Proceedings of the International Gas Turbine Congress 2003 Tokyo
November 2-7, 2003

IGTC2003Tokyo TS-105

Technology Requirements for Revolutionary Propulsion Systems of the 21st Century

Woodrow Whitlow, Jr.[1] Julian M. Earls[2] and Vernon W. Wessel[2]

[1]National Aeronautics and Space Administration Glenn Research Center
Mail Stop 3-5, 21000 Brookpark Road, Cleveland, OH 44135 USA
Phone: 1-216-433-3193, FAX: 1-216-433-8581, E-mail: Woodrow.Whitlow-1@nasa.gov
[2]National Aeronautics and Space Administration Glenn Research Center

ABSTRACT

The National Aeronautics and Space Administration (NASA) has defined goals that ensure the future health of the aviation industry. Revolutionary aircraft that will enable a new future of aviation and mobility are essential to that industry. This paper presents the objectives that must be achieved to revolutionize the aviation system and breakthrough technology solutions to meet the challenges. This paper highlights research accomplishments at the NASA Glenn Research Center that contribute to these solutions. The accomplishments include technologies that enhance aircraft safety, enable quiet aircraft engines as well as engines with reduced impact on air quality near airports and on global air quality, and will enhance our ability to move people and goods.

INTRODUCTION

In the United States, aviation is critical to the movement of goods and people. Americans per capita use aviation more than the citizens of any other country do, and personal trips account for more than 50 percent of U.S. air travel. Sixty percent of all trips over 1000 miles are completed by air, and the number of commercial travelers within the U.S. is expected to double in 10 years and triple in 20 years. This indicates that aviation has become an integral part of everyday American life, and its role will only continue to grow. To enable a safe, environmentally friendly expansion of the air transportation system, the National Aeronautics and Space Administration (NASA) has established a goal to revolutionize aviation.

One key to revolutionizing aviation is to make the safe air transportation system that we now enjoy even safer. The accident rate for commercial aviation is very low, but that rate has remained constant for the past two decades. Even with low accident rates, the anticipated growth in commercial aviation would mean a major accident frequency approaching one per week. NASA has established the objective to introduce technologies that would reduce the accident rate such that, with increased traffic and aging aircraft, the frequency of accidents in the future will be reduced drastically as compared with the baseline period of 1990 to 1996.

Technology solutions that ease the restrictions on the global aviation system must be found. Environmental issues related to aviation have resulted in limits being imposed on aircraft and airport operations worldwide. Community noise restrictions limit the hours and number of operations at all but the most remote airports. Fifty of the largest airports view noise as their largest concern, and noise concerns are among the major hurdles confronting improvements to the aviation infrastructure such as airport expansion. Because of the effects of aircraft and airport emissions on local air quality, regulations have constrained operations at several airports in the United States and prevented the basing of specific military aircraft within certain areas. Future efforts to address global warming concerns could lead to limitations on the number and type of aircraft flight operations. Clearly, noise and emissions issues must be solved to ensure that the air transportation of the future is not constrained and can provide the necessary capacity and accessibility.

This paper presents breakthrough technology solutions to accomplish the goal of revolutionizing the aviation system and research at the NASA Glenn Research Center (GRC) that contribute to achieving that goal. These solutions include propulsion controls and health management, methods for aircraft engine performance diagnostics, and containment systems for ultra-safe engine operations. Concepts for low-noise fans and nozzles to reduce aircraft engine noise are explored. Technologies for combustors that reduce nitrogen oxide emissions and improve local air quality near airports and that reduce carbon dioxide emissions to reduce aviation's impact on global air quality are discussed, including advanced combustor and active combustion control concepts. Energy storage devices that could enable all-electric aircraft that are whisper-quiet and pollution-free are discussed. Required advances in aerospace materials and electronics and sensors are presented and, finally, technologies that enhance freedom of movement for inter-city and long-haul travel are presented.

SAFETY

Using accident data from 1996 as a baseline, NASA established an objective to reduce aviation's fatal accident rate by a factor of five within 10 years and by a factor of 10 within 25 years. At GRC, the focus is on technologies that improve propulsion system safety.

When a propulsion malfunction is involved in an aviation accident or incident, it often is a contributing cause rather than the sole cause for the event. Simon (2000) defined propulsion health management (PHM) objectives to develop

Manuscript Received on April 19, 2003

and validate propulsion system health monitoring technologies. These technologies are designed to prevent engine malfunctions from occurring in flight and to mitigate detrimental effects in the event that such malfunctions occur. The NASA objective is to enhance safety by incorporating PHM technologies such as vibration diagnostics, model-based controls and diagnostics, advanced instrumentation, and general aviation propulsion system health monitoring into aircraft engines.

