

Acoustic Simulations of Two-stage Fans Behind a Supersonic Inlet

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NASA created, validated, and applied a high-fidelity simulation toolchain for noise prediction of a fan system for a near-term civilian supersonic aircraft engine. A high fidelity inlet and multistage fan design were acquired as the basis for physics-based computational studies. The overall tone noise was computed, which was used to help improve empirical models of fan inlet noise for system analysis purposes. Additional insights were gained during the study of the fan installation details and these are shared in this paper. Both overall amplitudes and variations due to design details should be of interest to engineers tasked with designing quiet fan systems for supersonic commercial aircraft. The outlook for high-fidelity simulations of aft fan noise and installation effects will also be discussed.

I. Introduction

The NASA Commercial Supersonics Technology project has been studying supersonic engine noise using physics based simulations in lieu of experiments. This requires high-fidelity geometry so NASA contracted with GE Aviation to design and deliver a fan and inlet geometry for study. This fan and inlet system (called Superfan for short) is shown in Fig. 1. The inlet is an axisymmetric spike designed for cruise speed of Mach 1.4 at 50,000 ft (15,240 m) altitude. The fan and inlet system are designed for efficient performance at cruise to maximize range. The size of the front inlet opening and position of the spike are thus intended for use with a Mach 1.4 free stream. When the aircraft is operating at speeds below Mach 0.6, the engine requires more mass flow than the front inlet can provide. Take-off, landing and climb are thus enabled by translating the front part of the cowl forward, opening an auxiliary inlet and allowing more airflow into the fan, which is seen in Fig. 1.

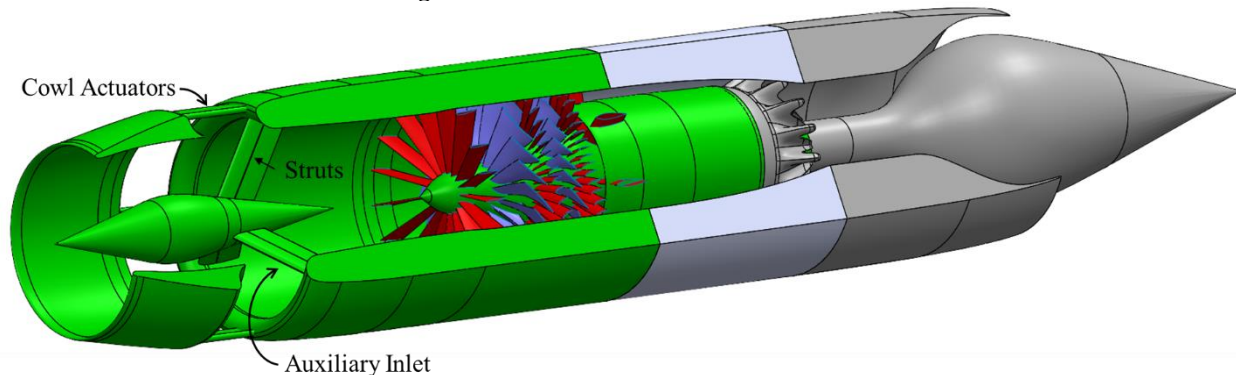


Fig. 1 Render of two-stage fan and inlet system on notional engine. Bypass duct and nozzle notional geometries produced by NASA acoustics research engineers.

This paper will focus on the simulation methods used for studying the Superfan and highlight some of the results. Two companion papers are also available, discussing the overall project [1] and the system noise analysis [2].

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II. Simulation Tool Description

A complete computational simulation capturing all the relevant physics over the entire necessary physical domain is outside the scope of the available resources at this time. Instead, a series of connected tool paths was used, with each computational tool covering a specific aspect of the simulation and exporting the relevant solution components to the next tool. A number of variations on this toolchain were tried, but the final workflow is shown in Fig. 2. Subsections A-D following describe the three main components of the workflow while subsection E describes the validation approach.

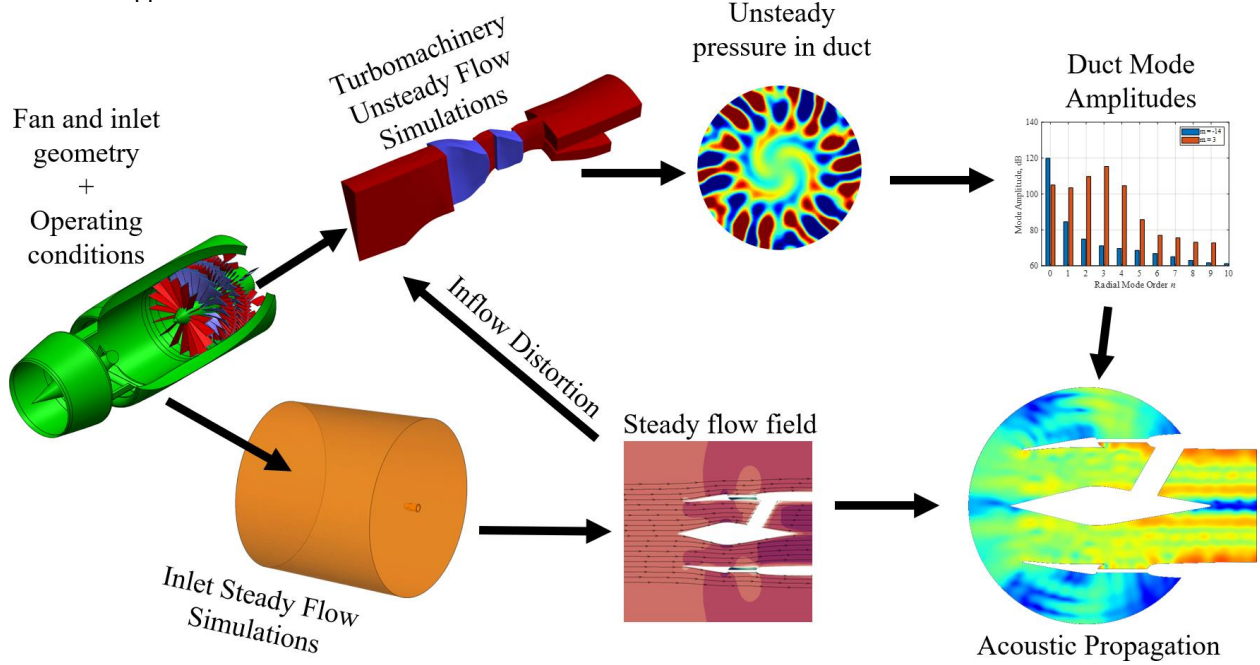


Fig. 2 Fan noise workflow.

The turbomachinery branch of the toolchain uses the external flow simulation as its upstream boundary condition. A steady Reynolds Averaged Navier-Stokes (RANS) solution is first computed through the turbomachinery. Next, a specialized Unsteady RANS (URANS) solver is used, which solves a Fourier-decomposed version of the flow field as a perturbation on the URANS solution. This yields unsteady pressure fields that contain the acoustic waves from the rotor-stator interactions—the fan tones. This solution is then sampled at a plane inside the inlet just upstream of the fan system and handed to an acoustics simulation for acoustic propagation to the far-field.

The far-field propagation branch of the toolchain solves the convected wave equation for the flow field given by the RANS simulation of the inlet with a specified unsteady source (duct mode amplitudes) from the unsteady RANS of the turbomachinery. The attenuation by an acoustic liner in the inlet duct can also be considered in this step. The convected wave equation is solved in this step on a near-field mesh of finite elements. An infinite element technique is used to propagate from the finite element domain to a set of observer locations, yielding the acoustic waves at the far-field as required for aircraft noise prediction.

A. Inlet Steady Flow Simulation

The inlet geometry with the fan removed is used to define a computational domain, shown in orange in Fig. 2. Using the mesh creation tool Pointwise [3], the computational domain is filled with grid points, from a fine structured boundary layer mesh on the solid surfaces to a coarser unstructured grid in the flow field away from the surfaces. Using an unstructured mesh offers considerable labor-hours savings for the relatively complicated engine geometry and allows for more features to be included, instead of using a simplified geometry for structured meshing.

