NASA PROGRAMS IN ADVANCED SENSORS AND MEASUREMENT TECHNOLOGY FOR AERONAUTICAL APPLICATIONS

Bruce A. Conway
NASA Langley Research Center
Hampton, Virginia 23665-5225

Abstract

There are many challenges facing designers and operators of our next-generation aircraft in meeting the demands for efficiency, safety, and reliability which are and will be imposed. This paper discusses aeronautical sensor requirements for a number of research and applications areas pertinent to the demands listed above. A brief overview will be given of aeronautical research measurements, along with a discussion of requirements for advanced technology. Also included will be descriptions of emerging sensors and instrumentation technology which may be exploited for enhanced research and operational capabilities. Finally, renewed emphasis of the National Aeronautics and Space Administration in advanced sensors and instrumentation technology development will be discussed, including projections of technology advances over the next 5 years. Emphasis on NASA efforts to more actively advance the state-of-the-art in sensors and measurement techniques is timely in light of exciting new opportunities in aircraft development and operation. An up-to-date summary of the measurement technology programs being established to respond to these opportunities is provided.

I. Introduction

In the development of new classes of aircraft, from the evaluation of design concepts in laboratories or flight to the application of sensors and instrumentation for routing flight operations, incorporation of highly-capable sensors or measurement instrumentation is crucial to the research or operational mission success. Typically, sensors to support research applications or flight operations have been "off-the-shelf" or developed in a short period of time in response to an urgent need. The fast pace of today's technology advances and the research programs undertaken to enhance or exploit them have necessitated earlier attention to measurement technology to fully capitalize on the improved capabilities. In some cases, existing technology can be readily extended to address new application regimes, as for example with the enhancement of microphone technology for applications to high-temperature, high-frequency regimes associated with aerothermodynamics measurements. In other cases, emerging technology can be focussed to address critical safety and reliability problems; use of fiber optic techniques for structural monitoring of aircraft and spacecraft is one promising utilization of such a technology. However, unless a concerted, coordinated effort is made early in the planning stages (for a new aircraft project) to address the measurement requirements (and available technology or capabilities) associated with development, test and operations, implementation of downstream project milestones can be delayed for lack of appropriate instrumentation or measurement techniques. "Hurry-up" development must then occur, which may result in inefficiencies, added costs, and ultimately project delays. The U.S. hypersonics research and technology program, including the National Aerospace Plan program, is an example where sensors and measurement technology had not kept pace with advances in computational aerodynamics, structures, materials, and propulsion technology. A preferable philosophy involves the "up-front" inclusion of measurement technology requirements early in the development phases of an aircraft program, particularly for those developments where new regimes of speed, physical environment, or aerodynamic and structural characteristics are to be encountered and dealt with.

A key part of the mission of the U.S. National Aeronautics and Space Administration (NASA) is to undertake research and development in support of the nation's military and civil aeronautics and space endeavors.[1] In support of this role, NASA conducts research and technology efforts in several associated disciplines, including electronics, sensors, and instrumentation techniques and systems. Agency programs are aimed at advancing the state-of-the-art and exploiting these and other advances for the furtherance of aerospace technology. In aeronautical sensors and measurement technology, various aeronautics discipline programs sponsor research that is focussed to meet discipline-specific needs, including schedules. There have been in the past, and are beginning to be re-established, more generic research activities not necessarily having a specific discipline or vehicle focus, but rather which have broad potential applications. The following sections in this paper will address aeronautical research measurements in view of the reawakening interest in longer-range research. The requirements for advanced technology to meet several current and future needs, and the emerging sensor and instrumentation technology being developed to address these requirements will be discussed in the context of NASA's research and technology programs in aeronautical sensors. The paper will conclude with presentation of potential future sensors research and applications activities.

II. Aeronautical Research Measurements

In the conduct of ground-based (for example, wind tunnel) and flight research tests, measurement of many different parameters may be required. The number, frequency, resolution, and precision of measurements can vary widely in practice, depending on the research objectives. The ability to make some desired measurements may be compromised by constraints such as environment (high or low temperatures, for example), physical limitations (model size, clearances available, or requirements for nonintrusion), transducer or instrumentation system bandwidth limitations (frequency response characteristics), and, in some cases, an incomplete understanding of physical processes involved in an observed phenomena (making it difficult to develop a measurement transducer concept). As might be imagined, hypersonics-related research has a large amount of measurement difficulty associated with it, while measurement of parameters related to subsonic aeronautics is much more straightforward. Table 1 illustrates this dichotomy by listing several key measurement parameters associated with several aerodynamic regimes along with an indication of the maturity of technology to make the required measurements.