Uncontained turbine engine rotor failure, an event that results in the escape of debris through the engine nacelle envelope due to a rotating component failure, can result in catastrophic damage to the aircraft structure and systems and/or serious injury or fatalities to passengers and crew. An on-line, automated crack detection system will be capable of detecting turbine rotor disks cracks in the early stages by noninvasive monitoring of vibration measurements. The concept of model-based controls and diagnostics, shown in Figure 1 (Garg, 2002) provides prognostic and diagnostic capability and fault accommodation, preventing or reducing the severity of potential failures. Component health can be diagnosed through interpretation of high-response pressure measurements, and affordable engine crack detection instrumentation is needed for operation within harsh engine environments.

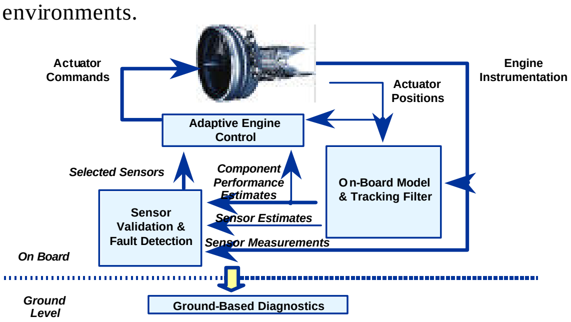

Figure 1. Model-based controls and diagnostics.

An aircraft engine life-extending control (Guo, 2001) is another method developed at GRC that can improve aviation safety. The controller design utilizes damage models to monitor the damage rate and accumulation for critical engine parts. Required technologies include sensors for crack detection and measurement, stress measurement, and tip clearance measurement. All of these sensors must be capable of operating in harsh engine conditions.

Kobayashi and Simon (2001) developed a model-based diagnostic method that used neural networks and genetic algorithms. Neural networks were used to estimate the engine internal health, and genetic algorithms were applied for sensor bias detection and estimation. Results showed that the approach is promising for reliable diagnostics of aircraft engines.

Kobayashi and Simon (2003) applied a bank of Kalman filters to aircraft gas turbine engine sensor and actuator fault detection and isolation (FDI) in conjunction with the detection of component faults. Each of the multiple filters is designed to detect a specific or actuator fault, and if a fault does occur, all filters except the one using the correct hypothesis produce large estimation errors, isolating the specific fault. The authors applied the FDI approach to a nonlinear engine simulation for nominal and aged conditions. This approach, which utilizes an on-board engine model, is possible due to the increase of digital computational power. In this work, Kobayashi and Simon demonstrated the ability to successfully detect and isolate sensor and actuator bias errors when faults are caused by foreign object damage, and the method is robust in the presence of engine degradation.

International aviation regulatory agencies require that aircraft turbine jet engines safely contain fan, compressor, and turbine blades should they be ejected during operation. To achieve this requirement, all commercial turbine jet engines include an engine blade containment system. In some cases, the system consists of a metal ring that is thick and strong enough to prevent blade penetration. Other systems consist of either relatively light metal or composite rings, a structure to provide stiffness, and a series of layers of impact-resistant dry fabric. In large turbofan engines, metal containment systems can have a mass of over 500 kilograms while fabric systems can have up to 25 percent less mass. Since polymers have yet to achieve the necessary long-term, high-temperature durability, metal systems are necessary for high-temperature applications such as around parts of the compressor and the turbine regions and for fans in supersonic jet engines where conditions are more demanding. For metal containment systems, Revilock and Pereira (2001) conducted impact tests in the GRC Impact Dynamics Facility (Figure 2) that showed that Inconel 718 and Titanium-6242 had better impact properties than three other candidate metals at room and at elevated temperatures.

Figure 2. GRC Ballistic Impact Facility.

Revilock et al. (2002) tested five braided fabric containment systems for ballistic impact performance and showed that for the same architecture, Zylon can absorb up to twice the kinetic energy before penetration than other materials (Figure 3), making it the better containment fabric.

EMISSIONS

The International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection is addressing worldwide concerns about local air quality and climate change. While not yet a significant concern at the global level, aircraft emissions already are a major concern in some communities. Some European airports are imposing landing fees based on aircraft emissions and in the United States, some of the busiest commercial airports are unable to increase flight operations because they are located in areas where air pollution levels consistently exceed the national standard. To enable further expansion of airport operations, nitrogen oxide (NO_x) emissions from future aircraft engines must be reduced in order to limit the resulting ground-level ozone.

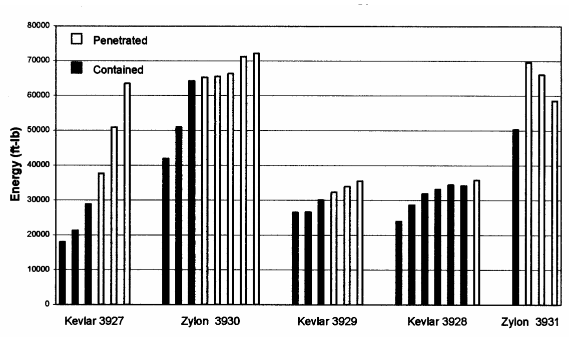

Figure 3. Fabric impact test energy.

