

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

## The Pennsylvania State University

### Project Lead Investigator

Philip Morris  
Boeing/A.D. Welliver Professor Emeritus  
Department of Aerospace Engineering  
Pennsylvania State University  
233C Hammond Building  
University Park, PA 16802  
814-863-0157  
pjm@psu.edu

### University Participants

#### Pennsylvania State University

- P.I.s: Dr. Philip Morris (P.I.), Dr. Daning Huang (co-P.I.)
- FAA Award Number: 13-C-AJFE-GIT-070
- Period of Performance: January 1, 2022 to December 31, 2022
- Tasks:
  - Perform LES for external flow on inner nozzle
  - Implement FWH surface data extraction
  - Calculate far field noise and compare with measurements
  - Develop grid and obtain RANS solution for internal flow of the dual stream nozzle.
  - Perform LES for external flow for dual stream nozzle
  - Use FWH analogy to calculate far field noise and compare with measurements.

### Project Funding Level

The project is funded at the following level: FAA: \$100,000. Cost sharing of \$100,000 is provided by the Pennsylvania State University through salary support of the faculty P.I.

### Investigation Team

#### Pennsylvania State University

- Principal Investigator: Dr. Philip Morris
- Co-Principal Investigator: Dr. Daning Huang
- Graduate Student: Dana Mikkelsen

### Project Overview

The purpose of this project is to develop and assess efficient computational tools to simulate the flow and noise of civil supersonic aircraft engines.

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 on the basis of acoustic analogies is highly efficient but becomes difficult when the nozzle lacks simple axisymmetry. Methods based on large eddy simulation (LES) provide considerably more information about the unsteady flow and the noise generated. However, LES is computationally expensive, particularly 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 LES can be made quite efficiently by using the Ffowcs Williams and Hawkings (FW-H) 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 limitations of RANS-based simulations. The simulations 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; subsequently, LES, coupled with the FW-H 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 process will require the addition of some unsteady information, as guided by a very limited number of LESs. This approach will reduce the total computational cost by removing much of the geometric complexity and the associated grid requirements for LES of the internal flow.

The utility 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.

In addition, the LES-based predictions will be supplemented by more traditional acoustic-analogy approaches based on RANS, with an emphasis on modeling high-Strouhal-number noise radiation.

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 the designs will meet current or anticipated noise certification requirements.

## Task 1 – RANS and LES of Single and Dual Stream Nozzles

Pennsylvania State University

### Objective

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 Institute of Technology (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, and is the work described in the present report.

