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AEROSPACE MEASUREMENTS: CHALLENGES AND OPPORTUNITIES

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Abstract

New aerospace research initiatives offer both challenges and opportunities to rapidly-emerging electronics and electro-optics technology. Defining and implementing appropriate measurement technology development programs in response to the aeronautical ground facility research and testing needs of the new initiatives poses some particularly important problems. This paper discusses today's measurement challenges along with some of the technological opportunities which offer some hope for meeting the challenges, and describes measurement technology activities currently underway in the Langley Research Center's Instrument Research Division to address modern aerospace research and design engineering requirements. Projected and realized benefits and payoffs from the ongoing measurement and instrumentation efforts will be emphasized. A discussion of future trends in the aerospace measurement technology field will be included.

I. Introduction

In the United States as well as in other technologically-oriented countries there is increasing interest in the efficient movement of people and cargo over wide geographical distances. The continued growth of the Pacific rim economies, as well as those of Europe, has solidified the characterization of Earth as a global marketplace. To provide the transportation network that will link the various entities associated with the suppliers and customers of the markets will require the continued development of enhanced aircraft technology in all speed regimes. Supersonic transports will become a key part of the transportation net, followed by hypersonic vehicles for those transfers requiring exceptionally rapid connections. And, the growing need to move large amounts of passenger and merchandise cargo will result in the development of very large, aerodynamically efficient subsonic aircraft. The technology base which will enable the building of all these vehicle types is currently being established on several fronts; the successful fruition of the many efforts underway will depend in large degree on the measurements made in support of research and testing of the aeronautical technologies involved.

A key contributor to the advance of aerospace vehicle technology is the research and testing undertaken in support of the development program, from design through flight operations. The timely, appropriate application of the most effective measurement techniques can result in substantial savings in the overall development cycle of an aerospace concept. This effectiveness in turn depends on successfully overcoming challenges in the measurement task, and the relation of this task to the goals of the vehicle or aeronautical technology development program/project. The ability to capitalize on opportunities which are afforded in the electronics, electro-optics, or other sensor or measurement discipline is equally valuable in enhancing the overall success of the program.

The Instrument Research Division (IRD) of the National Aeronautics and Space Administration's (NASA's) Langley Research Center has been addressing aerospace measurement challenges through the exploitation of instrumentation technology opportunities for many years. The design concepts for many of the United States' aircraft have been evaluated in the wind tunnels of NASA-Langley, and the development of modern instrumentation techniques to obtain needed validation or performance data from these tests has been achieved through exploitation of transducer and non-intrusive technique advances.

Extension of the advanced technology in fields such as force and strain, nonintrusive flowfield velocity and diagnostics, pressure, and thermal quantities to the measurement problems of today and tomorrow will be described in this paper. Leading off will be a discussion of the challenges facing the aircraft designer, and hence the measurement technologist, who must deliver data that will validate the ideas of the designer. Next will follow a consideration of some of the opportunities afforded the measurement system designer through improvements in disciplines such as microelectronics, solid-state lasers, high-temperature fiber-optics and other electronic materials, and high-resolution cameras. Examples will be given of current IRD programs that are working to marry opportunity to challenge, and a forecast of future directions will be presented.

II. Challenges

The challenges with which aircraft designers and measurement technologists must deal are led by test environments, which must simulate, as closely as practical, the effects of full-scale flight regimes. The pursuit of a hypersonic vehicle capability involves temperatures and heat transfer rates that are extremely high, affecting the choice of instrumentation to be used in the measurement of surface temperatures, pressures, strain, and skin friction (See Figure 1). The hypersonic propulsion systems will typically use cryogenic fluids such as liquid hydrogen; the instrumentation of candidate engine models requires the use of sensors that can withstand these cold temperatures. In addition, testing in the U.S. and Europe in high Reynold's number facilities with cryogenic test media (nitrogen, for example) poses problems for the measurement of aerodynamic force using such techniques as the 6-component strain gage balance, as indicated in Figure 2. Non-standard atmospheres (for example, in test media such as CF_4) provide additional complication to the instrumentation engineer's efforts to support scale model testing, and can confound the flight test engineer who has to account for its effects on scaling of results to compare flight experiment, wind tunnel experiment, and theory. The presence of high levels of turbulence renders the use of many conventional aerodynamic measurement tools, such as the survey rakes or other protuberances into the air flow, virtually impossible; severe turbulence can also adversely affect the application of surface-mounted instrumentation such as strain gages or thin-film anemometers.

Frequently coupled with these atmosphere or flow field-related test environment challenges are the use of very small models and/or test facilities with restricted access, such as is indicated in Figure 3.

