



# NASA Collaborative Research on the Ultra High Bypass Engine Cycle and Potential Benefits for Noise, Performance, and Emissions

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# NASA Collaborative Research on the Ultra High Bypass Engine Cycle and Potential Benefits for Noise, Performance, and Emissions

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## Abstract

The National Aeronautics and Space Administration has taken an active role in collaborative research with the U.S. aerospace industry to investigate technologies to minimize the impact of aviation on the environment. In December 2006, a new program, called the Fundamental Aeronautics Program, was established to enhance U.S. aeronautics technology and conduct research on energy, efficiency and the environment. A project within the overall program, the Subsonic Fixed Wing Project, was formed to focus on research related to subsonic aircraft with specific goals and time based milestones to reduce aircraft noise, emissions and fuel burn. This paper will present an overview of the Subsonic Fixed Wing Project environmental goals and describe a segment of the current research within NASA and also were worked collaboratively with partners from the U.S. aerospace industry related to the next generation of aircraft that will have lower noise, emissions and fuel burn.

## Introduction

NASA has a strong and successful history of collaborative research partnerships with the U.S. Aerospace Industry, Academia, and Other U.S. Government Agencies. Since the early 1990s, NASA research on subsonic aircraft propulsion has focused on the Ultra High Bypass (UHB) engine cycle to determine its potential for reducing noise, increasing aerodynamic performance and decreasing emissions. The NASA definition of the UHB cycle refers to a propulsive-to-power component mass flow ratio, or bypass ratio, greater than 13 to 1. Under previous NASA technology programs, UHB propulsion research efforts (Refs. 1, 2) were focused mainly on reducing noise of the propulsor and core components (principally fan and jet exhaust) of the turbofan, or ducted fan, engine through scale model testing in wind tunnel and component rig environments. With

the creation of the Fundamental Aeronautics Program (FAP) Subsonic Fixed Wing (SFW) Project, subsonic aeronautics research has been refocused to include the entire aircraft and technologies related to reducing its environmental impact (Ref. 3). The project metrics are focused on reducing noise, emissions and fuel burn, and are segmented into three time frames spanning three generations of aircraft (N+1, N+2 and N+3) beyond the current generation, N (Fig. 1).

CORNERS OF THE TRADE SPACE	N+1 = 2015*** Technology Benefits Relative To a Single Aisle Reference Configuration	N+2 = 2020*** Technology Benefits Relative To a Large Twin Aisle Reference Configuration	N+3 = 2025*** Technology Benefits
Noise (cum below Stage 4)	-32 dB	-42 dB	-71 dB
LTO NO <sub>x</sub> Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-40%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metro-plex* concepts
<small>***Technology Readiness Level for key technologies = 4-6                      ** Additional gains may be possible through operational improvements                      * Concepts that enable optimal use of runways at multiple airports within the metropolitan area</small>			

Figure 1. “Corners of the Trade Space” table showing Subsonic Fixed Wing Project system level metrics. Goals addressed by the research described in this paper (N+1) are shown highlighted in the red box.

SFW Project propulsion research has also centered on the Ultra High Bypass (UHB) engine cycle and advanced technologies applicable to it as the direction to pursue to reach the project performance goals. The nearer term project goals are aimed at aircraft entering the commercial market in the 2015 time period (N+1).

This paper will provide an overview of the collaborative, UHB-cycle focused research that the SFW Project and its U.S. industry partners are working on together to reach the N+1 environmental goals. Specific research subprojects will be highlighted that have contributed to meeting those goals, including a description of the subproject research, its objectives, and a brief summary of the test results obtained so far. Potential future NASA/Industry collaborative research

project plans in the area of UHB propulsion technology will also be briefly outlined.

