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# Design of a Distortion-Tolerant Fan for a Boundary-Layer Ingesting Embedded Engine Application

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**The design of a unique distortion-tolerant fan for a high-bypass ratio boundary-layer ingesting propulsion system has been completed and a rig constructed and tested in the NASA Glenn 8'x6' wind tunnel. The rotor blade had to meet significant design challenges created by boundary-layer ingestion, including severe mechanical and aerodynamic conditions. The design conditions were met through an integrated inlet/rotor design process, since boundary layer ingestion causes a highly coupled system. The unique rotor design manages high incidence angle fluctuations and high total pressure distortion levels through consideration of the unsteady aerodynamics. The test of this new fan design was successfully completed, showing significant stability margin for the application.**



## Nomenclature

| | | |
|---|---|---|
| ΔH/L | = | inlet offset ratio (change in height of the mean centerline divided by the inlet length) |
| L/D | = | length-to-diameter ratio for an inlet |
| N | = | physical speed, rpm |
| Nc | = | corrected speed, $N/\sqrt{\theta}$, rpm |
| Pt, Po, P | = | total pressure |
| Ps | = | static pressure |
| Pt∞ | = | free stream total pressure |
| ΔPc/P | = | circumferential distortion intensity |
| ΔPr/P | = | radial distortion intensity |
| Tt | = | total temperature |
| Tref | = | reference temperature, 519°R |
| θ | = | Tt/Tref |

## I. Introduction

**AS** aircraft designs continue to mature, it becomes increasingly challenging to develop new concepts that can provide significant improvements relative to existing systems. New designs must incorporate more highly integrated subsystems in order to exploit opportunities for improvements. A key goal of next-generation propulsion systems is to provide continued reductions in fuel burn relative not only to current technology, but in comparison to the vision gas turbine engines currently in development. One new technology currently receiving considerable attention is boundary layer ingesting (BLI) propulsion systems. Boundary layer ingestion can provide substantial propulsive efficiency improvements relative to clean-inflow systems by producing thrust using the reduced velocity air in the incoming boundary layer. However, in order to realize system-level benefits, the propulsion system must be capable of performing well in a high distortion environment. A distortion-tolerant fan will be a key element of

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such propulsion systems, and must possess high efficiency, acceptable aeromechanics, proper unsteady aerodynamic response characteristics, and sufficient operability margin.

With BLI propulsion, the usual separation of the performance of the aircraft and the propulsion system is more difficult than for traditional aircraft. Pylon-mounted engines in conventional installations ingest non-distorted, freestream flow. Normal propulsion bookkeeping accounting for ram drag, inlet pressure recovery, cycle efficiency, and thrust production can adequately capture the propulsion system performance. The associated aircraft performance is captured with the typical parameters of weight, airframe drag, nacelle drag, and interference drag associated with the propulsion system installation. When boundary layer ingestion is introduced, the airframe and propulsion system are more highly coupled. The propulsion system inflow no longer comes directly from the clean, freestream flow, so the conventional propulsion performance bookkeeping must be modified to account for this. In addition, the inlet flow distortion is at least an order of magnitude higher than is typically the case at cruise operation for conventional propulsion system installations. The wake of the aircraft / propulsive jet is also modified due to the fact that with a reduced inlet velocity, the jet exhaust velocity required for thrust production is reduced as well. All of these effects increase the degree of coupling between the airframe and the propulsion system, requiring new approaches for analyzing and designing BLI propulsion.

There are a number of elements that will impact the performance of BLI propulsion systems, including the characteristics of both the incoming swirl and total pressure distortion signatures, resulting fan incidence variations around the circumference during a full revolution, features required to improve fan aeromechanics and structural capabilities, inlet pressure losses, and the performance of the fan exit guide vane row and fan duct / nozzle components following distortion transfer across the fan. In order to maximize vehicle-level benefits, adverse impacts associated with these elements must be minimized, while taking maximum advantage of the benefits of boundary layer ingestion. The amount of boundary layer ingested into the propulsion system has a positive impact on propulsive efficiency due to the reduction in inlet velocity accompanying boundary layer ingestion, and the associated reduction in jet exhaust velocity that occurs for approximately equal thrust production under this condition. Both of these elements contribute to an increase in propulsive efficiency, which is the primary benefit of BLI propulsion.

Arguably the single most critical challenge associated with boundary layer ingesting propulsion systems is the ability of the turbomachinery to operate efficiently in the highly distorted flow, both preserving the BLI system-level benefits as well as meeting aeromechanics-related operating requirements. In particular, a high-performance, distortion-tolerant fan is required.