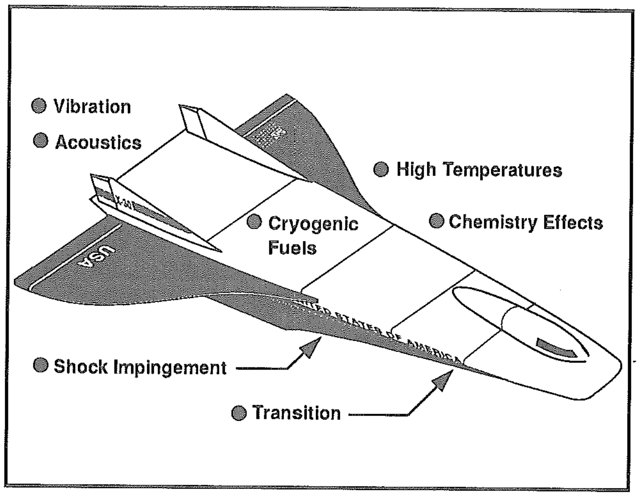

Figure 1. Measurement challenges on a hypersonic vehicle

- Temperature range: 77K – 325K
- Maximum load: 90,000 N
- Temperature-induced output errors:
  - loop hysteresis
  - non-linearity
  - large "no load" output change
  - sensitivity shift
- Temperature effects on adhesives, solders, wiring, moistureproofing

Figure 2. Force measurement challenges in a cryogenic environment

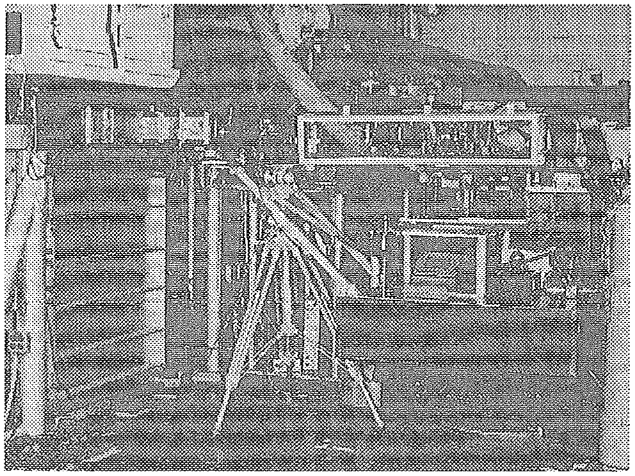

Figure 3. Challenges of constrained access

A second set of challenges arises from the imposition of tough measurement requirements themselves by the facility test engineer or aerodynamicist user of the test results. Leading the way are strong needs to have measurements made non-intrusively, to avoid having to correct for the measurement process itself in data reduction. Coupled with this requirement is the ever-increasing push for higher resolution and higher accuracy in the measured data, to provide more effective correlation with computational fluid dynamics (CFD) solutions to simulated flows. In particular, the determination of flow field parameters such as pressure, temperature, and velocity is often requested to fractions of a pascal, degree, or meter-per-second to enable comparison with CFD results such as those displayed in Figure 4. Also, because of increasingly expensive testing programs, there is a growing demand for global or wide-area measurements, whose attainment can result in reduced test times and energy or other resource savings. This requirement, like that for high accuracy and resolution, is frequently manifested in the call for nonintrusive sensing, whether it be of flow fields or of aerospace materials and structures undergoing nondestructive evaluation (NDE).

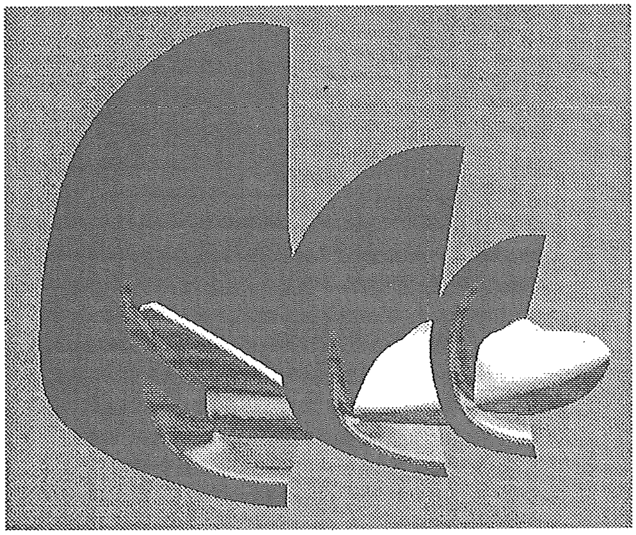

Figure 4. Computed pressure field about a candidate Personal Launch System vehicle

Finally, challenges exist with respect to other attributes of the measurement process. For example, to save valuable "real estate" in a test facility or setup, there has been an increasingly strong desire to make multi-parameter measurements using synergistic transduction techniques. The computational fluid dynamicist asks for several simultaneous (spatially and temporally) readings including pressure, temperature, and velocity; these are typically desired at multiple points in the test region, taxing the instrumentation engineer to obtain overlapping, global measurements at high data rates. Other challenges arise when the test article (and/or the instrumentation) is undergoing vibration or deformation, leading to the measurement technologist's having to "hit a moving or a changing target." Versatility is perhaps the characteristic that best describes these challenges. Having to "do more with less" becomes the byword which drives the test engineers and their instrumentation corps.