### NASA/P&W Ultra High Bypass Turbofan Research

Under the Engine Validation of Noise and Emissions Reduction Technologies (EVNERT) task of the NASA Glenn Revolutionary Aero Space Engine Research (RASER) contract, which was sponsored by the NASA Quiet Aircraft Technology program, NASA and Pratt & Whitney (P&W) formed a collaborative partnership to develop an Ultra High Bypass engine demonstrator (Refs. 4, 5). The goal was to verify the potential advantages in reducing fuel burn, noise and emissions that could be achieved with an engine cycle having a fan to core flow bypass ratio of 13 and a fan pressure ratio of 1.3. P&W designed their engine, which they labeled the Geared Turbofan (GTF), with a geared Low Pressure Core fan allowing the core and fan to operate at different speeds, thus optimizing the performance and reducing the complexity of the core. Figure 2 shows the projected noise and fuel burn reduction potential P&W predicted for the GTF compared with current technology turbofans.

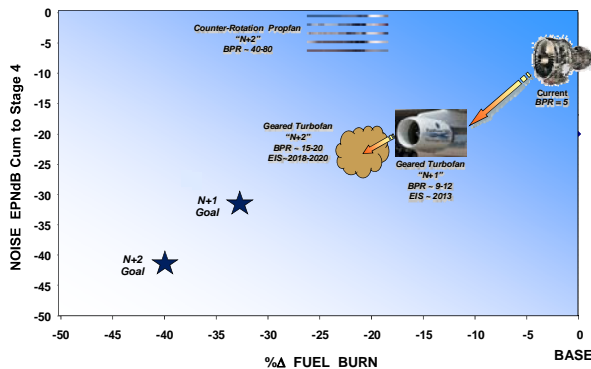


Figure 2. Pratt & Whitney chart of potential noise and fuel burn benefits of the Geared Turbofan compared with current generation UHB turbofans. Also shown is the potential fuel burn benefit of the P&W counter rotation propeller propulsion concept, as well as the progress required to achieve NASA N+1 performance goals.

The N+1 noise goal is also shown in the figure for comparison, as well as the estimated fuel burn for a potential P&W counter rotation propeller propulsion concept. Figure 3 is a cutaway illustration of the GTF engine and identifies the areas of research that were successfully impacted by the NASA and P&W collaboration. In order to mitigate the risk of this advanced engine design, NASA and P&W

collaboratively conducted two scale model wind tunnel tests to validate the design.

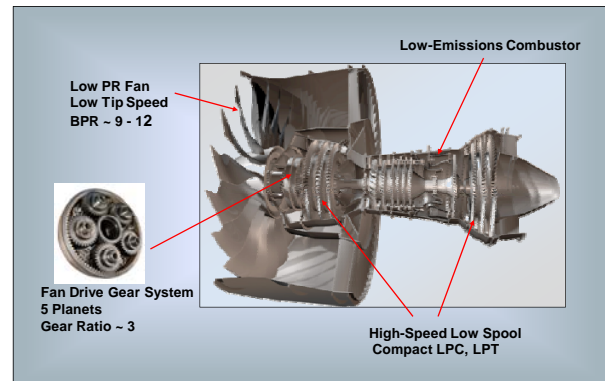


Figure 3. The P&W Geared Turbofan and collaborative component technologies studied by the NASA/P&W research partnership under the NASA Quiet Aircraft Technology Program (QAT).

The first was a 22” scale model test of the GTF bypass section, including the bypass fan, outlet stators, core inlet and nacelle simulation, conducted in the NASA Glenn anechoic 9- by 15-Foot Low Speed Wind Tunnel (9’x15’ LSWT) in 2006 (Left side in Fig. 4).



Figure 4. Highlights of NASA/P&W collaborative, scale model tests of the Geared Turbofan.

The test measured the aerodynamic performance, acoustic signature, and aeromechanical properties of the advanced bypass fan design. The model was run using the Glenn Ultra High Bypass Drive Rig propulsion simulator used to power turbofan models during testing in the wind tunnel. The test successfully met several key technology objectives: the high fan efficiency and low noise potential of the advanced, low pressure ratio, low tip speed UHB cycle were demonstrated; the design risk was successfully mitigated by identifying the aeromechanical properties, flutter or stall boundaries, of the advanced fan design. The data results from the 22” rig test were also used by

