Large-scale Boundary Layer Ingesting Propulsor Research

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ABSTRACT

NASA's Advanced Air Transport Technology (AATT) project is investigating boundary layer ingesting (BLI) propulsors for advanced subsonic commercial vehicle concepts to enable the reduction of fuel burn. A multidisciplinary team of researchers from NASA, United Technologies Research Center (UTRC), Virginia Polytechnic University, and the Air Force Arnold Engineering Development Complex developed and tested an embedded BLI inlet and distortion-tolerant fan (BLI^{2}DTF) system in the NASA Glenn Research Center (GRC) 8-foot by 6-foot (8x6) transonic wind tunnel. The test demonstrated the component performance goals necessary for an overall fuel burn reduction of 3 to 5 percent on a large hybrid wing body (HWB) aircraft. Special test equipment, including a raised floor with flow effectors and a bleed system, was developed for use in the 8x6 to produce the appropriate incoming boundary layer representative of an HWB application. Detailed measurements were made to determine the inlet total pressure loss and distortion, fan stage efficiency, and aeromechanic performance including blade vibration stress and displacement response. Results from this test were used as input to a vehicle-level system study performed by the AATT project to assess the impact of BLI on an alternative advanced concept aircraft referred to as the NASA D8 (ND8), which is somewhat similar to the HWB in its integration of the propulsor. This paper will provide an overview of the project timeline, special test equipment needed in the wind tunnel to develop the appropriate incoming boundary layer, and the difficulties in designing a propulsor for the test. The paper will conclude with some representative aerodynamic and aeromechanic data from the test itself and conclude with how this data was used in the ND8 system study.

Keywords: Boundary layer ingestion; inlet; fan; aerodynamic performance; aeromechanics; wind tunnel testing

NOMENCLATURE

8x6	8-ft by 6-ft Transonic Wind Tunnel
AATT	Advanced Air Transport Technology
AIP	Aerodynamic Interface Plane (a plane just forward of the fan)
AIPRRA	AIP Rotating Rake Array
BLI	Boundary Layer Ingestion
BLI^{2}DTF	Boundary Layer Ingesting Inlet / Distortion Tolerant Fan
CFD	Computational Fluid Dynamics
EGV	Exit Guide Vane (stationary blade row behind the fan)
FERRA	Fan Stage Exit Rotating Rake Array (at a plane just aft of the EGV)
FLA	Forward Looking Aft
FY	Fiscal Year (Oct-Sep)
GRC	Glenn Research Center
HWB	Hybrid Wing Body
ND8	NASA Version of the D8 architecture (aka Double Bubble)
PR	Pressure Ratio
RANS	Reynolds-Average Navier-Stokes
TRL	Technology Readiness Level
UHB	Ultra-High Bypass
UTRC	United Technologies Research Center
VAFN	Variable Area Fan Nozzle

1.0 INTRODUCTION

The vision of NASA's Advanced Air Transport Technology (AATT) Project is to enable aircraft with dramatically improved energy efficiency, environmental compatibility, and economic impact. The specific system level metrics for subsonic transports to be achieved in the near-term, mid-term, and far-term are defined in Figure 1. As part of AATT's mission to explore and develop game-changing concepts and technologies, a number of next-generation vehicle configurations employing boundary layer ingesting (BLI) propulsion systems are being investigated(1)(2)(3)(4). Propulsion systems utilizing BLI offer large benefits based on paper studies. Some of these benefits are significant aircraft fuel burn reduction and reduced aircraft wetted area as well as reduced wake mixing losses. Because of a tighter integration between the fuselage and the propulsor, the weight of the nacelle can also be reduced. One BLI configuration under consideration is the hybrid wing body (HWB) vehicle (also referred to as the blended wing body) shown in Figure 2. Results from an early system study of the HWB configuration indicate that BLI propulsion has the potential to reduce aircraft fuel consumption by 3 to 5 percent relative to a clean-inflow, pylon-mounted advanced baseline propulsion system. Larger benefits, on the order of 10 percent, are reportedly possible for far-term configurations with larger amounts of BLI(5).

There are two distinctive types of BLI applications that are based on how the propulsor is integrated onto the fuselage. The first application is called Type I and is also known as 180-degree distortion. Type I is characterized by a flat boundary layer that develops on the top of a fuselage. Ingestion of this flat boundary layer into a top mounted aft inlet would present itself to the inlet as a low total pressure region with a large variation in swirl (circumferential flow angle) over the bottom portion. The extent of this distortion would be dependent on the boundary layer thickness at the nacelle highlight. The upper portion of the inlet would see constant inlet total pressure and no swirl typical of a pylon mounted inlet. The second type of BLI application is called Type II or 360-degree distortion. It is characterized by an axisymmetric boundary layer that builds along the fuselage. The application for this distortion is typically an aft mounted propulsor at the closeout of the fuselage, resulting in an inlet with low total pressure and large swirl variation at the hub. The propulsor for this application ingests not only the axisymmetric boundary layer from the fuselage but also upwash from the wings and the effect of the vertical tail. This distortion presents a unique challenge in the design of an efficient propulsor to not only handle low hub total pressure but also filter out the once per rev signals from the vertical tail and the two per rev signals from the wings. The system studies of both types of BLI applications show that the more boundary layer that is ingested, the more benefit is derived from the system. To date, NASA AATT has only completed experimental testing of the Type I distortion (Type II is in progress). This paper reviews the Type I work, and will therefore only address Type I distortion.