The anticipated external airflow conditions and engine operating conditions are used to define a set of boundary conditions and the solution is solved using the NASA code FUN3D [4] and an output file is written in Tecplot format. Typical run times for a single configuration were under 24 hours on a 32-core desktop workstation, which enabled the team to avoid using high-performance computing resources.

The approach and lateral flight conditions were interrogated with and without an angle of attack. Furthermore, simulations with and without the cowl actuators and centerbody spike supports for the conditions with 0° angle-of-

attack were also conducted to determine the effect, if any, the supports have on the downstream flow upstream of the fan stacking axis. The set of conditions simulated is given in Table 1.

Table 1 CFD runs and conditions.

<i>Run #</i>	<i>Condition</i>	<i>AoA (α), degrees</i>	<i>Flight Mach Number</i>	<i>Struts & Actuators</i>
1	Approach	5.20	0.261	Yes
2	Approach	0.00	0.261	Yes
3	Lateral	6.70	0.350	Yes
4	Lateral	0.00	0.350	Yes
5	Approach	0.00	0.261	No
6	Lateral	0.00	0.350	No
7	Flyover	6.94	0.360	Yes
8, 9, 10	Takeoff	0, 9, 12	0.250	Yes

As an example, the result for Run #1 is shown in Fig. 3, giving axial flow velocity for the approach condition, corresponding to a Mach 0.26 external flow and 5.2 degrees angle of attack. The wake from the upstream cowl is visible in Fig. 3 (a), with some small recirculation. The flow is largely smoothed out by the long inlet by the time it reaches the fan face, shown in Fig. 3 (b). There are velocity deficits visible from the three struts, but they are small in amplitude.

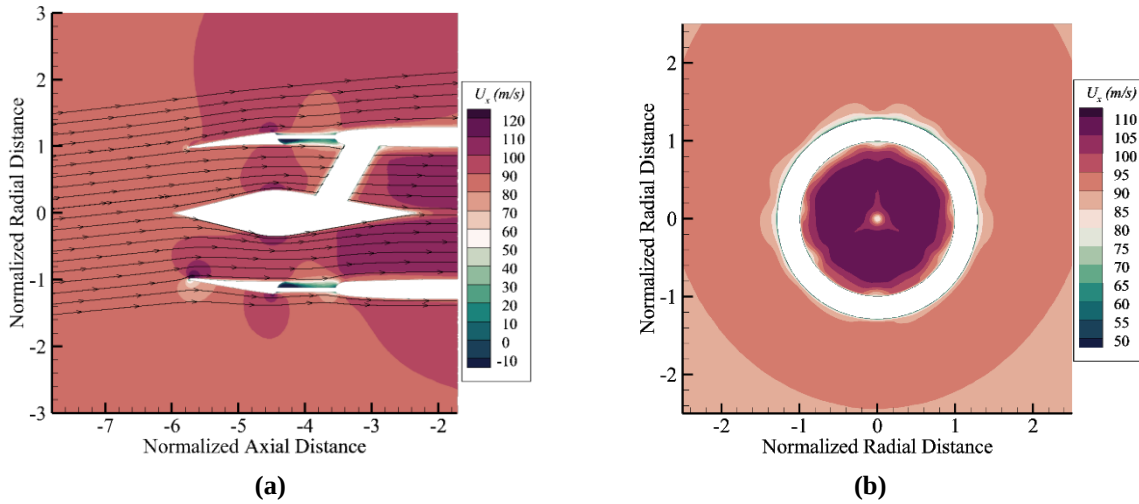


Fig. 3 Axial velocity at the approach condition (Run #1) showing (a) side view and (b) fan face.

This is one of ten conditions run, for different fan speeds, different angles of attack and different external flow speeds. In all conditions except takeoff at 12 degrees, the flow was well attached and showed largely similar characteristics inside and outside of the nacelle. Takeoff is not a noise rating condition for certification flights and so this case might be neglectable from an acoustics perspective. The other three “full features” runs (1, 3 and 7) show that the flow is largely attached through the inlet.

B. Turbomachinery Unsteady Flow Simulation

Due to the large disparity between the aerodynamic and acoustic scales involved in the fan-inlet systems, it was mathematically more tractable to decouple and treat the fan and inlet separately. In this work, they are decoupled in the acoustic sense. The aerodynamic coupling is retained by imposing the inflow distortion from the inlet as a boundary condition on the fan. Tbpffdshe modeling approach used here is a synthesis of high-resolution URANS simulations for the fan source noise prediction, and computational aeroacoustic (CAA) simulations for the inlet noise propagation to the far-field. The initial focus has been on the fan inlet tone noise but, in principle, the methodology is applicable to the fan exhaust tone noise as well, with the additional challenge of sound propagation through sheared flow.

A full URANS simulation that is adequately resolved to provide the necessary accuracy of the acoustic perturbations in the vicinity of the fan stage is very computer resource intensive and not practical for the purposes of this study. As a work around we relied on an approximation of URANS known as the non-linear harmonic (NLH) method. In the NLH approximation only a pre-selected set of frequencies is tracked in the simulation which results in significant reductions in the computing resource requirements. This is especially practical for turbomachinery applications where specific frequencies are driven by the machine design, in this case the blade passing frequency. For most applications, experience has shown it is sufficient for accuracy to retain the first three harmonics of the blade passing frequency of each blade row. The particular implementation of the NLH that was used in this work is incorporated into the commercial turbomachinery aerodynamic software package called FINE/Turbo [5]. It is a density-based URANS solver which incorporates a number of spatial numerical schemes including finite-difference and upwind, and temporal schemes such as explicit time-marching Runge-Kutta. It features a number of convergence acceleration strategies including local time-stepping, multigrid, and implicit residual smoothing. It offers a menu of optimized turbulence models and is an MPI-parallelized code.

The NLH computational domain for Superfan is shown in Fig. 4 in which the blocks associated with each blade row are shown in different colors for clarity. Change of color from one set of blocks to the other represents the transition from one frame of reference to another starting with the stationary blocks for the IGV shown in dark purple. This high-resolution grid, which contains one passage of each blade row, is comprised of roughly 19.8 million points. By contrast, the equivalent full wheel grid needed for a URANS simulation would have required 413 million grid points. The NLH simulations for Superfan were typically run to compute the first three harmonics of the blade passing frequency for each blade row, as described in reference [6]. For each operating condition of interest, average static pressure conditions were set at the bypass and core duct exit plane to achieve the total target mass flow rate for Superfan at that condition. The resulting predicted mass flow split, as well as the fan pressure ratio in each simulation, were consistent with those supplied by the designer, GE Aviation.

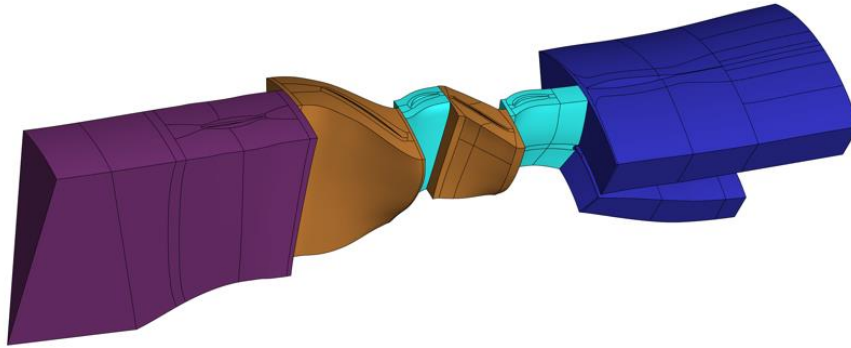


Fig. 4 Superfan NLH computational domain with various blade row blocks highlighted. The spinner and IGV block are dark purple, rotor blocks are brown, and stator blocks are cyan. The exit duct is dark blue.