Even with today's best technology improvements, global NO_x and CO_2 emissions are projected to increase by 400 percent and 300 percent, respectively, by 2050. NASA established the objective to reduce NO_x emissions by 70 percent within 10 years and by 80 percent within 25 years (using the 1996 ICAO standard as the baseline) and to reduce CO_2 emissions by 25 percent and by 50 percent in the same timeframes (using 1997 subsonic aircraft technology as the baseline). Reduction of NO_x will require advanced combustion technology, and CO_2 emissions reduction can be accomplished by reducing fuel burn through increased performance and efficiency. Meeting this objective requires overall engine pressure ratios as high as 55:1 – 60:1 and turbine inlet temperatures exceeding 1700ºC.

Demands for decreased emissions while increasing performance have resulted in advanced combustor designs that are dependent on effective fuel-air mixing and lean operation. Lean-burning, low-emissions combustors are susceptible to combustion instabilities that typically are caused by the interaction of the fluctuating heat release from the combustion process with naturally occurring acoustic resonances (Lefebvre, 1999). Due to non-uniformities in the fuel-air mixing and in the combustion process, hot areas that can be zones of increased NO_x formation exist in the combustor exit plane. Elimination of the hot streaks—reduction in pattern factor—can contribute to emissions reduction. It also is desirable to maintain a combustion zone fuel-air mixture ratio near stoichiometric to minimize the formation of carbon monoxide (CO) and unburned hydrocarbons (UHCs). However, mixture ratios near stoichiometric result in high flame temperatures and increased NO_x production. Control of the fuel-air ratio is required to minimize the production of CO, UHCs, and NO_x.

Active combustion control research at GRC includes combustion instability control, burner pattern factor control, and emission minimizing control (DeLaat et al., 2000). A neural network-based control approach, shown in Figure 4, was developed to attenuate thermo-acoustic instabilities observed in a lean premix-prevaporize (LPP) combustor flame tube. A burner pattern factor control system that is capable of producing a more uniform combustor exit temperature has been developed (DeLaat et al., 2000). The active distribution system delivers the required total fuel flow and, based on feedback from temperature sensors at the combustor exit plane, the control system sends signals to redistribute the total fuel inside the combustor. This results in as uniform a temperature distribution at the exit plane as possible. Preliminary testing showed that this method produced up to 52 percent reduction in pattern factor and up to 7 percent NO_x reduction. At some engine operating conditions, slight increases in CO (1 percent) and UHC (2 percent) were observed.

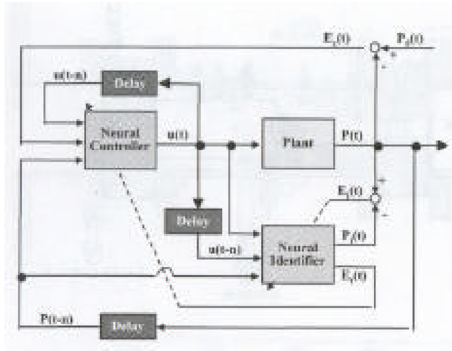

Figure 4. Neural combustion instability control approach.

LPP has demonstrated extremely low NO_x emissions in ground power applications. However, for higher pressure and temperature aircraft applications, LPP is susceptible to autoignition and flashback. An alternative to LPP systems is lean-direct injection (LDI) combustion in which the fuel is injected directly into the flame zone. While the potential for either auto-ignition or flashback is not present, it is important to achieve fine atomization and mixing of the fuel and air quickly and uniformly. This results in low flame temperatures and NO_x levels near those of LPP systems. Tacina et al. (2001) developed a lean-direct-wall-injection combustor concept in which fuel is injected into a swirling airflow from a fuel injector located on the combustor wall or mixer wall. The basic configuration is shown in Figure 5. A 75 percent NO_x reduction from the 1996 ICAO standard was obtained using this technology over a range of engine pressure ratios.

Tacina et al. (2002a) demonstrated multipoint, lean-direct injection concepts that had 25 and 36 fuel injectors in the size of a conventional single fuel injector. An integrated-module approach was used for the construction where photo-chemically etched laminates, diffusion bonded together, combine the fuel injectors, air swirlers, and fuel manifold into a single element (Figure 6). The top of Figure 6 shows the etched laminates, and the flame tube configuration is shown in the bottom of the figure. Flame tube tests of the 25-point configuration resulted in greater than 80 percent reduction in NO_x emissions from the 1996 ICAO standard. A 15-degree combustor sector test of the LDI concept using 36 injectors spaced farther apart (Figure 7) demonstrated a 70-percent NO_x reduction (Tacina et al., 2002b). The sector represented a realistic full annular combustor, including cooled liner.