This paper discusses the fan design challenges and the system-integrated design of the fan rotor performed at UTRC under the Boundary Layer Ingesting Inlet/Distortion-Tolerant Fan (BLI2DTF) effort sponsored by the NASA Advanced Air Transport Technology Project. While the primary focus of this paper is the fan rotor design, summary information and references are provided to allow visibility into the complete stage design. Tested in November and December 2016 at the NASA Glenn Research Center 8'x 6' Supersonic Wind Tunnel, the fan demonstrated the ability to perform in a highly non-uniform distorted inlet flowfield caused by the boundary-layer ingestion. The fan provided acceptable performance while meeting the mechanical challenges inherent in this type of system.

## II. General Design History

The ultimate goal of the program was to demonstrate the ability to design an inlet/fan stage that would perform in a boundary-layer ingestion environment. In the beginning of this program, significant effort was spent performing detailed system studies to clearly define the impact of the major design factors on the performance of the aircraft. This work is discussed in Ref. [1] and resulted in the determination that the inlet loss development and the fan efficiency were critical factors in the design of the boundary layer ingesting fan. Examination of the inlet flow parameters started with work examining the NASA "Inlet A" at Virginia Tech, and this work was reported in Ref. [2] and [3]. The inlet design effort went on for some time, leading to the low-loss inlet described in Ref. [4]. During the fan rotor design, this inlet was further modified to reduce the impact of the developed distortion profile on the rotor, as discussed later in this paper. The exit guide vane for the stage design contains several features to reduce the losses and to provide a more uniform flow out of the stage, including a non-uniform circumferential distribution of stators, a non-circular flow path, and stators of varying designs in sectors along the lower-half of the flow path, as presented in Ref. [5] and [6].

## III. Challenges of Inlet Distortion and Integrated Rotor Design

Boundary layer ingesting inlets inherently have a large total pressure distortion, as the air in the part of the inlet with the boundary layer is low-momentum fluid. The NASA "Inlet A" was a reference inlet for the program and is shown in Fig. 1 along with its associated total pressure distortion pattern. The inlet is a flush-mounted, S-duct inlet with a length-to-diameter ratio (L/D) of 3 with this fan and an offset ratio (ΔH/L) of 0.330. The circumferential total pressure distortion intensity (ΔPc/P) is 5.7% and the inlet total pressure loss (ΔPt) is 1.8%. The inlet is described in detail in Ref. [2].

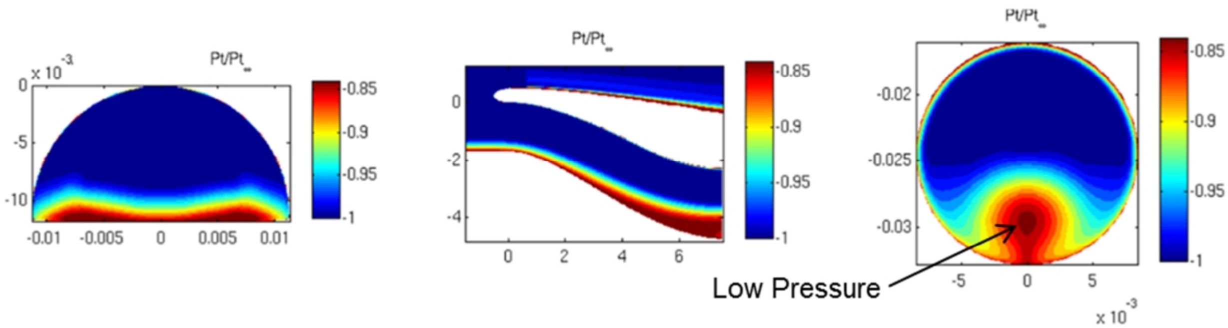


**Fig. 1 Total pressure field for NASA "inlet A" at the throat, mid-plane, and AIP (from Ref. [1])**

In the present program, the inlet was designed in a manner to minimize the inlet loss since that was a critical parameter for the BLI performance in the system study. The resulting inlet (Fig. 2) had an L/D of 0.6 and a total pressure loss (ΔPt) of 0.3%, significantly lower than the S-duct inlet. This inlet was further refined during the integrated fan rotor design to change the profile of the boundary-layer induced distortion and modify the incidence angle change for the rotor as it passed through the distortion.