C. Duct Mode Amplitudes

The acoustic portion of the unsteady pressure field is quantified by using the Actran [7] iTM tool. This utility extracts pressure and velocity on a plane in the engine duct and reconstructs a full wheel. The result of this process for the approach condition is shown in Fig. 5. The eigenfunctions for the wave equation in a duct with plug flow are used to reconstruct this pressure field and the complex amplitudes for the most significant duct modes are used as the boundary condition for the next step in the toolchain. The single plane pressure-velocity (SPPV) method is described more thoroughly in the Actran manual. [7]

After a series of investigations by the authors, the most important interaction noise source was determined to be between the inlet guide vanes (IGVs) and rotor 1. These blade rows have counts of 17 and 20 respectively. This interaction leads to strong interference patterns of orders 3 and -14, with the negative sign indicating rotation in the opposite direction from the rotor. The patterns of 3 and 14 are apparent by inspection of Fig. 5.

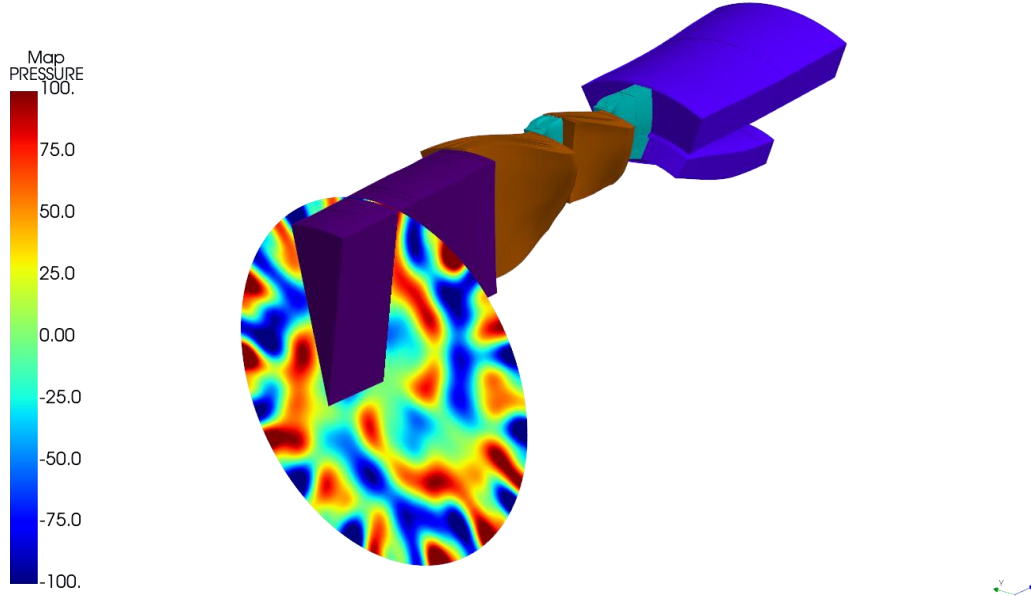


Fig. 5 Full wheel reconstruction of blade passing frequency at approach.

The output of Actran iTM is a table of radial and azimuthal duct mode complex pressure amplitudes, including upstream and downstream traveling components. These complex pressures are used as the boundary conditions for the subsequent acoustic simulations.

D. Acoustic Propagation

The duct mode amplitudes are the boundary condition for the acoustic propagation code. Simulations presented here were conducted using Actran 2022 [7] employing the Actran TM (turbomachinery) workflow. The frequency domain method solves the Möhring Analogy [8] which is the Navier-Stokes equations written as a wave operator on enthalpy. It handles convected acoustic waves in cases where the flow is reversible, adiabatic and irrotational. The solution is found with a matrix inversion method. Implementations are provided for both 2-D axisymmetric topologies as well as 3-D topologies. Due to the computational costs, the majority of the work to date has used the 2-D implementation with a short study of 3-D effects discussed in Section III F.

The 2-D inlet geometry was surrounded by a semi-circular domain of 3.4 m (135 in.) radius, centered on the mid-point between the front inlet and auxiliary inlet. This domain topology was chosen as providing a largely reflection-free computational domain when using the infinite element boundary condition. A quadratic grid with an element size of 8 mm (0.315 inches) gives 4 points per convected wavelength up to the frequency of about 4500 Hz, depending on the local flow speed. This results in approximately 550,000 elements and solution times on the order of a minute per frequency on a laptop class computer. An arc of virtual microphones at 46 m (150 ft) gives the sound radiation in the far-field. Actran uses an infinite element method to model the sound radiation from the finite element domain through a uniform medium to the specified field points. For the present simulations, these virtual microphones are in a flow convecting with the flight speed of the inlet. The layout is shown in Fig. 6

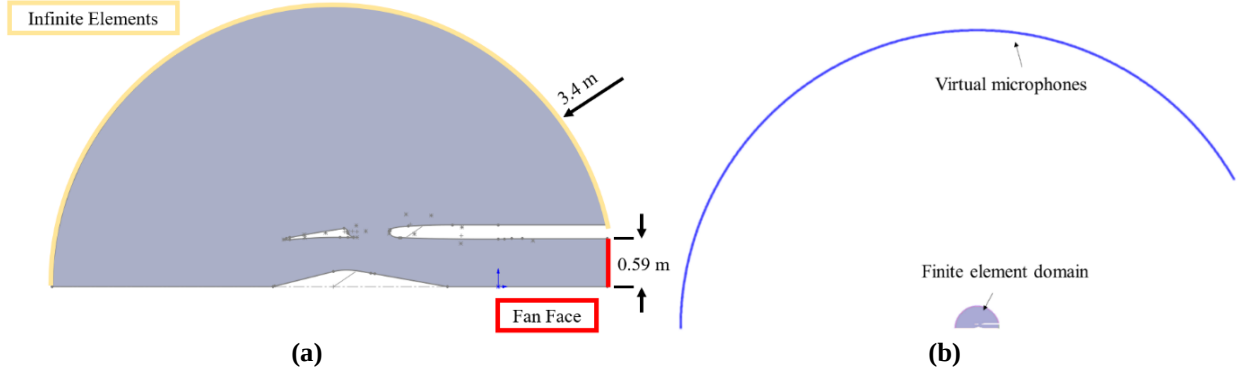


Fig. 6 Computational domain for 2-D simulations. (a) Finite element domain and (b) far field receivers.

The acoustic content extracted from the URANS simulations using the Actran iTM tool, can now be used as the modal input (i.e., boundary condition) at the fan face. The corresponding radiation simulations provide a series of sound maps like that shown in Fig. 7. In this case, the real part of the pressure is plotted with 11 input radial modes included simultaneously and with their respective phase preserved.

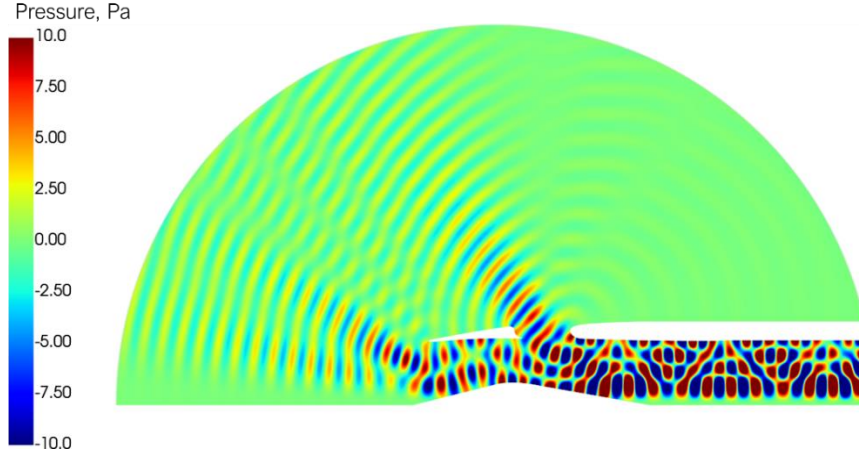


Fig. 7 Real part of frequency domain peak-to-peak complex pressure for approach conditions, azimuthal mode $m = 3$, blade-passing frequency.

The simulated far-field tonal amplitude for the approach operating condition is shown in Fig. 8. The upstream radiated noise (along the axis and near 0 degrees) is dominated by the $m = 3$ contribution. At approach, the radiated sound peaks at an angle of 50 degrees and at an amplitude of 80 dB. Results for other operating conditions are presented in [9]. At flyover and lateral conditions, the levels are approximately 20 dB higher and more forward-radiated. Inlet levels for all conditions fall off rapidly for angles past 90 degrees. These predictions can be used in system noise analyses where an aircraft trajectory is used to predict sound observed by a receiver on the ground. All cases presented in reference [9] were simulated with axisymmetric inflow and no additional noise due to distortion, which is discussed separately in Section III A and in reference [6].