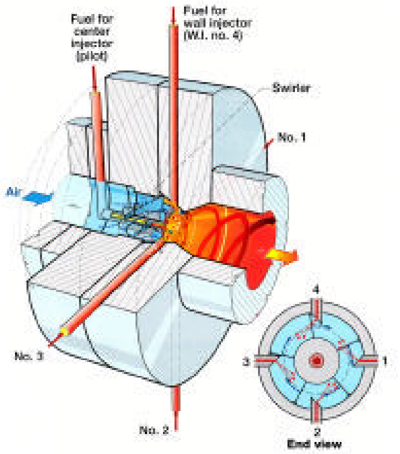

Figure 5. Lean-direct-wall-injection combustor concept.

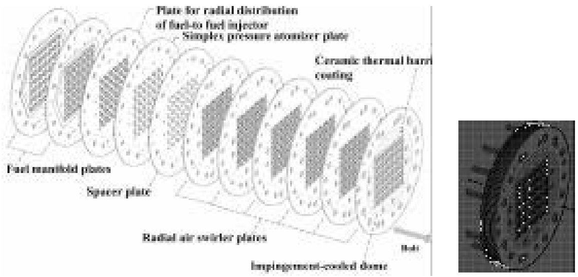

Figure 6. Multipoint integrated module.

An LDI concept that is a multiplex fuel injector concept (Figure 8) manufactured using conventional machining methods and containing multipoint fuel injection tips and multi-burning zones was developed to reduce NO_x emissions from advanced high-pressure aircraft gas turbine engines at all power conditions (Tacina et al., 2003). Flame tube tests of the multiplex LDI concept with 49 equally spaced injector tips in the size of a conventional, single-fuel injector demonstrated NO_x levels that are the same as the 25-point method developed by Tacina et al. (2002b) but slightly more than those obtained using the 36-point method reported in the same reference. This indicates that interaction effects are important in NO_x reduction and may represent a practical limit on the number of fuel injector sites.

Figure 7. 36-point, integrated module, 15º sector.

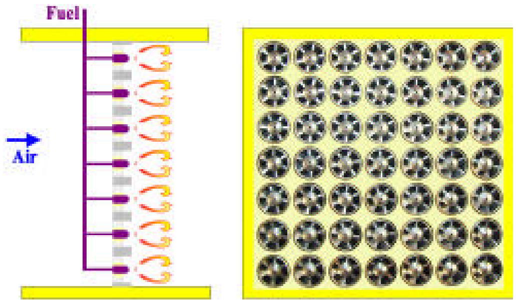

Figure 8. Multiplex fuel injector module.

Materials Challenges

Advanced high-temperature materials that lead to reduced NO_x and CO_2 emissions are being developed as part of NASA's Ultra Efficient Engine Technology Program (Misra, 2001). Meeting these goals requires overall engine pressure ratios as high as 60:1 and turbine inlet temperatures exceeding 1700ºC. Achieving an overall engine pressure ratio of up to 60:1 requires high-temperature disk alloys with temperature capabilities in the 700ºC – 760ºC range. Researchers from NASA, General Electric Aircraft Engines, and Pratt & Whitney developed a nickel-based powder disk superalloy for commercial and military engines that can withstand temperatures over 700ºC, an 80ºC increase over production disk alloys. The alloy was scaled up successfully to produce forgings typical of Boeing 737 aircraft engines (Figure 9), and over one million hours of testing demonstrated that the alloy has a balanced set of material properties that far exceeds state-of-the-art production material.

Figure 9. Boeing 737-size disk forging from new alloy.

The strategy for increasing turbine inlet temperature is to improve the capabilities of single-crystal nickel-based alloys and thermal barrier coatings (TBCs). An advanced, single-crystal nickel-base alloy with a 40ºC increase in temperature capability over the state-of-the-art alloy has been developed (Misra, 2001). One goal is to develop computational tools using multiscale models for the design of single crystal nickel-base alloys. Researchers at GRC and OAI have developed computational tools to design alloys at the atomistic level (Bozzolo et al., 1998). Coatings that will provide capability for a 165ºC increase in temperature gradient across the coating and surface temperature as compared to state-of-the-art yttria stabilized zirconia (YSZ) TBCs are under development. The approach is to develop low-thermal conductivity ceramic coatings that would be stable at higher surface temperatures and under large thermal gradients. Preliminary experiments showed that the thermal conductivity of YSZ could be lowered by up to 66 percent by adding various alloying oxides.

Silicon carbide (SiC) fiber reinforced silicon carbide (SiC/SiC) ceramic matrix composite (CMC) materials for combustor liners allow for higher temperature operation capability for gas turbine engines. Elimination or reduction of film cooling of the liner results in lower NO_x emissions (Misra, 2002). A CMC system with 1480ºC temperature capability has been developed in the Ultra Efficient Engine Technology Program. The system includes a CMC with 1315ºC temperature capability and an environmental barrier coating with 1480ºC capability and a 165ºC gradient across the coating (Misra, 2001). Activities are underway to develop a coating with 1480ºC capability. Use of SiC nanotubes as reinforcement for CMCs is being explored to develop a CMC system with 1650ºC capability. Vapor phase growth of SiC nanotubes by chemical vapor deposition and functionalizing the surface of carbon nanotubes to form SiC are being pursued as methods to produce SiC nanotubes.

