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A Survey of the Utilitarian Aspects of Advanced Flowfield Diagnostic Techniques

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Introduction

ADVANCES in electronics, material technology, and computers have made it possible to improve wind tunnel instrumentation at a rate commensurate with increasingly stringent demands for greater instrumentation accuracy and versatility in complex flowfields. As a result, the opportunity exists today to use diagnostic techniques that were not available a decade ago. It is necessary to learn enough about the strengths and weaknesses of each new technique to determine how and when to use it to good advantage. The literature contains ample information on the basic principles of operation, but many reports extol the virtues of the technique without discussing its limitations. Furthermore, there is a conspicuous absence of utilitarian information on cost, development time, and other considerations which may be important factors in deciding whether the technique should be applied to a specific flowfield measurement problem.

In order to obtain practical information on advanced diagnostic techniques, a questionnaire was sent to all members of the Supersonic Tunnel Association (STA) requesting detailed responses to questions on technique capabilities, cost, source, supporting instrumentation, calibration procedures, data reduction requirements, development time, and manpower needs. Nineteen STA organizations from seven different countries[1] returned more than sixty questionnaires which are summarized in this paper. Based on the returned questionnaires, the respondents have designated as "advanced" any diagnostic techniques incorporating nonintrusive (optical) measurements or requiring high data rates. The optical techniques surveyed in this paper include Raman and Rayleigh scattering, holography, interferometry, the electron beam, and laser velocimetry. In addition, completed questionnaires were received on time-resolved measurements from probes inserted into the flow, such as the hot-wire and rapid-response pressure probes. This survey paper cites basic references and reviews the operation, measurement capabilities, and utilitarian aspects of each of these advanced flowfield diagnostic techniques.

Raman Scattering Measurements

Raman scattering measurements of temperature, density, and species concentration are initiated by focusing laser light at any point of interest in the flowfield. The process in which energy is exchanged between the scattered light photon and the internal energy states of the molecule (rotational and vibrational) is called Raman scattering. Raman-scattered light is shifted in wavelength from that of the incident light, due to this energy exchange. The relative intensities of the shifted light at frequencies corresponding to different rotational (or vibrational) energy levels is a measure of the rotational (or vibrational) temperature. When the flowing gas system has sufficient collisions to insure equilibrium between translational and rotational (or translational and vibrational) gas temperatures, then the Raman temperature measurement corresponds to the gas static temperature. Species concentration measurements can be made because the spectrum of Raman-scattered light is different for different types of molecules. For pure gas flows, species concentration measurements can be interpreted as density data. Species concentration measurements are made using the Raman technique by calibrating the intensity of a Raman line at known concentrations and temperatures. The uniqueness of the Raman spectrum also makes it possible to identify various constituents in an unknown gas mixture.

Unlike electron beam fluorescence, Raman scattering techniques can be used at high densities because the light is not collisionally quenched and the incident laser beam is not appreciably attenuated by the background gas. Because the wavelength of Raman-scattered light is shifted, it is more easily distinguished from background "noise" than is Rayleigh-scattered light. The principal disadvantage of the Raman scattering technique is that the light levels are very weak, which poses a problem at low-density levels or when background light is significant. References 2-4 present the basic physics behind Raman scattering and discuss its application as a flowfield measurement system.

Both temperature and density were measured in the experiments described in Refs. 6-13. In addition, species concentration measurements (N_2, O_2, CO_2, H_2O, etc.) in reacting gases were made in Refs. 5-9. Most measurements are time-averaged because the Raman signal is relatively weak and must be observed over a period of time to obtain acceptable measurement accuracy. However, techniques for making time-resolved measurements are being developed. One technique[1] involves pulsing the incident laser beam at 20 ns or 1 ms at repetition rates which increase with flow density. Reference 9 reports a maximum measurable frequency of 50 kHz and a minimum frequency of 2 kHz at a repetition rate of 0.1 Hz. These rates and frequencies are adequate to make

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instantaneous flowfield measurements, and they are approaching values which would make feasible the measurement of fluctuating turbulent flow properties. Reference 9 describes the use of the Raman scattering technique in fundamental studies of turbulence in flames.