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TECHNOLOGY BENEFITS	TECHNOLOGY GENERATIONS (Technology Readiness Level = 5-6)		
	Near Term 2015-2025	Mid Term 2025-2035	Far Term beyond 2035
Noise (cum below Stage 4)	22 - 32 dB	32 - 42 dB	42 - 52 dB
LTO NOx Emissions (below CAEP 6)	70 - 75%	80%	> 80%
Cruise NOx Emissions (rel. to 2005 best in class)	65 - 70%	80%	> 80%
Aircraft Fuel/Energy Consumption (rel. to 2005 best in class)	40 - 50%	50 - 60%	60 - 80%

Figure 1. NASA AATT subsonic transport system level measures of success.

In order to realize the system level fuel burn benefit, the BLI propulsion system must be capable of performing well in a highly distorted flowfield. A high-performance BLI inlet and a distortion-tolerant fan are needed to ensure that the fuel burn benefit is not lessened due to excessive inlet pressure loss and reduced fan efficiency. Maintaining good operability of the fan is also critical to realizing this benefit as well as understanding and addressing any aeromechanical issues to prevent structural failures during operation. The goal of the BLI inlet and distortion-tolerant fan (BLI^{2}DTF) propulsor development effort was to understand the performance, operability and structural characteristics of the system at cruise conditions. The technical challenges that were addressed in this project began with developing a coupled inlet-fan stage design, which required first understanding how the flow distortion from BLI affects the performance and operability of the fan and developing the tools to determine the aeromechanic behavior of the fan and prevent high cycle fatigue during testing.

The research objectives of the BLI^{2}DTF project were two-fold: 1) generate and evaluate new technologies through design analysis and test of a multi-use wind tunnel experiment, and 2) achieve significant fuel burn reduction using BLI technology. In order to adequately quantify the second objective, a representative, non-BLI, baseline is required for fuel burn comparison. The baseline chosen for this comparison was a tube and wing aircraft with an advanced but conventional Ultra-High-Bypass propulsor. The NASA D8 (ND8) was used to assess the BLI benefits at a vehicle level system impact against a non-BLI version of the ND8 with underwing engines only.

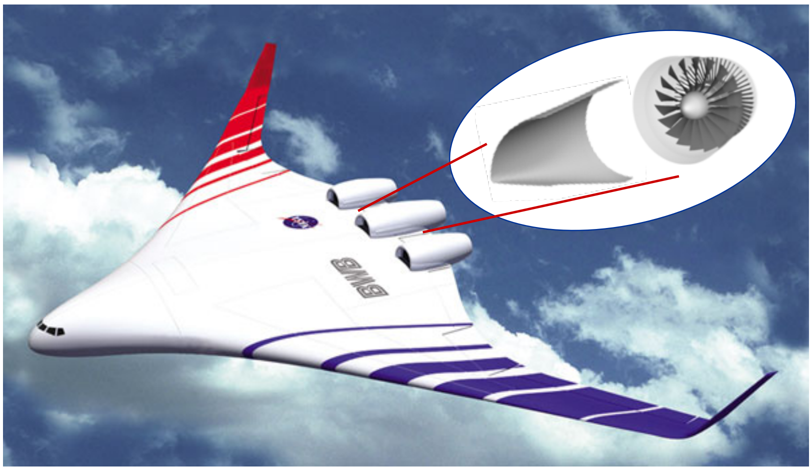

Figure 2. Embedded boundary layer ingesting propulsion system for hybrid wing body aircraft.

2.0 PROJECT TIMELINE

The timeline and major milestones for the BLI^{2}DTF propulsor development and test are shown in Figure 3. A multi-objective, CFD-based design approach that combined global and local shaping to optimize the BLI inlet aerodynamic design was completed in the fourth quarter of fiscal year FY2011(6). The fan design was performed by UTRC using an unsteady Reynolds-averaged Navier-Stokes (RANS) CFD code that integrated the inlet and fan geometries during analysis of the design iterations. The CFD needed to consider the full rotor wheel geometry in unsteady mode because the BLI distortion at the Aerodynamic Interface Plane (AIP) was concentrated in the lower 30% of the flow area while the remaining region was "clean" flow. During the design of the fan rotor, the inlet was further refined to reduce the impact of the incoming distortion profile on the rotor. This approach of integrating the fan and inlet design is necessary for good BLI propulsor design(7). Significant aeromechanics analysis was performed concurrently with the DTF design(8) (9) (10). The highly iterative aerodynamic and aeromechanical design of the BLI^{2}DTF hardware was ultimately completed in the third quarter of FY2015. In the second quarter of FY2016 fabrication of the BLI^{2}DTF hardware and the special test equipment consisting of the raised floor with flow effectors and a bleed system was completed. This special equipment was installed in the 8x6 and calibrated at the end of FY2016 to ensure that the appropriate incoming boundary layer representative of an HWB application was generated. In the first quarter of FY2017, following that calibration, the test campaign of the BLI^{2}DTF was completed. The test was conducted at corrected speeds of 70% to 105% and from near choke conditions to near stall. In general, the propulsor design subjected to the BLI distortion behaved well.