P&W to define the aerodynamic and acoustic design of the full scale GTF Engine Demonstrator. The second collaborative test to mitigate risk was an airframe integration test conducted in the Ames 11' wind tunnel in 2008. The test objectives were to validate the predicted impact of the UHB nacelle on the aircraft wing in both high lift and cruise configurations, and to optimize its location to minimize the impact (Right side in Fig. 4). A 12% half-span scale model was designed by P&W and incorporated a powered, bypass ratio 9, engine simulator in a potential GTF nacelle configuration. Force balance measurements of the half-span model under power were obtained to measure the change in wing lift and moment coefficients at several fan speeds and various nacelle mounting locations relative to the wing. Flow diagnostic data in the form of Pressure Sensitive Paint and static pressure measurement on the wing, nacelle and engine pylon were also obtained to quantify the local flow physics. The results from the test successfully showed that no adverse impact on wing lift was produced for the range of nacelle configurations investigated (Ref. 6). In addition, this test paved the way for future collaboration between NASA and P&W by providing a baseline for investigating more advanced UHB installation studies. Additional scale model fan testing is also planned in the Glenn 9'x15' wind tunnel for a NASA/P&W collaborative investigation of a second generation GTF, tentatively scheduled for late FY11.

In 2008, the collaborative design effort for the GTF led to the first full scale engine demonstration at P&W facilities (Ref. 7). The engine demonstrator successfully validated the noise, fuel burn and LTO NOx emissions reductions possible with the UHB engine cycle (Fig. 5).

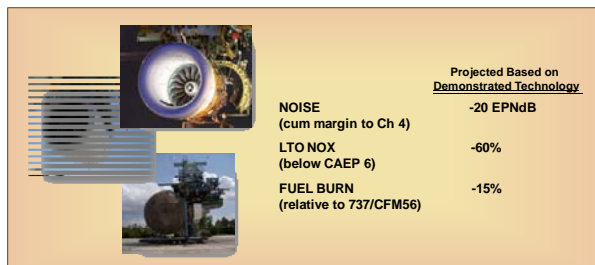


Figure 5. Performance goals demonstrated during the collaborative NASA/P&W Geared Turbofan Engine Demonstrator Test in 2008.

Engine component efficiencies met or exceeded P&W predictions, while the unique fan drive gear system demonstrated expected operational characteristics. As

part of the GTF Demonstrator Engine test, NASA sponsored the first successful demonstration of an alternative fuel and its impact on performance and emissions (Ref. 8). Figure 6 shows the engine on the test stand and the engine exhaust gas sampling configuration, including photographs of the sampling probes used.



Figure 6. Geared Turbofan Demonstrator Engine shown on P&W engine test stand during Alternative Fuels test. Inset in the center shows the exhaust gas sampling configuration. Inset on the right side of the picture is a close-up view of exhaust sampling probes used during testing.

The fuel was a 50/50 blend of a Fischer-Tropsch (F-T) synthetic fuel and JP-8 aviation fuel. The fuel blend properties met all specifications for aviation fuel. Comparative tests using the alternative fuel and standard JP-8 were conducted with the GTF to determine performance and emissions impacts. The results showed positive trends in emission performance with no significant difference in gas emissions and reduced particle emissions with the alternative fuel. The most significant impact occurred at idle conditions, where both emissions were greatly reduced. Aerodynamic performance results provided by P&W from the test showed a negligible impact on engine TSFC.

### NASA UHB Fan Noise Reduction Research

To help meet the aggressive N+1 noise reduction goal of 32 dB cumulative below the Stage 4 noise regulation, the SFW Project supported a high fidelity wind tunnel experiment of a scale model UHB turbofan simulator to investigate the potential of two advanced noise reduction technologies, called Over-the-Rotor (OTR) metal foam acoustic treatment and Soft Vanes (SV) acoustically treated stator vanes, for the UHB engine cycle (Fig. 7). The technologies were developed in a partnership between the NASA Glenn Research Center and the NASA Langley Research Center. The testing was conducted in the NASA Glenn 9'x15' LSWT using the Glenn UHB Drive Rig propulsion simulator at test section velocities

simulating aircraft takeoff, approach and landing speeds. The goal of these two technologies was to reduce the noise generated by the fan rotor, and that generated by the interaction of the rotor wakes with the stator vanes with a minimum impact on the aerodynamic performance of the fan (Ref. 9).