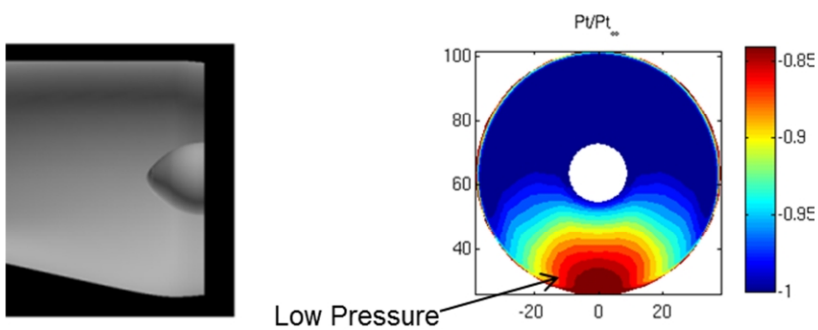


**Fig. 2 Inlet resulting from detailed design, prior to refining for distortion profile control**

Two issues were observed when designing the fan rotor. First, the mechanical excitation due to the rotor passing through the distortion was so great, the rotor was significantly over the failure limit. Second, the incidence angle change (initially over 25 degrees) would clearly drive the rotor to stall. As a result, the inlet was further refined to shape the distortion to a more acceptable pattern. The last inlet refinements were performed to help the mechanical design and to assist in the operability of the fan with regard to stall and flutter. This refinement (shown in Fig. 3) enabled a reduction in the incidence angle swing to approximately 17 degrees as shown in Fig. 4. The resulting circumferential distortion intensity (ΔPc/P) was 10%, the radial distortion intensity (ΔPr/P) was 4%, and the circumferential extent ($\theta^{-}$) was 125 degrees. The swirl angle distribution ranged from about +16 to -24 degrees, depending upon the circumferential position and the radial position relative to the wall. Operating in a BLI flowfield under these conditions means that the rotor dynamic response design is critical to the successful operation of the fan.

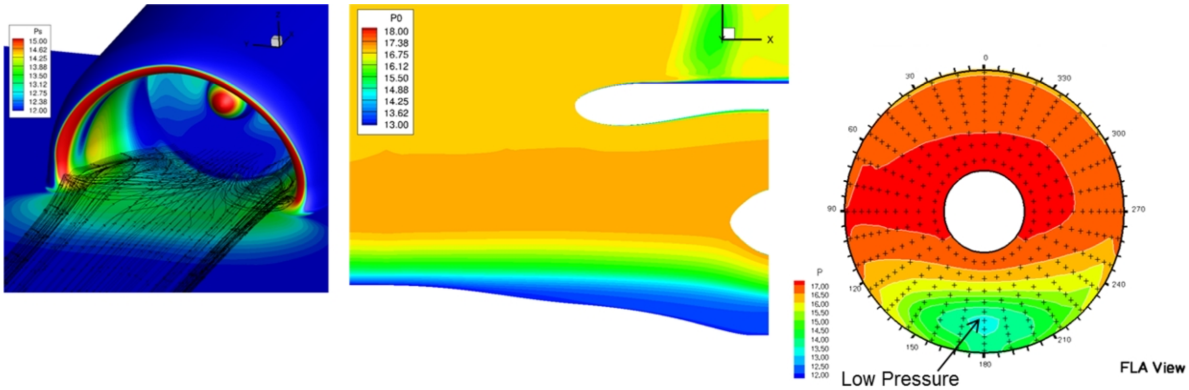


**Fig. 3 Final inlet design optimized to control mechanical excitation and incidence angle swing**

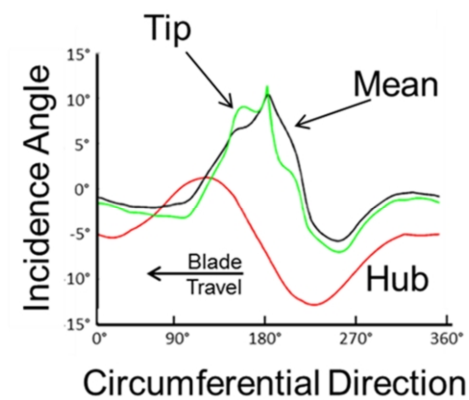


**Fig. 4 Incidence angle swing after final inlet refinement**

## IV. Fan Rotor Design for Dynamic Response & Stability

Continuously operating at cruise under boundary-layer ingestion conditions causes the fan rotor to travel through this distortion every revolution. Because of this, the blade design was performed using an in-house unsteady RANS CFD solver and modeling the full inlet/fan combination. The dynamic response of the designed rotor blade is critical to successfully achieving stable operation in this flow field. The incidence angle change of the rotor drives each fan blade from choke to stall on every revolution. The industry standard SAE ARP-1420 [8] discusses a "critical angle" for rotor blade response. While only determined by measurement when this document was developed, a physical explanation and calculation to determine the true rotor dynamic response was first presented in Ref. [7]. The rotor dynamic response can be designed into the blade through control of the blade loading and the throat location in the rotor [7]. In this rotor blade, the dynamic response was designed into the rotor to force the rotor to recover from the unavoidable stalling behavior behind the distortion. As the blade leaves the distorted sector, it recovers from stall and operates on the stable side of its characteristic, rather than operating on the post stall characteristic. One manner in which this can be observed is through the examination of the spanwise diffusion factor as the blade travels around the annulus. Both stall and recovery are experienced every rotor revolution, as shown in the four diffusion factor plots in Fig. 5. Comparing the incidence angle distribution in Fig. 4 and the diffusion factor in Fig. 5 shows the choke and stall behavior as the incidence changes. Both Fig. 4 and Fig. 5 are produced at the design point, so as the operating point moves to a lower flow (and higher pressure) along the speed line, the time constant of stall and recovery changes. The same is true for lower speed off-design conditions.