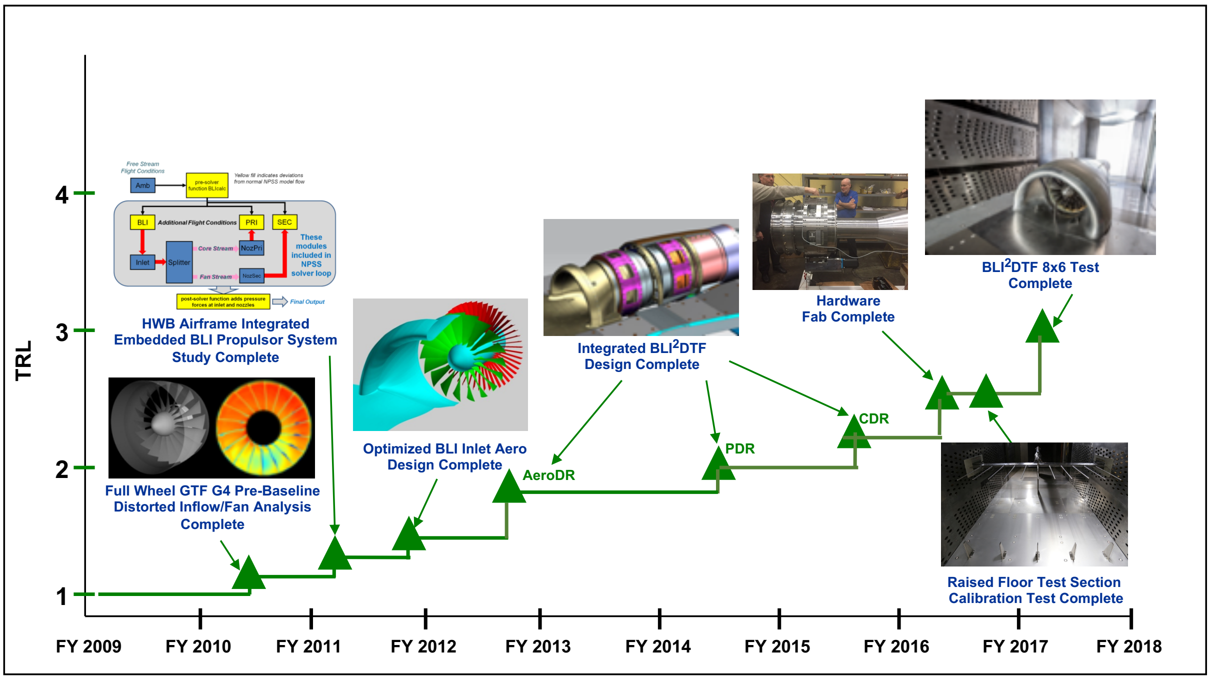

Figure 3. Technology Readiness Level (TRL) timeline for BLI2DTF propulsor.

3.0 BLI2DTF PROPULSOR & TEST SETUP

The BLI^{2}DTF propulsor was installed in the 8x6 with the raised floor, flow effectors, and bleed system required to produce the appropriate incoming boundary layer. This additional hardware is shown in Figure 4 and reduced the test section size by 18 inches at the floor. The raised floor of the test section was designed and fabricated with forward and aft ramps to elevate the wind tunnel floor and enable the BLI^{2}DTF propulsor to be embedded entirely within the test section. Measurements confirming that the target incoming boundary layer, as determined by CFD, was achieved in the new test section and are shown in Figure 5. The raised floor contained a section of roughness pins followed by a bleed box upstream of the nacelle to control the incoming boundary layer height being ingested (11).

Within the nacelle, the propulsor consisted of an inlet, a fan stage and a variable area fan nozzle. An assembly called the Aerodynamic Interface Plane Rotating Rake Array (AIPRRA) was designed to measure the inlet distortion in terms of swirl (circumferential flow angle), static and total pressure, and total temperature at a location just upstream of the fan which was designated the Aerodynamic Interface Plane (AIP). The AIPRRA was designed to be removable to avoid creating blockage with the fan present and thus impede the propulsor performance but provided the inlet conditions to compute stage performance measurements.

At the fan stage exit, a rotating rake array called the Fan Exit Rotating Rake Array (FERRA) was designed to acquire flow data to compute fan stage efficiency coupled with the data collected from the AIPRRA. This array was also used to compute the mass flow behind the exit guide vanes (EGV). The FERRA was present for all testing. Both arrays were designed to rotate circumferentially about the hub to cover most of the planar area and provide information on the flow state from the boundary layer being ingested.

The variable area fan nozzle (VAFN) was movable and designed with fast response to provided control to the experiment allowing the propulsor to be throttled through the speed line at a given RPM. The VAFN allowed quick test operation out of stall or the ability to stay away from crossing modes on the Campbell diagram which could damage the BLI propulsor hardware.