Raman scattering has been applied in a wide variety of flow conditions. As far as aerodynamic simulation facilities are concerned, there are no practical limits on the temperature or Mach number range over which Raman scattering measurements can be made. The lower limit on flow density is determined by the laser power, optical arrangement, data acquisition time, and acceptable accuracy. Measurements have been made for number densities between 10^{22} molecules/m^3 (Ref. 13) and 10^{25} molecules/m^3 (Ref. 8). Calculations[8] indicate that no collisional quenching effects should be expected for number densities below 10^{29} molecules/m^3. Several of these STA Raman systems were constructed as prototypes to learn about the capabilities of the Raman technique, but a few STA laboratories[1,6,9] are using their systems in developmental test programs. Reference 10 describes results from a prototype of a combined Raman/laser velocimeter diagnostic capability which will be dedicated to an $M=6$, 20-in. wind tunnel.

Raman scattering measurements require sophisticated, expensive equipment, including a laser, spectrometer, and optical components. Since the Raman cross sections are small, high-power lasers may be needed at low densities to obtain adequate signal-to-noise ratios. Special optics can be used to compensate in part for low-power lasers.[13] Standard spectrometers are used in most Raman systems, but a double monochrometer may be needed for accuracy when the Rayleigh line obscures low-J Raman lines. All respondents recommended the use of a computer for final data analysis, and nearly all users considered an on-line minicomputer to be desirable or necessary. STA Raman systems ranged from \$23,500 to over \$200,000 in 1977, with the more expensive systems including the cost of data reduction. No unusual space or power requirements, peripheral hardware, or safety precautions (other than eye goggles to protect against the laser beam) are needed to operate these systems.

Personnel requirements for Raman systems are moderate. Depending upon the application, between 2 man-months and 1 man-year are needed to set up and use this diagnostic technique. Calibrations are straightforward, not time consuming, but require care. Once the system has been set up, it can be operated by one or two people.

Raman spectroscopy can be used in conjunction with other flowfield diagnostic techniques in "cold" flows to define completely the properties of the gas. However, current interest in the use of this technique is centered in combusting/reacting flows where high temperatures and corrosive gases make measurements with conventional probes very difficult. Raman spectroscopy avoids this problem by being nonintrusive, and it is also attractive because it measures species concentration as well as thermodynamic properties of the mixture. References 14-20 discuss how Raman spectroscopy can be used in combustion research. Reference 21 summarizes the application of Raman scattering to a variety of other flow measurement problems. It is the consensus of STA users that the basic operation of this diagnostic technique is well understood, but each application will probably require a specialized setup. The use of Raman spectroscopy in aerospace simulation facilities will undoubtedly increase as this technique is refined and current users gain experience with it.

Rayleigh Scattering Measurements

A second light-scattering technique is Rayleigh scattering, which is different from Raman scattering in that the collision between the incident photon and gas molecule is elastic rather than inelastic. Rayleigh scattering does not involve any significant exchanges of energy during the collision and, therefore, the reflected light has the same wavelength as the incident beam. This technique is used primarily to measure the density of a gas mixture by monitoring the intensity of the scattered light. Density measurements can be made as long as the flow constituency is known or if the Rayleigh cross sections for the predominate scatterers are nearly equal. This technique cannot be used to identify various components of the gas mixture. Temperature measurements are possible if the Gaussian profile of the scattered light can be observed, but high-resolution spectroscopy is required for profile measurements. Rayleigh scattering may also be used as a flow visualization technique for observing the onset of condensation in a wind tunnel.

The principal advantage of Rayleigh scattering is that it is the strongest of the molecular light-scattering techniques and is well suited as a density measurement technique at low gas densities. Rayleigh signals are approximately 100 times stronger than rotational Raman signals and more than 1000 times stronger than vibrational Raman signals in nitrogen gas.[4] Unfortunately, extreme care is necessary to insure that light scattered from particles in the gas or nearby surfaces is minimized, since this light has the same wavelength as the Rayleigh signal and can cause erroneous measurements. Techniques for separating Rayleigh-scattered light from background light are discussed in Ref. 4.