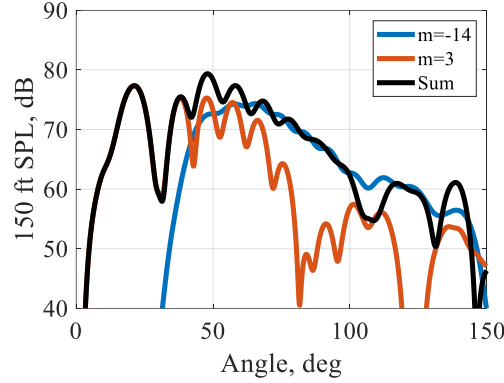


Fig. 8 Far-field tone amplitude predicted for blade-passing frequency (BPF) at approach condition.

E. Validation exercises

The accuracy of the NLH approach was assessed using wind tunnel data from the NASA Source Diagnostic Test (SDT) fan model, tested in 1999. The SDT fan had 22 rotor blades and 54 stator vanes and represents a large, high-bypass turbofan engine of the mid-1990's. The simulations were carried out for a range of fan tip speeds and the results were analyzed to establish statistics regarding the accuracy and robustness of the simulations for predicting the acoustic content. These are summarized in [10] and were deemed satisfactory for the present work to proceed.

III. Simulations of Superfan and Variants

In discussions with acousticians in industry a few commonly raised questions about fan noise from supersonic propulsion were:

- What noise will the distortions from the centerbody and its struts, and from the auxiliary opening and its actuators produce?
- Will the strut and actuator count impact the noise like rotor and stator counts do?
- What is the impact of angle of attack on these inlets with multiple openings?
- What is the noise sensitivity of the close rotor-stator spacing of a two-stage fan?
- Will noise from the second rotor-stator be heard coming from the inlet through the first stage or can it be ignored?

Only one known acoustic test has been performed on a multi-stage fan (Quiet Supersonic Propulsor, in 2002 [11] [12]) and that was operated with a simple conventional inlet. Data from the QSP test was not analyzed due to budget and programmatic issues, thus the simulation and analysis of the Superfan is very important for the development of supersonic propulsion. If these supersonic-specific features are critical, then empirical fan noise models must incorporate these features so that trades between inlet performance and noise can be worked out at the system level.

To address these questions and provide the fan noise modeling effort with acoustic data, a succession of simulations were done on variations of the Superfan design. First, under assumptions of axisymmetry the impact of the auxiliary opening in the inlet on the fan noise source and its propagation out the inlet were investigated. Next, different non-axisymmetric aspects, such as struts and actuators and angle of attack, were introduced and simulated. Finally, given the importance of rotor-stator spacing on the length of a multi-stage fan, the Superfan geometry was stretched to change the location of the IGV relative to the first rotor. Taken together, these findings informed the fan noise model as presented in a companion paper [2]. Details about the individual studies are presented in the following subsections.

A. Assessment of inlet distortion from auxiliary inlets on tone sources

As discussed previously, the aerodynamic impact of the inflow distortion caused by the airflow through the auxiliary doors and around the struts and actuators is modeled as a boundary condition for the fan NLH fan simulations. Using RANS simulations, the flow field around and through the inlet was computed and total pressure and total temperature profiles were extracted at the fan inflow domain, near the tip of the spinner. Examples of the computed total pressure contours are shown in Fig. 9 for the 0° and 5° angles of attack at the approach condition. The

wakes of the three inlet struts are visible in both contours as are the subtle circumferential distortions caused by the four actuators of the translating cowl. For the angle-of-attack case, additional circumferential distortion is also visible around the circumference of the contour plot. Radial profiles of total pressure and total temperature as a function of circumferential angle were extracted and supplied as the inflow boundary conditions for the NLH fan stage simulations.

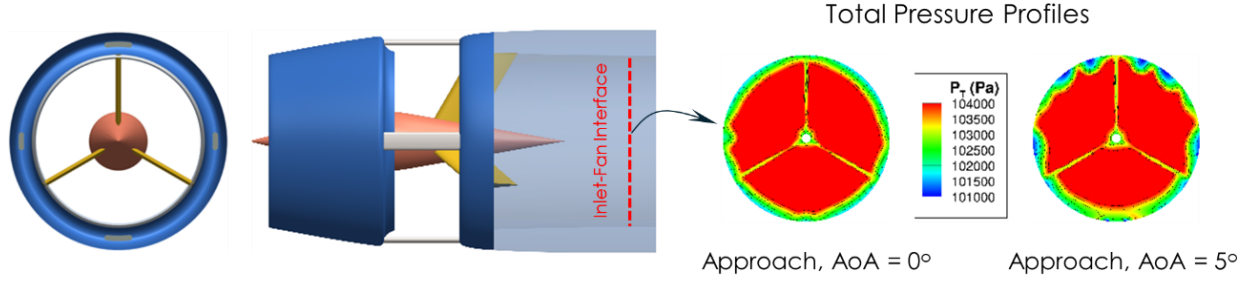


Fig. 9 Predicted contours of total pressure in the distorted inflow upstream of the Superfan.

The Superfan NLH simulations took around 76 hours to run for 4000 iterations to achieve convergence of the relevant criteria. The flow solutions include a large set of the mean flow and thermodynamic variables as well as the real and imaginary parts of the associated harmonic perturbations. An example of the simulation results for the real part of the harmonic pressure perturbations are shown in Fig. 10 for an axial slice of the computational domain just upstream of the spinner at the lateral condition with open auxiliary doors and the inlet at 7 degrees angle of attack. The 1×BPF harmonic pressure perturbations are dominant upstream of the IGV and are in the range between -500 Pa to 500 Pa. The corresponding 2×BPF harmonic levels are an order of magnitude smaller, and the 3×BPF harmonic levels are much smaller yet and between ± 1 Pa. The dominant propagating Tyler-Sofrin circumferential modes at 1×BPF are $m = +3$ and $m = -14$. These modes are clearly discernable in the contour plots for 1×BPF showing a 14-interlaced pattern in outer portion of the contour surrounding a 3-interlaced pattern in the inner region. There are other propagating circumferential orders at this frequency, but they are weaker and do not contribute significantly to the total sound pressure level at 1×BPF. The process has been documented in much more detail in reference [6].