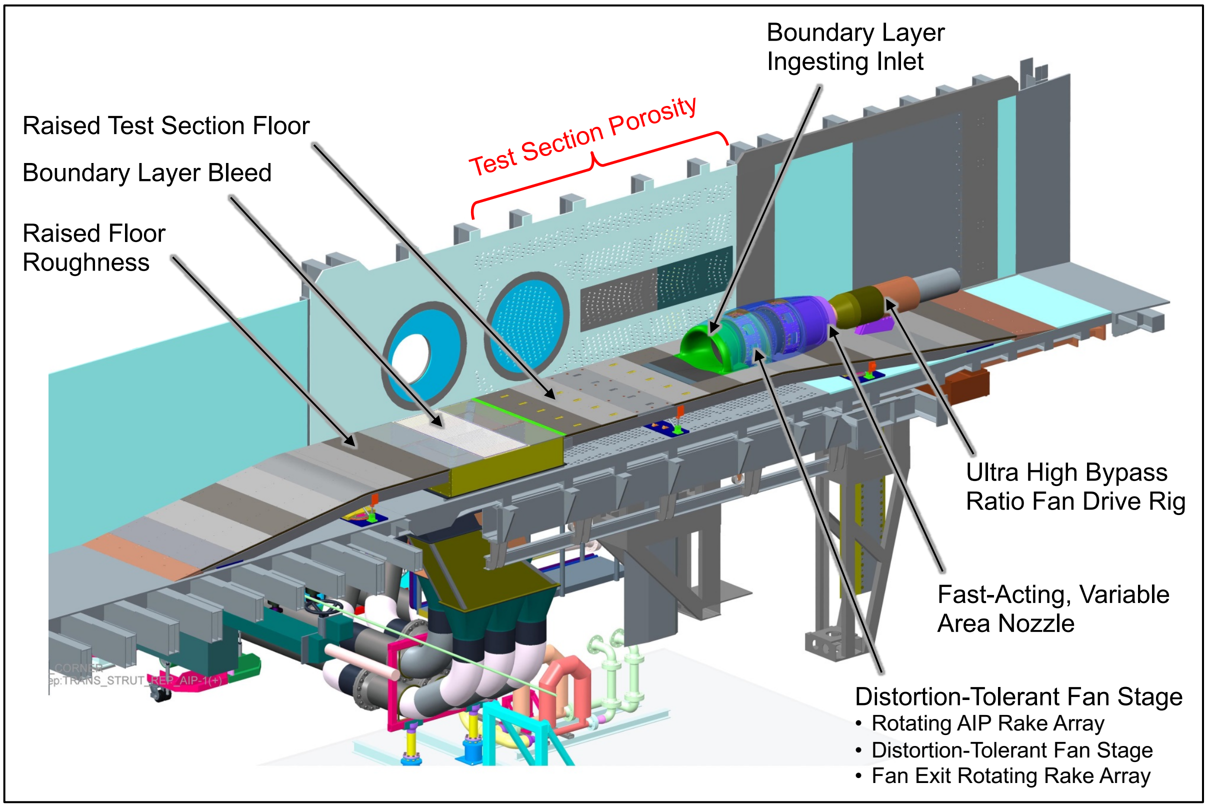

Figure 4. BLI²DTF propulsor installed in 8x6 with special test equipment.

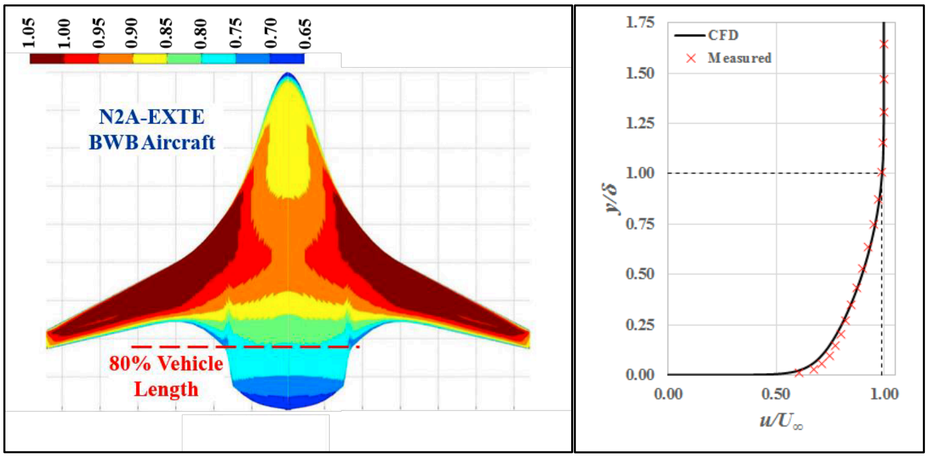

Figure 5. [Left] CFD prediction of normalized static pressure on the vehicle surface. The location at which the target boundary layer was extracted is marked. [Right] Comparison of target CFD boundary layer profile and measured profile along tunnel centerline.

As illustrated in Figure 6, the BLI^{2}DTF propulsor consisted of a BLI inlet with a distortion-tolerant fan stage. The boundary layer ingesting inlet was designed and manufactured by UTRC and consisted of two main parts - a pre-entry diffusion ramp which fed flow into an enclosed inlet duct. The 22-inch diameter distortion-tolerant fan stage consisted of a rotor with 18 blades followed by an exit guide vane with 48 vanes. UTRC designed and fabricated the fan blades, exit guide vanes, and spinners. The challenge in designing a propulsion system that works in a boundary layer ingesting flow is to operate efficiently in a highly distorted flow state characterized by large total pressure distortion and large variation in swirl. Note that the fan undergoes a load shift every blade revolution as it rotates through the distortion. The rotor design developed by UTRC was a low-pressure ratio fan (~1.35) which was thickened and refined near the tip to provide more structural integrity. This design was coupled with an inlet shape that reduced the incidence angle change from the distortion. The exit guide vane used different blade shapes in different sectors depending on the extent of the distortion to take swirl out of the flow and provide uniform flow at the exit.

NASA designed and manufactured the fan nacelle and the non-rotating portion of the flow path. The 22-inch diameter DTF was powered by NASA's existing Ultra High Bypass (UHB) turbofan drive rig which was extensively modified in order to be integrated into the experiment(12).