Only two STA laboratories, ARO, Inc. and NASA Langley Research Center, are planning to use Rayleigh scattering. ARO expects to measure mean-flow density with their system at number densities down to 10^{19} molecules/m^3, which is well below the minimum density at which Raman scattering measurements have been made. NASA is investigating the applicability of Brillouin scattering[4] for making both mean-flow and time-resolved density measurements. The higher signal strength may give Rayleigh scattering an advantage as a time-resolved density diagnostic over Raman scattering. ARO also plans to use the Rayleigh scattering technique to make time-resolved measurements. All of this work is presently in the developmental stage, so there are no reports from these laboratories in the literature. References 22 and 23 describe Rayleigh scattering measurements made by the other experimenters.

Components for a Rayleigh scattering measurement system are similar to Raman components, but they may be less expensive for several reasons. Because the Rayleigh signal is stronger than the Raman signal at any given flow density, it may be possible to use lower power lasers and less sophisticated spectrometers and signal detectors to make density measurements. Corrections to data are not needed at moderate temperatures; therefore, Rayleigh scattering data may be reduced using hand calculators instead of on-line computers. As a result, STA Rayleigh scattering systems cost only \$15,000-\$30,000; the more expensive systems included a more sensitive spectrometer needed for Rayleigh temperature measurements.

Approximately 6 man-months are required to set up Rayleigh scattering equipment, but significantly more time may be necessary to insure that scattered light has been eliminated from the experiment. One or two people can operate a Rayleigh scattering measurement system once it is set up. Calibrations are easier and less time-consuming than for Raman scattering experiments once background light has been eliminated.

The absence of much activity in developing Rayleigh scattering diagnostics (compared to Raman spectroscopy) suggests that other techniques are preferable for wind-tunnel testing. This is certainly true in combusting flows, "dirty flows," and gases of unknown composition, where the high-temperature corrections, unknown scattering cross sections, and background light problems associated with Rayleigh scattering are severe. Rayleigh scattering can be used in clean "cold" flows, but a variety of other techniques (including probes) can also be used under those conditions. At low-density conditions where Rayleigh scattering may be preferable over Raman scattering, electron beam fluorescence competes with Rayleigh scattering for consideration as a flow diagnostic. At the present stage of development, it is not clear that Rayleigh scattering will become an important flowfield diagnostic technique.

Electron Beam Fluorescence Measurements

Electron beam fluorescence measurements of density, temperature, and species concentration are initiated by the inelastic collision of a small beam of high-energy electrons with molecules (or atoms) in the flowing gas. The excited gas molecules (atoms) give off radiation as they become de-excited or recombine. A small segment of the radiation from the beam is observed optically to infer properties of the gas. The density of pure gas flows can be obtained from measurements of the intensity of the fluorescence. The intensity distributions in the fine structure of the fluorescent emission can be used to measure temperatures. Species concentration measurements in gas mixtures are possible because the light radiates at wavelengths characteristic of the emitting atom/molecule. This technique has been used extensively in wind tunnel flows for several years, and is discussed widely in the literature. Reference 24 is recognized as one of the best detailed descriptions of the electron beam fluorescence technique.

The electron beam is an attractive diagnostic technique at low densities where Raman scattering is difficult to use. Additionally, the electron beam can be used in gases which have no Raman spectrum, such as the helium experiments in Refs. 25-27. Disadvantages of the electron beam include quenching effects at higher densities, secondary electron effects which may give erroneous measurements of temperature, beam spreading, and changes in the flowing gas induced by the beam. Much of the difficulty in using this technique is caused by the procedures required to eliminate or compensate for these undesirable effects on the measurements. Detailed discussions of measurement problems and the variety of techniques for wind tunnel usage are given in Refs. 4, 24, and STA Refs. 25-40.

The electron beam has been used to measure static temperature,[24-26,30-34,37] vibrational and rotational temperatures,[24,28,29,35,38] fluid density,[24-26,29,39,40] and species concentration in combusting flows,[35] as well as for flow visualization.[34] Mean-flow properties were measured in each of these references, and a few experimenters have made time-resolved flow measurements. Smith and Driscoll[25] have used the electron beam to measure turbulent density fluctuations in a hypersonic boundary layer. However, the use of the electron beam as a turbulence diagnostic may be limited by the fact that turbulence occurs at high Reynolds numbers (i.e., high-density levels), whereas the electron beam is best suited to low-density levels. The upper limit on number density in helium is approximately 10^{24} molecules/m^3. The upper limit for nitrogen has not been defined, but it is probably less than 10^{22} molecules/m^3. Very little is known about the application of the electron beam to species other than helium and nitrogen.