There is a relationship among aeronautical measurements made to satisfy the requirements of (1) ground-based research and testing, (2) flight research and testing, and (3) operational applications (both ground and flight). Oftentimes the solution to a measurement problem in a ground research facility may be extended to application on a full-scale aircraft or remotely-piloted vehicle, and then made part of the aircraft's instrument complement. The obvious inference from the existence of this relationship is the strong potential influence that mature technology which supports aircraft operations has on availability of measurement techniques for additional research in the particular regime. Also, a lack of such operational applications may infer that a definitive program to develop required sensors and measurement technology should be carried out. The dearth of measurement techniques in a given regime or discipline (as indicated, for example, in Table 1) generally necessitates the application of advanced technology. The next section addresses some of the drivers and requirements for advanced technology to solve critical aeronautical measurement problems.

III. Requirements for Advanced Technology

As other aeronautical disciplines mature, driven by changing mission requirements, economics, or as a result of conscious fundamental research efforts, the need for measurement technology to keep pace grows acute. For instance, in hypersonics technology, great strides are being made in high-temperature structural material capabilities, with carbon-carbon composites being a leading example of advanced technology. However, as noted in the preceding section (Table 1) there is a lack of sensors or measurement techniques to make high-fidelity temperature measurements in the ranges expected to be encountered in hypersonic flight. Similarly, the ability to measure skin friction in the boundary layer of a hypersonic vehicle necessitates sensor operation in the same high-temperature ranges. In fact, all in situ measurements will involve hostile environments in hypersonics, including those made in and around the propulsion system.

In another regime, that of low-disturbance flow (such as might be sought in so-called "quiet wind tunnels"), it becomes necessary to make measurements with minimal or no disturbance to the airflow. This same constraint applies to sensors used in flight for the determination of parameters associated with laminar flow. Low-forward-velocity flight also has characteristics that make it more difficult to accurately measure the parameters of angle-of-attack and velocity using conventional sensor techniques. And, although the phenomena have been known for awhile, accurate detection and warning of meteorology-related hazards such as wind shear, wake vortices, and clear air turbulence is not yet routine.

The above-cited cases are but a few examples of areas where measurement technology must be improved to support advances in other aspects of aeronautics technology, including enhanced aviation safety. A major impetus for enhanced measurements capability is the dramatically-increased power of digital computers used to model aerodynamic, structural, and propulsion quantities. The computational fluid dynamics and computational structural mechanics programs run by today's supercomputers can calculate parameters such as temperatures, pressures, and flow velocities to fine numerical and spatial precision. The validation of the computer software codes used in these computations requires measurements that are of comparable precision. The need for such precision directly leads to the requirements for advanced sensor and instrumentation technology to

MEASUREMENT PARAMETER	VELOCITY			IMPEDIMENTS
	SUBSONIC	SUPERSONIC	HYPERSONIC	
STRAIN	A	A	B	HIGH TEMPERATURE
TEMPERATURE	A	A	B	MATERIALS/INTRUSIVE
SURFACE PRESSURE	A	A	B	HIGH TEMP/INTRUSIVE
SKIN FRICTION	A	B	C	HIGH TEMP/MATERIALS
FLOW VELOCITY	A	A	B	OPTICS/INTRUSIVE
CHEMICAL SPECIES	B	B	C	INTRUSIVE/PRECISION

TECHNOLOGY MATURITY: A - HIGH B - PARTIAL C - LOW

TABLE 1. AERONAUTICAL MEASUREMENT TECHNOLOGY MATURITY

achieve it. Satisfying these requirements is a key problem of today's research efforts, and will be a crucial aspect of tomorrow's aeronautical research and applications. The following section discusses emerging sensors and instrumentation technology in several areas, which may be useful in satisfying many of the advanced measurement requirements in aerospace research and applications.

IV. Emerging Sensors and Instrumentation Technology

Technology advances supporting aeronautical sensor and instrumentation techniques have been made on several fronts. Achievements in high-temperature materials (both metallic and non-metallic), lasers and electro-optics (including fiber-optics), high-speed pressure transducers, and photo-optics are being reported by researchers in government, industry, and academia. NASA is involved in many of these areas of achievement, either as contributing researchers, or through adaptation of the advances for improved measurement technology. This section will cover some of the emerging technology areas highlighted by recent advances, with emphasis on the role NASA is playing in their achievement and applications.