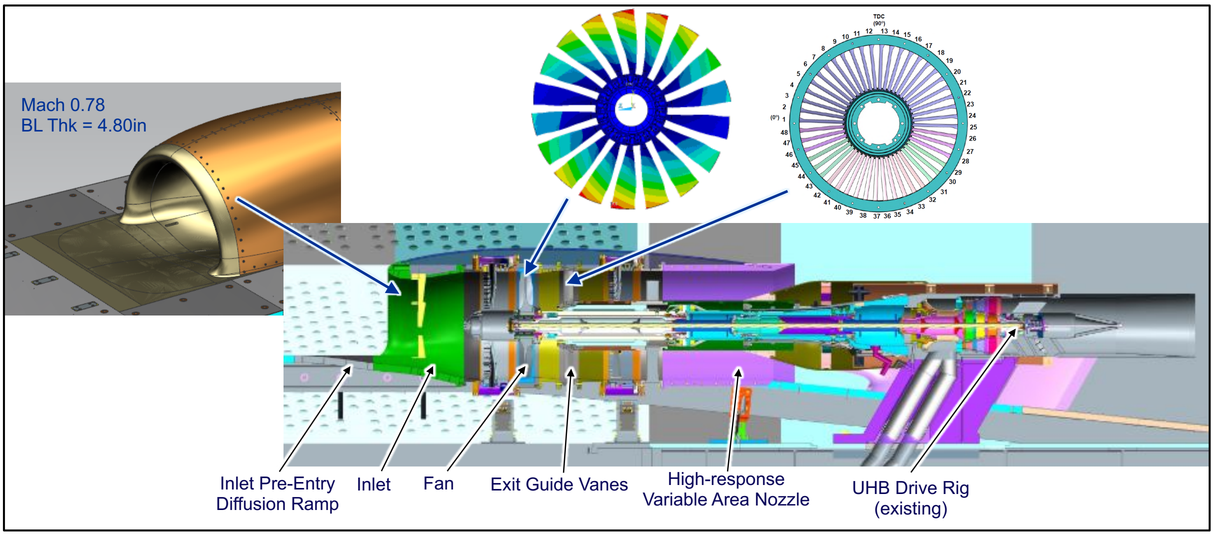

Figure 6. BLI2DTF propulsor design.

4.0 RESULTS

A vast array of instrumentation was used to make the measurements that were acquired in the BLI²DTF wind tunnel tests. Figure 7 is a cutaway of the nacelle and shows the various locations and types of instrumentation in the inlet, the aerodynamic interface plane rotating rake array (AIPRRA), the fan stage, the fan exit rotating rake array (FERRA), the VAFN, and the UHB drive rig. The planned BLI²DTF test matrix was successfully completed, obtaining valuable inlet, turbomachinery and aeromechanics data. Before the test commenced, a series of vacuum spin rig tests were conducted which provided the mechanical characteristics of the rotor. Those tests collected blade strain, tip displacement and tip gap measurements to help clear the rotor for the wind tunnel tests. The results that will be presented here address the overall research objectives of the test which concentrated on the aerodynamic design point cruise performance and operability of the propulsor. Typical preliminary aerodynamic and aeromechanics results are provided in Figures 8 through 12.

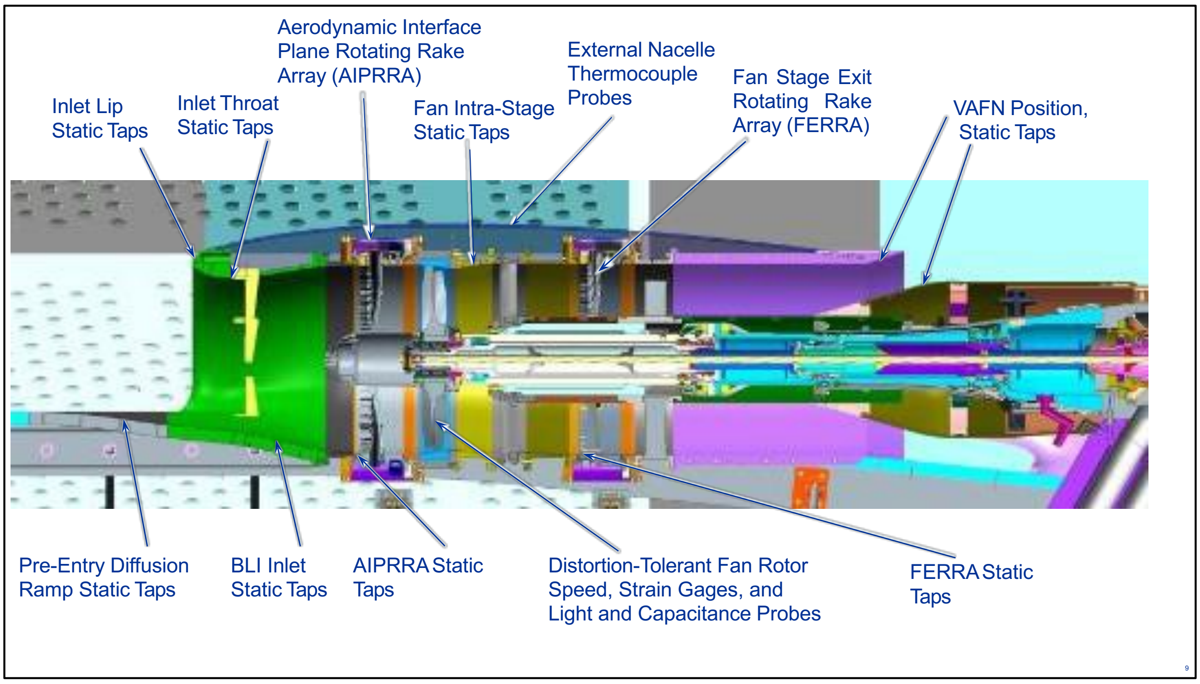

Figure 7. BLI2DTF propulsor instrumentation.