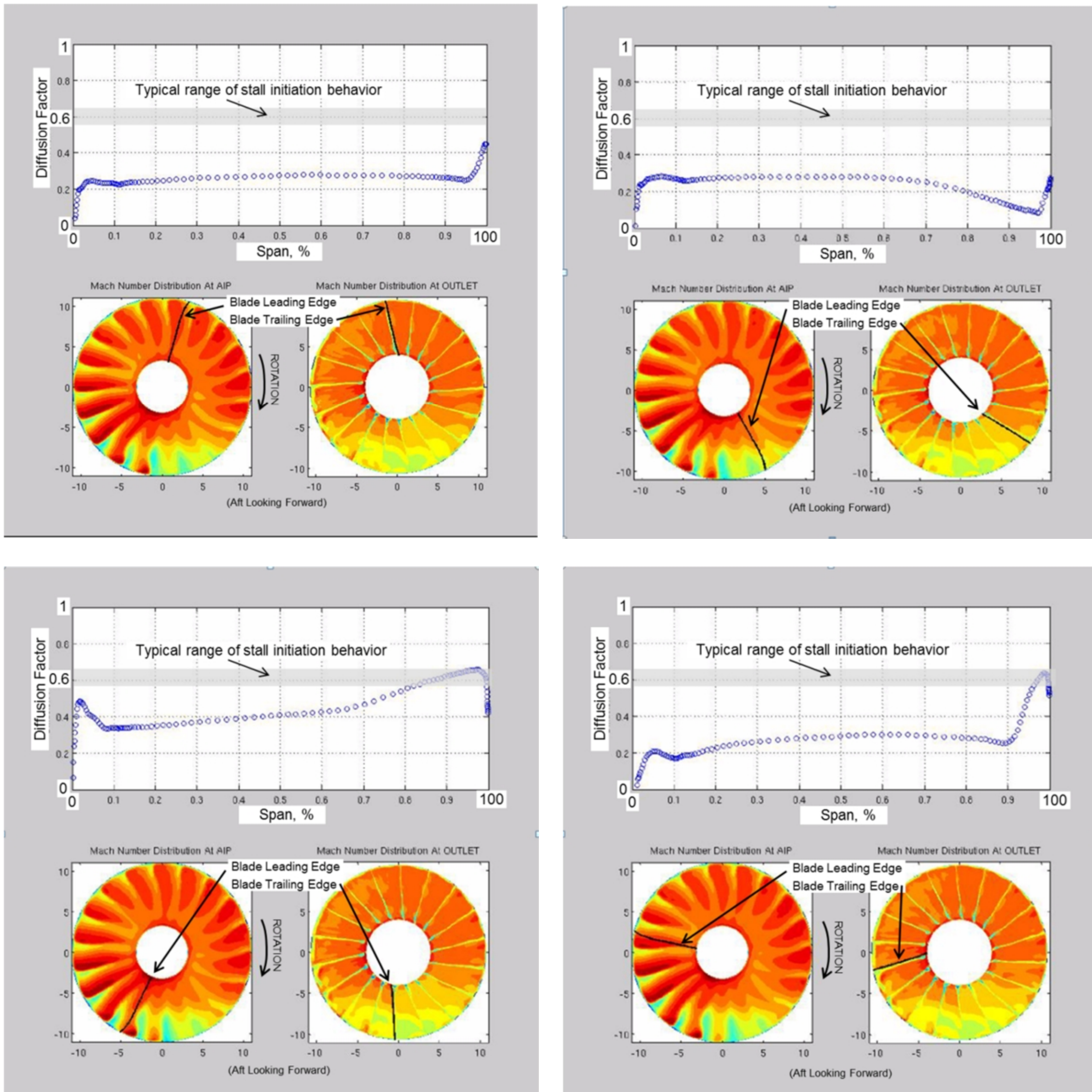


**Fig. 5 Diffusion factor distribution at four positions around the rotor at the design point, showing the blade leading and trailing edge position**

## V. Fan Rotor Design for Mechanical Requirements

The starting point for the rotor blade design was a rotor designed for an on-wing application at a pressure ratio of 1.35, which for purposes of this paper will be called the reference blade. The refinement of the inlet and the control of the distortion-driven incidence angle variation are driven in the design by the examination of the mechanical impact of the boundary-layer-induced distortion on the reference blade. Examination of the Goodman diagram in Fig. 6 shows the significant reduction in vibratory stress due to increasing the extent of the distortion while reducing the incidence angle variation and modifying the swirl distribution through better vortex control at the wall. The Campbell diagram for the reference blade (Fig. 7) also shows low resonance margins and the approximate range of interest. Clearly a blade designed for on-wing applications is not adequate for the boundary-layer ingesting environment.