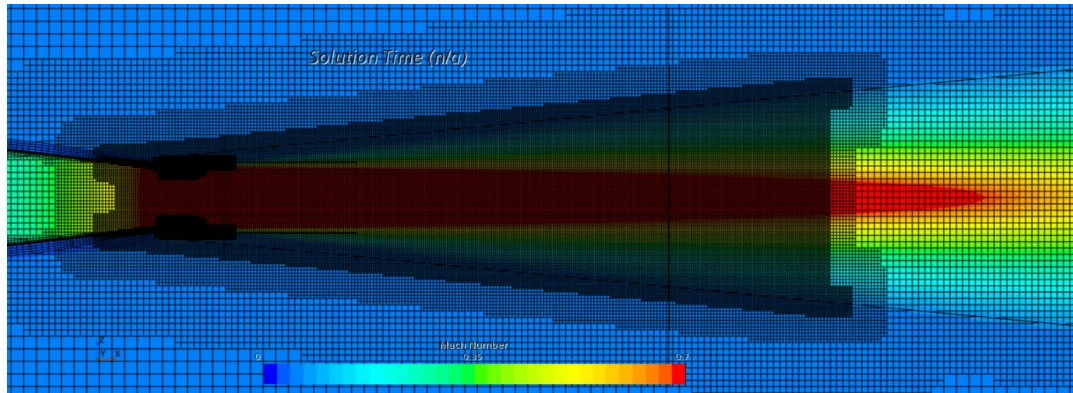
### Research Approach

#### **Grid Generation, RANS, and LES Simulations**

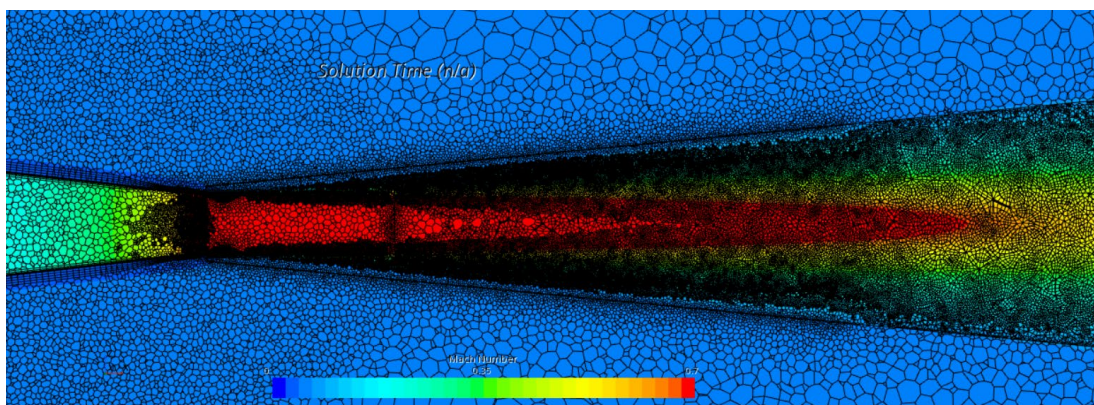
A computational mesh of the inner nozzle of the coannular nozzle geometry being used by Georgia Tech was provided by Gulfstream. The exit diameter of the nozzle is 40.64 mm. The grid originally used a trimmed hexagonal mesh with a base size of 4 mm. A conic refinement zone of base size 1 mm encapsulated the end of the nozzle and extended 0.4 m (approximately 10 jet diameters) beyond the nozzle exit. This refinement zone was necessary to capture the eddies present in the LES. However, simulations with this grid created a longer potential core and a steeper drop-off in a baseline RANS simulation than was present in the experiments. Figure 1 shows the trimmed hexagonal mesh with Mach number contours from a RANS simulation overlaid. The nozzle pressure ratio (NPR) was 1.86.

In view of the issues with trimmed hexagonal mesh, an unstructured, adaptive polyhedral mesh was used instead. This polyhedral mesh used the same base size of 4 mm and included the same 1-mm refinement zone around the nozzle exit, extending 0.4 m downstream. A larger volumetric control of 1 cm was used farther downstream of the nozzle. Both the previous mesh and this polyhedral mesh included four prism layers along the walls of the nozzle. The adaptive polyhedral mesh underwent two mesh refinement iterations and contained 41.6 million cells, whereas the trimmed hexagonal mesh contained 43.2 million cells. Figure 2 shows the adaptive polyhedral mesh with Mach number contours from a RANS simulation overlaid. The NPR was 1.86.

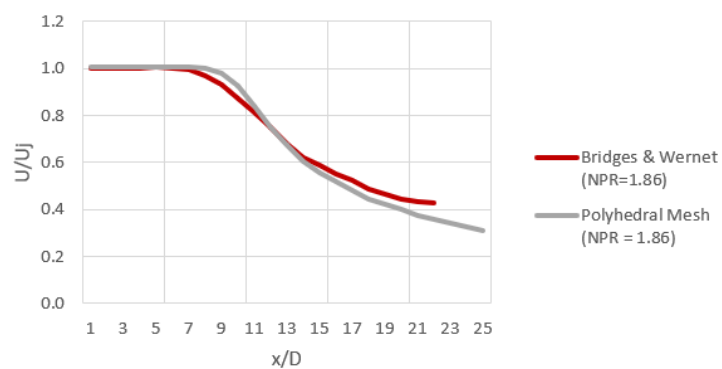
Figures 3 and 4 show a comparison of the predicted centerline and lipline velocity relative to the exit velocity as a function of downstream distance and the measurements by Bridges and Wernet (2010).