High-Temperature Materials

Because high-temperature operation is a key facet of many hypersonic aerodynamics and propulsion research and technology measurement problems, there has been a concentration of effort recently in this area. For example, researchers D. Englund and R. Seasholtz at NASA's Lewis Research Center have investigated several alloy compositions for application to strain measurements at high temperatures.(2) One of these alloys, PdCr, has been extensively characterized by J. Lei of Sverdrup Technology at NASA-Lewis and found to exhibit a high degree of repeatability and very low thermal output due to expansion from room temperature up to 700 °C.(3) Use of these strain gage materials is expected to significantly enhance research of turbine engine hot sections, at temperatures up to 1000 °C, as well as find utility in strain measurements on models in high-temperature wind tunnels or arc jets.

A problem encountered in attempting to use either conventional or high-temperature strain gages in a hot environment is the reliability of the application or bonding, particularly when newer surface materials such as composites are involved. Promising advances are being made by T. Moore at NASA-Langley, who has demonstrated application of several types of high-temperature strain gages on carbon-carbon surfaces with a SiC coating, with successful operation to 555 °C.(4) Recently, successful application and tests at 833 °C have been achieved.

As mentioned, aerothermodynamic measurements on the surface of an aircraft model of flight vehicle in hypersonic flows can be difficult, particularly at the high frequencies characteristic of phenomena in hypersonic boundary layers. As temperature ranges extend outward, microphone sensors are being developed to capture the acoustic energy associated with, for example, transition from laminar to turbulent boundary layer flow. Figure 1 depicts progress being made in this field. A. Zuckerwar of NASA-Langley and F. Cuomo of the University of Rhode Island have recently developed a Ni 200 membrane, fiber-optic microphone capable of operating at 600 °C.(5) This microphone has recently been successfully tested.

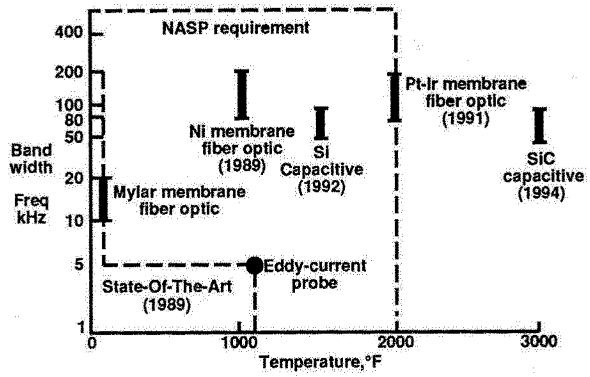

FIGURE 1. High-Temperature, High Frequency Microphone Development

Other emerging sensor and instrumentation technologies in the high-temperature materials area (some still requiring substantial work) include liquid crystals for pressure or temperature measurements on aerodynamic surfaces and sputtered or vapor-deposited thin-film thermocouple and strain sensors.(2)

Lasers and Electro-Optics

A major constraint when making many aeronautical measurements is minimizing the sensor's influence on the parameters being measured. The field of nonintrusive measurements is thus aimed specifically at avoiding this conflict. Remote sensing techniques utilizing various forms and spectral regions of electromagnetic energy are particularly suitable, with lasers as a well-known solution which is being rapidly improved.

A flow visualization method which is proving increasingly effective is the so-called laser light sheet. This technique utilizes a single cw laser with either a scanning galvanometer-driven mirror or a cylindrical lens to generate the "sheets" of light in a seeded flow. J. Franke, D. Rhodes, B. Leighty, and S. Jones of NASA-Langley have made several advances in this field in recent years.(6) The plane of the light sheet can be moved along a model surface to visually follow the growth and burst of vortices, as illustrated in Figure 2. The laser light sheet nonintrusive flow visualization technique has been applied in supersonic flow experiments as well as subsonic flows. An indication of the power of this method is its ability to delineate subtleties in the flow, such as the tertiary vortices easily visible in the photograph made from a television record of a supersonic (M = 2.4) experiment (Figure 3).

