Project 059(E) Moderate-Fidelity Simulations for Efficient Modeling of Supersonic Aircraft Noise

The Pennsylvania State University

Project Lead Investigator

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Project Funding Level

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Investigation Team

Pennsylvania State University

- Principal Investigator: Dr. Philip Morris
- Co-Investigator: Dr. Daning Huang
- Graduate Students: Dana Mikkelsen and Stephen Willoughby

Project Overview

The purpose of this project is to develop and assess computational tools to simulate the flow and noise of civil supersonic aircraft engines. The simulations will focus on the models and conditions being used in validation experiments conducted at Georgia Institute of Technology (Georgia Tech) under Project 59B.

The prediction of noise from supersonic jets, particularly when noise reduction devices are present, is a challenging computational task. Methods based on Reynolds-averaged Navier–Stokes (RANS) solutions are relatively inexpensive to perform and provide satisfactory predictions of the average flow field, even for quite complicated geometries. The subsequent prediction of noise based on acoustic analogies is highly efficient but faces difficulties when the geometry of the nozzle is not a simple axisymmetric one. Methods based on large eddy simulations (LES) provide considerably more information about the unsteady flow and the noise generated. However, LES are computationally expensive, especially when the engine geometry is complex. This situation is encountered in the case of nozzles with noise reduction devices, such as internal mixers. Noise predictions based on the LES can be made quite efficiently by using the Ffowcs Williams and Hawkings (FWH) acoustic analogy (Farassat and Succi, 1983; Ffowcs Williams and Hawkings, 1969), but long time records are required to predict the noise radiated to far-field observers, thus adding additional expense to LES.

The approach in Project 59E is a compromise between the accuracy and high computational cost of LES and the noise-prediction inaccuracy of RANS-based simulations. The initial simulations being conducted in the initial stage of the project use RANS, and these calculations serve as a starting point for the LES. In anticipation of the addition of internal mixers to the nozzle geometries, only RANS simulations are planned to be conducted for the internal flow; then LES, coupled with the Ffowcs Williams and Hawkings acoustic analogy, will be used to predict the external flow and the noise generated. The RANS solution at the jet exit will be used as an initial condition for the external LES. This will require the addition of some unsteady information, which will be guided by a very limited number of LES. This approach will reduce the total computational cost because it removes much of the geometric complexity and the associated grid requirements for LES of the internal flow.

The usefulness of this approach is that it will make LES for nozzles with noise reduction devices more accessible to more users, particularly industry engineers with very limited computational resources and time available for multiple simulations in the design process.

If successful, the ASCENT Project 59E research will develop methods to predict the noise generated and radiated by civil supersonic aircraft engines. The developed tools should enable airframe and engine manufacturers to assess the noise impacts of engine design changes and to determine whether particular designs will meet current or anticipated noise certification requirements.

Project Introduction

During the first project year, because of a change in direction from the originally proposed research, the original project 59A was split into two parts. The new project 59A, being conducted at Georgia Tech, will examine the effects of different inlets and the introduction of noise reduction devices on the performance of selected engine cycles and geometries. The new project 59E focuses on the prediction of the flow and noise from different nozzle configurations. The latter project is the work described in the present report.

Major Accomplishments

The tasks for the first project year centered on RANS simulations for the internal and external flow from a single convergent nozzle. The details of the model geometry were provided by Georgia Tech from the model used in ongoing experiments for Project 59B. The subtasks included grid development for the RANS simulations, RANS simulations, and comparisons with available experimental data. In addition, grid development for the LES has been initiated, and preliminary LES have been conducted.

Task 1 - Grid Generation for RANS Simulations

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The primary nozzle of the co-annular nozzle geometry provided by Georgia Tech was modeled by using STARCCM+. An initial mesh was created with a base mesh size of 7.87 in, with a target surface mesh size of 10% of the base size and a minimum surface mesh size of 5% of the base size. This initial mesh contained eight prism layers near boundary walls, with a prism-layer total thickness of 5% of the base size as well as two volumetric controls in which the smallest maximum cell size was 3% of the base size. In total, this mesh had approximately 5.9 million cells. Figure 1 shows the initial surface mesh.

This initial model underwent several iterative changes to achieve the current model. An interface between the rear spoke volume and the main nozzle volume was eliminated by combining the two to create one part. The mesh was refined to a smaller base size, and additional volumetric refinements were added in the core region. To compensate for the increased mesh density, the size of the outer domain was reduced. The thickness of the nozzle wall was included, and an interface between the nozzle exit and the domain was removed.