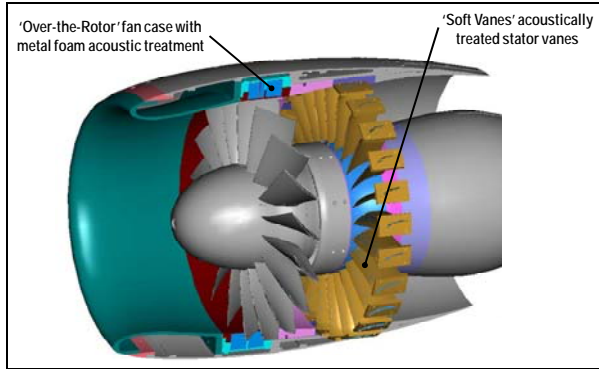


Figure 7. Illustration of the UHB Fan Model identifying the locations of two noise reduction technologies used during the NASA Ultra High Bypass Fan Noise Reduction Test, which were Over-the-Rotor acoustic treatment and Soft Stator Vanes.

Both technologies were designed to modify the local unsteady pressure response to the flow perturbations and reduce the strength of the local noise sources by mitigating and absorbing the acoustic energy (Refs. 10, 11).

The Over-the-Rotor acoustic treatment was designed to replace the traditional hardwall fan case and rubstrip over the fan tip. The new design consisted of a 0.10" thick perforated hard plastic polymer flow surface with a 1.5" thick porous metal foam material behind it and contained within a steel shell which interfaced with the rest of the model hardware (Fig. 8). The hard plastic flow surface had 0.035" holes drilled into it resulting in a 20% open area and allowing the acoustic pressure disturbances to pass through into the metal foam liner behind it. The size and number of holes was designed to minimize impact on the fan aerodynamic performance. The metal foam had a density of 6% to 8% (or 94% to 92% open area) with extremely small holes of approximately 100 pores per cubic inch of material. The metal foam presented a random and tortuous path to the incoming acoustic waves, forcing dissipation of the wave energy internally in the foam.

The Soft Vanes were acoustically treated stator vanes designed as replacements for the cut-on set of 25 hard wall stator vanes that were used as the hardware baseline. The SV design consisted of a hollowed out

metal shell in the aerodynamic shape of the existing vane. Internally, the hollow cavity was divided into four chambers of varying volumes, separated by thin metal membranes (Fig. 9). Each chamber was sized to dissipate the acoustic energy in a specific frequency, with the size of the chamber dependent on the target frequency. On the suction side of the vanes, from about 10% to 40% of the airfoil chord, the solid flow surface was perforated with 0.035" holes providing 10% to 15% open area in the material. A fine metal mesh was placed over the surface holes to form a smooth aerodynamic flow surface.

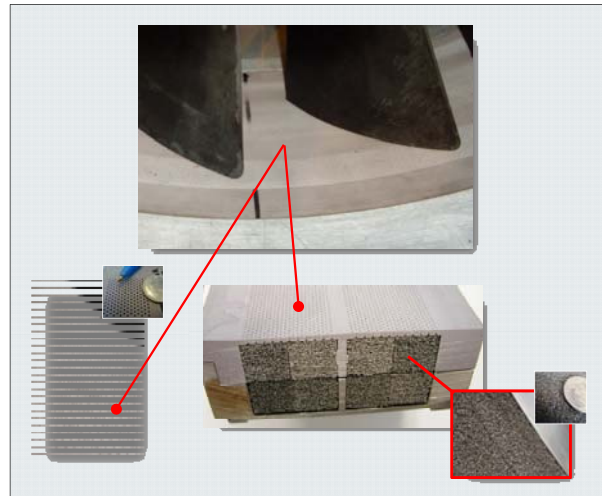


Figure 8. Photographs showing the porous Over-the-Rotor metal foam acoustic treatment used to replace the traditional fan case and rubstrip. Insets show close-ups of the porous flow surface of the replacement rubstrip and the foam metal treatment enclosed behind the porous rubstrip and metal fan case.