Another group of related laser-based techniques for nonintrusive determination of flow properties are laser transit anemometry (LTA), laser Doppler velocimetry (LDV), and laser Doppler anemometry (LDA). These methods typically require that the flow be seeded in order that either time-of-flight or Doppler velocity components can be detected via the laser beams; the resultant measurements are also point measurements, necessitating the scanning of the measurement volume to obtain a complete

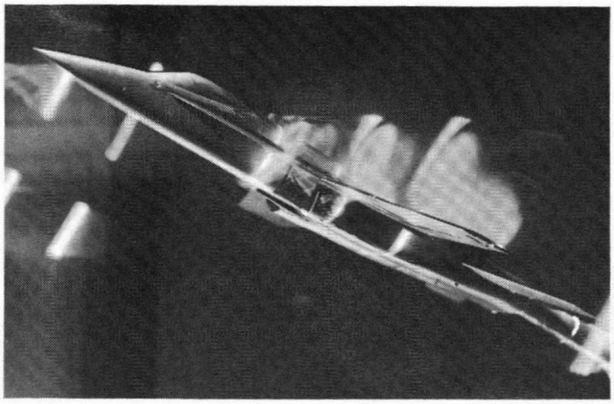

FIGURE 2. Three Light Sheets Normal to F-18 Model at $\alpha = 25^{0}$

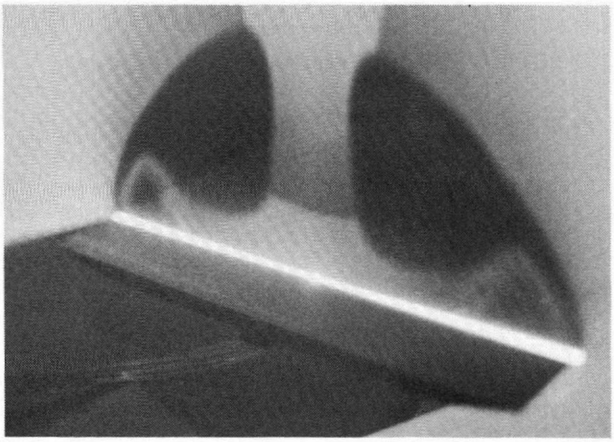

FIGURE 3. Complex Vortex Structure on Delta Model at $\alpha = 24^{0}$, M = 2.4

mapping of the flow field. With advances being made in computational capability (speed, capacity) and detector algorithm sophistication, the relatively new fields of particle image velocimetry (PIV) and Doppler global velocimetry (DGV) are emerging; these can ascertain a planar flow velocity field in real- or near real-time. This is accomplished through a "double exposure" in the PIV case, or by selective filtering of a laser light sheet-illuminated flow-field plane in the DGV case. Both means can significantly reduce the amount of time needed to characterize a flow field. Figure 4 illustrates a coarse PIV image of the flow over a standard airfoil, as compiled by W. Humphries of NASA-Langley.

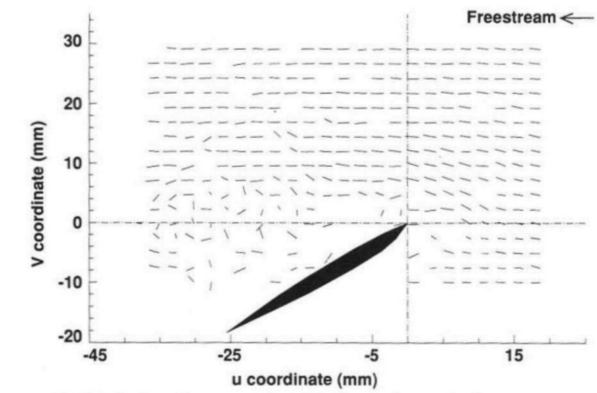

FIGURE 4. Coarse Particle Image Velocimetry Flow-Field Map for Stalled NACA 0012 Airfoil at $\alpha = 30^{0}$

Laser-induced fluorescence (LIF) is another nonintrusive method of determining flow parameters over a wide range of airspeeds. LIF can be used to determine species concentrations, making it particularly suitable for combustion flows. G. Laufer, D. Fletcher, and R. McKenzie of NASA-Ames Research Center have shown laser-induced fluorescence of O_2, in combination with Raman scattering to be an accurate means for acquiring measurements of temperature, density, and their fluctuations due to turbulence in high-speed flows.(7) Application of LIF to hypersonic flows is proceeding at both Langley and Ames.

Reliable tunable solid-state lasers is one example of emerging technology applicable to aerodynamic measurements. The lighter weight and lower power requirements, in comparison to dye or gas lasers used for several years, holds great promise for enhanced laboratory operations such as Doppler velocimetry, laser-induced fluorescence, and laser transit anemometry, as well as enabling similar measurements on flight vehicles for the first time.

One promising use of laser technology is in the so-called aviation meteorology field, providing an ability to measure wind velocity in such meteorology-related phenomena as wind shear, wake vortices, and clear-air turbulence (see Figure 5). M. Storm and W. Rohrbach of NASA-Langley have demonstrated for the first time single-longitudinal-mode lasing of Ho:Tm:YAG using a laser diode pump.(8) This demonstration, at a wavelength of 2.091 μm, paves the way for potential application to coherent Doppler measurements in the eye-safe region of the spectrum. The ability to achieve the requisite lasing with an all-solid-state system also holds promise for other applications in laboratory and ground-based systems.