In general, electron beam systems are less expensive ($3700-$50,000 in 1977) than Raman systems. High-powered lasers are replaced by a relatively inexpensive electron beam gun and power supply. Some laboratories save money by buying beam generation components and assembling the system themselves. Expensive spectrometers can be eliminated in cases where the data consists of light intensities from widely separated wavelengths; lower cost filters and photomultipliers can be used instead. Less reliance on computers to acquire and reduce density data is possible since results may be obtained by comparing measurements to calibrations of light intensity. A second reason for reduced mandatory computer support is the absence of the need for complex corrections to the measurements at low-density flow conditions.

One or two people are required to operate an electron beam system and between 0.5 and 1 man-year were estimated to set up the system. More time may be needed if many beam components are built in-house. Calibrations are straightforward, but must be performed carefully since the measurement accuracy depends upon the calibration accuracy. Personnel should be protected from mild X-ray radiation and high voltage associated with the electron beam gun.

Current utilization of the electron beam fluorescence technique appears to be more dependent upon the current trends of aerospace research and development rather than any lack of enthusiasm for the technique. When hypersonic flow research was enjoying considerable attention and funding, electron beams were used often because they were one of the best diagnostics for the low-density flows associated with hypersonic wind-tunnel testing. Current interest in transonic aerodynamics at high Reynolds numbers gives rise to flows whose densities are beyond the range of the electron beam. However, this technique may still be useful in studies of high-power lasers[35] and isotope separation schemes that operate at low densities.

Laser Velocimetry

The idea of using laser light scattered from small particles in a flowing gas to determine the velocity of the particles was first proposed by Yeh and Cummings[41] in 1964. The success of their system in obtaining accurate velocity data without placing a probe in the flow was obvious, and work began all over the world to refine the technique and apply it to fluid flow experiments. Early efforts concentrated on investigating different optical systems, such as the reference scatter (direct Doppler) and dual scatter (interference fringe) techniques discussed widely in the literature. As this work progressed, optical systems were refined, signal processing problems were investigated, and methods for seeding the flow with particles were studied. At the present time, commercial laser velocimeters can be purchased "off the shelf," and specialized systems are being applied to an even wider variety of flow measurement problems.

A detailed description of how a laser velocimeter (LV) works is not practical in this survey paper because there are several different optical arrangements. References 4 and 42 describe the basic LV techniques in detail, and newer LV applications are reported in symposium proceedings from Purdue University,[43,44] the University of Minnesota,[45] the Technical University of Denmark,[46] the Royal Military College of Science,[47] and the Deutsch-Französisches Forschungsinstitut.[48] All laser velocimeters rely on particles in the flow to scatter laser light into collection optics; particle velocity is inferred by analyzing the collected light signals with sophisticated electronic signal processors. By using more than one incident laser beam and additional optics, velocities in two or three directions can be measured simultaneously. Turbulent velocity statistics can be obtained in stationary flows by making many velocity measurements at each point of interest. Other methods for making nonintrusive velocity measurements in flowing gases are rated substantially inferior to the laser velocimeter.[4]

The large number (11) of STA laboratories using laser velocimetry is indicative of the enthusiasm for this technique worldwide. All but one laboratory are dependent upon laser velocimetry as the only technique that can provide the required velocity or particle size data. Most STA applications measure two or three components of mean-flow velocity, and more than one-third of the experiments involve the measurement of turbulent velocities. Experimental conditions run the gamut from special LV tests to developmental aero tests, from low-speed testing to hypersonic flows, and from atmospheric pressures and temperatures to combustion environments. Details on STA laser velocimeter systems can be obtained from Refs. 49-70.