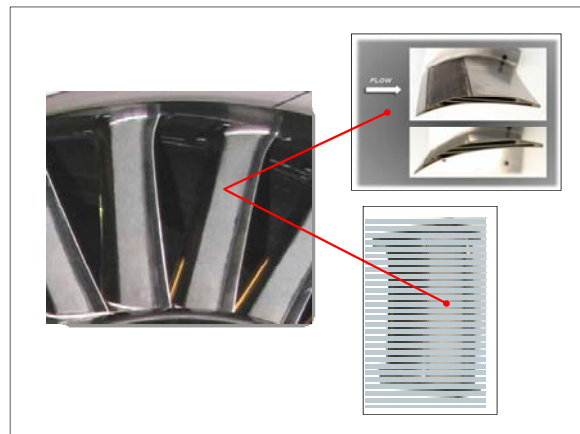


Figure 9. Photographs of the Soft Stator Vanes model assembly. Insets show an individual Soft Stator Vane as well as the internal cavities and the porous, suction surface open area near the vane leading edge, which



allows acoustic pressure disturbances to penetrate into the cavities.

The design allows the local acoustic waves on the vane suction surface to penetrate into the vane's four internal chambers, where the acoustic energy would dissipate. There were a total of three metal foam designs investigated. The acoustic results obtained in this experiment showed that these first generation OTR and SV noise reduction technologies were successful in reducing the fan noise sources. Two of the three OTR acoustic treatments did reduce the fan noise in terms of Overall Sound Pressure Level produced by the fan tip flow interaction with the fan case up to 2 dB at fan speeds from 62% to 92% of the fan design speed. In terms of the corresponding fan aerodynamic performance, challenges remain to decrease the OTR impact at the blade tip. Fan adiabatic efficiency for the two promising OTR treatments decreased between 0.5 and 4 percent across the fan operating speed range (Ref. 9). The SV acoustically treated stator vanes also showed up to 1 dB reduction in rotor-stator interaction noise achieved at most fan speeds. With the hardwall fan case installed with SV, there was negligible change in fan efficiency or thrust, and less than 0.5% loss in stage thrust (the combined fan and stator thrust). However, in both cases fan blade hardware problems prevented a full assessment of their potential acoustic benefits. The acoustic tests and results are described in Reference 12. Under the new NASA Environmentally Responsible Aviation (ERA) Project, second generation OTR and SV technologies are currently being considered for further investigation into their potential acoustic benefits. The anticipated scale model demonstration test of these second generation designs in the 9'x15' LSWT is tentatively planned for late FY11.

### **NASA/GE Open Rotor Research**

With high oil and fuel prices in 2007 and 2008, the SFW Project embarked on new research campaign, in collaboration with General Electric Aviation (GE), to investigate open rotor propulsion for the next generation of commercial passenger aircraft. This type of propulsion had been previously investigated via another NASA/GE partnership in the late 1980s and early 1990s under the NASA Advanced Turboprop Project and GE's GE36 Unducted Fan Program. A counter rotation propeller test rig developed for and last used during those programs was brought out of storage, the mechanical components revitalized, and the data systems and controls technology modernized by NASA.

Scheduled to start in September 2009, a new test campaign will begin using this test rig, now known as the Open Rotor Propulsion Rig (ORPR), to investigate a series of advanced propeller fan blade designs to determine the potential fuel burn reduction that can be achieved today with open rotor propulsion (Fig. 10). Current estimates by GE are that modern open rotor propulsion will save 10% in fuel burn (with a commensurate reduction in CO<sub>2</sub>) immediately compared to current generation turbofan engine technology, and ultimately up to 25% with advanced open rotor designs (Fig. 11).



Figure 10. Illustration of the NASA Glenn Open Rotor Propulsion Rig in a 12x10 propeller fan blade configuration in the Glenn anechoic 9'x15' Low Speed Wind Tunnel. Also shown in the illustration is the generic engine pylon simulator and support sting installed in front of the rotors to determine installation effects on the rotor system performance.