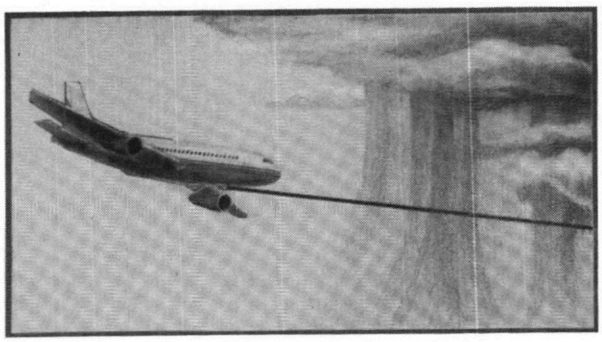

FIGURE 5. Laser Beam Wind Shear Measurement

Solid-state lasers are also seeing increased use in such techniques as Rayleigh and Raman scattering in supersonic flows. For example, B. Shirinzadeh, M. Hillard, and R. Exton of NASA-Langley have utilized a frequency-doubled Hd:YAG pulsed laser (at 532 nm) to obtain simultaneous Rayleigh and Raman scattering in Langley's M = 6 wind tunnel to infer density and pressure in the tunnel flow. Their experimental setup, shown in Figure 6, has enabled the demonstration that Rayleigh scattering for gas density measurements in the free stream of a supersonic tunnel can be seriously hampered by flow-generated interference (which they have postulated results from a nucleation process). Another solid-state laser application is in the Coherent Anti-Stokes Raman Spectroscopy (CARS) technique; R. Antcliff,

O. Jarrett, T. Chitsomboon, and A. Cutler at NASA-Langley have utilized a 10 Hz pulsed Nd:YAG laser to pump broadband dye lasers which produce the CARS probe beams. In recent experiments, two beams were generated to simultaneously examine oxygen and nitrogen temperature and density in a supersonic combustor flow.[9]

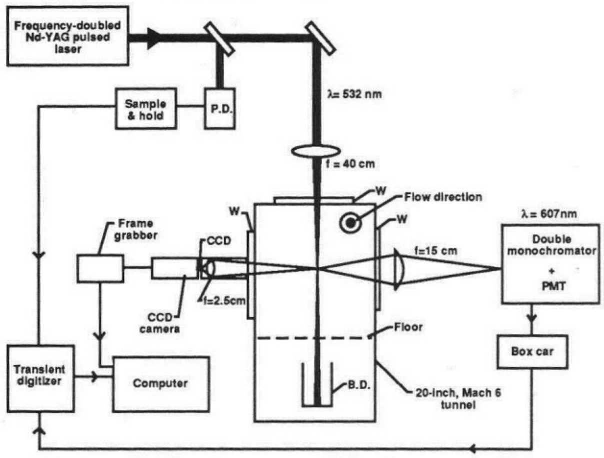

FIGURE 6. Test Setup for Simultaneous Raleigh, Raman Measurements in M = 6 Wind Tunnel

The use of optical fibers is becoming more commonplace in aeronautical measurement applications. They are being employed in harsh environments, such as those associated with turbine engines, for quantities such as temperature[10] and shaft position (via a wavelength-division multiplexed optical position transducer,[11] and for qualitative purposes such as combustor viewing.[2] Fiber optics have recently been applied in CARS measurements, to remotely route Raman signal energy through harsh vibration environments to the receiving photodiodes and electronics. Other examples of emerging fiber optics technology use is in so-called smart structures. R. Rogowski of NASA-Langley has, in collaboration with other Langley and U.S. Air Force Astronautics Laboratory investigators, been conducting research into the use of embedded fiber optic sensors in aerospace materials for strain measurements.[12][13] Nondestructive evaluation and damage detection are other functions emerging as amenable to implementation via fiber optics/smart structures.

Photo-Optics and Thermography

Classical photo-optic instrumentation techniques are seeing reemergent application to many of the nonintrusive measurement problems of today's aeronautical research programs. In addition to the requirements for avoidance of flow interference, these techniques enable the determination of parameters in harsh environments. The ballistic range is one example of a research facility needing such nonintrusive measurements. A. Strawa and J. Cavolowsky of NASA-Ames have been developing instrumentation for use in the Ames Research Center's Hypervelocity Free-Flight Aerodynamic Facility.[14] One technique is the use of holographic interferometry; the Ames system employs dual-plate, double-pass interferometry to infer the density ratio across a standoff shock wave. Figure 7 is an interferogram of a free-flight model in the ballistic range portion of the Ames facility.