The above-mentioned challenges to the aerodynamics researcher's or test engineer's ability to make global, nonintrusive, highly-accurate, and precise measurements represent obstacles that are not easily overcome. However, in recent years there have been advances on several technology fronts that offer some hope for achieving large improvements in measurement capability. A discussion of some of the more exciting advances is given in the following section.

III. Technological Opportunities

Key among the opportunities afforded the measurement technologist by innovation in related disciplines are the high-speed digital computer, microelectronics, lasers, and other electro-optics instrumentation. The understanding of many newly-identified and complex physical processes is now enabled through the advances in these discipline technologies. For example, the capability to make multiple-location, high-rate pressure measurements is now possible mainly through the upgrades in digital data acquisition systems technology and the ability to incorporate a lot of the processing required at or near the sensor itself. Digital computer advances also make possible the acquisition and processing of large area image-type data, enabling 2- and 3-D measurements of surfaces and flow fields.

Coupled with the progress in digital technology is the rapidly-advancing state of the art in solid-state electronics technology, including microelectronics. In particular, the blossoming field of microelectronics technology promises to enable a wide range of concurrent parameter measurements in tightly packed arrays of surface-mounted sensors. Temperature, pressure, and heat flux levels at (essentially) a single point are but one example of the powerful capabilities offered. Another electronics-related breakthrough with potentially great impact is the application-specific integrated circuit (ASIC), which offers the possibility for unprecedented power in so-called "smart" sensors and instrumentation systems.

Solid-state lasers highlight a third technology opportunity for the measurement and instrumentation engineer. The current use of lasers for such investigations as flow field diagnostics features predominantly gas and dye lasing media, which typically engender large volume and environment constraints for the lasers and their supply fluids. All-solid-state laser systems are proving to be more efficient (and reliable) and require less encroachment on valuable test space. Their fast-emerging application to space and aircraft flight remote sensing can be expected to have a payoff in aeronautical research and testing. Progress being made in developing broadly tunable solid-state laser materials promises to result in virtually unlimited bandwidth for the widest variety of aerodynamics, structures, and propulsion investigations.

Closely allied with the solid-state electronics advances is the increased sophistication of computer-aided design and engineering programs for single and integrated circuits. These tools allow the electronics design engineer to devise required circuits, develop component lists, perform simulation and emulation investigations to "wring out" the design, and, finally, to electronically transmit his or her design to a foundry for prototyping or production. The dramatic savings in engineering time and effort is already beginning to result in an ever-increasing supply of effective transducer and processor technology for the measurement technologist.

Taking advantage of some of the breakthroughs in imaging technology (associated with the digital computation progress), the use of surface coatings to qualitatively and quantitatively ascertain the value of parameters such as skin friction, temperature, heat flux, and pressure is beginning to expand. The formulation of phosphor-bearing "paints" and the development of techniques for applying liquid crystals to a wind tunnel model's surface is expected to produce measurements of critical aerodynamic and aerothermodynamic data over an entire vehicle. Also, the material manufacturing and application technology promises to enable matrix formulations of some of these coatings to potentially indicate virtually continuous (space and time) variations in the sensed parameters simultaneously.

The above-mentioned technology opportunities are by no means a complete list, but they do highlight some of the more exciting areas for capitalization. Many of the areas discussed are being exploited at the NASA Langley Research Center, and particularly by its Instrument Research Division (IRD) in the development of new measurement technology. The following section describes some of the exciting areas being addressed by IRD today.

IV. IRD Measurement Technology Programs

In this part examples of ongoing research and technology application programs will be given to illustrate the contributions being made by the various organizations within the Instrument Research Division. To carry out its mission of providing support to NASA's and Langley's aerospace research programs the Division is organized in five branches. Figure 5 shows the IRD organization. The Chief Scientist and the Chief Engineer conduct research and technology activities on a broad scale; the individual Branches conduct research and applications studies in their discipline areas.