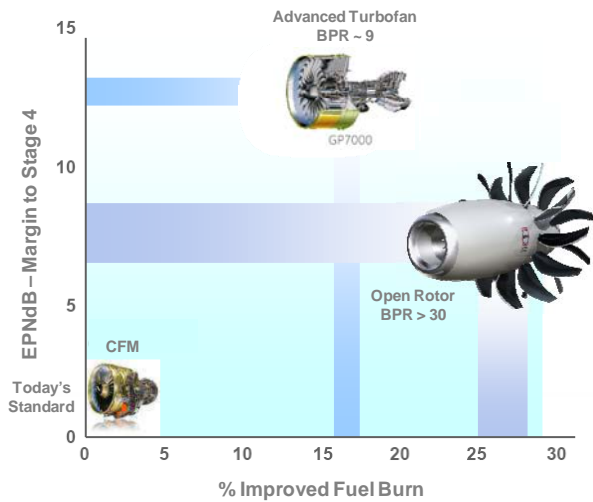


Figure 11. Noise reduction and improved fuel burn potential of GE open rotor propulsion compared with current and advanced GE/CFM turbofan engine technology.

During the test campaign, the acoustic noise levels produced by the new open rotor designs will be measured and characterized. Previous open rotor research during the 1980s had shown that while tremendous fuel savings were possible, the open rotor designs produced strong noise signatures that would need to be overcome before they could be incorporated into new aircraft designs. Based on previous experience and using today's more advanced design, analysis, and performance prediction tools, the propeller fan blade designs can take advantage of modern materials and manufacturing techniques to produce three dimensional geometries to increase performance and reduce noise. Once the low speed flight regime has been investigated, promising fan blade candidates as well as the baseline design will undergo further high speed tests in the Glenn 8'x6' High Speed Wind Tunnel. The aerodynamic performance of the fan blade designs at the simulated aircraft max climb/cruise flight regime will be investigated during this test campaign which is planned to start in mid 2010.

The NASA ORPR has the two, independently driven air turbines capable of producing up to 750 shp per shaft to power each fan rotor. Each rotor assembly consists of a rotating dynamic force balance, rotating telemetry unit and fan blade hub (Fig. 12).

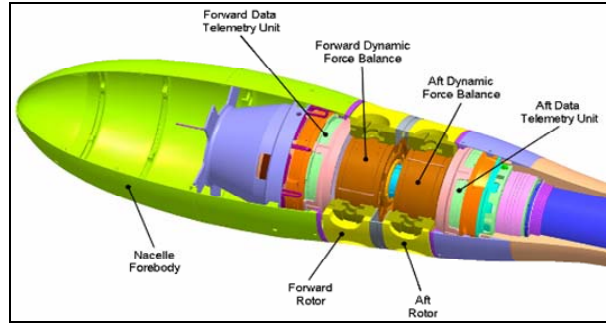


Figure 12. Illustration of Open Rotor Propulsion Rig component layout, including orientation of the rotors, force balances and telemetry data systems.

Aerodynamic forces produced by each rotor are measured with rotating dynamic force balances. Each rotor balance is capable of measuring up to 400 lbs of thrust and 450 ft-lbs of torque. The rotor telemetry unit has a 40 channel digital system through which fan blade strain gage signals and other pressure and temperature data acquired with each rotor are transmitted. The data signals are received by a non-rotating, co-located antenna, which sends the signals to a base ground station and then onto the facility data acquisition computer system.

The current NASA/GE open rotor test campaign, initiated by SFW Project and now sponsored by the ERA Project, is a 12x10 fan blade configuration, meaning 12 blades on the forward row and 10 blades on the aft row (Fig. 13). In addition, NASA will investigate installation effects on the system aerodynamic and acoustic performance using a generic engine pylon simulator mounted in front of the first rotor (Fig. 13).

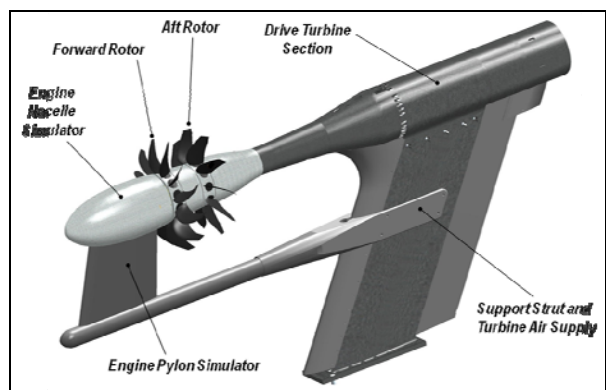


Figure 13. Illustration of the complete Open Rotor Propulsion Rig test assembly with propeller fan blades, and shown in the Installed Configuration with engine pylon simulator.