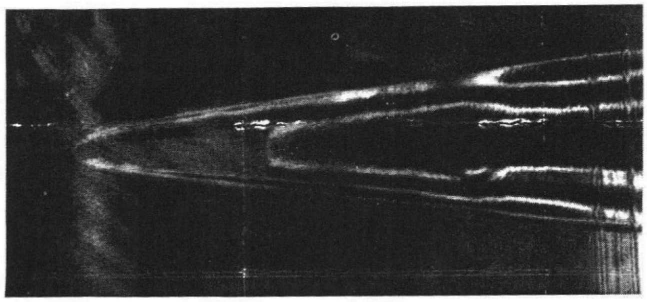

FIGURE 7. Interferogram of Free-Flight Model in Ballistic Range at 5 km/s Velocity, Reynolds No. = 1 x 10^6

Application of close-range photogrammetry to determine wind-tunnel model deformation is being carried out. A. Burner, W. Snow, W. Goad, and B. Childers of NASA-Langley have developed a digital video model deformation system for application in the U.S. National Transonic Facility (NTF).[15] Figure 8 shows the experimental configuration; the two CCD cameras are 36 inches apart, and each is approximately 72 inches from the center of the wing. The technique has been validated by measurements on a Boeing 767 model in the NTF.

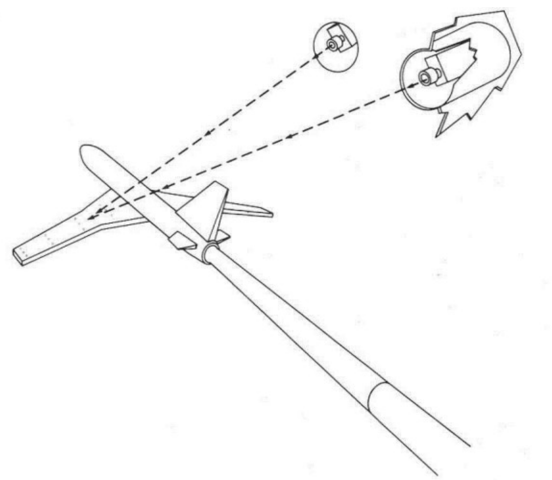

FIGURE 8. Digital Video Photogrammetric Model Deformation System

Infrared thermography is an example of emerging technology used in several aeronautical applications. It has been demonstrated effective in nondestructive evaluation of bonded or laminated space and aeronautical structures.[16] In particular, it shows promise in providing large area inspection capability for airliners as part of the U.S. aircraft structural integrity program. IR thermography also has been demonstrated in surface temperature measurements on models in high-speed flows. There are indications that it can provide qualitative delineation of flow transition regions on aerodynamic surfaces.[17]

V. NASA Research and Technology Programs in Aeronautical Sensors

The United States National Aeronautics and

Space Administration supports aeronautics research and technology programs in several disciplines; among these are structures and materials, aerodynamics, propulsion, flight controls, and human factors. NASA also sponsors research and project activities in vehicle-related classes such as rotorcraft, hypersonics, vertical/short takeoff and landing (V/STOL), and high performance military aircraft. The agency participates with other organizations in such major programs as the National Aerospace Plane (NASP). In all of these research programs and projects there are resources identified for generally nearer-term (up to 2 years or so) discipline-specific instrumentation development. In some cases, a discipline (such as aerodynamics) may sponsor sensors and measurement techniques research of a more fundamental or unfocussed nature to address longer-range needs (3 or more years in the future). An example of this type of research support was the development of instrument technology capable of operating in cryogenic environments, in parallel with the 5-year construction schedule of the National Transonic Facility. There is currently no separate aeronautical sensors program sponsored by NASA to provide generic long-range measurement technology, although proposals are under consideration by NASA management to reestablish this type of broadly-applicable technology activity.

NASA's aeronautical instrumentation and measurement technology program activities are conducted in four locations: The Langley Research Center in Hampton, Virginia; the Lewis Research Center in Cleveland, Ohio; and the Ames Research Center, in facilities at Moffett Field, California, and at the Dryden Flight Research Facility at Edwards Air Force Base, California. The Langley and Ames-Moffett Centers conduct research in several measurement research and applications disciplines, while the effort at Lewis is focussed primarily on propulsion applications and the Ames-Dryden is concerned principally with sensors and measurements for flight research.