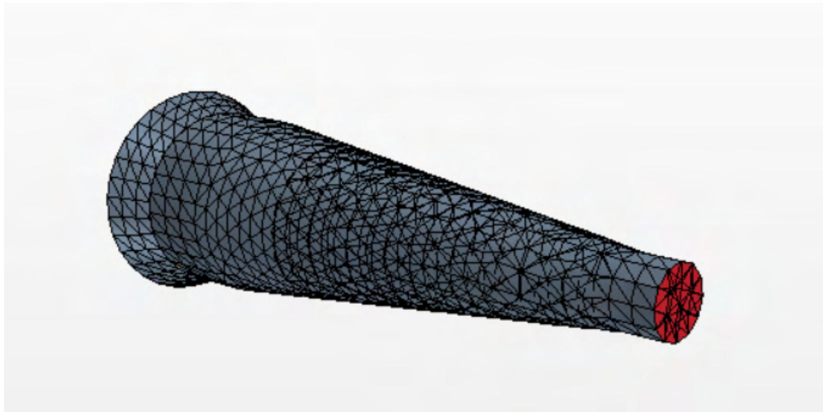

Figure 1. Initial nozzle surface mesh.

The current mesh has a base mesh size of 1.6 in, with the target and minimum surface mesh sizes held the same as before (10% and 5% of base mesh size, respectively). It contains 10 prism layers near boundary walls, with the prism-layer total thickness remaining at 5% of the base size. There are four volumetric controls. The innermost maximum cell size is 2.5% of the base size, with subsequent maximum cell sizes of 5%, 10%, and 20% of the base size. The total domain is 70 in long, with a start radius of 34 in and an end radius of 50 in for a domain size of 392,615 in^2. This mesh has approximately 13.8 million cells.

The revised surface mesh is shown in Figure 2. Figures 3a and 3b show cross-sections of the volume mesh, including the near nozzle region and the different refinement regions. The full computational domain is not shown.

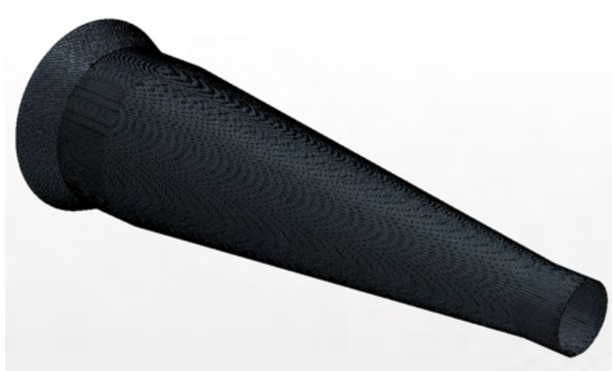

Figure 2. Current refined nozzle surface mesh.

Task 2 – RANS Simulations

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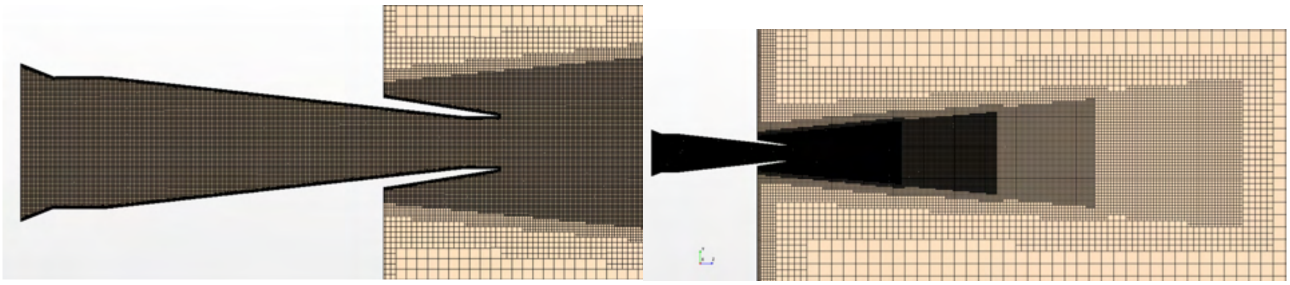
A steady RANS calculation was then performed by using STARCCM+. An implicit MUSCL third-order central-differencing scheme with an upwind blending factor of 0.1 was used. Sutherland's law was implemented for dynamic viscosity and thermal conductivity. A MinMod limiter was applied as well as a *k*-omega turbulence model.