The laser velocimeter uses specialized equipment that is different from the hardware needed for laser Raman and Rayleigh scattering measurements. For example, particle generators are often needed to introduce particles of specific size (usually $\sim 1\mu m$) and density into the flow. Control of these particle parameters is essential to obtain adequate signal strength and to insure that the particles travel at the instantaneous local flow velocity. A variety of commmercially available and "home-built" particle generators have been developed to seed solid and liquid particles into the flows under investigation. Particle agglomeration and the effect of particle density on local sound speed are problems that must be avoided. One solution to these problems has been described by Hackett,[62] who formed TiO_2 particles in a supersonic gas stream by means of an in situ chemical condensation process. Particle seeding may not be nearly as difficult at low speeds or in liquids; natural dust particles may often be used in these instances without additional seeding. Regardless of the seeding source, problems may arise when the turbulent intensity is very large with respect to the mean flow and when the mean-flow velocity changes rapidly with time or location in the flow. In these cases, the particles may not be able to maintain the instantaneous velocity of the flow, especially if the fluid density is low. To summarize, particle seeding is a science in itself. Seeding techniques, particle size, particle type, and problems with particles assuming the instantaneous flow velocity must be resolved based on the specific experimental configuration and flow conditions.

A second specialized instrument needed for LV velocity measurements is the signal processor. References 4 and 66 describe the various kinds of counters, frequency trackers, and spectrum analyzers that can be used to validate data and convert the LV signal into velocity. Commercial units are available, but some STA laboratories build their own processors to save money. Special optical components are also needed to create fringe patterns, focus the laser light into the flowfield, and collect scattered light for signal processing. The laser itself need not be modified specifically for LV measurements, however. Since the laser light is scattered from particles instead of gas molecules, high-power lasers are usually not necessary unless back-scattered light is used or the test section is very large. Several wavelengths from a single laser can be used instead of several lasers to measure multiple velocity components simultaneously.

Laser velocimetry is becoming a computerized diagnostic technique. While it is possible to obtain limited velocity and particle dynamics data without using a computer, it is the consensus of STA laser velocimeter users that a computer is necessary for a versatile LV system. This is particularly true when multiple velocity components and turbulent velocity statistics are desired. Computer control of the optics for changing the measurement location in the tunnel is also possible; such a system is described in Refs. 60 and 61. In general, the minicomputers, which are already used for wind tunnel testing, are adequate for processing, reducing data, and controlling the LV. Costs of LV systems within the STA ranged between \$21,000 for home-built systems (exclusive of minicomputer costs) to over \$200,000 for permanent wind tunnel LV systems with dedicated computer support.

The references and returned questionnaires make it clear that the laser velocimeter is an extremely useful diagnostic technique with proven capabilities in a wide variety of flows. The LV is the subject of vigorous research and development programs throughout the world, and should, therefore, provide even greater versatility in the future. It takes time (0.5-1.0 man-years for most systems, and up to 2 man-years for large, computer-controlled LV's) and money to develop and use an LV system to good advantage, but in return, the LV offers a direct measurement of velocity in flows where probing techniques cannot be used.

Holography, Interferometry, and Flow Visualization

Because of their coherent light, lasers have given rise to a new class of density and flow visualization instrumentation called holography. Holographic systems split the beam of a laser into a reference beam and an object beam. Both beams are collimated; the object beam is passed through the flowfield of interest onto a photographic plate, where it is combined with the reference beam. The plate is processed and will reconstruct the information contained in the object beam when it is illuminated by the reference beam. Holographic interferometry is an extension of holography in which an interference fringe pattern is recorded on the plate by exposing the plate to the object beam twice instead of once. The interference pattern is reconstructed, as before, by illuminating the processed plate by the reference beam. These techniques are discussed in detail in Refs. 72-75 and in the references cited by these texts.

In addition to these new techniques, lasers have caused improvements in existing interferometry and Schlieren systems. Pulsed lasers, with very short pulse times and high peak power levels, are preferred over conventional light sources in these systems, especially in luminous flows. Unwanted light is easily filtered from the laser light, and good temporal resolution is possible due to the short pulse times. Reference 76 cites applications, new developments, and additional references.

Eight STA laboratories are operating laser holography and interferometry techniques,[1] and nearly all of them are being used to measure fluid density. Several laboratories[1] use their systems to make time-resolved measurements. STA holography systems are used at Mach numbers between 0.2 and 14 for free-flight tests, in wind tunnels, shock tunnels, and expansion tubes. These techniques are best suited to high-density flows because the system sensitivity is proportional to density. The 1977 cost of these systems varied widely, from "\$0" for a flow visualization system constructed entirely with existing laboratory hardware to over \$100,000 for large, dedicated wind tunnel systems with computer support. Costs are very dependent upon the size of the system, the specific experimental configuration, and whether quantitative density data or flow visualization is required. Personnel requirements for operation are higher (2-4 people) than for the other techniques discussed so far. Holography requires no calibrations, but holographic interferometry density measurements require both calibrations and careful optical alignment. Measurement accuracy and spatial resolution are good enough to warrant continued application to wind-tunnel testing. More information on STA activities in holography and interferometry are given in Refs. 77-88.