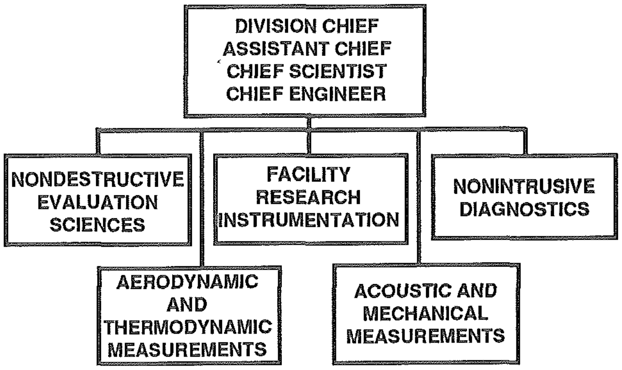

Figure 5. Organization of the NASA Langley Instrument Research Division

In the following, a compilation of selected recent and current accomplishments is given to indicate the marriage of technical opportunity to measurement challenge.

Nondestructive Evaluation (NDE)

A major research area being pursued in the Nondestructive Evaluation Sciences Branch is the development of effective techniques for rapidly assessing the condition of an aircraft's structure – a problem which is becoming crucial for the vehicles in the so-called "aging aircraft" fleet. A promising method has recently been developed and demonstrated which combines improved imaging technology with enhanced computational techniques. Rather than simply making an infrared image of a subject part undergoing thermal excitation, measuring the rate of diffusion of heat energy in response to a metered amount of thermal stimulation allows information to be captured about the subsurface structure through which the energy is being diffused. (1) Figure 6 includes an image made with this technique. The figure depicts a disbond (not visible in an external visual inspection) in an aircraft skin panel lap joint. This thermal diffusivity technique has been successfully demonstrated on an entire aircraft structure at an airline maintenance facility in the United States. Application of the method has also been successfully made to examination of solid rocket motor casings for hidden damage or disbonds. Extension to composite airframes is projected.

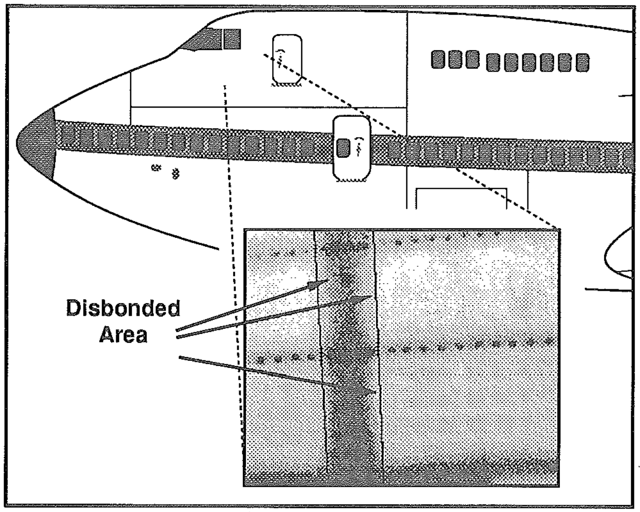

Figure 6. Thermal diffusivity image of aircraft lap joint disbond areas

Another advance in NDE instrumentation technology makes use of the coupling of laser and imaging technology in a technique called shearography. In this method a laser is used to first illuminate a specimen in a reference (unstressed) state. After pressure, temperature, compression, tension, or other type of energy is applied, the now distorted (even if only slightly) image is compared in real time to the reference to generate an image of stress fields within the material being studied.(2) Figure 7 shows the results of applying this technique to NDE of a spacecraft nickel-hydrogen battery case, for which internal gas pressure buildup is of potential concern to users. This application has been a cooperative effort between NASA's Langley Research and Lewis Research Centers.

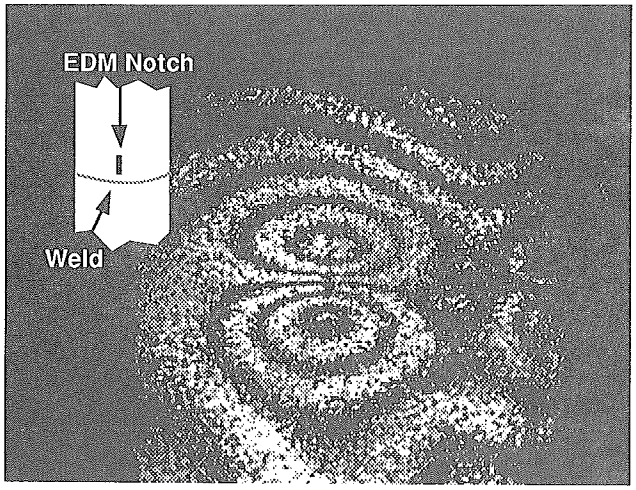

Figure 7. Shearograph of a Ni-H_2 battery case with an indicated stress concentration from an electrode-discharge-machined (EDM) notch

Impressive progress is being made in the development of equipment and instrumentation which combine computer-aided tomography with a load frame, so that internal materials characterization can be accomplished under loaded conditions. The Nondestructive Evaluation Sciences Branch has placed such a machine into operation, and projects that feature resolution of 50 micrometers can be routinely achieved.