One of the highlights of this program was the development of aeromechanical analysis tools to guide and identify potentially hazardous conditions to avoid during testing. These were developed pre-test utilizing a vacuum spin rig in NASA's Engine Research Building. Figure 8 shows a Campbell diagram of Frequency vs. Rotational speed. The first ten engine orders are the linear lines emanating from the origin with each engine order labeled on the left hand side. The first four modes are shown in color and are labelled inside the left side. Design speed is indicated at just under 12,000 rpm and is labelled at the top of the figure. The conditions to avoid for operational clearance are circled in the figure. At 6000 rpm, a crossing occurred at Mode 1, Second Engine Order and another crossing occurred at Mode 2, Engine Order 4. During testing, operation near those rpms is avoided or kept as brief as possible.

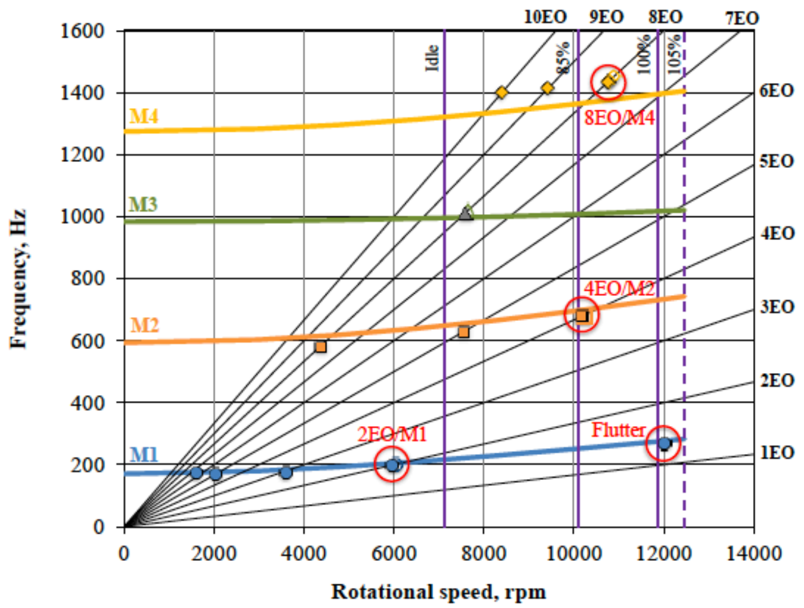

Figure 8. Campbell diagram (solid-FEA, filled symbols-wind tunnel results, unfilled symbols-vacuum spin rig results)(13).

Figure 9 shows the inlet performance map given by Inlet Total Pressure Recovery vs. Corrected Weight Flow. The data is shown at 100% corrected speed and 87.5% corrected speed. The pressure recovery ranges from 95.3% at 105 lbm/sec and drops off slightly at lower flow. This is consistent with 87.5% corrected speed over a much larger flow range.

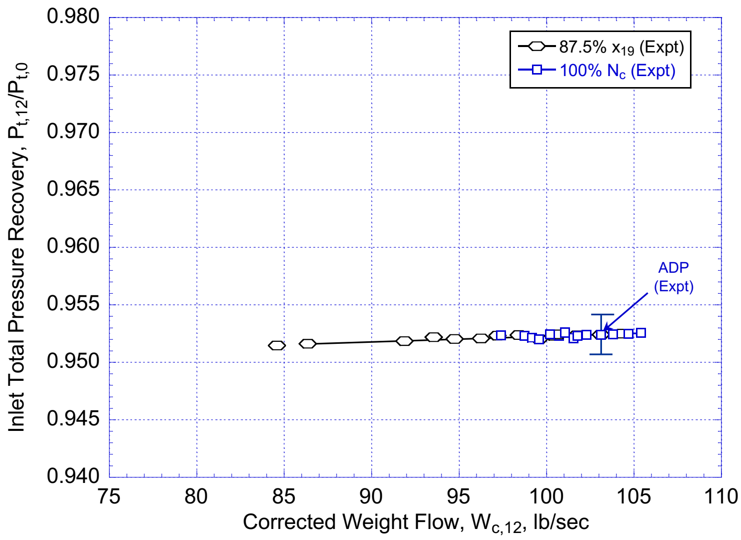

Figure 9. BLI²DTF inlet performance map.

At the peak efficiency point at design speed, the measurements of total pressure from the AIPRRA were used to plot contours of steady state total pressure shown in Figure 10. This data was obtained by rotating the AIPRRA 220 degrees in increments of 2.5 degrees. The contours show that a large amount of boundary layer, indicated by the low total pressure, is ingested into the fan at the bottom portion (lower 30%) of the annulus. The remaining portion of the annulus is clean or non-boundary layer ingesting flow.

