Modern Developments in Flow Visualization

Gary S. Settles
The Pennsylvania State University, University Park, Pennsylvania

Introduction

THE importance of visualizing the phenomena of fluid mechanics has been stated many times. Indeed, it can hardly be overstated. One need only recall Leonardo's sketches of vortices, Reynolds' transition experiments, and Mach's visualization of shock waves about a bullet to appreciate how breakthroughs in fluid mechanics traditionally have been paced by careful visual experiments. This may be due, in part, to the process of the human mind: a global view or picture of a phenomenon is an essential prerequisite to its understanding.

Fluid mechanics has undergone rapid changes in recent years. The advent of the computer and the laser have changed many scientific endeavors, including fluid mechanics. We are recently in possession of the means to solve "intractable" partial differential equations by computer, a capacity that was far out of reach a few decades ago. This has shifted the emphasis of modern fluid mechanics research in various ways, most of them positive.

Nonetheless, it is the posture of this survey article that flow visualization is as essential to fluid mechanics now as it has ever been. This assertion is supported by at least two arguments: First, it is well known that one can "solve" only a few fluid mechanics problems purely by mathematics. The very nature of the governing Navier-Stokes equations endows fluid phenomena with multiple regimes and subregimes, across whose boundaries the forms of the solutions usually change. Further, our knowledge of fluid physics is incomplete, particularly in the area of turbulence, and is likely to remain so for many years. Otherwise stated, this is an argument in favor of continuing the long tradition of careful experimentation in fluid mechanics *in concert with* the newfound numerical capacity. Obviously, flow visualization is an integral part of this tradition. Second, a renewed need for flow visualization arises directly as a result of computational fluid dynamics. One of the hazards of computed solutions is that both good and bad results appear in crisp, seemingly identical columns of numbers. To distinguish between these, and to grasp the essence of correct solutions, the computed results must be presented (visualized) in a form amenable to human understanding. Further, there is the need to *verify* the computed results by comparison with direct observations of fluid behavior, wherein visualization is again critical.

Having thus concluded that flow visualization is alive and well, this survey will proceed to list and critique some recent developments in the field. The survey is by no means exhaustive; some subjects, such as holography and digital image processing, are vast domains in themselves, which will only be touched upon here. Similarly, tutorial material on the established techniques of flow visualization (surface patterns, tracers, and optical methods) is available in many good references and is thus omitted here. Instead, the intention is to point out recent trends, bring forth related material from adjacent fields of research, and draw some connections that seem significant. Some of the author's views on the subject are also given in a separate commentary at the end of the survey.

Resources

The literature resources on flow visualization, many of which were consulted for this survey, include texts, journals, conference proceedings, technical papers, indices, and literature searches. There is only one comprehensive English text on the subject (though quite a good one), by Merzkirch.[1] However, significant subsets of the material are covered in several texts, including the recent *Fluid Dynamics* volumes edited by Emrich,[2] Weinberg's *Optics of Flames*,[3] Vest's *Holographic Interferometry*,[4] Hyzer's[5] volume on high-speed photography, and Frungel's four-volume *High Speed Pulse Technology*.[6] Though not a text, Van Dyke's excellent *Album of Fluid Motion*[7] clearly ranks with the above, as do the Maltby[8] and Holder and North monographs.[9] The major Western archival journals that publish works on flow visualization include the *AIAA Journal, Applied Optics, Experiments in Fluids, Fluids Engineering, Journal of Fluid Mechanics, Optical Engineering,* and *Physics of Fluids.*

The volumes of the International Symposium on Flow Visualization Proceedings[10-12] are an important resource, especially in that the recent work of investigators worldwide is collected only there. These symposia are held every three years. Related conference proceedings include those of the International Congress on High Speed Photography and Photonics, the International Congress on Instrumentation in Aerospace Simulation Facilities, and various volumes of the prolific Society of Photo-Optical Instrumentation Engineers conference series. Further, sessions devoted to flow visualization are often held at the AIAA Aerospace Sciences, Fluid and

Gary S. Settles received a B. S. degree from the University of Tennessee in 1971 and a Ph.D. from Princeton University in 1975, both in Mechanical and Aerospace Engineering. He has held the positions of Research Scientist with Flow Research, Inc. (1975-77) and Research Engineer and Lecturer in the Mechanical and Aerospace Engineering Department of Princeton University (1977-1983). Currently he is Associate Professor of Mechanical Engineering at the Pennsylvania State University. He is the author or coauthor of over 50 publications on experimental fluid dynamics, flow visualization, and supersonic flows. His current research concerns swept shock wave/boundary-layer interactions and the application of flow visualization to industrial clean-room contamination problems. His flow visualization studies using color schlieren optics have been featured in a variety of educational films, books, magazines, and television programs worldwide. He is a Member of AIAA and has served on the AIAA Fluid Dynamics Technical Committee and as Associate Editor of the *AIAA Journal*.

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Plasma Dynamics, and Aerodynamic Testing Conferences, as well as the ASME Winter Annual and Fluids Engineering Meetings. The Annual Meeting of the American Physical Society Division of Fluid Dynamics now includes a gallery display of flow visualization results.

There are thousands of technical papers on this subject, including several previous surveys.[13-36] Access to this voluminous information is simplified somewhat by the availability of regular indices, including the *Engineering Index, Science Citation Index, International Aerospace Abstracts,* and NASA's *Scientific and Technical Aerospace Reports* and *NASA/SCAN.* Further, at least five published literature searches on flow visualization are available from the National Technical Information Service, and custom searches based on selected key words can be obtained from both NASA and the Defense Technical Information Center. Much of this information is also available in on-line bibliographic data bases (DIALOG, ORBIT, BRS) which can be searched from a remote terminal at modest cost considering the time saved over a manual search.

Finally, there are several short courses held regularly by various institutions that treat the subject directly. These include "Flow Visualization" (W. J. Yang, University of Michigan), "Techniques in High-Speed Photography and Videography" (C. E. Miller and H. E. Edgerton, MIT), "Holography and Laser Applications" (J. Trolinger and M. Chang, Spectron Development Corp./Newport Corp.), and "Photographic Science" (R. Francis, Rochester Institute of Technology).

