation. This is simple in practice, since the cameras usually use commercial lenses (typically c-mount or f-mount). It is also possible to calibrate a blurred grid, when the focus is set to the schlieren object plane, though, this requires a more complex procedure to account for the broad point spread function (PSF). This would mainly come into play for a "prime focus" schlieren system, in which the image array captures the first schlieren focus directly, rather than after a relay lens. In such systems, the cutoff grid has to be placed extremely close to the image array, necessitating a more complicated optomechanical system.

In either case, the next step is to introduce a controlled offset to the complementary grid. One of the easiest ways to do this is to measure the grid period and direction and simply shift the image. The vector spatial frequency is fairly easy to detect using Fourier analysis since the grid pattern is quite strong and periodic. The only real difficulty is in ensuring that higher harmonic frequencies are not detected, but still the procedure only requires a modicum of image processing. The actual shift of the grid image can be done with subpixel interpolation, either in Fourier space (since we already have the transform), or in the direct space. Our proprietary control software, called SchlierenView, allows offsets to be programmed in percentages. Normally, the 25% shift is used, though, as discussed above, we can set 0% to obtain dark field or 50% to obtain bright field operation. However, with digital schlieren, because the grids are inherently granular, dark field operation is usually not as sensitive as with a well-aligned analog system because the grids do not match perfectly. For the ¼ period shift though, the granularity usually does not degrade the schlieren sensitivity substantially, as long as the grid period is more than 4 pixels. Generally, we choose cutoff grids to allow somewhere between 6 and 8 pixel periods, which for a 1920×1080 (high definition) display gives around 250–350 line pairs.

Many different image-processing steps can also be applied to improve the schlieren image. The schlieren background subtraction procedure is different from conventional background subtraction in that it must be a signed subtraction because schlieren contrast can be positive or negative relative to the background.

The result of these developments is that we can now produce high-quality schlieren images for a wide range of sizes, speeds, and system configurations, with substantially reduced cost and difficulty compared to previous analog focusing schlieren technologies. Fig. 7 shows a background subtracted digital schlieren image generated with a commercial 46 inch 1080p LCD television and the receiver apparatus pictured in Fig. 4.

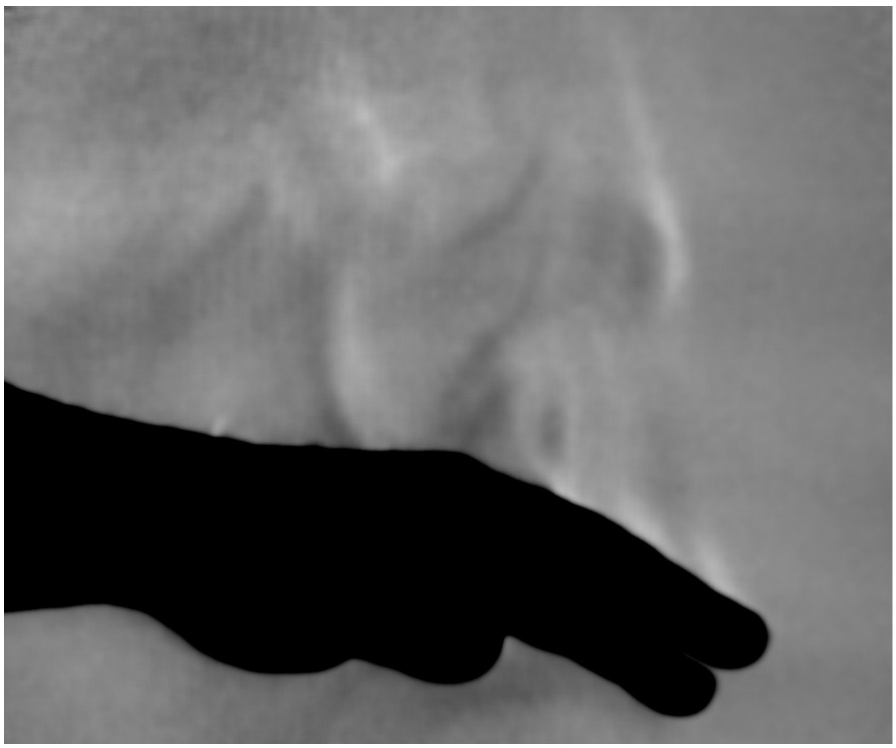

Figure 7. Closeup of schlieren image of experimenter's hand with body heat convection using an LCD television.

This system is easily capable of imaging convection currents from bare skin, and in this case with a nearly 2 ft. diagonal (approximately half the background display size). Because the calibration procedure is automated, alignment is simple (usually requiring less than a minute) and the system can be set up in conditions without elaborate mounting systems, since alignment drift or movements of equipment can be easily compensated, sometimes by simply shifting the grid in software or resetting the background reference image, both of which are essentially instantaneous.

We have also been able to demonstrate similar performance with backlit systems with transparent LCD displays, digital projection systems based on commercial digital projectors, and digital projection systems with high speed laser illumination and an LCoS modulator, all using the same core calibration software.

CONCLUSIONS

Digital focusing schlieren is an advance in schlieren imaging technology that radically reduces the cost and complexity of this valuable aerooptic analysis technique. The essential components, the software and the schlieren cutoff receiver, are highly versatile and can be used with a wide array of digital display technologies. Considering the vast array of display technologies now available, from mobile retina displays to billboard-sized advertising display systems, schlieren imaging can conceivably be performed in many situations and applications where it would formerly be completely impractical or cost-prohibitive. The new technology is also much easier to set up and use since the complex alignment procedure is now handled by a computer, putting it in the reach of moderately skilled technicians.

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