Alternate Power

GRC researchers are developing electric power and propulsion technologies to reduce emissions from aircraft. Concepts under investigation include airbreathing fuel cells to produce environmentally benign, competitively priced, and durable systems for aircraft power and propulsion. Technologies under investigation include cell chemistries, advanced materials, and novel cell, stack, component and systems designs.

Solar cells have been used to produce electric power to run propeller motors during the day for an ultralight flying wing aircraft (Burke, 1999). Because there is no energy storage system aboard the aircraft to provide power in absence of sunlight, the planes are forced to glide back to earth at night. Regenerative fuel cell energy storage systems would produce reactants via electrolysis during the day using solar array power and, at night, use those reactants in a fuel cell to produce power to maintain the solar in flight. This would allow the aircraft to fly indefinitely. The energy storage system for such an airplane has been projected to require an energy density of at least 400 W-hr/kg (Burke, 1999), making regenerative fuel cell energy storage systems viable candidates.

Solid oxide fuel cells (SOFCs) are being explored as a means of alternate power and propulsion. Current gas turbine auxiliary power units (APUs) contribute 20 percent of airport ground-based emissions, and a fuel cell APU will lead to near zero emissions, lower noise, and could reduce aircraft fuel consumption. SOFCs are simpler in concept; their solid construction alleviates corrosion problems and gas crossover associated with liquid-electrolyte-based cells. Hydrogen and light hydrocarbons are suitable fuels and stack operating temperatures are compatible with fuel reforming techniques. To enable near-term application of SOFCs to aircraft power systems, efforts are underway to identify and characterize promising candidate hydrocarbon fuels. Fuel desulfurization techniques and sulfur-tolerant anodes are being developed to increase the durability of SOFC systems operating with sulfur-containing jet fuels. For aircraft operations, fuel cell power densities are required to be at least an order of magnitude greater than current state of the art. Current efforts include reducing anode thickness by a factor of 10 – 15, developing advanced interconnect and electrolyte materials to increase SOFC operating temperature, and developing durable high-temperature seals.

Kahout and Schmitz (2003) presented the results of a first-order feasibility study for an all-electric personal air vehicle utilizing a fuel cell-powered propulsion system. They considered the following configurations: a proton exchange membrane (PEM) fuel cell with liquid hydrogen storage; a direct methanol PEM fuel cell; and a direct internal reforming solid oxide fuel cell (SOFC)/turbine hybrid system using liquid methane fuel. The SOFC/hybrid system appears to offer the most potential in terms of achieving an acceptable range and take-off weight.

High-Temperature Electronics and Sensors

In order for future aeronautic engines to meet the increasing requirements for reduced emissions, reduced fuel burn, and increased safety, it is necessary to include intelligence in the engine design and operation. This implies the development of sensors, actuators, control logic, signal conditioning, communications, and packaging that will be able to operate under the harsh environments present in an engine. This requires technology advancements in four areas: high-temperature electronics, sensors, packaging of harsh environment devices, and silicon carbide electronic materials.

SiC appears to be the strongest candidate semiconductor for near-term implementation of 500ºC – 600ºC integrated electronics (Hunter et al., 2002). Discrete SiC devices such as pn junction diodes, Junction Field Effect Transistors (JFETs), and Metal Oxide-Semiconductor Field Effect Transistors (MOSFETs) have demonstrated excellent electrical functionality at 600ºC, but only for short periods. For such electronics to be useful in turbine engine applications, much longer 600ºC harsh-environment lifetimes must be realized. The operational lifetime of SiC-based transistors at 600ºC is governed primarily by the reliability and stability of various interfaces with the SiC crystal surface. Junction-based transistors without gate insulators appear more feasible in the near term. Hunter et al. (2002) reported that the pn junction gate JFET is closest to demonstrating long-term operation at 600ºC.

SiC-based pressure sensors have a much wider temperature range than standard sensors and can have high-temperature SiC electronics integrated with the sensor. However, improvements in micromachining and packaging for operating in harsh environments are required. Reactive ion etching to form well-defined diaphragm structures has been developed by Beheim and Salupo (2000), and a novel packaging strategy that decouples thermomechanical interactions between the sensors and packaging components has been demonstrated. A chip-level electronic package was designed, fabricated, and assembled for high-temperature harsh environment microelectronic systems using ceramic substrates and gold thick-film metallization. This packaging system has been tested successfully at 500ºC in an oxidizing environment for over 5000 hours.

To advance SiC electronic materials, improved SiC starting material should significantly enhance the development of electronics and sensor technologies. Recent work by Powell et al. (2000) has been aimed at improving the quality of the SiC starting material on which devices are fabricated. Eliminating the defects and growing step-free SiC surfaces are used to improve the starting material. They reported the formation of SiC mesa surfaces as large as 0.2 x 0.2 millimeters completely free of a single atomic step. Further work needs to be done to characterize these new material growth mechanisms and to realize the advantages in device properties that the uses of these new materials can provide.