Tracer Techniques

A comprehensive review of particle tracing for flow velocity measurement was recently published by Somerscales.[37] While this holds much in common with the present subject, there is a distinction based on whether the goal is a local quantitative measurement or a global qualitative or semiquantitative one. The latter properly constitutes flow visualization while excluding LDV, CARS, and the like. Modern tracer techniques for flow visualization include the smoke-wire and related aerosol methods, spark tracing, neutrally buoyant bubbles, laser-induced fluorescence, and laser light-screen imaging.

The laser light-screen technique[35] involves the spreading of a laser beam into a planar light sheet by a cylindrical lens. This can then be used to illuminate a two-dimensional "cut" through a flow that may be highly three-dimensional. The flow must be seeded with scattering centers that may range from molecular dimensions to many micrometers in size. The flow is observed at an oblique or normal angle to the light screen by collecting the light scattered by the seed particles. While Mie scattering is standard, particle fluorescence may also be used.

Though the use of tracers is one of the oldest flow visualization methods and light-screen illumination has been available for decades,[38] the modern state of this art certainly depends on the laser. Its high level of collimation makes it ideal for producing the required thin planar light sheet. In this regard a one-watt laser beam is superior to kilowatts of poorly collimated noncoherent light. Inexpensive He-Ne lasers in the mW range are sometimes adequate, though a 1-4W Ar^+ or Kr^+ laser ($10,000-$20,000) may be required for lightly seeded flows, high-speed flows, or fluorescence applications. The more expensive ruby and Nd-YAG lasers also provide the capacity for short pulses to resolve high-speed and unsteady flow phenomena.

Some recent applications of laser light-screen flow visualization include vortex visualization about aircraft and other models in subsonic and supersonic wind tunnels[35,39] and the investigation of turbulent boundary-layer and mixing-layer structures,[40,41] internal supersonic flows,[42] and shock/boundary-layer interactions.[43,44] Extensions of the technique include both streak and multiple-exposure photography[37,45-47] for particle tracking and velocity measurement as well as visualization. One novel scheme[48] uses an interferometer to produce fringes proportional to the Doppler shift of the light scattered from the light screen. Another[49] produces an intermittent laser light screen containing fine interference fringes in order to combine the advantages of particle tracking and laser anemometry. Still another[50] combines a series of light-screen images into stereo views and a multiplex hologram. An example of laser light-screen flow visualization is shown in Fig. 1.

Given suitable seeding and illumination, the particles may be excited to fluorescence, allowing observation of the fluorescent rather than scattered light from a light screen. This method, laser-induced fluorescence,[51-59] has inherent advantages in that molecular seeding (e.g., iodine or sodium) may be used in place of gross particle seeding and that tuning of the laser illumination wavelength can be used to visualize selectively different velocity, density, or concentration regimes of the flow. It also has inherent disadvantages of complexity, corrosiveness of the seed vapor, and low fluorescent light levels. An example of laser-induced fluorescence is shown in Fig. 2.

Smoke flow visualization is a classical tracer technique in which recent developments have been thoroughly summarized and referenced by Mueller.[26,60] Briefly, the smoke-wire technique, in which fine aerosol filaments are produced by resistive heating of oil droplets on a wire, has been popularized by some remarkable low-speed visualizations at IIT[61] and Notre Dame University (see Fig. 3). Developments in smoke generator technology and the design of special smoke tunnels are also covered by Mueller,[60] who points out that the laser light screen discussed above is a primary illumination means for smoke visualization. Traditionally a low-speed technique, smoke visualization is now available at least up to transonic speeds in routine facilities,[62] and at supersonic speeds in special facilities.[63]

Finally, the collection of other recent tracer visualization techniques includes high-frequency spark tracing,[6] neutrally buoyant soap bubbles,[64] special aerosols[65] for the cryogenic testing environment, and a new colorimetric technique[66] to

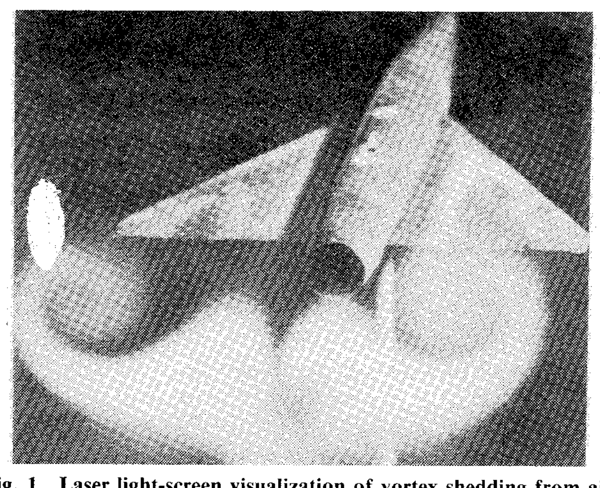

Fig. 1 Laser light-screen visualization of vortex shedding from aircraft model.[35]

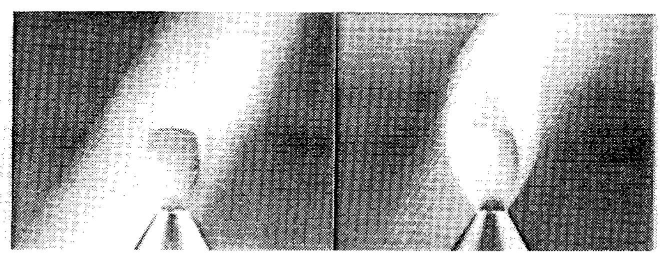

Fig. 2 Laser-induced fluorescence visualization of underexpanded supersonic jet, showing effect of velocity discrimination.[54]