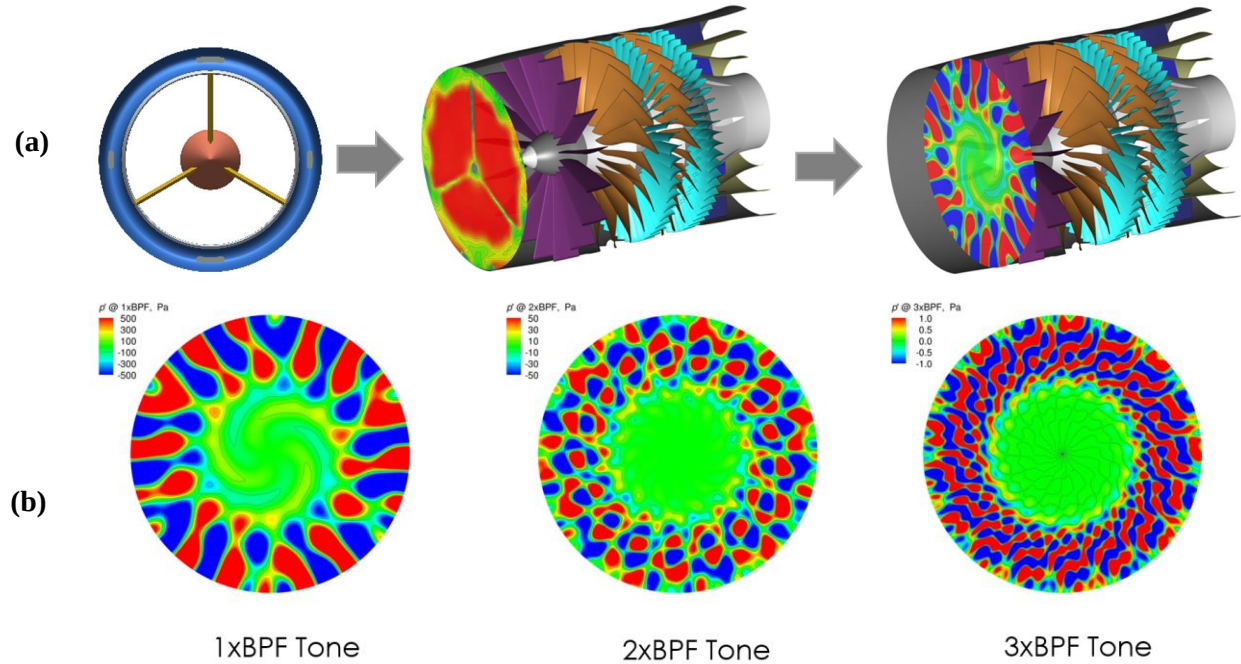


Fig. 10 Simulation steps. (a) The inflow distortion is the boundary condition for the fan simulations. (b) Contours of the real part of the pressure perturbations for the first three harmonics of BPF.

To investigate the impact of the inlet components on the inflow distortion noise levels generated by the fan, a parametric study was carried out by systematically removing various hardware components of the inlet and running NLH simulations with the resulting inflow distortion patterns. The configurations studied are depicted in Fig. 11. In part (a) the baseline configuration, for which the translating cowl is removed, is shown which is essentially a conventional axisymmetric inlet causing no inflow distortion. Part (b) depicts the complete inlet with the translating cowl in the forward position, so the auxiliary inlet doors are fully open. This configuration represents the most realistic inlet configuration for LTO operability. Part (c) is the same as the full inlet, but with the inlet centerbody struts removed. Part (d) is the inlet without either the centerbody struts or the inlet actuators. Simulations were run with and without an angle of attack for each configuration except for the baseline configuration which was run only at the zero angle of attack to serve as the reference noise level. Two fan operating conditions were considered, approach and lateral. The inlet angle of attack for approach is 5° and for lateral is 7° degrees. In all cases, the first three harmonics of the blade passing frequency of each blade row were included in the simulations. Acoustic contents were extracted at an axial location just upstream of the spinner nose in order to compute a first-order estimate of the impact of the various inlet configurations on the inlet source acoustic tone levels.

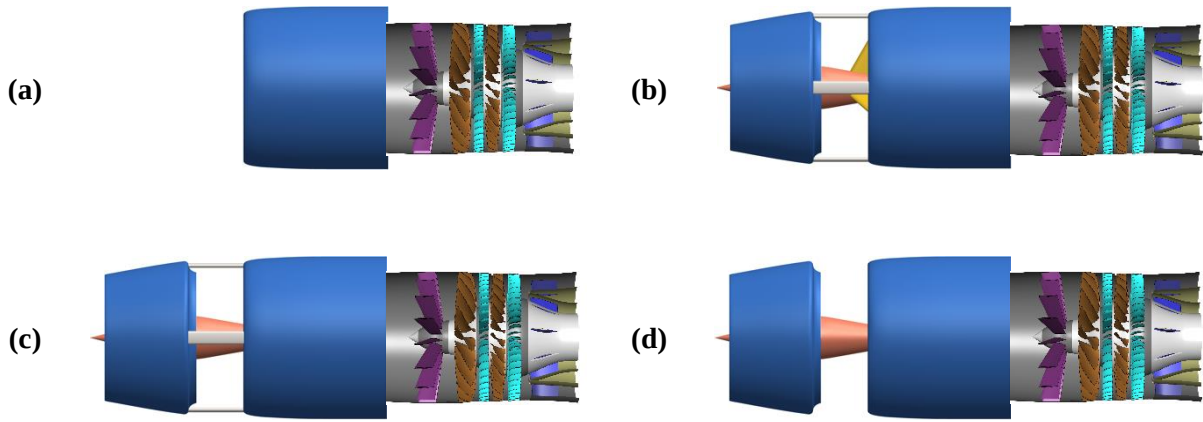


Fig. 11 The inlet configurations investigated. (a) The axisymmetric baseline pictured as a subsonic inlet. (b) The complete supersonic inlet configuration with the inlet cowl in the forward position. (c) Same as (b) but with the centerbody struts removed. (d) Same as (c) but with translating cowl actuators also removed.

Given the large number of propagating radial modes present, acoustic power level was deemed the best metric for judging the impact of the various inlet configurations on the noise source levels. Computing the acoustic power for all the inlet configurations shown in Fig. 11, the influence of the various contributors to the inflow distortion noise can be explicitly shown. The results are summarized in Fig. 12. In this figure, the baseline acoustic power level is shown as black bars. The acoustic power levels for the inlet configurations (b) through (d) are shown as colored bars. For the zero angle of attack conditions, they are shown as yellow, orange, and brown bars. The corresponding results for the angle of attack conditions are shown as light, medium, and dark blue bars. The results for approach are shown in the top part of the figure and those for lateral in the bottom part. For each condition, the power levels for the blade passing frequencies $1 \times \text{BPF}$ through $3 \times \text{BPF}$ are plotted. The introduction of the inflow distortion generally increases the inlet noise levels as was expected. Note that for the lateral condition, the $3 \times \text{BPF}$ acoustic power level is below 90 dB and not visible in the plot. The power level increases are significantly larger at the lateral condition (e.g. ~ 3.5 dB at $1 \times \text{BPF}$) than for the approach condition (e.g. ~ 0.5 dB at $1 \times \text{BPF}$). Comparing the power level increases for the various inlet configurations makes it clear that the increase is principally caused by the inflow distortion through the open auxiliary doors but is otherwise is essentially insensitive to the details of the inlet hardware. Furthermore, that the angle of attack in the range investigated has a negligible effect on the inflow distortion noise levels.

Legend:

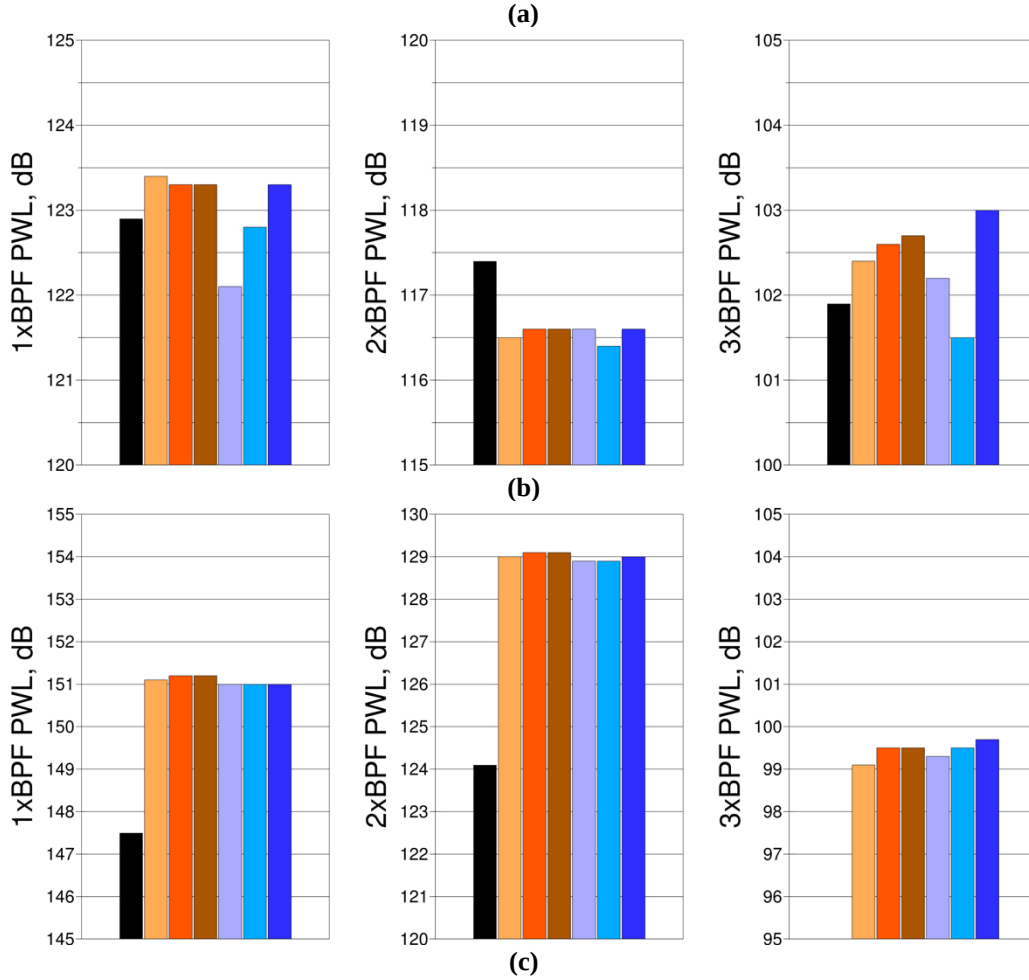
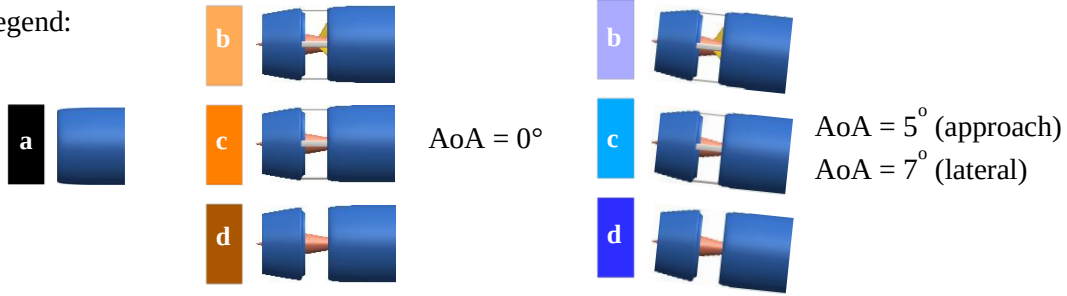