NOISE

Airports once built in remote areas now are located closer to sprawling communities, and noise typically is the primary objection to airport and runway expansion. Airports are subject to an increasing number of noise restrictions affecting their operation and the operations of aircraft. Since 1980, the number of airports operating under noise restrictions worldwide has grown from 250 to over 825 and continues to increase. To address this issue, NASA established the objective to reduce the perceived noise levels of future aircraft by a factor of 2 (10 decibels) within 10 years and by a factor of 4 (20 decibels) within 25 years, using 1997 subsonic aircraft technology as the baseline. Reducing perceived noise levels by 20-decibels, in most cases, will contain objectionable aircraft noise within airport boundaries.

Quieting aircraft propulsion systems will provide significant progress towards meeting the noise objective. With the advent of high-bypass-ratio turbofan engines, the fan has become a major source of noise from modern commercial aircraft propulsion systems. At takeoff and on approach, fan and jet noise tends to dominate the engine total flyover noise signature even when noise suppression due to acoustic liners is included. Figure 10 (Kumasaka et. al, 1996) shows representative flyover noise levels, on a component basis, for several types of aircraft using turbofan engines representative of 1992 technology.

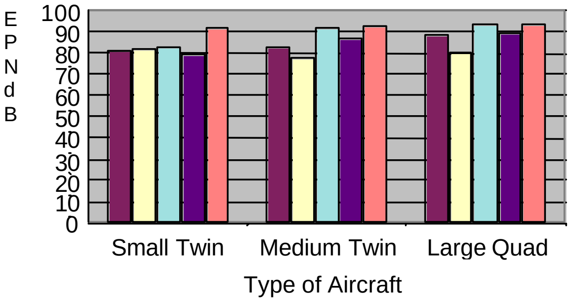

Figure 10a. Representative takeoff (sideline) noise levels.

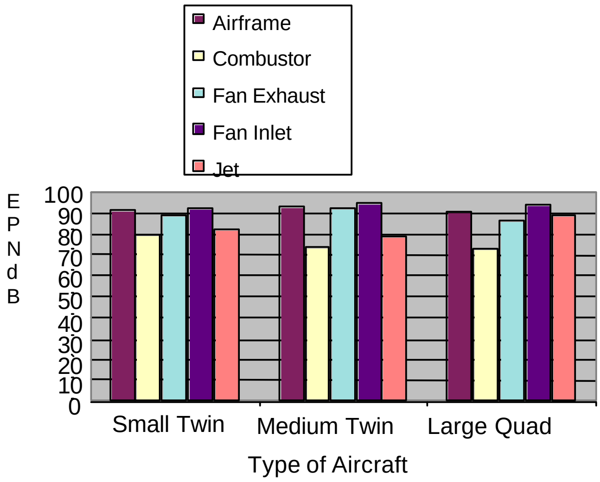

Figure 10b. Representative approach noise levels (1992 technology).

The anticipated increase in engine bypass ratio is likely to increase the importance of fan noise, making controlling and reducing this component of engine noise even more important.

A major source of engine noise comes from the interaction of the rotor viscous wake with the stators. Traditional methods of reducing this interaction noise have been to select blade/stator ratios to satisfy the cut-off criterion for propagation of the fundamental rotor tone and increased axial spacing between the rotor and stator. Increased rotor-stator axial spacing may degrade fan aerodynamic performance and increase engine weight.

NASA tested an advanced high-bypass-ratio fan with swept and leaned stators, shown in Figure 11, and demonstrated the benefits of this technology in reducing fan noise (Woodward et al., 1999). The results clearly showed that incorporation of either sweep and lean or sweep only could reduce rotor-stator tone levels significantly beyond what is achieved by relocating the conventional radial stator to the downstream location. When scaled to a two-engine aircraft, the results suggest that this technology could be used to achieve a significant portion of the NASA noise objective.

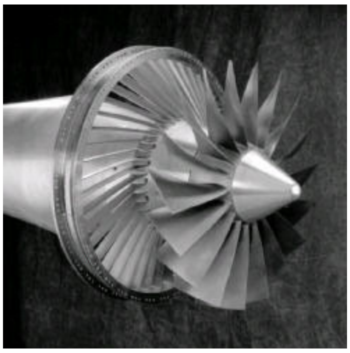

Figure 11. Partially assembled fan stage showing swept and leaned stators.

Testing at takeoff and approach flight conditions showed that acoustics benefits similar to those obtained for low-speed fans might be achieved for higher-tip-speed fans with similar stator sweep and lean (Woodward et al., 2002).