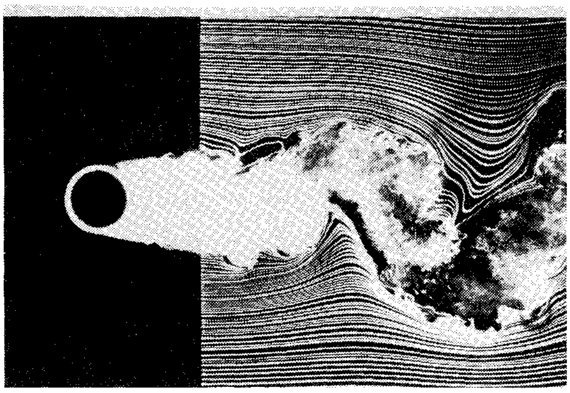

Fig. 3 Smoke-wire visualization of the wake of a circular cylinder at high Reynolds number.[61]

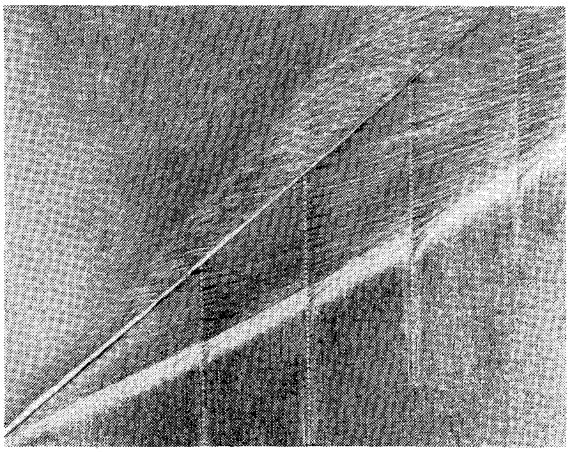

Fig. 4 Kerosene-lampblack-adhesive-tape trace of the surface flow pattern due to a swept shock boundary-layer interaction at Mach 3.[105]

reveal the concentrations of liquid mixing boundaries by color changes.

When these techniques are compared, it is clear that many simple flows, especially in liquids, are adequately visualized by classical tracer methods. The smoke wire is a simple, inexpensive technique for a wide range of low-speed gas flows. For more complex flows at all speeds, the laser light screen is an important tool, subject only to the disadvantages of laser cost and eyesight hazard. Neutrally buoyant bubbles also require expensive equipment but have an advantage in that individual particle tracks may be clearly visualized. Laser-induced fluorescence is both expensive and complex and, though it has strong possibilities for the future, has been more the subject of instrument research than a practical tool.

Surface Flow Visualization Techniques

The classical methods of surface flow visualization[1,8,10-12] involve applying liquids or coatings to surfaces exposed to the flow and then observing the resulting patterns generated by wall shear forces, temperature, etc. This ubiquitous visualization method is not without some problems, including difficulty of interpretation, pattern renewal during a test, and recording of results. While surface patterns are usually photographed through wind-tunnel windows during or after a test, the actual pattern can be lifted off the surface with transparent adhesive tape and preserved in some cases.[43] An example of such a visualization is shown in Fig. 4. Pattern renewal during a test can be done with special methods involving porous oil dispensers[67] or reversible dyes.[44]

The interpretation of surface visualization patterns has been the subject of recent research,[68-70] which brings the principles of topology to bear on the problem. For three-dimensional flows, the experimental patterns are usually quite complex, yet they must obey certain topological rules concerning the relationships of streamlines and singular points if they are to correspond to the "footprints" of physically real flowfields. On this basis, topological structure, structural stability, and bifurcation theory[69] aid in pattern interpretation. In principle, such interpretations assume that the flow is steady in the mean, and therein lies a danger: most surface flow visualization methods have essentially zero time response. Thus, the interpretation of surface patterns due to truly unsteady flows is not known.

Other recent developments in surface flow visualization include a reactive surface coating that changes color on contact with an injected gas,[71] the use of artist's colored pigments and fluorescent paints for pattern contrast, and an ink-dot technique[72] to produce surface streak lines. When a clear oil indicator is used, interferometric observation[73] can provide semiquantitative wall shear data in addition to the usual qualitative picture of the surface flow. Finally, though liquid crystal surface indicators are not new,[74] they appear to have some undeveloped potential for surface temperature, shear, and pressure indication.

Surface flow visualization methods are inexpensive and usually easy to carry out, as evidenced by their wide use. They are also effective over wide ranges of flow speed. Their main disadvantage lies in the difficulties of interpretation noted above.

Infrared Thermography

Infrared thermography is a modern engineering tool that deserves mention here even though it has had little application in flow visualization per se. Since the thermographic camera records variations in thermal radiation, most flows, excepting radiating flows from combustors, engines, etc., will appear transparent to it. The technique is useful, however, for observing surface temperatures produced or influenced by the flow,[75,76] and for visualizing infrared-absorbing gases injected into the air. Apparently, however, the potential of this technology in flow visualization remains largely unexplored.

Laser Interferometry and Holography

Laser interferometry and holography have had considerable recent influence on flow visualization. The interferometer, one of the three principal tools of optical flow visualization, existed without an adequate light source until the laser was developed. Holographic interferometry now provides the means to re-create and adjust the visualization after, rather than during, a test, to observe minute temporal flow changes, and to record high-speed events in extremely short exposure times.

The subject area is far too broad to be covered comprehensively here. Instead, the reader should consult several good references of broader scope.[1,4,14,16,31,77,78] The present consideration is limited to a brief review and some recent developments that appear to have important implications for the future.

Holography provides for the "storage" of one or more coherent optical beams on a photographic plate. Solid objects and fluid flows containing dispersed particles reflect or scatter a coherent light wavefront to expose a hologram. This wavefront may be reconstructed from the developed hologram by laser illumination. The result is a true three-dimensional image of the original object or flowfield. Recent developments in white-light holography[79] allow holograms to be viewed by ordinary illumination, as seen in several emerging examples of jewelry, magazine covers, credit cards, etc.