Aerodynamic and Thermodynamic Measurements

Among the measurement disciplines associated with aerothermodynamics research, heat flux and species characterization are important and have traditionally been difficult to measure precisely, or over large areas. Electronics advances in surface acoustic wave (SAW) devices are being exploited in the case of species determination. Using a gas-specific absorptive material on the device surface, the resultant change in frequency of the surface waves is measured to be proportional to the mass of gas absorbed (which in turn is proportional to the partial pressure of that gas in the medium under study). Figure 8 illustrates the principle of this device. Application can be to wind tunnel or flight environments.

Great strides are being made in the application of infrared imaging to the measurement of surface temperature, with extensions being made to the determination of transition in the boundary layer on an airfoil. Accurate, high-speed, high-resolution digital cameras now available, in conjunction with appropriate computer algorithms, can provide very precise temperature data at standard video rates or faster. The advent and maturation of scanning arrays of infrared detectors (now under development) is expected to result in even higher precision and resolution in these measurements. An example of the data being obtained is given in Figure 9, which maps temperature as intensity variations in the infrared radiation emitted from the model.

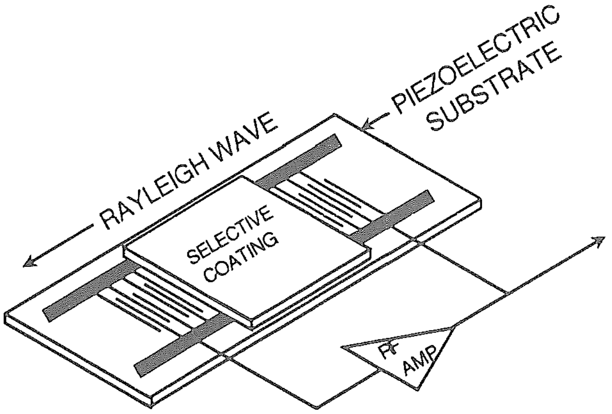

Figure 8. Species detection using SAW device

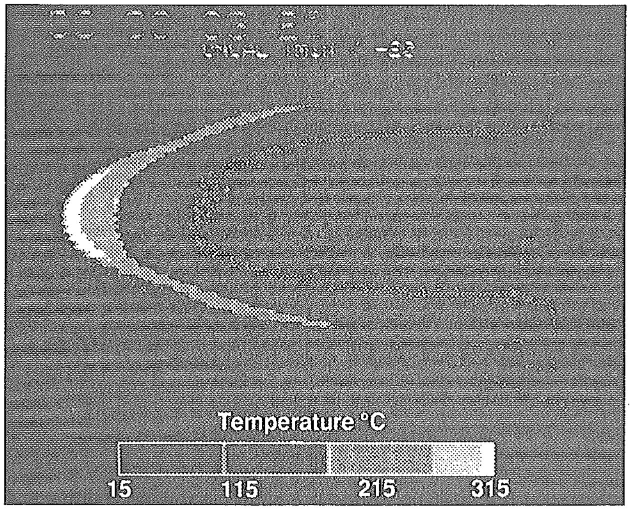

Figure 9. Infrared signature from a hypersonic vehicle model in the NASA Langley 31-inch (0.75m) Mach 10 wind tunnel facility. $\alpha = 25$ degrees

In the field of pressure measurement, researchers are developing devices and techniques for both low-temperature and high-temperature applications. For testing in cryogenic environments, small, temperature-compensated electronically-scanned pressure sensors have been developed and validated (8 channels) in the laboratory. Extension of this technology to 32 channels has been demonstrated, and wind tunnel verification will be accomplished in 1993. The payoff for success in these endeavors is less tubing to be run through models, which can interfere with precise, repeatable force balance measurements.

An exciting technology being exploited is that of pressure-sensitive phosphors or paints. The Aerodynamic and Thermodynamic Measurements Branch is working with NASA-Ames, universities, and industry to extend the application of this technology from the low subsonic flight regimes (Mach number less than 0.2) to the hypersonic. In addition, Branch researchers are working to develop alternate formulations that overcome the earlier paints' limitations of sensitivity only to the partial pressure of oxygen. This will lead to applications in a variety of facilities with different working fluid media (such as helium, nitrogen, and CF_4).