Rotor trailing edge blowing where the velocity deficit from the viscous wake of rotor blades is reduced by injecting air into the wake from a trailing edge slot was demonstrated for low-speed fan noise reduction (Sutliff et al., 2002). Figure 12 shows a model of a composite hollow rotor blade with the pressure side skin removed to show the internal flow passages. The passages are designed to deliver the injected flow at the design pressure and flow rate to fill the wake momentum deficit. Substantial reduction in the fan tone levels was achieved by filling the viscous wakes at a blowing rate of 1.6 percent – 1.8 percent of the fan mass flow rate. Figure 13 shows a typical result in which trailing edge blowing caused a more uniform mean flow profile. The inset shows that the wake harmonic amplitudes were reduced by more than a factor of two for the first four harmonics. This indicates the potential for significant noise level reductions using wake management technology.

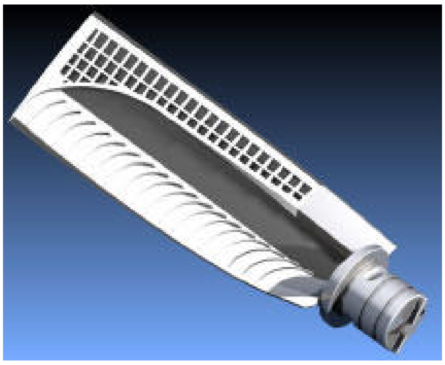

Figure 12. Internal flow passages for hollow fan blade, tested on low-speed fan rig.

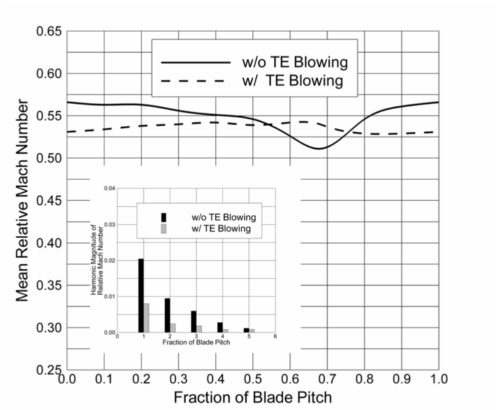

Figure 13. Effect of fan trailing edge blowing on mean flow profile in fan wake.

MOBILITY

The essence of freedom of movement hinges on aviation, and improving mobility by reducing travel time for long and short journeys requires a wide range of innovations and improvements. In response to these needs, NASA established an objective to reduce intercity door-to-door time by half in 10 years and by two-thirds in 25 years and reduce long-haul transcontinental travel time by half within 25 years.

For long journeys, affordable supersonic travel will be essential, but the technological challenges are significant. NASA is developing technologies to resolve problems that include engine emissions. The section on materials challenges in this paper contains technology solutions that could address engine emissions issues for supersonic transports.

NASA researchers developed technology that would reduce the cost of operating short-haul regional jets. Such jets could provide service to more airports and reduce the travel time between more destinations. Foil air bearings (Figure 14) (DellaCorte and Valco, 2000) and a high-temperature, shaft coating could replace ball bearings and lubricating oil found in conventional gas turbine engines (DellaCorte, 2002). The coating is used to reduce friction and wear of the air bearings during start-up and shut down when sliding occurs and prior to the formation a lubricating air film. The coating technology allowed the bearings to operate successfully at temperatures up to 650 °C. Studies have shown that for a 50-passenger jet, oil-free technology can reduce direct operating costs by 8 percent.

Figure 14. Photograph of foil air bearing.

CONCLUDING REMARKS

Since aviation has become an integral part of everyday life, NASA has defined a goal to revolutionize aviation. This will ensure the health of the air transportation industry by enabling a safe, environmentally friendly expansion of aviation. Revolutionary aircraft are required to reach the goals, and propulsion systems are a critical part of the strategy. Significant progress has been made in developing technology solutions that enhance the safety of aircraft engines, and that reduce their noise and emissions. Technologies that will enable people and goods to be moved farther and faster to anywhere at any time have been demonstrated. As the technologies critical to the advancement of aircraft propulsion systems continue to be developed, the goal of a safe, environmentally friendly air transportation will become closer to reality.

BIBLIOGRAPHIC REFERENCES

Beheim, G. M., and Salupo, C. S., 2000, "Deep RIE Process for Silicon Carbide Power Electronics and MEMS" Wide-Bandgap Electronic Devices, R. J. Shul, F. Ren, M. Murakami, and W. Pletschen, Eds., Warrandale, PA USA: Materials Research Society.

Bozzolo, G., Noebe, R. D., Ferrante, J., and Amador, C., 1998, "An Introduction to the BFS Method and its Use to Model Binary NiAl Alloys," NASA/TM-1998-208820.

Burke, K. A., 1999, "High Energy Density Regenerative fuel Cell Systems for Terrestrial Applications," NASA/TM-1999-209429.

DeLaat, J. C., Breisacher, K. J., Saus, J. R., and Paxson, D. E., 2000, "Active Combustion Control for Aircraft Gas Turbines," AIAA-2000-3500.