Holographic techniques are continually being refined and applied to new flow measurement problems. Schimmel[89] is using a laser holographic interferometer system to deduce heat-transfer coefficients in free-convecting flows. Mayo and Allen[90] have developed an extension of holographic techniques called holographic velocimetry, wherein a double-pulsed hologram is made of particles in a flowfield to measure the velocity at many points simultaneously. Holographic measurements in test facilities are well within the state-of-the-art, but their utility would be increased if improvements in techniques for digitizing photographic data rapidly and accurately are developed.

Hot-Wire Anemometry and Fine-Wire Temperature Probes

The hot-wire anemometer is a veteran of fluid flow experimentation, having served for many years as the only available method for obtaining instantaneous velocity measurements in turbulent flows. The sensor consists of a fine wire whose diameter is only a few microns stretched between two probe support needles. An electronic circuit passes a current through the wire, causing its temperature to rise above the adiabatic recovery temperature of the gas. The response of the hot wire to changes in the flow is governed by a heat balance between the wire and flow. At high densities and low temperatures where heat conduction down the support needles ("end losses") and radiation effects can be ignored, the sensor responds to changes in flow stagnation temperature T_0 and mass flux ρU.

The electronic circuit contains a feedback system which maintains the sensor at a constant wire resistance (constant temperature anemometer) or provides a constant current through the sensor (constant current anemometer). The constant temperature anemometer is easier to use in incompressible flows, but the constant current anemometer is usually preferred in compressible flows.[91,92] Both feedback systems are able to respond "instantaneously" to changes in T_0 and ρU of the flow past the wire. The small thermal inertia of the wire enables it to detect fluctuations in the flow at frequencies as high as 0.5-1.0 MHz for state-of-the-art hot-wire systems.

The hot wire was first used in incompressible, isothermal flows. Under these conditions, the wire response is a function of velocity alone[93]; hence, it was relatively easy to obtain mean-flow and turbulent velocity information by performing a straightforward calibration and monitoring the voltage across the bridge. As flight regimes progressed toward higher velocities, the hot wire was retained as a diagnostic technique simply because there were no alternatives for measuring turbulent flow properties. The simplified relationship between bridge voltage and velocity gave way to performing complex calibrations, operating the wire at various temperatures relative to the flow recovery temperature, and carrying out a modal analysis[94-96] in order to obtain fluctuating velocities.

Today, the hot wire is still used extensively at both low and high speeds, even though it is no longer the only method for measuring mean-flow and turbulent velocities. Compared to the laser velocimeter, the hot wire is much less expensive and easier to use in incompressible flows. Techniques for making hot-wire measurements have been improved, refined, and documented for many more years than the laser velocimeter has existed. Using the hot wire in high-speed flows is still as complicated as before, but these complexities are no less difficult than the problems associated with particle seeding for the LV.

The laser velocimeter however, does have several advantages over the hot wire. Hot wires are extremely fragile; measurements are sensitive to pressure loading on the wire if mounted improperly, and the wires frequently break after they have been calibrated but before they can be used. Hot wires cannot be used conveniently in "dirty" flows, high-density flows, high temperature flows, or corrosive flows because of their fragility, whereas the laser velocimeter has no such limitations because it is a nonintrusive technique. The laser velocimeter measures velocity directly, but the hot-wire output is a mixture of temperature, density, and velocity which must be separated using calibrations and complex mathematical expressions. Finally, it is more difficult to measure two or three velocity components simultaneously with a hot wire than with a laser velocimeter, especially in transonic flows. At the present time, neither technique threatens to make the other obsolete; experimental fluid mechanics will be able to use both the hot wire and the laser velocimeter for some time to come.