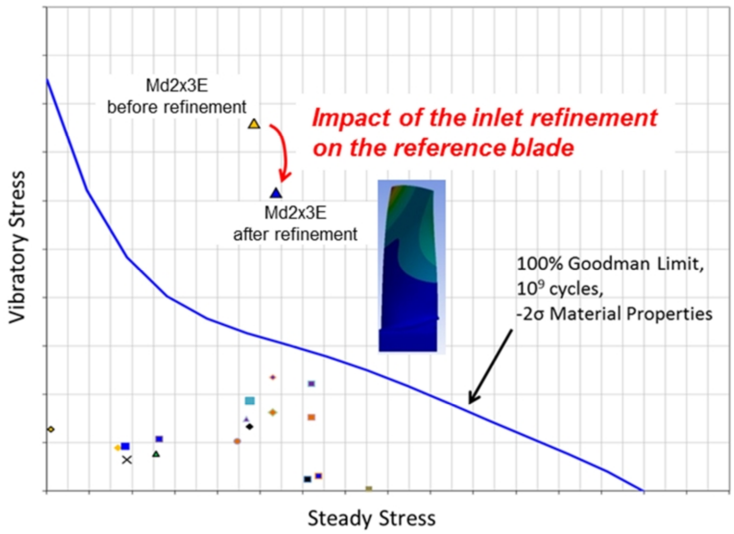


**Fig. 6  Goodman diagram showing the significant impact of the final shaping of the boundary-layer-induced distortion by the final modification of the inlet**

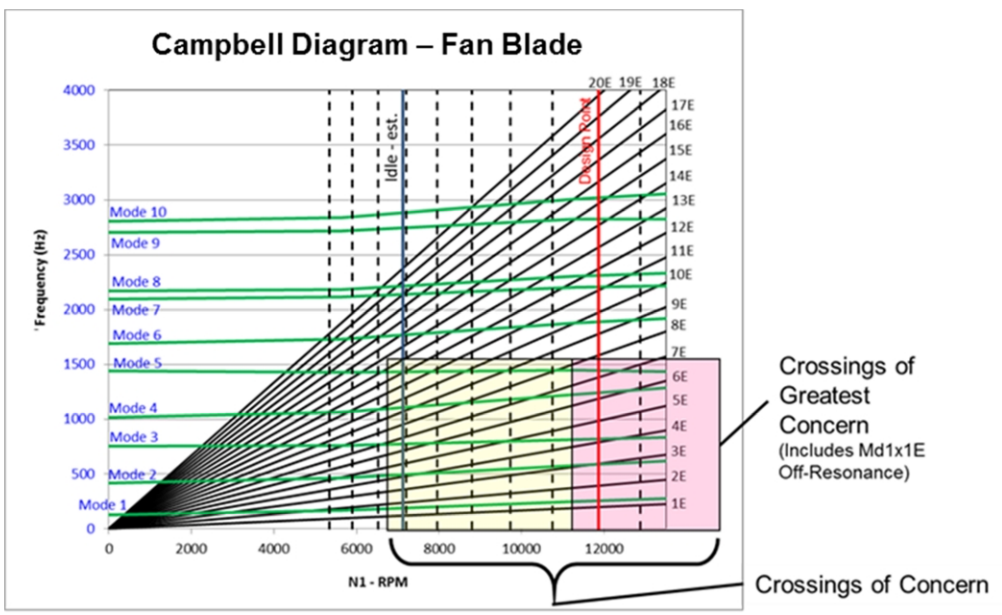


**Fig. 7  Campbell diagram showing the reference blade crossings and low resonance margins (the reference blade is for an on-wing application rather than an embedded engine configuration)**

The desired goal of the blade design was to achieve a 60% Goodman limit while maintaining reasonable performance. At the same time, the dynamic response of the airfoil loading and the stability and flutter margins were of concern. Blade failure was not an option, so while reasonable performance was a goal, structural integrity was a requirement. One of the first design considerations for the fan blade was to examine the thickness distribution, as this would be a major influence on structural integrity. As shown in Fig. 8, the blade required a thickness distribution quite different from the reference blade.

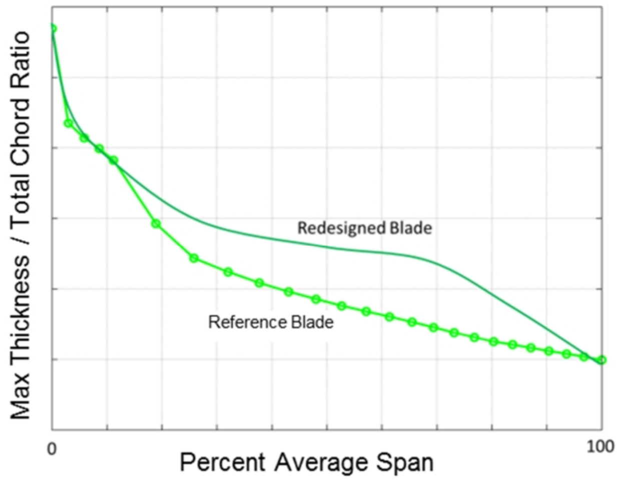


**Fig. 8  Blade thickness distribution relative to the reference blade**

The high levels of circumferential distortion along with the radial distortion content and high flow angle variation caused high stress levels near the tip of the blade. In addition, the leading and trailing edges were modified to reduce stress levels and the leading edge was reshaped to manage the high incidence and Mach number variations. The blade camber and work distributions were adjusted to provide the dynamic design previously discussed. The tip chord was shortened, the distribution changed, and the blade restacked to provide the proper balance at the center of gravity as shown in Fig. 9.