Fig. 12 Impact of the inlet distortion on tone acoustic power levels for the inlet configurations. (a) Visual legend showing configuration number and flight condition for bar charts. (b) Tone power levels for approach operating condition. (c) Tone power levels for lateral operating condition.

B. Assessment of IGV-rotor spacing on tone sources

It is understood that tone noise, being produced by the interaction of the wakes and even potential fields of the rotor and stators, is impacted by their axial spacing. Given that investigations of modal strength propagating upstream show that the first stage interactions produce the most inlet noise, the sensitivity of the noise to IGV/R1 spacing was investigated. More details can be found in [6].

Three different IGV/R1 spacings of the Superfan model were created by moving the IGV upstream and downstream from the nominal design position. An IGV/R1 spacing parameter (s^*) was defined as the IGV/R1 spacing normalized by the axial tip chord length of the IGV. The three configurations and associated IGV/R1 spacing values

are shown in Fig. 13. Surprisingly, when checked, the fan performance was not found to deviate by more than 1% among these changes in spacing.

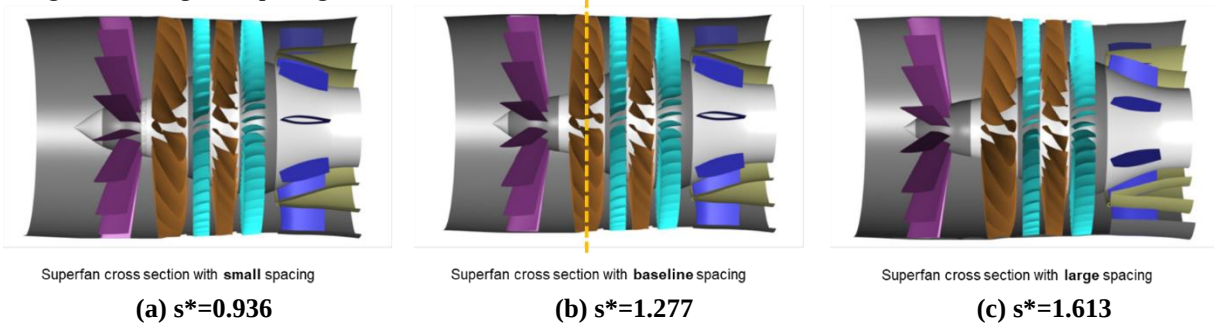


Fig. 13 Superfan IGV/R1 spacing configurations simulated, spacing given by s^* , spacing relative to IGV tip chord. (a) Small spacing, (b) design spacing, (c) large spacing.

These three spacing configurations were run at four different power/RPM settings corresponding to approach (63% power), flyover (80% power), lateral (93% power), and takeoff (100% power) conditions. The results generated sound power levels for the first three harmonics of the R1 rotor as a function of axial distance from the R1 rotor ($x=0$). These results were computed for each combination of spacing/power setting. An example showing the results for the 1xBPF at the flyover condition is shown in Fig. 14. The drop-off in sound power level to the left of the circles is due to the change in the grid stretching away from the source region and is not physical. Tone power was assessed at the point just before the grid change (e.g. at the circled points). As in this figure the tone levels usually drop monotonically as IGV/R1 spacing increases. However, there were some combinations of spacing/power condition where the tone power did not vary monotonically with spacing. This is most likely due to non-optimal phasing of the wakes off of the IGV into R1, a factor noted in a slightly different context with sweep and lean rotors [13].

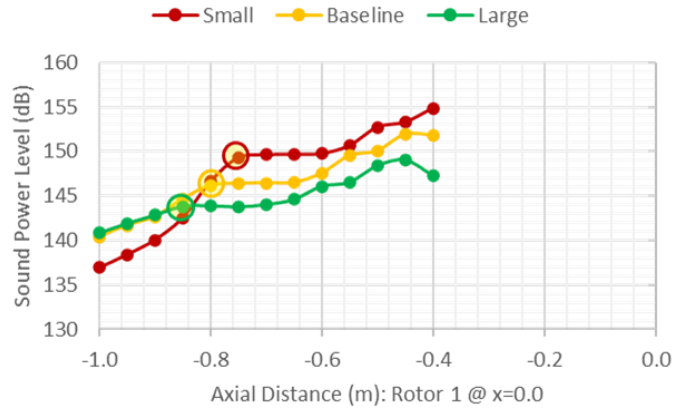


Fig. 14 Example of tone power in duct varying IGV/R1 spacing: 1xBPF sound power level results for three spacings at Flyover condition.

C. Assessment of multi-stage fan noise sources

The present work identified the IGV/R1 interaction as the primary contribution to inlet noise. The sound generated by the second stage is partially blocked by the first fan, which has a particularly high solidity in the present design. Prior work [12] on supersonic fan noise suggests that the first stage is far and away the main contributor to inlet noise. The second stage is identifiable in the data but a negligible sound strength. Perhaps the total fan pressure rise can be distributed to be higher on the second stage, where it is blocked, and so achieve noise reduction for the fan inlet tone.

D. Assessment of acoustic liner placement

The supersonic inlet considered here is long compared to current subsonic inlets. Modern subsonic inlets have length-to-diameter (L/D) ratios of around 0.3 to 0.5, while this axial spike inlet has an L/D of ~ 1 between the IGVs and the downstream edge of the auxiliary inlet. This provides ample area for noise-attenuating liners to help reduce the inlet radiated fan noise. Using the liner methods demonstrated on the NASA ADP fan liner test [14], the liner

design from GE was evaluated in COMSOL and implemented in Actran for simulation, as shown in Fig. 15. The blue colored area is the lined section and it is shaded to indicate that the liner length was varied during the study.