In a typical year the estimated funding from all discipline programs for aeronautical sensors and measurements research in NASA is approximately US$10 million. This amount does not include those instruments or systems bought essentially "off-the-shelf" for direct application and use in a laboratory or flight experiment. Additional resources (about US$3 M) are made available through the jointly-sponsored NASP program, specifically for instrumentation technology maturation directly applicable to hypersonics. In addition, other resources are made available by NASP technology maturation discipline teams such as aerodynamics and structures/materials. NASA shares this funding with other U.S. government and industry organizations.

While there is a strong inhouse research program at NASA (as evidenced by the many contributions noted in the preceding section), much of the basic sensors research is conducted by, or in collaboration with, universities and nonprofit research foundations. There is also industry participation in some of the measurements research, particularly in applications phases. NASA participates in a domestic technology transfer program, where several concepts annually are incorporated by commercial firms in their product line. Thus, results of aeronautical sensors and instrumentation research programs can be applied to non-aerospace uses.

VI. Future Aeronautical Sensors Research and Applications

A major aeronautics research focus in the United States as well as in other countries is hypersonic flight. The development of reliable single-stage-to-orbit transportation and the promise of the "Orient Express" will continue to require the focus of measurements technology on the validation of the aerodynamic, aerothermodynamic, structures/materials, and propulsion concepts employed. Key efforts will continue to be expended toward making measurements nonintrusively in high-temperature environments. High-temperature thermocouples and strain gages, capable of 1670 ^{o}C operation, will be developed; a synergistic program may well be the development of similar capabilities for the U.S. Exploration initiative, which features aerobrakes in some orbital transfer vehicle concepts. Nonintrusive techniques will continue to be emphasized in hypersonic as well as in other speed regimes involved in aeronautical research. It is anticipated that two- and three-dimensional real-time flow visualization methods will be in heavy demand. In all of these research thrusts, increased precision will be sought, in deference to the increasingly powerful computational capabilities being applied to aeronautical problems.

As in space disciplines, smart sensors should become increasingly widely used. The concept of the "smart structure" will likely find application in aircraft structures as well as space structures. The desire for essentially continuous NDE capability for health monitoring could lead to the fiber optic-based capability depicted in Figure 9. Self-contained sensor/data reduction chips (based in Applications-Specific Integrated Circuit, or ASIC, technology) will enable more sophisticated onboard information gathering from small free-flight models (models in a ballistic range, for example). And smart transducers with interpretive ability can be expected to enhance knowledge acquisition from a wide variety of flight research vehicles when data acquisition capacity is at a premium.

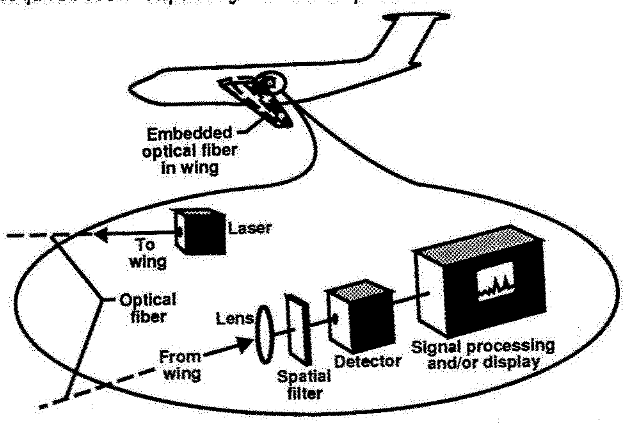

FIGURE 9. Optical Fiber-Based Structural Monitoring Concept

NASA sensors and measurement technology programs will be molded to meet these and other challenges. Increased attention to reliable and economical supersonic transportation, renewed emphasis on fuel-efficient subsonic transports, and focus on enhanced-maneuverability military aircraft will all result in increased ground and flight testing programs which must be supported by advanced sensor technology. It is anticipated that the efficiency of a longer lead time for measurement instrumentation development will be incorporated into the advanced sensors development programs of NASA. And finally, there will be many synergistic or joint technology development activities between space and aeronautics programs, including such technologies as solid-state lasers and fiber optics, high-temperature transducers, and advanced photo-optical techniques.

VII. Summary

A review from a NASA perspective of several advanced aeronautical sensor and measurement technology developments has been presented. This has been framed in the context of requirements for advanced technology in aeronautical research measurements. Highlights from many programs at NASA's research centers have been noted, and illustrations given for several of them. The review shows contributions in a wide variety of technology areas, which should serve well as a basis for advances needed in the next few years. Finally, a few projections are made which indicate that measurement techniques applicable to hypersonics and smart sensors may be two of the more widely-addressed areas in the near future.