In contrast, the three-dimensional imaging of flows containing only refractive index variations but no scattering particles requires tomography (to be discussed below). However, two-dimensional visualizations of such flows can be obtained by the technique of holographic interferometry, in which a hologram is exposed both by a test beam passing through the

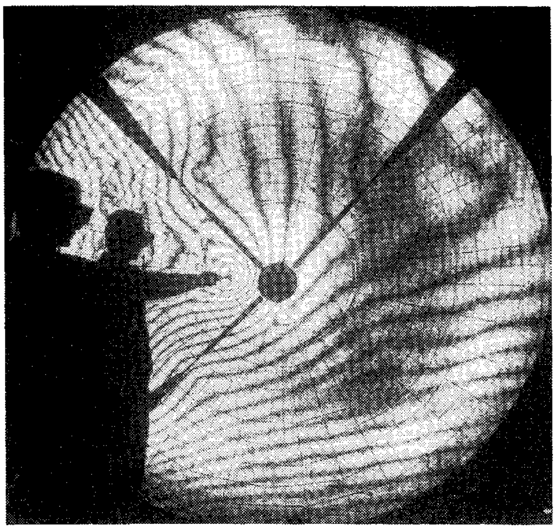

Fig. 5 Double-pulse holographic interferogram of the thermal plume of a human subject touching a microwave antenna.[82]

flow under study and a reference beam having undergone a different history. Upon reconstruction, interference fringes appear in the image due to the phase differences of the two original light beams.

Holographic interferometry methods are characterized by such descriptors as real-time, double-pulse, double-plate, and time-averaged. The real-time method involves pre-exposing a hologram plate with the flow off, then illuminating the developed plate with the flow-on test beam to produce a real-time interferometric image of the flow. The double-pulse method exposes the plate twice at different times, so that the reconstructed image reveals dynamic flow features that changed between exposures. Double-plate holographic interferometry involves the separate exposure of two plates and the mixing of the corresponding reconstructed beams, yielding versatility in fringe spacing, sensitivity, and vibration immunity. The time-averaged technique reveals dynamic flow features by their absence, since they fail to register on the hologram if they were in motion during the length of its exposure. Some of the above methods allow schlieren and shadow as well as interferometric processing of the reconstructed beam. In others, the common path of test and reference beams somewhat relaxes the need for expensive high-quality optical components.

This relaxation is important in such applications as large-field holographic interferometry and in imaging flows across which no clear optical path is available.[80-82] For example, a wind-tunnel model may be given a coating of 3M's Scotchlite retroreflective paint. In double-pulse holographic interferometry, both pulses reflect identically from the model surface. One can then observe path differences in the flow, say, at a wing/body junction, which would have been obscured by the model itself under observation by any conventional optical technique.

The same principle opens the way for relatively inexpensive large-field holographic interferometry,[82] which could be done, for example, using an outdoor cinema screen. Obviously, precise reflectors of that size (which would be needed for ordinary interferometry of such large fields) are not available anywhere in the world. Figure 5 shows a large-scale visualization of the human thermal plume and the distortion of a radar antenna obtained in this manner.

The promise of holography in conventional imaging—true three-dimensional observation—has been realized only partially in flow visualization. Most of the techniques described above, despite their holographic nature, still integrate flow information along the optical path just as conventional optical methods do. In order to obtain three-dimensional flow visualization, one must have multiple viewing angles of the flow under study. Despite the fact that many wind tunnels are not designed for multiple viewing angles, such visualizations have been attempted several times with some success.[82-85]

A related method[86] involves producing many test beams in a holographic interferometer by way of a lenticular lens array, then applying schlieren filtering at the foci of the reconstructed beams. The result of this is a sharp-focusing holographic schlieren system that can reveal sections through a three-dimensional refractive flowfield. Since the adjustment of this requires some tinkering, the wavefront storage of the hologram is a real advantage. Notwithstanding these developments, true three-dimensional holographic flow imaging appears to be still in its infancy.

The advantages of holographic interferometry are high sensitivity, the ability to adjust the visualization after the fact, and the ability to average out optical path distortions common to both the test and reference beams, or to both pulses in double-pulse interferometry. Disadvantages include the expense of the equipment (especially a suitable laser), and sometimes severe vibration sensitivity.

Some other frontiers of holography listed by Trolinger in his state-of-the-art review[14] include automated data reduction,[87] on-line interferogram production, heterodyne holographic interferometry, cine holography, and tomography.

Tomography

Closely related to the previous discussion, tomography is the technique of reconstructing "cuts" through three-dimensional flows from information obtained over a wide range of viewing angles. The success of this approach in medical radiography is well known.[88] Vest[14] has recently summarized the state-of-the-art of tomography for flow visualization and diagnostics.

Briefly, flow tomography may be accomplished by performing a series of line-of-sight projections through a flow with different viewing angles, either simultaneously or sequentially by rotating the optics about the fixed steady flow. Diffused light from a large source or array of sources may also be used. The analysis and reduction of such data are numerically intensive and thus require the use of a computer algorithm that performs a series expansion, convolution, or Fourier transform on the data. Some of the problems that arise include incomplete data (ideally a 180-deg viewing range is needed with no opaque objects in the field), experimental error, and ray deflections due to strong refractive index gradients.

As it now stands, tomography is not a simple flow visualization technique. It requires elaborate equipment and is not recommended for the novice. Although it has great possibilities for three-dimensional flow visualization and diagnostics, tomography[89-91] as such has seldom been used for that purpose up to the present.

There are, however, several related techniques worthy of mention. One study[92] supplements the limited data of interferometric views with additional information from schlieren images, surface oil flow patterns, and pressure distributions. Stereoscopic flow imaging[43,50,93,94] constitutes a limited form of tomography that is much easier to implement. Stacked planes of multicolored light have been used to take three-dimensional "tomographic" movies of particle tracks in water.[95] Finally, acoustic flow imaging,[96] though also in its infancy, holds considerable promise for tomographic flow visualization in the future.

Large-Field Flow Visualization

Conventional optical flow visualization methods require precise optical elements (lenses or mirrors) of a size comparable to the flow under study. The cost of such elements rises exponentially with size and quickly becomes impractical. A holographic means of partially avoiding this problem was discussed earlier.[82] Other than that, the subject of large-field optical flow visualization has been dominated by Weinberg and colleagues,[97,98] who developed several large-field divergent-beam laser techniques for use in fire research.