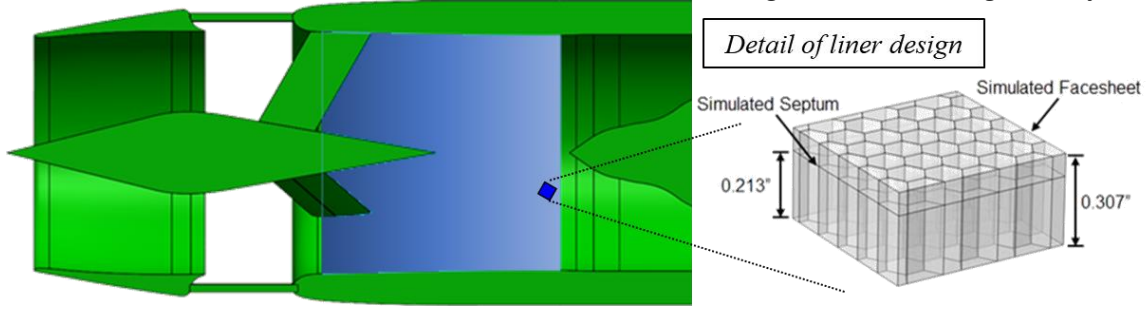


Fig. 15 Acoustic liner for supersonic inlet shown in blue

Since the fully treated area prescribed by GE was quite large compared to modern subsonic designs, a study was conducted investigating the effect of liner length. This turned out to be a rather complicated question since the fan tone source is changing between operating conditions. Results for the three noise certification conditions are shown in Fig. 16.

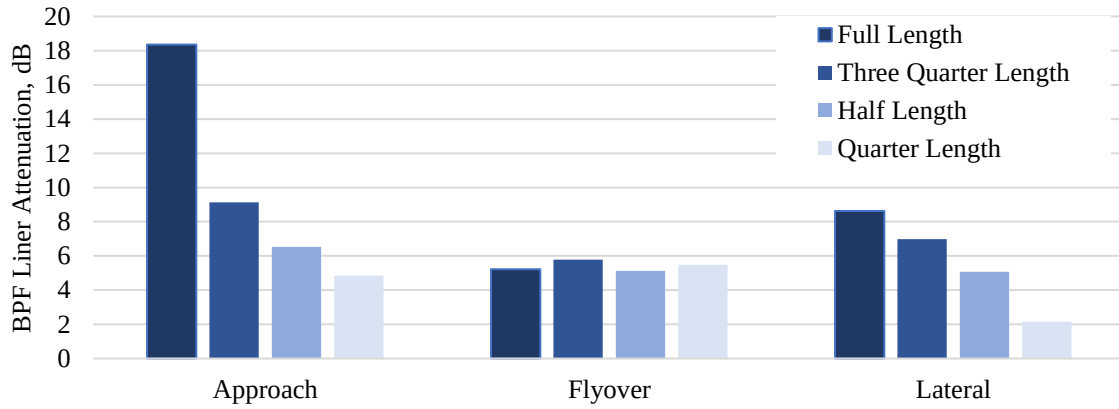


Fig. 16 Effect of liner length for supersonic engine inlet

The effect is non-linear and non-monotonic, although generally the longer liner is more effective. The liner is most effective at approach condition, which was likely the design intent. At flyover condition, the noise source is dominated by the $m = -14$ mode, as discussed in [10]. This means that even a short liner will be effective, while at approach and lateral the $m = 3$ mode is important and so additional liner length is helpful.

E. Assessment of axisymmetric propagation from source to far-field

A study was conducted isolate the effect of inlet topology on the noise radiation to the far-field [15]. In this study, axisymmetric versions of a subsonic and supersonic inlet were compared, as shown in Fig. 17.

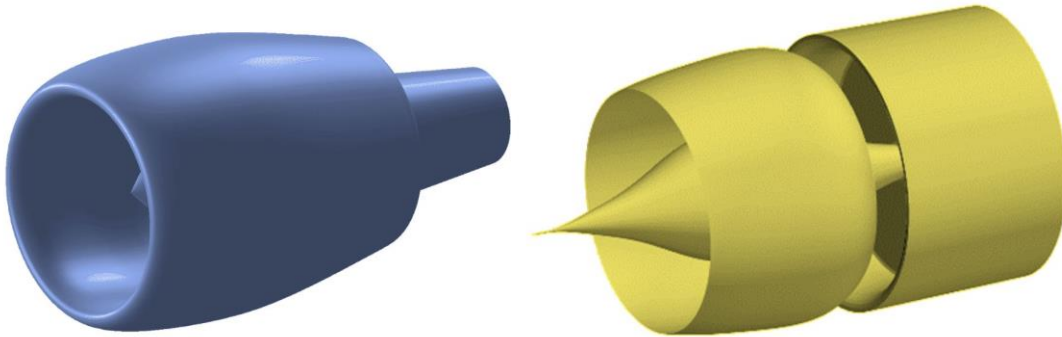


Fig. 17 Axisymmetric subsonic and supersonic inlets used for the inlet effect study.

The idea of this study was to use the same boundary conditions for the acoustic and flow simulation and compare the resulting far-field noise. This study predates the delivery of the GE fan system to NASA, so the fan noise source was conceptual, and intended to be generic. The forward flight speed was varied and flow calculations were conducted for both geometries. The workflow described previously was used to propagate the sound from the fan face to the far-field. A typical result is shown in Fig. 18.

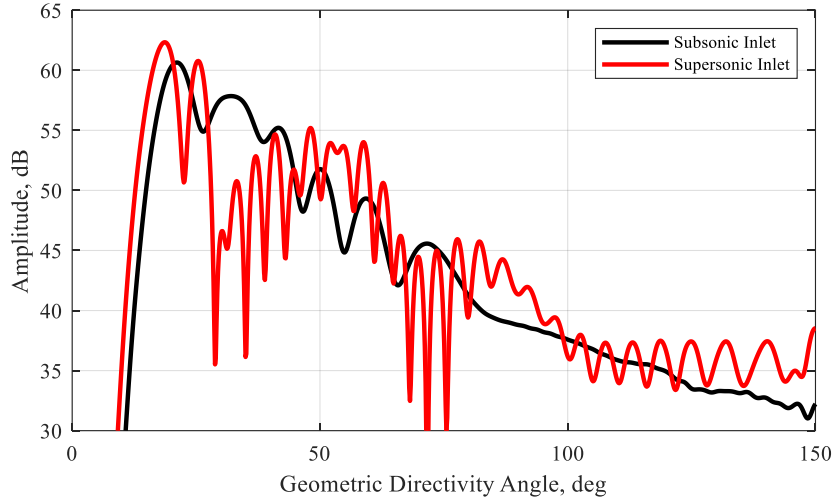


Fig. 18 Example directivity of a subsonic and supersonic inlet with the same boundary conditions.

It is apparent from this example that the overall trends are similar between the two inlets, with peak noise at a similar geometric angle and the noise falloff at sideline angles similar overall, although there are more ripples in the directivity from the supersonic inlet (red). This is principally because the supersonic inlet acts like a two-port system and causes constructive and destructive interference in the wave pattern. The sound propagation modeled here is linear so there is no mechanism for increasing or decreasing the sound power due to inlet geometry. Overall, the study concluded that inlet geometry alone had a weak effect on the radiated noise and the effect of the inlet geometry on the fan noise is likely more important. It might make a modulated tone sound as it flies over and have an effect on integrated noise metrics.

F. Assessment of azimuthal features on propagation of tones to far-field

All of the noise propagation work presented previously used a 2-D method, where the convected wave equation is expressed in an axi-periodic form. This is computationally extremely beneficial because it allows sufficiently large near-field domains while the finite element mesh size can be fine enough to capture all relevant frequencies with computational times of minutes or hours. The periodicity is needed to capture the spinning modes generated by the turbomachinery, differentiating the solution method from a purely axisymmetric result. This solution method is commonly used for subsonic fan noise, especially for inlets which are nearly axisymmetric. However, the supersonic inlet is not purely axisymmetric and includes a few major features that might affect the radiated sound. The centerbody struts and the actuators for the upstream inlet cowl cannot be included in the axisymmetric model, nor can the effect of inflow angle of attack.

To include the full three-dimensional effects, we used the FUN3D RANS solver to generate a flow field and used a CAD model to generate a geometry of the fluid domain for meshing in Actran. The Actran iCFD tool is used to interpolate from the CFD mesh to the acoustic mesh. The far-field sound is captured on a set of arcs around the finite element domain. Both near-field and far-field geometries are shown in Fig. 19.