Facility Research Instrumentation

Many research facilities at NASA Langley conduct aerodynamic testing on a schedule approaching that of a production facility. Others are specifically dedicated to research, and thus will undergo many configuration and test protocol changes over the period of a year. In each case, however, measurements to be made are similar, and require at least some amount of facility-dedicated instrumentation and data acquisition systems. Of increasing use are optical techniques to both qualitatively and quantitatively characterize flow phenomena and test object (model) response to them. Such visualizations complement other methods of acquiring quantitative information during a test. In addition to traditional techniques such as shadowgraph and Schlieren, advances are being made in the sophistication of application of the newer laser light sheet visualization technology. Along with enhancements such as multiple light sheets, swept light sheets, and rotated-orientation light sheets, a novel technique has been developed by Research Facility Instrumentation Branch personnel for strobing the light sheets, for the first-ever laser light sheet visualization of flow about a helicopter rotor.(3) Figure 10 depicts a frame from a video record of such a test.

A rapidly-emerging technology applicable to flow visualization, model deformation measurements, or the measurement of displacements in large structures is the so-called videogrammetry technique. This method takes advantage of advances in digital (charge-coupled device) camera technology and digital computation technology to apply sophisticated algorithms to precisely determine locations and angles associated with model motion. In an increasing number of cases, this determination can be made in real time or near real time; in others, there is still substantial savings in time over the operations required with developing film from multiple cameras and performing the resultant manually-driven data reductions. At Langley, videogrammetric systems are being considered for use in the National Transonic Facility, the unique vertical free-flight spin tunnel, and the Transonic Dynamics Tunnel.

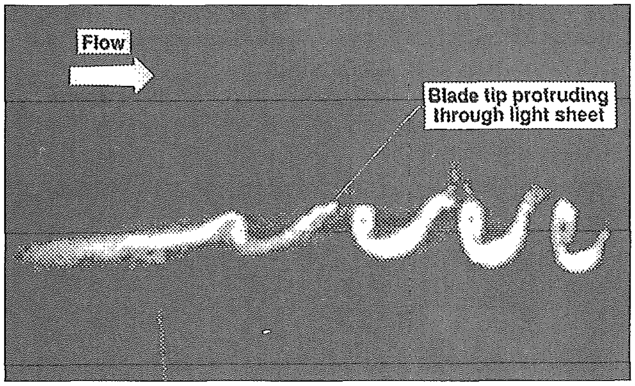

Figure 10. Strobed laser light sheet visualization of flow about a four-blade rotor model in the NASA Langley 14 ft by 22 ft (4m x 7m) wind tunnel $M_\infty = 0.23$

Acoustic and Mechanical Measurements

Of key importance in many aerospace research programs is the measurement of aerodynamic forces and moments. The six-component strain gage balance has become the instrument of choice for most wind tunnel investigations, except for those involving very large models or test articles. The problem of temperature compensation for the balance becomes crucial at either high or low temperatures. Acoustic and Mechanical Measurements Branch (AMMB) researchers have successfully developed temperature compensation techniques for balances used in the environment of the National Transonic Facility (NTF), which uses cryogenic nitrogen as its test medium. The NTF balance incorporates a temperature-compensation circuit, in addition to a unique set of axial reference gages to account for length changes from the temperature excursions. Figure 11 depicts an NTF balance with these features identified.

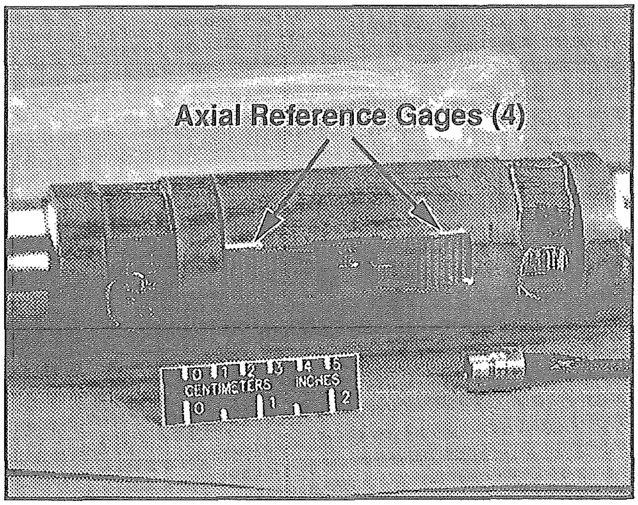

Figure 11. National Transonic Facility balance with temperature compensation

Acoustic measurements frequently must be made under extreme physical and environmental conditions. The investigation of noise signatures from a wide variety of aircraft is typically done in remote locations, to preclude the presence of confounding sound which could contaminate (or at least make difficult the extraction of) test data. The rapid advance of digital technology has provided an opportunity to maximize data return from extended missions, through the marriage of digital microphones and high-speed digital data acquisition systems. Because arrays of microphones have to be set up over thousands of square meters, the digital technology eliminates the problems associated with analog amplifiers and their attendant noise effects. Bandwidth is increased and data recording, storage, and playback capability have been greatly enhanced.