These techniques include an infinitesimal-shear interferometer, which projects two slightly displaced laser wavefronts on a large screen. The resulting fringes are distorted by refractive disturbances in the path, providing a visualization that indicates refractive index gradients. However, such fine fringe patterns are difficult to record on a small scale, so a moiré method was developed to combine the fringe patterns with and without the disturbance present, yielding the equivalent of an infinite-fringe interferogram. The use of large holographic optical elements is also proposed.

While none of these methods can approach the ultimate sensitivity of schlieren or holographic interferometry, they appear to be reasonable alternatives when large fields must be visualized. Holographic interferometry requires an expensive laser and a complex technique, while large schlieren mirrors are also quite costly. Good mirrors up to about 0.5-m diam may be purchased for under $1000, however, from amateur telescope supply houses.

The author's activity in this field uses a conventional parabolic schlieren mirror of 1-m diam for studies of human aerobiology, ventilation, airborne particle contamination, and shock waves.[18] This mirror collects and refocuses divergent light in a coincident double-pass schlieren arrangement with pseudo-color coding of the image. The resulting sensitivity is quite high, such that body convection and room currents are clearly visualized (see Fig. 6).

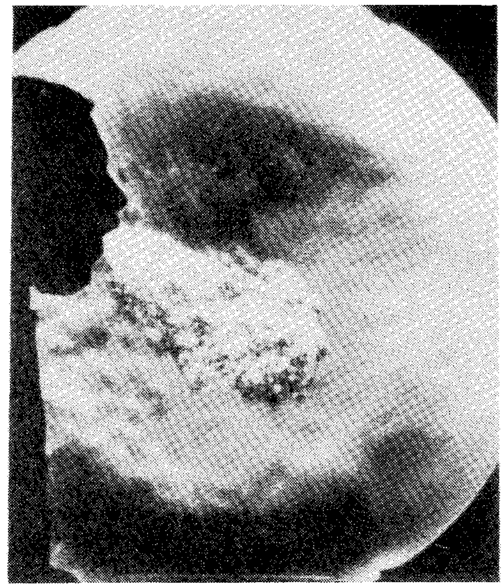

Fig. 6 Microsecond-exposure color schlieren photo of a human cough.[18]

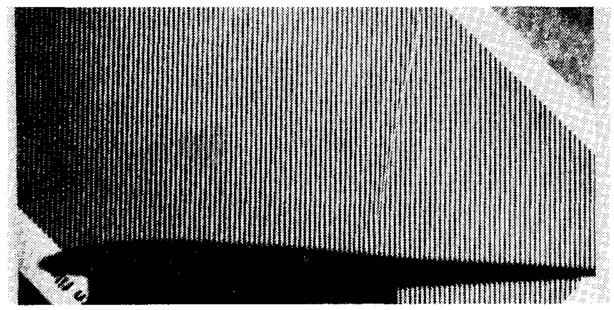

Fig. 7 Background-grid photo of shock wave above airfoil in transonic wind tunnel.[34]

Other Optical Techniques

In addition to the above methods, several other optical flow visualization techniques have been proposed in recent years. Resonant refractivity, developed by Bershader at Stanford University, seeks to amplify weak refractions in flows by way of using an optically active fluid with appropriate illumination. The Wollaston prism schlieren interferometer,[1,29] which produces a fringed image due to small wavefront shearing and subsequent interference in a schlieren system, has seen considerable use in heat-transfer research.[29] It can be implemented in an existing schlieren setup by the addition of a $400 Wollaston prism. Moiré deflectometry[99] produces pseudofringes in a schlieren image as an aid to interpretation, though at a price in terms of image resolution. Finally, simple generalized deflection methods using background grids[13,34,43] are sometimes useful where complex optics are impractical or where there is no clear optical path. An example of such is shown in Fig. 7.

High-Speed Photography

High-speed photography[1,5,6,9,17,28] is a crucial adjunct for the recording of most flow visualization results. Only at very low flow speeds of 1 m/s or so are standard cinecameras able to resolve fluid motion without smearing. High-speed photography is understood to include both single exposures of short duration as well as multiple frames at high repetition rates. Figures 6 and 8 are examples of the former with exposure times in the microsecond range.

High-speed photography rivals flow visualization in the size of its domain and has its own texts, symposia, and experts. The scope of the present treatment only permits citing some recent developments that affect flow visualization. These include MHz framing cameras, microsecond through picosecond light sources, streak and CCD (charge-coupled device) cameras, and fast photographic films.

For single exposures, white-light xenon arc lamps are available in the microsecond range with repetition rates up to 1 KHz for under $1000. More sophisticated spark sources are available for nanosecond or faster exposures.[6] Coherent illumination from pulsed lasers tends to be both faster (picosecond range) and considerably more expensive, with repetition rates from a few Hz up to more than 1 MHz.

Ratchet-driven cinecameras such as the Redlake Hycam II are effective up to a maximum 12-kHz frame rate, which is useful but not adequate for all flow visualization. Above this level no cameras produce "movies" that can be shown on standard projectors. Rotating-mirror cameras push the ultimate framing rate above 1 MHz and the cost above $100,000. These devices can produce several hundred frames of a single event. An alternative is the Cranz-Schardin camera, which uses optical image separation in a schlieren or shadow system and thus has no moving parts. One commercial version[6] produces 8 frames at up to a 1-MHz rate at a cost of about $25,000. A variety of electronic streak cameras, image converters, and image-dissection cameras have also recently become available.[28]

Two related methods of pseudo-high-speed photography deserve mention. For periodic flows such as might occur in acoustic-driven jets,[100] an electronic feedback system can be used to synchronize strobe illumination with the flow. Another simple pseudo-high-speed method[18] involves microsecond strobe illumination at conventional cine or video frame rates, producing a series of "frozen" images of the flow that can be viewed as a movie or videotape.