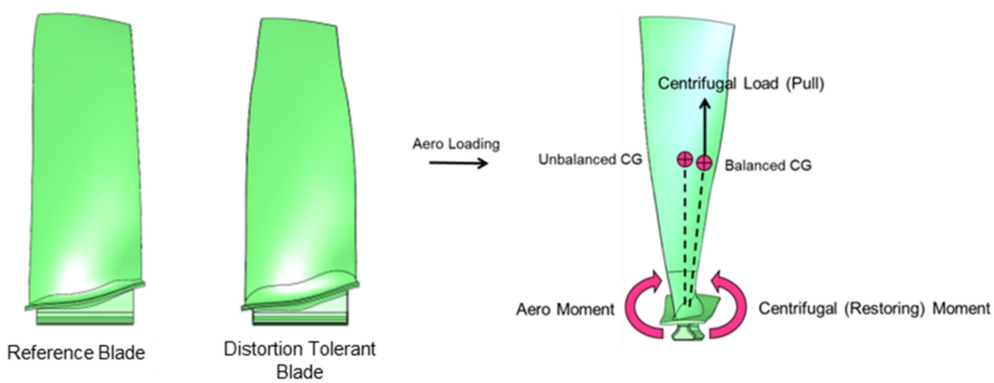


**Fig. 9  Many modifications were performed to the reference blade to provide a distortion-tolerant blade**

Since the fan blade was being designed for the rig demonstration as an inserted blade, special care had to be taken in the dovetail design and the under-platform stresses had to be managed, as the rapid loading shift that occurred every blade revolution caused high stress levels in this area. The blades were also designed to take advantage of a shot peening operation to reduce the static stresses.

The Campbell diagram for the final blade is shown in Fig. 10. The analysis showed the blade to have over 22% frequency margin for the critical Mode 1x1E excitation and over 12% for the Mode 2x3E excitation, meeting the desired design criteria. The Goodman diagram for the final blade is shown in Fig. 11 for both the 100% and the 105% aerodynamic design point. Using a worst case superposition method, the blade was shown to meet the desired stress criteria of 60% of the Goodman limit. The final fan and assembled configuration is shown in Fig. 12.

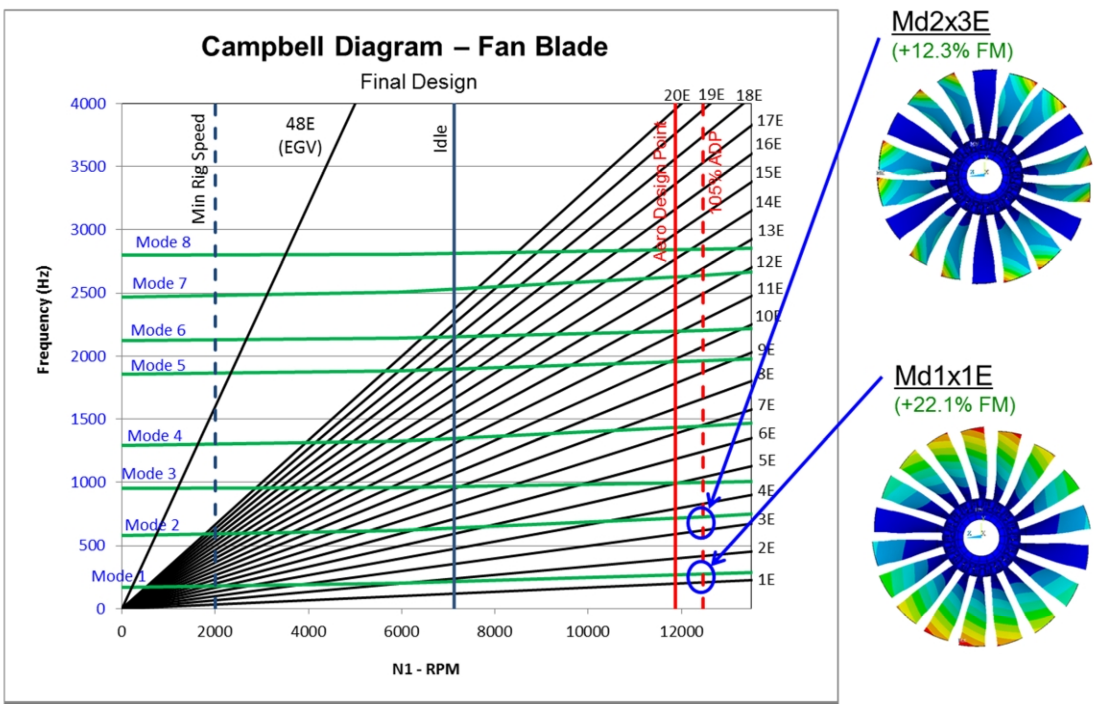


**Fig. 10 Campbell diagram for the final distortion-tolerant blade, showing the Mode 1 and Mode 2 margins of over 22% and 12% respectively**