References 91, 92, and 97-108 give details on the hot-wire systems operated by ten STA laboratories.[1] Each organization uses the hot wire to provide data on the fluctuating components of the flowfield. Hot wires have been applied to supersonic or hypersonic flows by seven STA laboratories.[1] All of these experiments were conducted using air, nitrogen, or helium gas at relatively low stagnation temperatures. Six laboratories[1] measured more than one velocity component by using multiple-crossed wires or a rotating wire. The frequency response of STA hot-wire systems ranged from 50 kHz for low-speed flow studies to 1 MHz for hypersonic turbulence studies.

A variety of hot-wire calibration procedures for high-speed flows are practiced by STA members. Some organizations do not perform calibrations, some use calibrations reported in the literature, and some build special facilities for calibrations. One reason for the variety of calibration procedures is due to the fact that calibrations should be performed over the range of flow parameters expected in the experiment; hence, calibrations will necessarily vary between experiments. Often, calibrations are not performed because they are difficult and time-consuming, or because the additional accuracy they provide is lost in the assumptions of the data reduction routines. More work is needed to put hot-wire calibration procedures on a rational basis and to reduce the time and effort involved. Calibration procedures and results in high-speed helium and air flows are described in Refs. 91, 104, and 109-113. Corrections to measurements have not been determined for other gases or for flow conditions which are much different from those described in these references.

In view of the large quantities of data to be processed and the complicated expressions in the modal analysis data reduction procedures for high-speed flows, it is surprising that on-line computer support of hot-wire anemometry is not used regularly. Computers are usually used to reduce data from high-speed experiments, but the data are usually stored on tape and processed later. The use of on-line processing of data and computer control of the anemometer to automatically set overheat ratios and wire time constant would considerably reduce the time and effort of making hot-wire measurements in high-speed flows. On-line computers are optional when the hot wire is used in the incompressible flow of a pure gas because the expressions and/or calibrations used to convert the anemometer output to velocity are straightforward and no corrections for end losses, radiation, or free-molecular effects are required.

Hot-wire electronics and probes are much less expensive than commercial LV signal processors. Both commercial anemometers and home-built units are used in STA hot-wire systems. The cost of these systems ranged from \$350 to \$40,000 in 1977, exclusive of data reduction equipment; a good quality, single-wire anemometer averages well under \$10,000. Most systems can be operated by 1 or 2 people, and require only a few months to set up. Preparation of a data reduction program is trivial for low-speed applications, but is time consuming for high-speed applications.

Two other diagnostic techniques are listed in this section of the paper along with the hot-wire anemometer. One is the fine-wire temperature probe, which uses hot-wire fabrication techniques to construct a total temperature probe with much finer spatial resolution than earlier temperature probes. A junction is made using two small-diameter thermocouple wires midway between the support needles of the probe. A second thermocouple junction is made where the thermocouple wire joins one of the support needles. By measuring both the "mid-wire" and "end-wire" temperatures, the data can be corrected for end-loss conduction effects. The second technique is a mass flow probe, which swallows a small stream tube of the flowing gas. The amount of mass swallowed per unit time is measured by balancing the incoming mass flow rate with the mass being pumped out of the other end of the probe.

Fine-wire temperature probes require no special electronics (just one thermocouple reference for each junction) and no elaborate data handling support (these probes are used only for mean-flow data). Probes can be made in the laboratory for much less than \$1000. The result is a temperature measurement technique which is very inexpensive, has excellent spatial resolution, and includes a secondary measurement (support temperature) which can be used to correct the data to obtain improved accuracy. Fine-wire temperature probes are less fragile than hot-wire probes because the thermocouple wires are approximately an order-of-magnitude larger in diameter. Nevertheless, clean wind tunnel flow is a prerequisite for using this technique. Calibrations are straightforward, and data reduction can be performed on hand calculators instead of computers. Details of these probes are given in Refs. 114 and 115.

References 116-120 describe the use of a probe which measures mass flux directly in supersonic flows. The mass flow probe is both accurate and easy to use in gases of known composition. A variation on the mass flow probe is described by Brown and Rebollo[121] which permits the measurement of the composition of binary gas mixtures. This probe is very small (0.025 mm inlet diameter), is used in subsonic flows, and has a response time of approximately 200 μs in nitrogen.