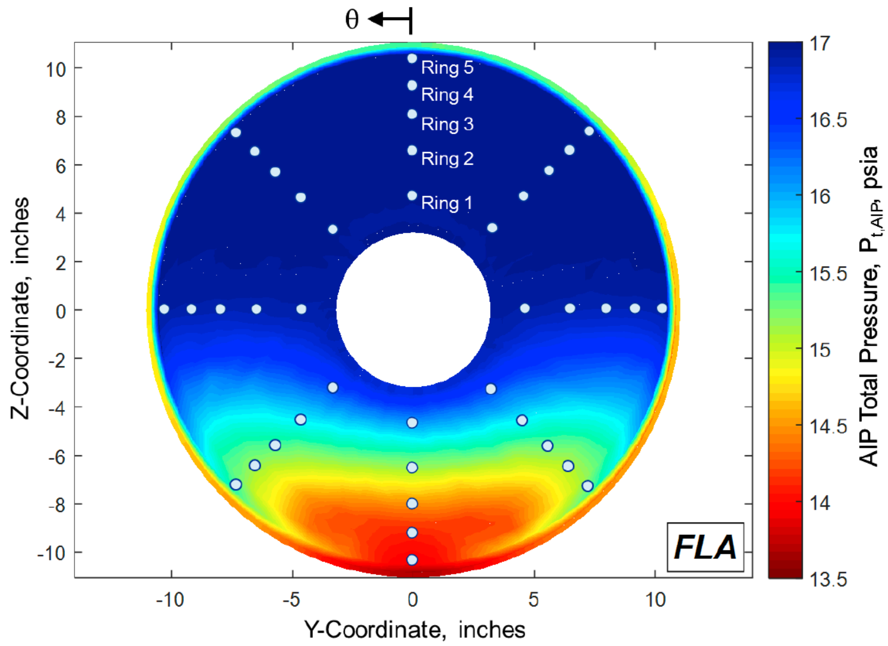

Figure 10. Experimentally measured steady state total pressure distribution at the AIP and at ADP Conditions (12).

Figure 11 shows the fan stage efficiency vs. corrected flow rate at 100% corrected speed and at 87.5% VAFN area. At 100% speed, the fan stage achieves an adiabatic efficiency of almost 90% at 103.5 lbm/sec which is 4 to 5 points lower than a typical non-BLI fan with equivalent Pressure Ratio (PR). The stage efficiency then falls over to near stall condition at about 100.5 lbm/sec. The ingestion of boundary layer flow near the hub probably caused the fan stage to stall early relative to purely clean flow but this conjecture cannot be proven as there is no data available for this fan stage in clean flow. The line for 87.5% nozzle area exhibits increased efficiency for lower speeds, peaking around 85% speed. No data was taken of this fan stage in clean flow and no rotor only instrumentation was available in the test to determine how much loss was attributable to the exit guide vane.

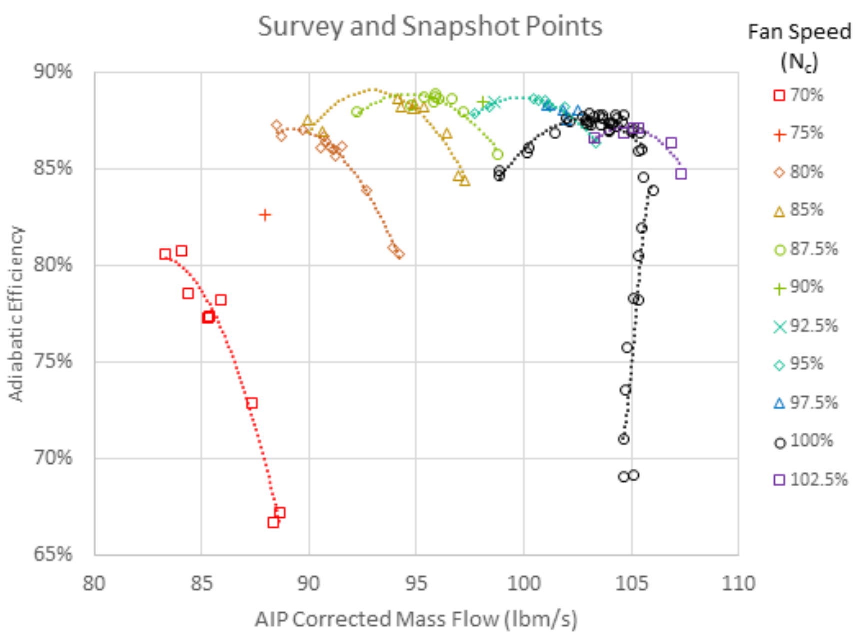

Figure 11. BLI²DTF fan stage efficiency map.

The operating map is the fan stage pressure ratio vs. corrected flow and is shown in Figure 12. This map shows data from 70% to 105% corrected speed. The dashed line is the operating line of the fan stage. The figure also indicates the stall margin that was achieved at the indicated speed and what caused the stall to occur. Note that during rotation, each fan blade stalls as it rotates into the boundary layer and then recovers as it rotates out of the boundary layer. However, based on high response data, the fan did not exhibit rotating stall. At 80% corrected speed, the stall margin was greater than 24% because the VAFN could not be closed any further to reduce the mass flow.

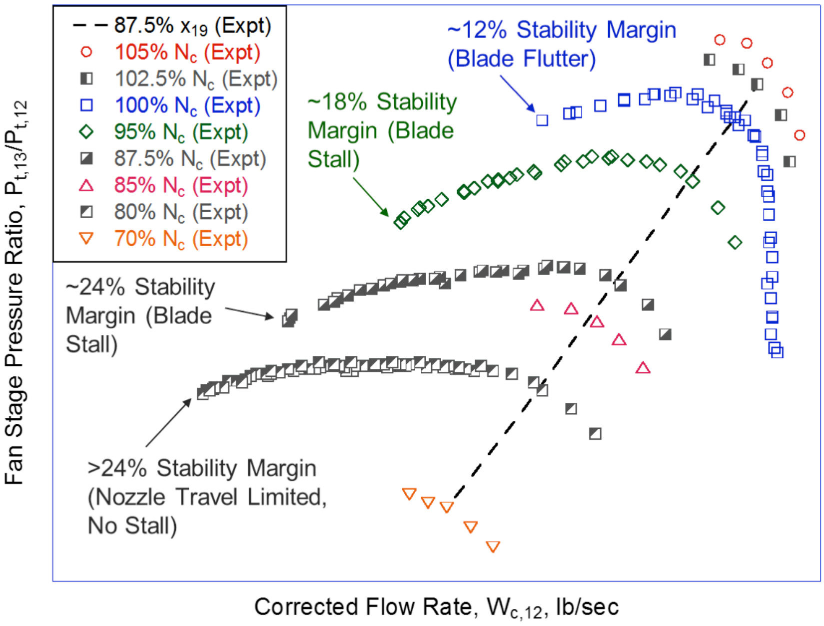

Figure 12. BLI²DTF propulsor nominal operating map.