Testing in the NASA Glenn 9'x15' LSWT simulates aircraft flight conditions at takeoff, approach and landing, including angle of attack. The variable-pitch fan blades are a 1/5 scale model representation of a potential full scale engine design. The first blade set that will be tested (Fig. 14) will provide a baseline for comparison with other, more advanced GE designs. The model operating conditions investigated will provide data on fan blade performance across the range of expected aircraft operating conditions during the aircraft flight transition from ground idle to near takeoff rotation speed. Several freestream Mach numbers, rotor operating speeds, rotor power loading variations, fan blade pitch angles and model angles of attack will be investigated to determine their effect on the aerodynamic performance and acoustic noise signature of the system. The objective will be to determine the optimum conditions to maximize performance and minimize noise for the open rotor system. Test results obtained from the baseline propeller fan configuration will be used by NASA to compare and validate computer based design, analysis and optimization codes as well as aerodynamic and acoustic performance prediction codes. Six additional blade sets designed by GE and their industry partners will be tested to investigate and quantify the effect of blade geometry and configuration on the open rotor system aerodynamic efficiency, acoustic signature, and mechanical and aeroelastic stability.

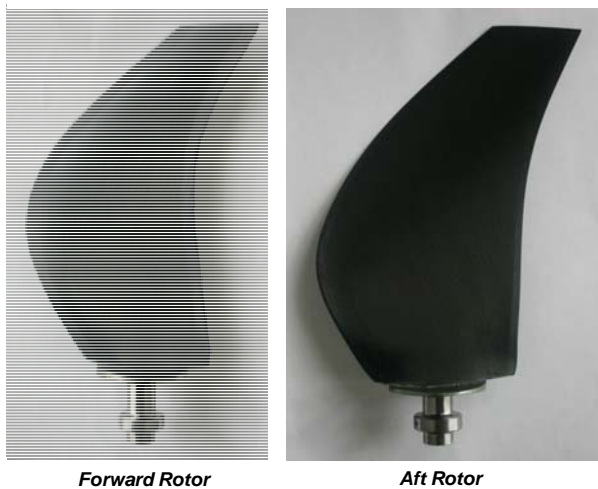


Figure 14. Photos of the Open Rotor Baseline Propeller Fan Blades that will be tested in the NASA Glenn 9'x15' LSWT in 2009 as part of the collaborative NASA/GE research test campaign into new Ultra High Bypass Propulsion Concepts for future aircraft.

In addition to using the force balance to measure aerodynamic performance of each rotor, rotor disk loading profiles will be measured downstream of the aft rotor using a multi-sensor pressure/temperature rake and a flow angle rake. Diagnostic information such as flowfield turbulence in front of and behind each rotor will also be obtained using a traversing hot film sensor. Fan blade deflections under aerodynamic and centrifugal load will be recorded with a high speed video imaging system. NASA will test three new diagnostic testing techniques at the end of the test to understand the flowfield dynamics. The first diagnostic technique is Particle Image Velocimetry (PIV) (Ref. 13), which will be used to understand the flow field surrounding and between the rotors. PIV uses a sheet laser to illuminate seeding material dispersed throughout the flow field to visualize its characteristics. The images are recorded with cameras located near the model. The second diagnostic technique is Pressure Sensitive Paint (PSP) (Ref 14), which will be used to visualize the pressure and temperature distributions on the propeller fan blade surfaces. A special light sensitive paint is applied to the individual blades which are then illuminated with a black light during testing. The illumination changes color as the pressure and temperature on the fan blades change. The images are recorded with sensitive high speed cameras. The last diagnostic technique is an acoustic Phased Array (PA) (Ref. 15). An array of microphones is accurately mounted in a spiral arrangement on a flat plate. The system is used to simultaneously record acoustic information from the microphone array in a specific area on the model, and then special software algorithms are used to quantify the noise levels in the measurement area. This technique will be used to identify high level noise sources on the model for further investigation.