High-Speed Videography

High-speed videography[101,102] is a new technology developed in the last 15 years. It is being rapidly improved and thus may have considerably more influence on flow visualization in the future than it does now, though it is already in use[103,104] for this purpose (Fig. 9). The cost of the equipment is one drawback: over $100,000 for the fastest system currently available, 2-kHz full-frame to 12-kHz split-field. Several

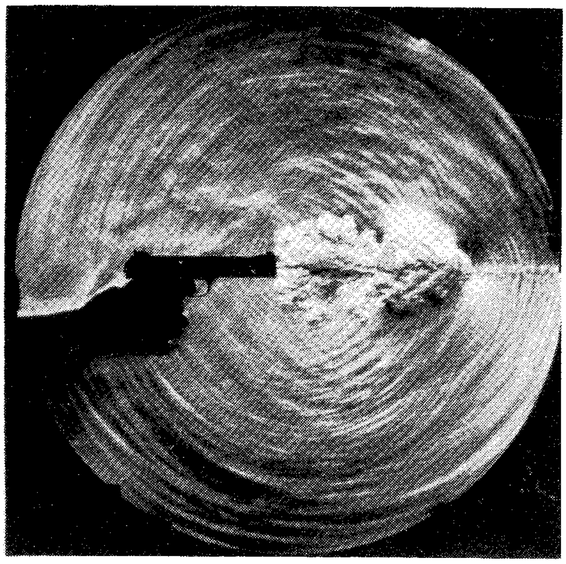

Fig. 8 Microsecond-exposure color schlieren photo of muzzle blast, bullet wake, and sound field of a .22-caliber pistol.[18]

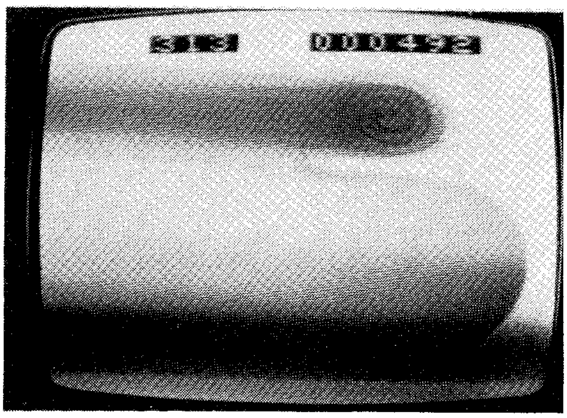

Fig. 9 High-speed video frame of a vortex ring in water striking a wall.[104]

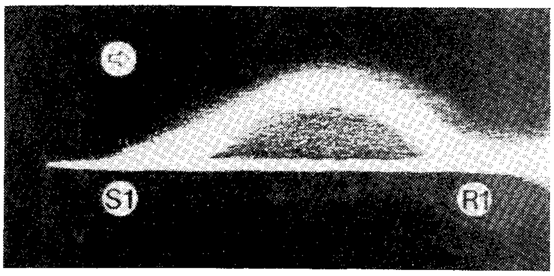

Fig. 10 Video frame of boundary-layer separation zone caused by fin-generated shock boundary-layer interaction.[105]

slower but still expensive systems are available in the 60-200-Hz range, one of them providing color images. Compared to photography, the image resolution of high-speed videography may also be a drawback, though the capability of instant replay is a definite advantage.

On the related issue of flow visualization videography in general, excellent standard-speed (30-Hz) video equipment is now available at a reasonable cost, thanks to the home video market. For example, a four-head VHS videocassette deck with professional stop-frame and slow-motion capability, along with a color camera of similar quality and a monitor, can be bought for under $3000. Such equipment is definitely valuable for a wide range of flow visualization work despite its

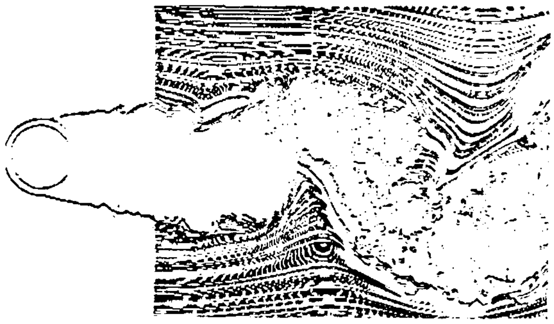

Fig. 11 Digitally edge-enhanced image of cylinder flowfield shown previously in Fig. 3.[61]

inability to record at higher speeds. It can be used, for example, to maintain an image data bank analogous to numerical data banks stored on analog computer tape. Recent microcomputer/VCR interfaces and tape management software promote this idea. There also exists the possibility of using such imagery for subsequent digitization and computer processing. An example from the author's video records of shock/boundary-layer interaction laser light-sheet visualizations is shown in Fig. 10.[105]

Optical Image Processing

Optical image processing[106-108] is a recent technology that has had a major impact in remote sensing and other fields but almost no impact in flow visualization. This technology depends on the inherent Fourier transform capability of lenses and uses spatial filtering to process images with texture pseudo-color coding, image addition and subtraction, deblurring, edge enhancement, bandpass filtering, density encoding, pattern recognition, etc. The equipment required (known as a Fourier optical processor) is essentially identical to the optical train of a schlieren flow visualization system. Though the connection seems obvious, only one reference[109] was found in which optical processing was applied to flow visualization. This appears to be fertile ground, relatively untouched.

First, consider the optical processing of flow visualization images obtained in the conventional manner; for example, identification of coherent structure patterns, improvement of signal/noise ratio in turbulent flow visualizations, and the characterization of turbulence itself. Many of these operations can be performed in real time and with greater economy by optical rather than digital processing means.

Second, and perhaps more important, is the possibility of performing optical processing *during* the capture of a flow visualization image, thus combining the processor with the optical visualization train. Some existing schlieren methods accomplish this in a rudimentary way by matched spatial filtering,[18] but the potential remains largely untapped. Considering both laser and white-light illumination, some of the possibilities include on-line flow visualization spectral analyses, pattern recognition and enhancement of flow structures, velocity differentiation and color-coding, color processing of holographic images, and colored image storage on monochrome film.