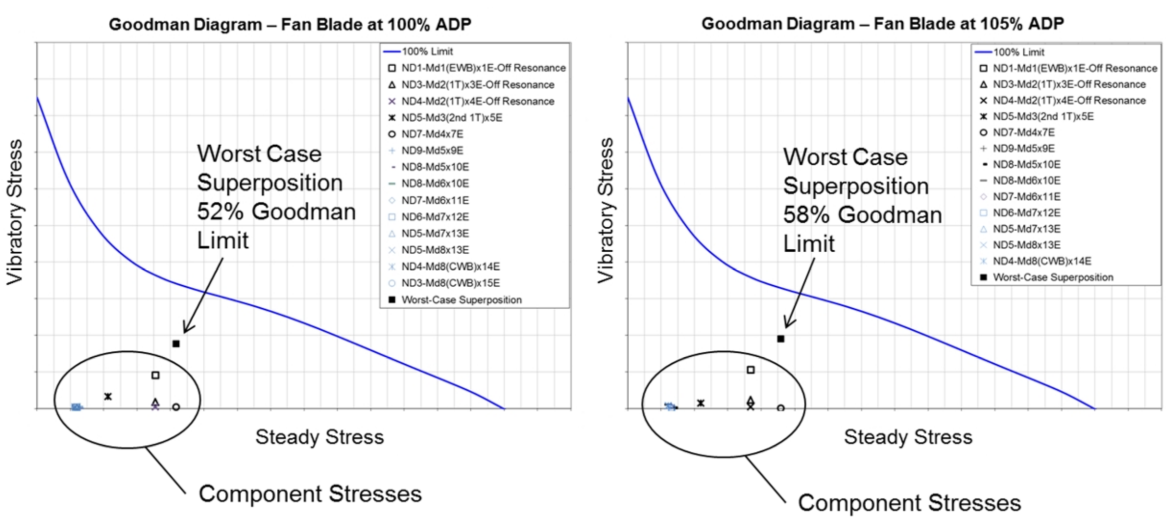


**Fig. 11 Goodman diagrams at 100% and 105% of the Aerodynamic Design Point showing the final blade worst case superposition of the component stresses within the desired 60% Goodman limit**

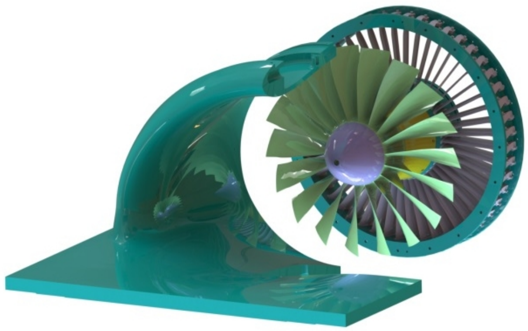

**Fig. 12 Fan configured in the final design with the inlet and exit guide vanes**

## VI. Testing at NASA Glenn

The fan was tested in November-December of 2016 in the NASA Glenn 8'x6' Transonic Wind Tunnel, providing successful validation of the design and demonstrating the operation in the Mach 0.78 environment. Significant modifications of the test facilities were performed by NASA to enable testing this type of system. References [9], [10] and [11] further describe the test configuration and some of the test results. The test rig was installed making use of a raised floor with a vacuum bleed system to enable adjustment of the boundary layer entering the fan (Fig. 13 and Fig. 14).