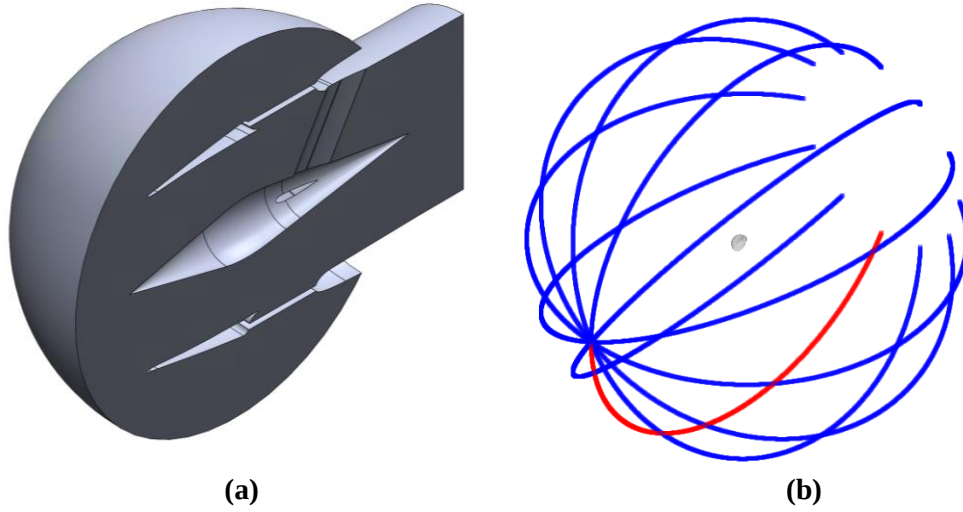


Fig. 19 Acoustic finite element domain for symmetric-antisymmetric solution method. (a) CAD model and (b) Far-field points around infinite element domain, bottom arc highlighted.

The workflow, challenges and findings from this study are described in [16]. The three-dimensional geometry was determined to be somewhat ambitious for the computational resources available, limiting the finite element region to a small size and solution times on the order of 7 hours per condition. A total of six conditions were run, with three variations on geometry combined with two operating conditions (approach and lateral). The geometry was varied in increasing complexity from axisymmetric to non-axisymmetric and then at angle of attack. Example results of the radiated sound are shown in Fig. 20. The directivity plots were somewhat irregular and required some interpretation. It can be seen that the major features match, so we can say the 3D features should not impact noise certification metrics.

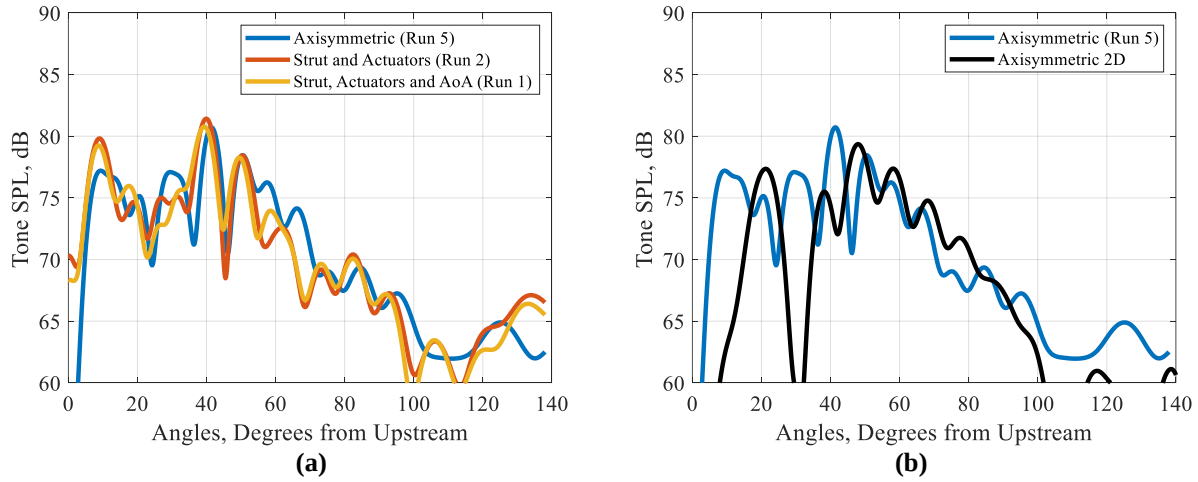


Fig. 20 Sound at far-field points for approach condition. (a) Average directivity over all azimuthal angles comparing three-dimensional effects. (b) Comparison of 3-D simulation with RANS flow field vs 2-D simulation with potential flow.

The reference [16] contains more discussion, but the overall findings were that the angle of attack had the smallest effect while the flow field type (RANS vs potential flow) had the largest effect on the propagation of sound out through the supersonic inlet. Being of order 1 dB, the 3-D effects on tone power can certainly be neglected to give first-order results but for a final noise prediction it is likely worthwhile to investigate whether they are important.

IV. Knowledge Gaps Identified

As with any research into novel areas, this project uncovered new areas for further investigation. The most compelling are described in the following subsections.

A. Aft fan noise simulations

We have been neglecting the aft fan noise because the aft noise has historically been expected to be jet-dominated. This may not be true for lower flight speeds or with advanced nozzle installations. The aft fan noise is a dominant source for subsonic fan noise at some flight conditions and shaft speeds. The aft noise propagation is complicated due to sheared flow. Additionally, the supersonic engine will likely include a long bypass duct with a mixed flow nozzle. It is not known if anyone has ever experimentally studied or simulated the noise of this configuration.

B. Broadband fan noise modeling

In this work, the leading source of fan noise was simulated and modeled: inlet tone noise. Broadband inlet noise is not amenable to direct simulation, in contrast to the tone noise simulation workflow presented. Its source is more robust than the tone source, making statistical models, such as acoustic analogies, more tractable. However, the propagation of broadband sound through the multiple stages of the rotor-stator system and the supersonic inlet should be investigated and the models for inlet broadband noise should be enhanced. The Actran portion of the fan noise simulation toolchain could be applied to produce the custom Green's functions required to predict this propagation.

C. Empirical fan noise shielding models

A recurring idea for noise reduction in supersonic aircraft is to integrate the propulsion such that the inlet is above the delta wing, shielding the ground observer from the noise coming from the inlet. Indeed, the empirical models currently being used predict a substantial reduction in fan noise from this noise-shielding method. However, detailed studies of advanced concepts of subsonic aircraft designed to achieve shielding have found that the empirical models are very optimistic when predicting noise reduction. High-fidelity prediction methods should be deployed on supersonic configurations with inlets located over shielding surfaces. The results can be used to create more realistic models for shielding of inlet fan noise for system-level studies.

D. Acoustic liners in hot, high-speed flows

For both fan and internal shear layer noise sources, liners would be a useful noise reduction technology in the hot section of an internally mixed exhaust system. The technology for creating acoustic liners generally exists; what is missing is the ability to predict the effective impedance of the liner for acoustic waves propagating in a mixed flow exhaust duct. The combination of grazing flow and variable speeds of sound make the design of the liners difficult and their acoustic impact hard to predict. High-fidelity simulations could produce the data and insights required to make lower-order models of liners in hot flow possible.

V. Conclusion

A workflow was presented for predicting tone noise generated by a two-stage fan designed for commercial supersonic air travel. A combination of software tools both commercial and NASA-developed was used to simulate an external and internal flow field, compute the turbomachinery noise source, and then propagate sound to the far-field. These tools were used on high-performance desktop workstations, avoiding the costs and turnaround time limitations of high-performance compute clusters. The workflow was validated by comparisons with model scale subsonic fan geometry tested at NASA in a wind tunnel.

The absolute level of far-field sound was predicted for several operating conditions. These results were supplemented by a series of investigations for the fan model with different variations, including inflow distortion effects and acoustic liners. Several of these findings were used to inform an empirical fan model developed from a combination of experimental data and these physics-based simulations. These simulations were used in lieu of extremely expensive wind tunnel rig tests which were out of scope for the present resources. Finally, a set of future work was identified to fill in knowledge gaps.

Acknowledgments

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