Digital Image Processing

In contrast to the situation with optical processing, digital image processing is now a recognized part of flow visualization. Several investigators,[12,47,61,110-115] all within the last few years, have applied digital processing to flow visualization images that began as photographs or video frames. As an example, Fig. 11 shows the result of digital edge enhancement applied to the original smoke-wire image shown in Fig. 3.

As before, the goals are similar: pattern recognition, texture and density slicing, noise reduction, spectral analysis, velocity

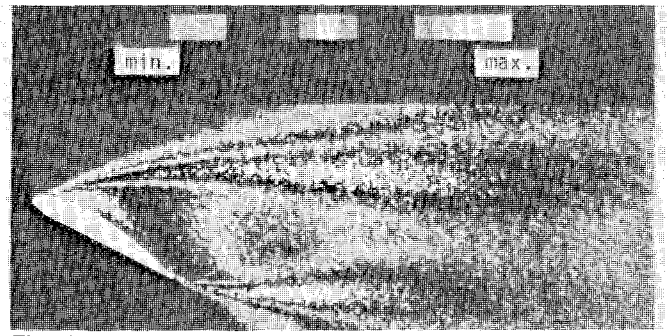

Fig. 12 Computer-graphics display of hot-wire anemometer fluctuation data obtained in the wake of a stalled subsonic airfoil.[117]

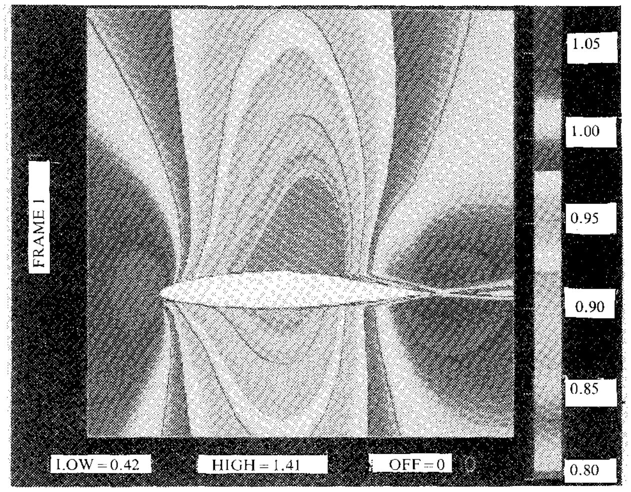

Fig. 13 Computer-graphics display of computed density contours about a transonic airfoil.[120]

and concentration discrimination, etc. The image digitization step has yet to be properly automated and is expensive, as is the equipment involved. Microcomputer image digitization and enhancement hardware and software offer the promise of more reasonable cost than dedicated commercial systems.

The usefulness of digital flow visualization image processing is growing rapidly and promises at least semiquantitative results from otherwise qualitative images. The advantage of such digital processing is especially strong for complex turbulent flows, where processed images can allow an easier interpretation of the flow phenomena than the originals. The digital enhancement of weak or smeared images is also useful, as amply illustrated by examples of processed medical x-rays.

Computer Graphics

Given digitally processed images, large pointwise data sets, and arrays of numerical CFD results, the need for automatic display of these voluminous results in the form of computer-graphic flow visualizations is obvious. Once again, the technology of computer graphics in general and its application to flow visualization in particular has grown rapidly from a recent start and is now in a state of rapid change. For example, the 2nd International Symposium on Flow Visualization (1980) contained only two papers on the subject, while the 3rd Symposium (1983) had two sessions devoted to it. Colored computer flow graphics are enormously popular and have adorned the covers of both AIAA and ASME magazines in the same month (not to mention one of the *Starship Enterprise's* bridge displays in the movie "*Star Trek II*").

Anything that grows this fast is bound to have problems. Computer flow graphics are now being done on mainframes and on mini- and microcomputers with little in terms of a standard for either hardware or software. The equipment is often expensive and subject to rapid obsolescence. There is no

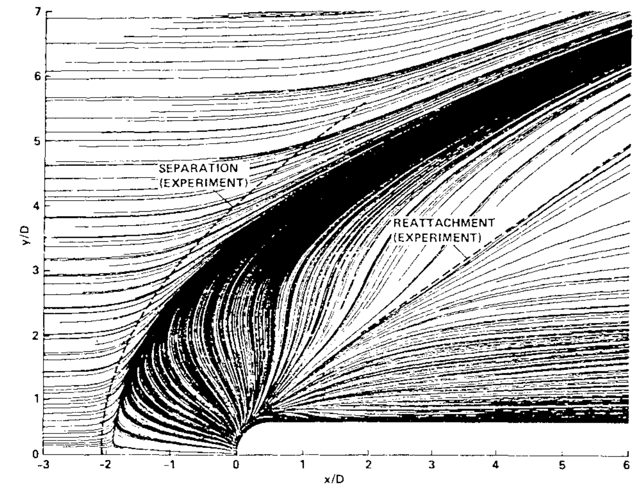

Fig. 14 Computer-drawn surface flow pattern from numerical simulation of shock wave boundary-layer interaction due to a fin with a blunt leading edge.[124]

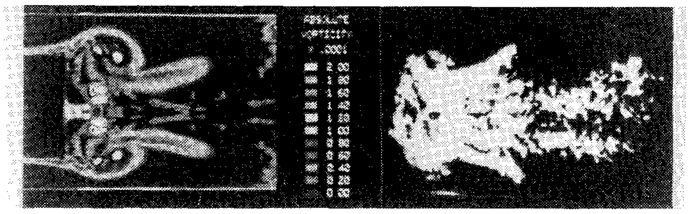

Fig. 15 Computer-graphic simulation and actual photo of combustor flowfield.[123]

apparent standard even for color-coding. (A "natural" system would seem to call for a correspondence of low numerical values to cool colors and high values to warm colors, but this is roundly violated.) Also the standard problems of displaying three-dimensional results on two-dimensional paper and the expense of printing color in technical journals remain. However, despite these problems, and public relations use notwithstanding, computer-graphic flow visualization has real technical value and potential.