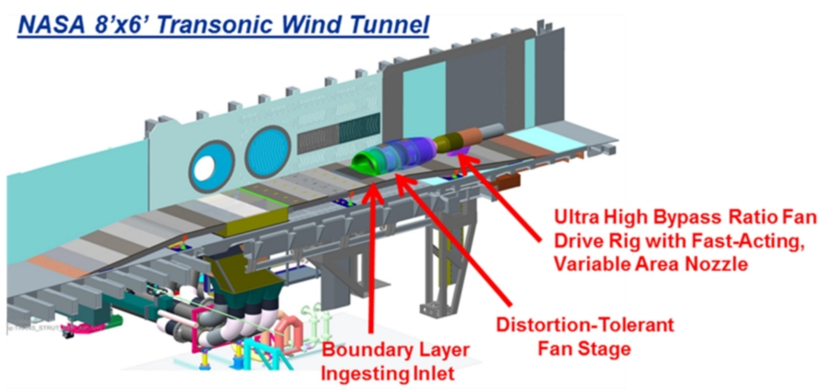


**Fig. 13 Configuration of the test rig in the NASA Glenn facility**

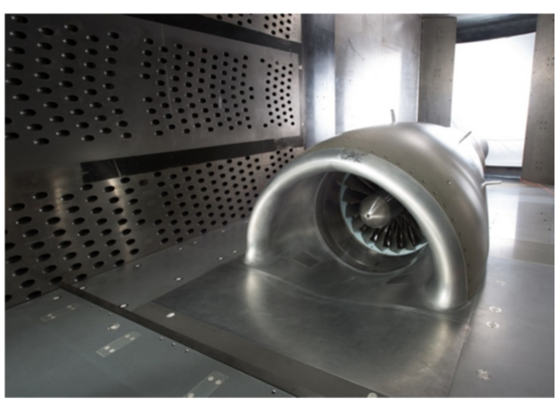

**Fig. 14 Rig installed in the NASA Glenn 8'x6' Transonic Wind Tunnel**

The design performed well and the fan rig was operated over its full range. The dynamic stalling and recovery of the fan every rotor revolution was monitored with high-response measurements. The fan was operated to the stability limits, which were fan flutter at 100% speed and fan stall at lower speeds. The stall boundary was defined as the point where the fan blade no longer recovered from stall as it passed circumferentially into the undistorted sector. The constant speed stability margin is shown in Fig. 15, which is a preliminary fan map for the overall stage (not the rotor alone). While this preliminary stage map includes instrumentation effects from probes in the inlet and the scales have not been absolutely finalized, it does represent the stability margin achieved in the design and shows that the dynamic design of the fan blade was very successful, achieving significant constant speed stability margin across the operational range. Both the steady and unsteady data is still being resolved at the time of this publication and much more final steady and unsteady data will be presented in greater detail in the future.

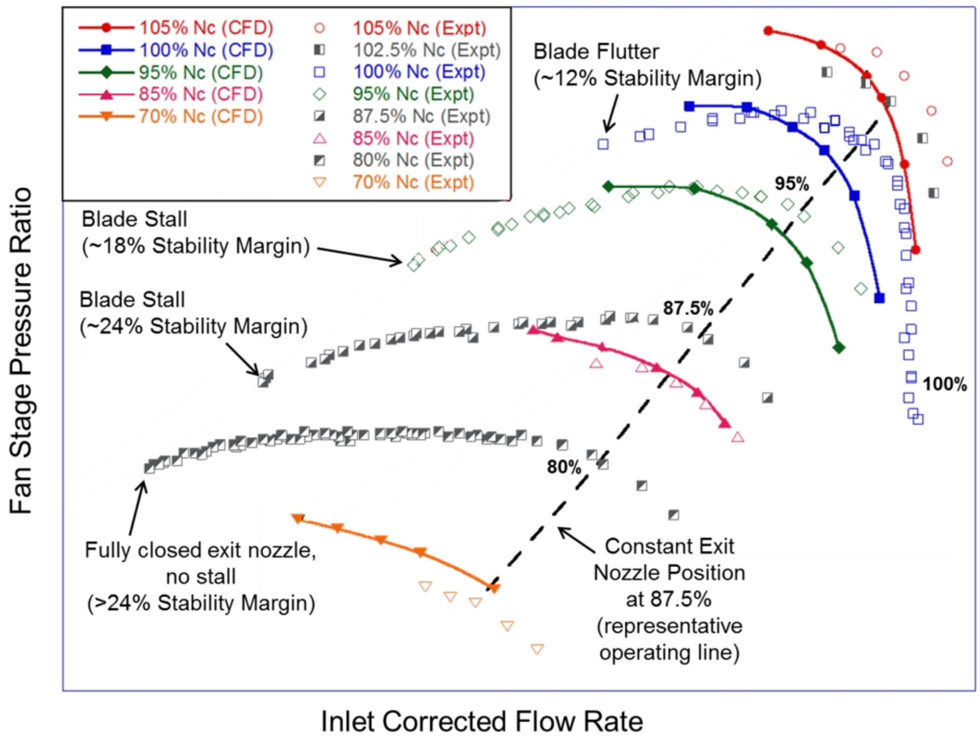


**Fig. 15 Preliminary fan stage map showing the approximate achievement in stability margin**

## VII. Conclusion

A first-of-its-kind high-bypass ratio distortion-tolerant fan has been designed to operate in a BLI environment of significantly high total pressure distortion levels. The distortion levels cause large mechanical excitations and also aerodynamic stability concerns. The successful fan design was performed through an integrated inlet/fan unsteady RANS CFD technique and demonstrates the need for this type of integrated design practice for BLI fan design. Application of dynamic stability concepts in the design demonstrate the ability to design for aerodynamic stability needs. The testing of the fan rig demonstrated the success of the aerodynamic and mechanical design.

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