VIII. References

1. U.S. National Aeronautics and Space Act of 1958 (PL 85-568, July 29, 1958).
2. Englund, D.R., and Seasholtz, R.G.: "Advanced High-Temperature Instrumentation for Hot Section Research Applications." Journal of Engineering for Gas Turbines and Power, Vol. 111, January 1989.
3. Lei, J.: "Development and Characterization of PdCr Temperature-Compensated Wire Resistance Strain Gage." NASA CR 185153, October 1989.
4. Moore, T.C.: "High-Temperature Strain Gage Installation Techniques for Carbon/Carbon with Silicon Carbide Surfaces." Presented at the Seventh National Aero-Space Plane Technology Symposium, October 1989.
5. Zuckerwar, A.J., and Cuomo, F.W.: "Fiber Optic Sensor for Measurement of Pressure Fluctuations at High Temperatures." Presented at International Congress on Instrumentation in Aerospace Simulation Facilities, Gottingen, West Germany, September 1989.
6. Leighty, B.D.; Franke, J.M.; Jones, S.B.; and Rhodes, D.B.: "A Two-Mirrored Laser Light Sheet Generator." Presented at the AIAA/NASA/AFWAL Conference on Sensor and Measurement Techniques for Aeronautical Applications, Atlanta, Georgia, September 1988. Paper No. AIAA-88-4680-CP.

7. Laufer, G.; Fletcher, D.; and McKenzie, R.: "A Method for Measuring Temperatures and Densities in Hypersonic Wind Tunnel Air Flows Using Laser-Induced O_2 Fluorescence." Presented at the AIAA 28th Aerospace Sciences Meeting, Reno, Nevada, January 1990. Paper No. AIAA-90-0626.
8. Storm, M.E., and Rohrbach, W.W.: "Single-Longitudinal-Mode Lasing of Ho:TM:YAG at 2.091 μm." Applied Optics, Vol. 28, No. 23, December 1989.
9. Antcliff, R.R.; Jarrett, O.; Chitsomboom, T.; and Cutler, A.: "CARS Measurements of Temperature and Species Number Density in Supersonic Combusting Flow." Presented at the AIAA/NASA/AFWAL Conference on Sensors and Measurement Techniques for Aeronautical Applications, Atlanta, Georgia, September 1988. Paper No. AIAA-88-4662.
10. Seng, G. T.: "Overview of NASA in Fiber Optics for Aircraft Controls." Proceedings of the ISA 88 International Conference and Exhibit, Houston, Texas, October 1988. Paper No. 88-1512.
11. Fritsch, K., and Beheim, G.: "Wavelength-Division Multiplexed Digital Optical Position Transducer." Optics Letters, Vol. 11, p. 1, January 1986.
12. Rogowski, R.S.; et al.: "Fiber Optic Strain Measurements in Filament-Wound Graphite-Epoxy Tubes Containing Embedded Fibers." SPIE Proceedings (Conference on Fiber Optics for Smart Structures and Skins), Vol. 986, p. 194, 1988.
13. Rogowski, R.S.; et al.: "Thermal Effects on Fiber Optic Strain Sensors Embedded in Graphite-Epoxy Composites." SPIE Proceedings (Conference on Fiber Optics for Smart Structures and Skins II), Vol. 1170, p. 435, 1989.
14. Strawa, A.W., and Cavolowsky, J.A.: "Development of Non-Intrusive Instrumentation for NASA-Ames' Ballistic Range and Shock Tunnel." Presented at the AIAA 28th Aerospace Sciences Meeting, Reno, Nevada, January 1990. Paper No. AIAA-90-0628.
15. Burner, A.W.; Snow, W.L.; Goad, W.K.; and Childers, B.A.: "A Digital Video Model Deformation System." Presented at the International Congress on Instrumentation in Aerospace Simulation Facilities, Williamsburg, Virginia, June 1987.
16. Winfree, W.P.; Welch, C.S.; James, P.H.; and Cramer, E.: "Thermographic Detection of Delaminations in Laminated Structures." Review of Progress in Quantitative Nondestructive Evaluation, Vol. 8, p. 1657, 1989.
17. Hall, R.M.; et al.: "Comparisons of Boundary-Layer Transition Measurement Techniques in the Langley Unitary Plan Wind Tunnel." Presented at the AIAA 7th Applied Aerodynamics Conference, Seattle, Washington, July 1989. Paper No. AIAA-89-2205.