In the display of experimental data, computer graphics have been used to great advantage[116,117] to transform large tabular data sets into visualizations accessible to human understanding (Fig. 12). The same can be said for the display of the results of numerical computations[118-121] (Fig. 13). Perhaps at its best, computer-graphic flow visualization has also been used for the direct comparison of experimental and numerical results,[122-124] as illustrated in Figs. 14 and 15.

Flow Visualization for Pratical Aerodynamic Testing

A special subset of the available flow visualization techniques is included in the routine procedure of practical aerodynamic testing in large production wind-tunnel facilities. Recent developments in this regard are discussed by the present author in Ref. 34, to which the reader is referred. Deserving special mention are the "wake imaging system"[125] and the fluorescent minituft method,[126] both developed by J. P. Crowder. These were developed subject to the constraint that, if they became too complex or expensive, there were not likely to be useful. Examples of the results of these new techniques are shown in Figs. 16 and 17.

Also important in the regard is the water tunnel which, while not new in itself, has nonetheless shown renewed utility in the visual investigation of such practical aircraft problems as high-angle-of-attack aerodynamics.[127] The undisputed master of water-tunnel flow visualization is H. Werlé,[128,129] whose many visualizations over the years approach a new art form.

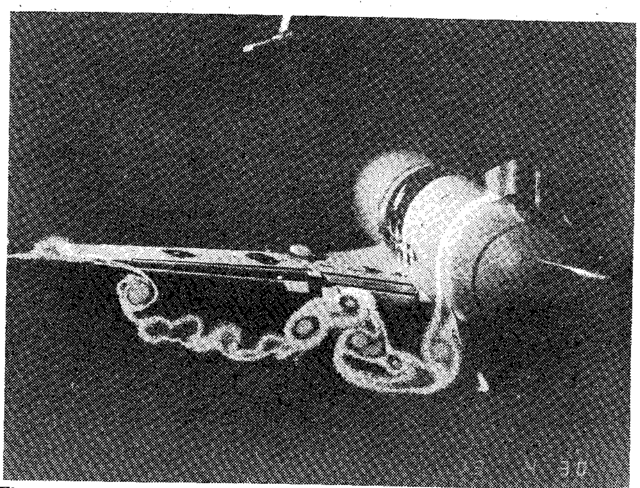

Fig. 16 Wake-imaging-system visualization of the total pressure distribution behind the wing of an airplane model.[125]

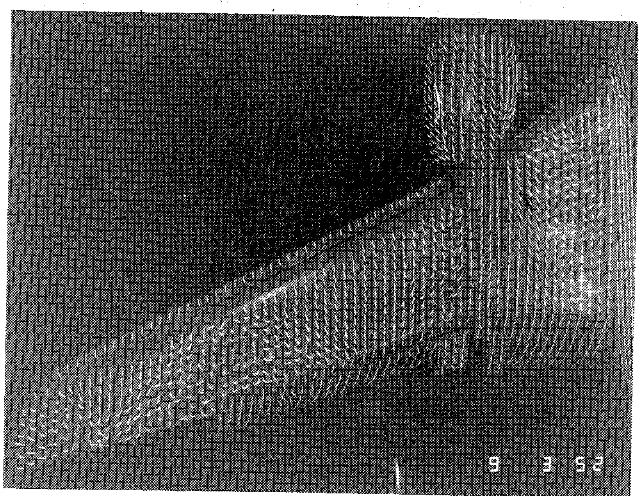

Fig. 17 Fluorescent minituft visualization of surface flow over an airplane wing.[126]

Commentary

In conclusion, the following comments (some of them admittedly subjective) are offered on the state-of-the-art of flow visualization and its current directions of development.

Flow visualization, when it is done at all, should be done as an early step in the investigation of an unknown flow. A global view of the phenomenon will then aid in selecting the locations of discrete quantitative measurements to be made later if necessary. Studies in which vast amounts of laser Doppler velocimetry data are obtained to the end product of a vector-map visualization appear to proceed backward in this respect since, if a flowfield visualization is all that is required, it can be had by much simpler and cheaper means. Similarly, there is little point in obtaining holographic interferograms of a flow if simple shadowgrams suffice.

Despite the many advantages of laser illumination, it is well known that laser light does a poor job of imaging due to coherent artifact noise. While lasers are both modern and popular, they do not always make good flow visualization light sources. In conventional schlieren systems, for example, white light is still preferable. One of many examples can be seen in Ref. 130.

Given the wide array of available flow visualization methods, many of the older ones appear to be inadequately utilized. Examples include the stereoscopic viewing of three-dimensional flows, the Cranz-Schardin high-speed camera (1929), and the conical shadowgraph technique for supersonic flows (1953). These may not be modern, but they are still uniquely suited for certain applications.

Finally, flow visualization and quantitative surveys of flow properties in the same flow may occasionally reveal radically different views of the phenomenon under study. Vortices are especially notorious for this problem. In such cases, it is important to obtain both views[131] since there may be interpretational pitfalls in depending entirely on either one.

Future Needs

Listed below are several areas, based on this survey, in which lie some of the future needs and opportunities of flow visualization:

1) Research on the possibility of expanding optical flow visualization methods via the principles of optical image processing.

2) Further research on liquid crystals with the goal of developing shear- and pressure-indicating mixtures for surface flow visualization.

3) Development of a philosophy of how to gain physical understanding from CFD flow solutions beyond the mere verification of algorithms. (Flow visualization should play an important part, both computationally and experimentally.)

4) Standards for computer-graphic flow visualization: color-coding, symbology, etc.

5) Better means of displaying three-dimensional visualizations and colored images in technical publications.

6) Higher-speed videography equipment at a more affordable price.

7) Development of new techniques in several areas of flow visualization, such as acoustic flowfield imaging, better optical methods for the visualization of three-dimensional refractive flowfields, and methods suited especially to unsteady flows.

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