The AATT project performed an internal assessment of the vehicle-level system impact for BLI on a representative aircraft configuration using NASA tools and methods (14). The NASA D8 (ND8) aircraft was chosen as the representative aircraft because it is highly dependent on BLI for its performance gains. The ND8 is a NASA design based on the original MIT/Aurora/Pratt & Whitney D8 concept aircraft. The results and knowledge gained from the BLI²DTF test were used in the AATT project's assessment of the vehicle-level system impact for BLI on the ND8 aircraft. The learning from the BLI²DTF test was able to be used by researchers to estimate the fan efficiency penalty between a conventional fan operating in uniform flow and the ND8 DTF. This fan efficiency penalty was estimated to be 3.5 percent. Figure 14 illustrates the BLI impact on block fuel consumption showing a 5.3 percent fuel burn benefit with BLI²DTF technology. The abscissa is percent fan efficiency and the ordinate is Block Fuel Change where larger is less fuel burn benefit. The original BLI study assumed no fan efficiency loss and is shown on the abscissa at 95% fan efficiency. The non-BLI ND8 with typical pylon mounted engines under the wing shows an 8 point increase in block fuel change, i.e., higher fuel burn. By utilizing the efficiency loss penalty from the BLI2DTF test, the BLI benefit of the ND8 with fan loss is still 5.35 percentage points better than the non-BLI configuration.

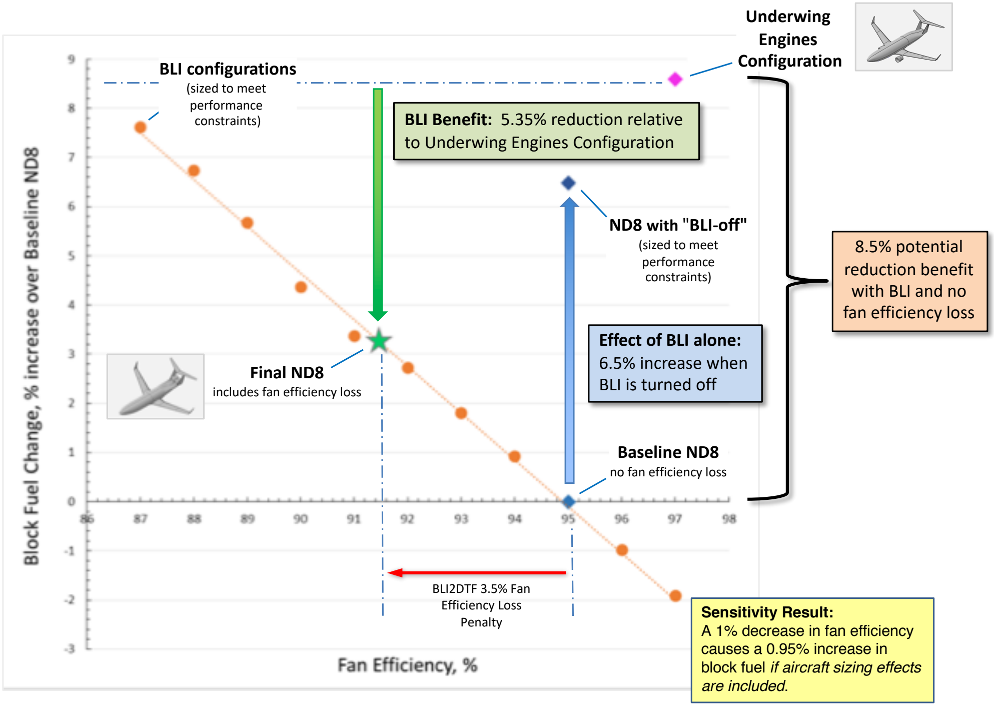

Figure 13. ND8 results: BLI vehicle-level benefit (14).

5.0 CONCLUSION

A Type I boundary layer ingesting propulsor was tested at high-speed in the NASA GRC 8x6 wind tunnel. This experiment proved to be challenging on many technical levels because of the unknown aerodynamic and aeromechanical issues involved. Some of the new tools and devices were:

1) a new unique design paradigm was developed incorporating both the inlet and fan that provided a more integrated propulsor;
2) aeromechanics tools were developed and exercised to deal with potential rotor excitations at critical modes due to the ever-present boundary layer being ingested;
3) a raised floor in the 8x6 wind tunnel was designed and built to deliver the right boundary layer to the nacelle;
4) rotating rake arrays were designed and built to capture the data in the nacelle and provide performance and operability data; and
5) unique post-processing capabilities were developed to account for the non-clean nature of the upstream boundary layer flow being ingested.

The test results and follow-on system study showed that BLI has good potential to reduce fuel burn. The test was very successful and demonstrated that a robust propulsor can be designed to operate in a boundary layer ingesting flow with good performance and operability margins. This activity opens the door to the design and development of other types of BLI propulsors and is a pull for researching new types of propulsion airframe integration designs.

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