### Summary

The collaborative research on the Ultra High Bypass engine cycle conducted by U.S. Industry and NASA through the Fundamental Aeronautics Program's Subsonic Fixed Wing Project has been reviewed in this paper. Three specific areas of research have been highlighted: UHB fan noise reduction technology in collaboration with NASA Langley; Open Rotor propulsion technology in collaboration with GE Aviation; and Geared Turbofan technology in collaboration with Pratt & Whitney. In all three areas, research was performed to address the system level metrics of the SFW Project to mitigate the impact commercial aircraft have on the environment by reducing aircraft noise, fuel burn and emissions.

Under Ultra High Bypass Engine Cycle research, NASA has teamed with P&W to develop and demonstrate an UHB demonstrator engine which P&W has labeled the Geared Turbofan. The tremendous performance potential of this engine cycle was successfully demonstrated by P&W in a full-scale static engine test in 2008. Prior to this test, NASA and P&W jointly conducted two scale model wind tunnel tests to understand the performance and operating characteristics of the fan and impact of the UHB installation on the aircraft. A 22" fan test was conducted in the Glenn 9'x15' wind tunnel which successfully documented the fan blade aero design performance and noise characteristics. The results were directly used to in the full scale GTF design. The second test was a 12% half-span aircraft wing test in the Ames 11' wind tunnel to understand and minimize the impact of the UHB fan/nacelle on the wing aerodynamics. The successful test results defined the optimum position of the engine on the wing.

Under the NASA fan noise reduction technology effort, two technologies have been investigated to reduce the noise signature of fan noise sources: Over-the-Rotor acoustic treatment and Soft Vanes acoustically treated stators. Testing recently completed in late 2008 show first generation designs were able to reduce the noise signature of the fan tip flow interaction with the fan case by as much as 2 dB in certain flight regimes, but model hardware problems prevented a demonstration of its full potential. Fan performance losses were on the order of 0.5 to 4 percent in adiabatic efficiency in the same fan speed operating ranges. Soft Vanes were able to reduce the rotor-stator interaction noise source up to 1 dB over the fan operating speed envelope. Further research is being planned to enhance noise reduction capabilities of these technologies.

Under Open Rotor propulsion technology, NASA and GE have entered into a Space Act Agreement to collaboratively explore open rotor technology to significantly reduce fuel burn and carbon footprint. NASA has reactivated and modernized its counter rotation propeller test rig previously used during the 1980s with GE in the Unducted Fan program under the NASA Advanced Turbo Prop Project. The new rig named the Open Rotor Propulsion Rig will be used by GE in testing in the NASA Glenn anechoic 9'x15' Low speed Wind Tunnel to investigate new, modern fan blade designs and establish the potential fuel burn reduction that can be achieved, as well as document the acoustic signature of the concept and establish noise levels relative to Stage 4 aircraft noise regulations.

Testing will begin in September 2009 with a baseline fan blade configuration. Follow-on testing to establish the high speed cruise performance of the open rotor configurations in the Glenn 8'x6' High Speed Wind Tunnel is also planned for mid 2010.

Under the Subsonic Fixed Wing Project and the new Environmentally Responsible Aviation Project, NASA will continue its collaboration with the U.S. Industry, Academia and other Government Agencies to investigate new technologies to reach the aggressive goals set forth by U.S. President and Congress and minimize the impact of commercial aviation on our environment.

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<b>14. ABSTRACT</b> The National Aeronautics and Space Administration has taken an active role in collaborative research with the U.S. aerospace industry to investigate technologies to minimize the impact of aviation on the environment. In December 2006, a new program, called the Fundamental Aeronautics Program, was established to enhance U.S. aeronautics technology and conduct research on energy, efficiency and the environment. A project within the overall program, the Subsonic Fixed Wing Project, was formed to focus on research related to subsonic aircraft with specific goals and time based milestones to reduce aircraft noise, emissions and fuel burn. This paper will present an overview of the Subsonic Fixed Wing Project environmental goals and describe a segment of the current research within NASA and also were worked collaboratively with partners from the U.S. aerospace industry related to the next generation of aircraft that will have lower noise, emissions and fuel burn.					
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