Another digital technology being exploited is the digital signal processor (DSP) circuit, which can be captured on an integrated circuit chip. Two applications are currently underway in the Instrument Research Division's AMMB. One involves using the DSP in compensation circuitry for a dynamic force balance to be employed in Langley's Unitary Plan Wind Tunnel. The other features use of the DSP in a novel scheme to measure engine duct noise, process the signal to determine spectral content, and use this data to generate cancellation noise further downstream. Figure 12 illustrates this innovation. The key is the extremely fast computational capability offered by the DSP technology.

Other quantities whose measurement is being improved by AMMB personnel include skin friction (through the use of mechanical, electro-optic, and liquid crystal coating techniques), flow transition (through high-speed, thin-film hot-wire anemometry technology), and micro-forces (employing balances using piezo-electric materials).

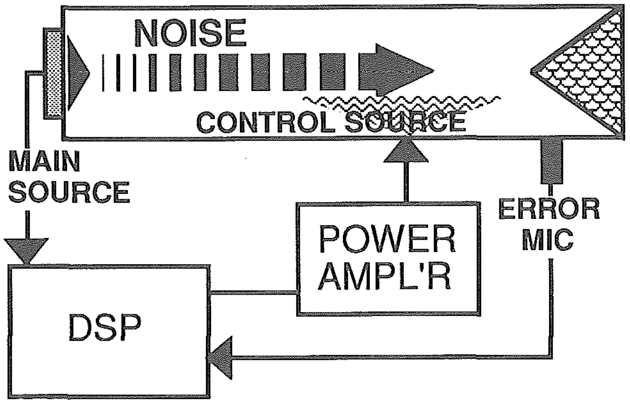

Figure 12. Noise cancellation technique using DSP technology

Nonintrusive Diagnostics

Perhaps no other aspect of aerospace measurement technology has benefitted from enhancements in the state-of-the-art of laser technology as has the broad field of nonintrusive diagnostics. Today lasers are used in making virtually every measurement associated with the flow field about test models or airfoils. Pressure, temperature, density, velocity, and species concentration are all amenable to remote sensing with lasers. Of increasing importance is the concept of "global" or wide-area measurements to shorten the data acquisition time and achieve spatial simultaneity of measurements. A major breakthrough in global flow field velocity measurements has recently been achieved by members of the Nonintrusive Diagnostics Branch (NDB) and will be described next.

The Doppler Global Velocimetry (DGV) technique has been under development for the past three years. It makes use of selective filtering of light from a light-sheet-illuminated flow field in comparison with a reference view of the same plane. Doppler velocity data is then extracted through application of appropriate algorithms to the intensity variations seen by a video detection system (camera). Through variation in laser illumination direction, laser light wavelength, or viewing camera placement, three components of velocity can be measured. With sufficient equipment, these components can be obtained simultaneously. And, through the incorporation of video and digital technology, real-time records of flow field velocity are possible. Earlier demonstrations of this technique were able to extract only relative velocity information from wind tunnel tests. Recently, however, the first quantitative measurements have been made of three velocity components.(4) Figure 13 depicts a single frame of normalized velocity data about an airfoil model in the Langley Basic Aerodynamics Research Tunnel. This achievement promises to provide a dramatic enhancement to the velocity measurement capabilities in wind tunnels, and perhaps more importantly, is expected to find application to the measurement of 3-dimensional velocity in the flow field about an aircraft in flight.

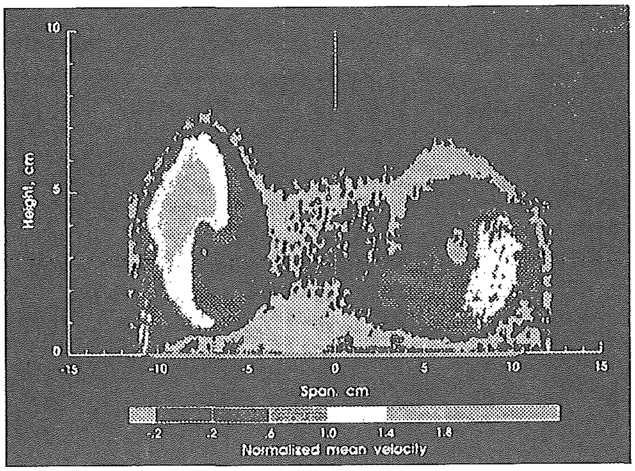

Figure 13. Normalized vortex radial velocity from application of Doppler Global Velocimetry technique; $M_\infty = 0.2$

Hypersonic flight will require propulsion systems which must be efficient. Developing an understanding of the combustion processes is a major ongoing effort at NASA Langley. Crucial measurements which can provide insight into the characteristics of the process include the measurement of key species such as the OH (hydroxyl) radical. Here also, as with other measurements, planar information is highly desirable to minimize test runs and assure concurrency of data. NDB researchers have recently achieved global looks at the combustion characteristics of a supersonic hydrogen combustor. Using a high-power excimer laser whose beam was broadened into a sheet, planar laser-induced fluorescence (PLIF) studies were made to obtain

OH concentrations. Through the pulsed operation capability of the excimer, time-ordered data has been obtained to provide never-before-seen insights into the process. Figure 14 illustrates the PLIF technique being implemented at Langley.