A) B)

Figure 3. RANS grid. A) Near nozzle region. B) Grid showing different resolution levels.

The run conditions for this simulation were taken from experimental data provided by Georgia Tech. The ambient pressure and temperature were set to 14.051 psi and 530.2 R, respectively. The NPR and TTR were 1.53 and 0.98, respectively, for an expected nozzle Mach number of 0.8. Figure 4 shows the calculated Mach number contours for the inner nozzle.

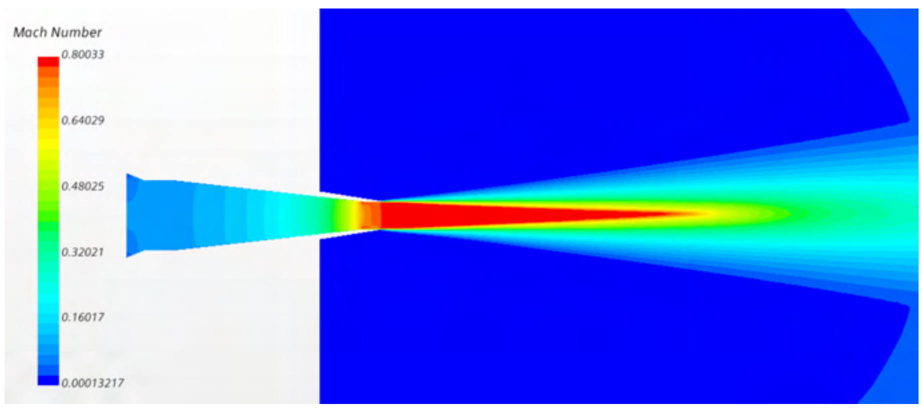


Figure 4. Mach number contours for primary nozzle RANS calculation.

The RANS calculation yielded an exit Mach number of 0.8 and an exit velocity of 256.77 m/s. This result is in good agreement with the experimental exit velocity measurement of 257.53 m/s.

The next steps concerning the RANS calculation are to complete a validation study of the primary nozzle against experimental data and to generate a grid to obtain a RANS solution of the full dual-stream nozzle.

Task 2 – Large Eddy Simulations

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Although this task was not an original task for the first year of the project, some preliminary LES were conducted.

As with the RANS model, the grid underwent several iterative changes to achieve the current configuration. An additional complication in the LES grid is the need to include an Ffowcs Williams and Hawkings acoustic data surface. A surface control has been added to the FWH surface to improve interface conformity. Instead of modeling the two domains (inside and outside the acoustic data surface) as separate regions, they were added to the same region.

The current mesh has a base size of 1.6 in with a target surface mesh size of 10% of the base mesh size and a minimum surface mesh size of 5% of the base mesh size. It contains five prism layers near boundary walls, including the FWH surface, with a prism-layer total thickness of 5% of the base size. The four volumetric controls follow those of the RANS model: the innermost maximum cell size is 2.5% of the base size, with subsequent maximum cell sizes of 5%, 10%, and 20% of the base size. The target surface mesh size and the minimum surface mesh size of the surface control on the FWH surface are both 4% of the base size.

The outer domain of this model is identical to that of the RANS model. It is 70 in long, with an initial radius of 34 in and an outflow radius of 50 in. The domain contained by the FWH surface is 48 in long, with an initial radius of 1.5 in and an outflow radius of 6 in. The mesh has approximately 16.6 million cells. Figure 5 shows a close-up view of the FWH surface embedded in the LES mesh.

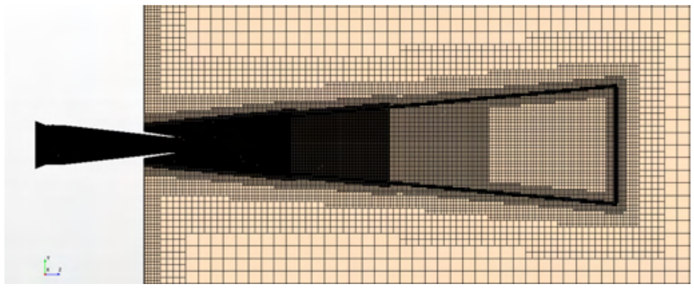

Figure 5. Close-up view of the FWH acoustic data surface embedded in the LES mesh.