DellaCorte, C., and Valco, M. J., 2000, "Load Capacity Estimation of Foil Air Journal Bearings for Oil-Free Turbomachinery Applications," NASA/TM-2000-209782**.**

DellaCorte, C., 2002, "The Effects of Substrate Material and Thermal Processing Atmosphere on the Strength of PS304: A High Temperature Solid Lubricant Coating," NASA/TM-2002-211483.

Garg, S., 2002, "Propulsion Controls and Health Management Research at NASA Glenn Research Center," NASA/TM-2002-211590.

Guo, T.-H., 2001, "A Roadmap for Aircraft Engine Life Extending Control," 2001 American Control Conference.

Hunter, G. W., Neudeck, P. G., Okojie, R. S., Beheim, G. M., Powell, J. A., and Chen, L., 2002, "An Overview of High Temperature Electronics and Sensor Development at NASA Glenn Research Center," ASME Turbo Expo 2002.

Kahout, L. L., and Schmitz, P. C., 2003, "Fuel Cell Propusion systems for an All-Electric Personal Air Vehicle," NASA/TM—2003-212354.

Kobayashi, T., and Simon, D. L., 2001, "A Hybrid Neural Network-Genetic Algorithm Technique for Aircraft Engine Performance Diagnostics," AIAA-2001-3763.

Kobayashi, T., and Simon, D. L., 2003, "Application of a Bank of Kalman filters for Aircraft Engine Fault diagnostics," GT2003-38550.

Kumasaka, H. A., Martinez, M. M., and Weir, D. S., 1996, "Definition of 1992 Technology Aircraft Noise Levels and the Methodology for Assessing Airplane Noise Impact of Component Noise Reduction Concepts," NASA CR-198298.

Lefebvre, A. H., 1999, *Gas Turbine Combustion*, 2nd Edition, Taylor & Francis.

Misra, A. K., 2001, "Development of Advanced Engine Materials in NASA's Ultra Efficient Engine Technology Program," ISABE 2001-1106.

Misra, A. K., 2002, Ceramics and Ceramic Matrix Composite Research at Glenn Research Center, Presented at the 2nd NASA Advanced Materials Symposium, Cleveland, OH USA, May 30, 2002.

Owens, R. E., 1979, "Energy Efficient Engine Performance System – Aircraft Integration Evaluation," NASA/CR 159488.

Powell, J. A., Neudeck, P. G., Trunek, A. J., Beheim, G. M., Matus, L. G., Hoffman, R. W., Jr., and Keys, L. J., 2000, Growth of Step-Free Surfaces on Device-Size – (001)-SiC Mesas, *Appl. Phys. Lett*., **77**, pp. 1449 – 1451.

Revilock, D. M., and Pereira, J. M, 2001, "Ballistic Impact Performance of Metals for High-Temperature Jet Engine Fan Containment Applications," PVP Vol. 421, Thermal Hydraulics, Liquid Slushing, Extreme Loads and Structural Response, J. Moody, Ed.

Revilock, D. M., Jr., Pereira, J. M., Hopkins, D., and Braley, M., 2002, "Ballistic Impact Response of Braided Zylon and Kevlar for Jet Engine Fan Containment Applications," International Conference on Composites Engineering 9, July 2002.

Simon, D. L., 2000, "An Overview of the NASA Aviation Safety Program Propulsion Health Monitoring Element," AIAA-2000-3624.

Sutliff, D. L., Tweedt, D. L., Fite, E. B., and Envia, E., 2002, "Low-Speed Fan Noise Reduction With Trailing Edge Blowing," NASA/TM-2002-211559.

Tacina, R. R., Wey, C., and Choi, K. J., 2001, "Flame Tube NO_x Emissions Using a Lean-Direct-Wall-Injection Combustor Concept," AIAA-2001-3271.

Tacina, R., Wey, C., Liang, P., and Mansour, A., 2002a, "A Low NO_x Lean-Direct Injection, Multipoint Integrated Module Combustor Concept for Advanced Aircraft Gas Turbines," NASA/TM-2002-211347.

Tacina, R., Wey, C., Liang, P., and Mansour, A., 2002b, "Sector Tests of a Low-NO_x, Lean-Direct Injection, Multipoint Integrated Module Combustor Concept," GT-2002-30089.

Tacina, R., Mao, C.-P., and Wey, C., 2003, "Experimental Investigation of a Multiplex Fuel Injector Module for Low Emissions Combustors." AIAA 2003-0827.

Woodward, R. P., Elliott, D. M., Hughes, C. E., and Berton, J. J., 1999, "Benefits of Swept and Leaned Stators for Fan Noise Reduction," AIAA-99-0479.

Woodward, R. P., Gazzaniga, J. A., Bartos, L. J., and Hughes, C. E., 2002, "Acoustic Benefits of Stator Sweep and Lean for a High Tip Speed Fan," AIAA-2002-1034.