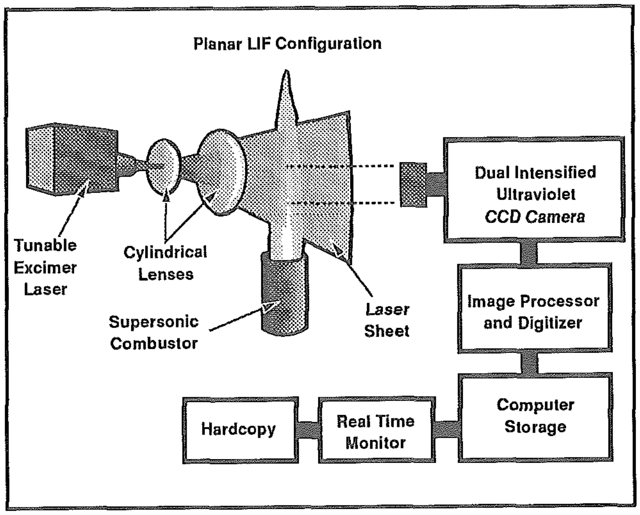

Figure 14. Advanced two-dimensional laser diagnostic technique

Other technology advances being made in the nonintrusive diagnostics field include particle image velocimetry (where demonstration of the technique has recently been accomplished in a Mach 6 flow over an aerodynamic shape), Raman doppler velocimetry (which requires no seeding as do particle image and conventional laser doppler velocimetry techniques), and application of Rayleigh scattering techniques (using excimer lasers to generate a sheet of light for planar studies of such phenomena as fluid mixing). In each of these techniques, exploitation of digital computer technology is crucial because of the large amounts of image-related information involved.

V. Future Trends

It is expected that advances will continue in the digital computer and microelectronics technology areas. The marriage of these two disciplines will strengthen as the "smart" sensor becomes more prevalent in both ground and flight instrumentation applications. The ability to conformally cover a model's or flight vehicle's surface with multi-parameter arrays of sensors and their associated processing circuits will result in dramatic savings in data reduction hardware and software, in addition to providing information of a more global nature.

Another area where improved technology should play a widening role is that of video-photogrammetry. As mentioned previously solid-state camera technology, along with high-speed specialized computer algorithm processing (using ASIC, for example), will result in facilitated real-time 3-dimensional position tracking or structural deformation monitoring. It is even conceivable that this technology will result in implementation of a capability to monitor critical parameter limits during testing, to protect valuable hardware and facilities, as well as providing ready access to data for more rapid data reduction and application to design processes.

Along with conformal arrays of microelectronics sensors, technology for continuous coatings of aerodynamic parameter-sensitive materials such as phosphors, paints, and liquid crystals, will be further developed so that virtually unlimited spatial precision and resolution can be obtained for values of the specific parameters over an entire model surface. Coupled with advances in imaging and computational technology, the promise of virtually automated data collection and reduction should be realized, thus further shortening the design, testing, and evaluation phases of an aircraft's life-cycle.

Finally, the rapidly-accelerating progress in solid-state laser technology should continue, resulting in their availability in a wide variety of powers and wavelengths. Benefits to be realized are improved test efficiency, more compact and rugged instrumentation systems, and the ability to address more and varied test environments. In this area, there are opportunities for synergism with laser developments for spaceborne and airborne remote sensing.

VI. Summary

As aircraft designers work to meet the demands of aviation in the next century, there arise many challenges to the successful conduct of research and operational testing in support of the development process. These challenges manifest themselves as physical constraints in test environments, stringent coverage and resolution requirements by aerodynamicists and test engineers, and the necessity to effect economical (or efficient) testing in the various phases of aerospace investigations. The demands on the measurement technologist can be offset by the opportunities which continually arise in related technological disciplines. This paper has presented a discussion of some of the typical challenges, current opportunities, and example applications to the aeronautical research and testing process, all from the perspective of the Instrument Research Division of NASA's Langley

Research Center. State-of-the-art technology exploitation has been highlighted for many of the component organizations of the Division, with results presented of actual problem solutions. Finally, a brief synopsis of some key future trend projections has been outlined, which states that continued enhancements in microelectronics and digital technology will be crucial to the evolution of "smart" sensors.

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