An unsteady LES calculation for the primary nozzle was then performed. An implicit MUSCL third-order central-differencing scheme with an upwind blending factor of 0.25 was used. Sutherland's law was implemented for dynamic viscosity and thermal conductivity. A dynamic Smagorinsky subgrid scale was used, and a MinMod limiter was applied. A second-order temporal discretization was used with a timestep of 0.5 μs. Figure 6 shows instantaneous Mach-number contours from the preliminary LES simulations. The operating conditions are the same as those for the RANS case in Figure 4. The LES calculation yielded an exit Mach number of 0.798 and an exit velocity of 256.88 m/s. This result is in good agreement with both the RANS exit velocity of 256.77 m/s and the experimental exit velocity measurement of 257.53 m/s.

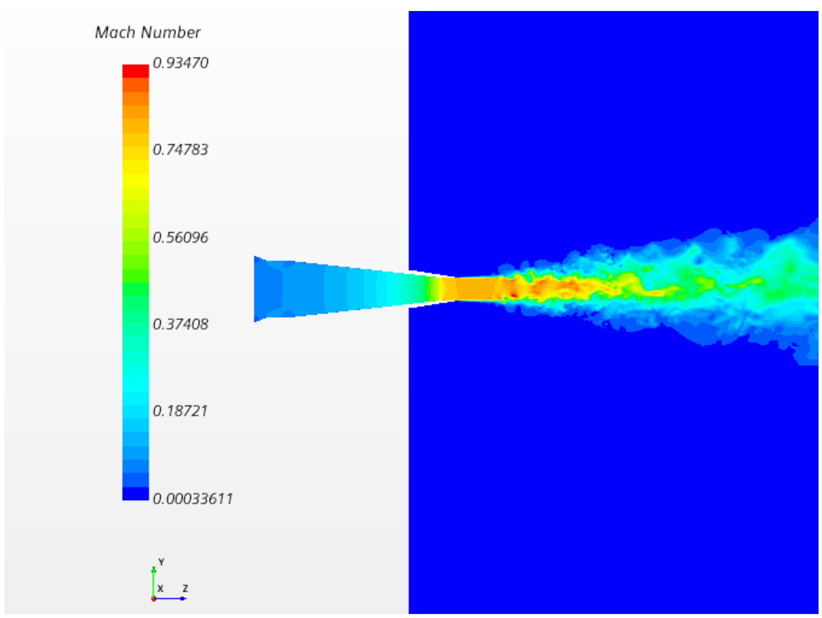

Figure 6. Mach number contours for primary nozzle LES calculation.

Publications
None

Outreach Efforts
ASCENT Advisory Board Meeting

Awards
None

Student Involvement
For the first year, the Penn State team consisted of two graduate research assistants. Ms. Dana Mikkelsen has been the lead on the computational fluid dynamics simulations and will continue in this role for the remainder of the project. Mr. Stephen Willoughby assisted with the project for 6 months and has now been assigned to a different research topic.

Plans for Next Period
During the next research period, the LES for the single nozzle will be completed. Data will be extracted from the FWH data surface, and noise predictions will be made. These predictions will be compared with experimental measurements, and modifications to the simulations will be performed. An LES using the RANS solution at the jet exit as an initial condition will be performed. RANS simulation will then be performed for the dual-stream nozzle, followed by an LES for that configuration. Finally, noise predictions will be made for the dual-stream nozzle and compared with measurements.

Table 1 shows the anticipated list of milestones for the next research period.

Table 1. List of anticipated milestones for the next research period.

Task	Milestone	Planned Due Date
1	External LES for inner nozzle completed	1/31/2022
2	FWH surface data extracted	2/28/2022
3	Inner nozzle noise predictions and comparisons with measurements completed	4/15/2022
4	LES simulations using RANS initial conditions at the jet exit	5/31/2022
5	RANS solution for dual-stream nozzle completed	5/31/2022
6	Dual-stream nozzle LES completed	6/30/2022
7	Dual-stream nozzle noise predictions and comparisons with measurements completed	7/31/2022
8	Annual report submitted	11/30/2022

References
Farassat, F., & Succi, G. P. (1983). The prediction of helicopter rotor discrete frequency noise. Vertica, *7*(4), 497–507.

Ffowcs Williams, J., & Hawkings, D. L. (1969). Sound generation by turbulence and surfaces in arbitrary motion. Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, *264*(1151), 321–342.