Rapid-Response Pressure Instrumentation

Several semiconductor pressure gages are available commercially which make it possible to measure high-frequency pressure fluctuations in aerodynamic test facilities. The pressure transducers contain miniaturized circuitry located near the sensor to optimize response. They are packaged in different shapes so that both surface pressures and pitot pressures may be measured using these gages. Rapid-response pressure instrumentation is intended for making time-resolved pressure measurements, but time-averaged data can also be obtained. Most of these gages are differential transducers. The reference side of the transducer may be connected either to a known pressure or to a tube which measures approximately the time-averaged value of the pressure whose fluctuations are desired. Constant current excitation of the sensor is recommended to minimize the temperature sensitivity of the semiconductor gages.

References 122-125 summarize the operational experiences of eight STA laboratories[1] with rapid-response pressure instrumentation for measurements of wind tunnel turbulence and noise. Although the gages can be damaged by particulates in the flow, they are much stronger than hot wires and therefore have been used to characterize turbulence levels in wind tunnels which operate at high dynamic pressure levels. Another advantage that these probes have over hot wires is the fact that they respond directly to pressure alone, rather than to the combination of temperature and mass flux which comprises the hot-wire signal. Rapid-response pressure instrumentation is less expensive than laser velocimeter hardware and requires no flow seeding. Most systems cost less than $2000 per channel, exclusive of data reduction and acquisition equipment. Several users suggest recording data on FM tape (~$25,000), with subsequent data reduction using analog equipment. Spectrum analyzers and correlators ($25,000-$50,000) are needed if specific frequency information is required, but simple rms-to-dc converters can be used if measurements of total turbulence or noise are sufficient. Many laboratories cut costs by using electronic equipment which was already available in the laboratory. If analog spectrum analyzers are not available, frequency data can be obtained using digital spectral analysis techniques[126] on a computer.

Rapid-response pressure instrumentation has been applied in a wide variety of flows with good spatial resolution and acceptable accuracy. The only limitations on use, in addition to requiring minimal particulate in the flow, are certain restrictions on sensor temperature and pressure. High temperatures may cause changes in the calibration and may ultimately damage the sensor. At low-pressure levels, sensitivity and accuracy of the sensors is reduced. The sensors should be placed as close as possible to the flowfield of interest in order to minimize response time. However, it is possible to connect the sensors to the flow with tubing as long as the frequency transfer function of the tubing is determined by calibration. Calibration procedures for harmonic pressure oscillations have been derived in Ref. 124.

Summary and Conclusions

Operational experience and utilitarian information on advanced flowfield diagnostic techniques were provided by members of the Supersonic Tunnel Association. Their first-hand experiences make it obvious that these new flowfield measurement techniques represent a major contribution to experimental fluid mechanics. Optical diagnostics provide us with both mean-flow and time-resolved measurements in complex flows where probes cannot be used at all. Improved probe sensor designs and supporting electronics have expanded the utility of existing techniques while holding down costs. Each technique works well over a range of test conditions and, for many wind tunnel applications, more than one technique may be used to make a specific flow measurement. Users of this advanced instrumentation found that each technique has excellent spatial resolution and accuracy when it is applied to the flow conditions for which it was designed.

Despite their versatility, however, advanced diagnostic techniques should not be applied categorically to all new flow measurement problems. None of these techniques is the answer to our prayers for the "ideal" diagnostic; the previous sections indicate that they all have limitations which must be recognized if they are to be used in a cost-effective manner. It should also be pointed out that the advances in these new flowfield measurement systems in no way detract from the proven capabilities of "conventional" pressure and temperature probes. These older methods still work very well over a large range of test conditions,[127,128] and they are much cheaper and easier to use than the new optical diagnostic techniques. None of the new techniques work well enough over a sufficiently wide range of flow conditions to make older methods unnecessary or obsolete. The temptation to use without question the more glamorous optical diagnostic techniques should be resisted unless time and money are no object. It is the author's opinion that advanced diagnostic techniques should be used only if conventional probes cannot be used at all or if conventional probe data must be supplemented with additional measurements to define the flowfield adequately.

The trend in flowfield instrumentation is toward increased use of computers to handle the more complex data reduction schemes associated with most of these new techniques. Computer control of data acquisition and operation of this instrumentation is not common yet, but within a few years, it should become routine on techniques such as the laser velocimeter and hot wire which generate large quantities of data. Computers, like lasers, will advance significantly the capabilities of flowfield diagnostic techniques.

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