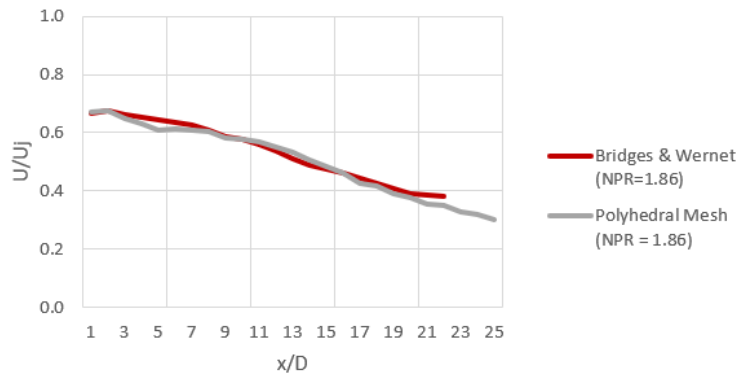
**Figure 1.** RANS simulation at NPR = 1.86 with the trimmed hexagonal mesh overlaid.



**Figure 2.** RANS simulation at NPR = 1.86 with the adaptive polyhedral mesh overlaid.

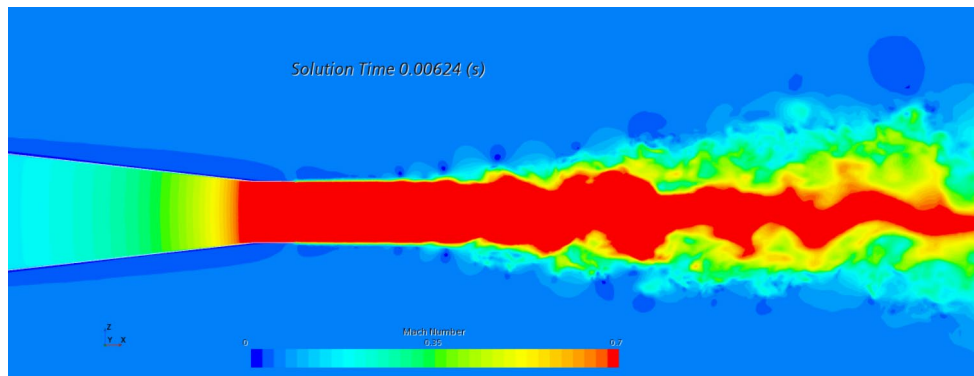


**Figure 3.** Comparison of experimental and simulation centerline axial mean  $U/U_j$  for the polyhedral mesh at NPR = 1.86.



**Figure 4.** Comparison of experimental and simulation lipline  $U/U_j$  for the polyhedral mesh at  $NPR = 1.86$ .

The simulation with the polyhedral mesh was then run as an LES at  $NPR = 1.86$  and Total temperature ratio,  $TTR = 1$ . It used a second-order temporal discretization with a time step of  $2 \times 10^{-6}$  s. Figure 1 shows instantaneous Mach number contours for  $NPR = 1.86$  and  $TTR = 1.0$ .

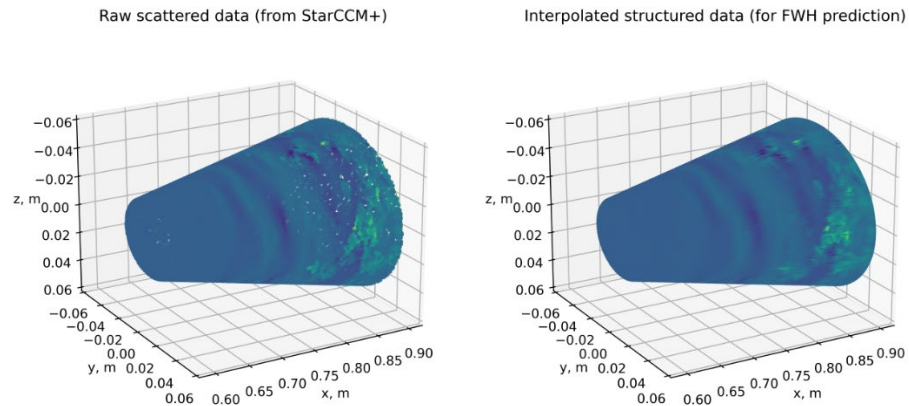


**Figure 5.** LES at  $NPR = 1.86$  and  $TTR = 1$  using the polyhedral mesh.

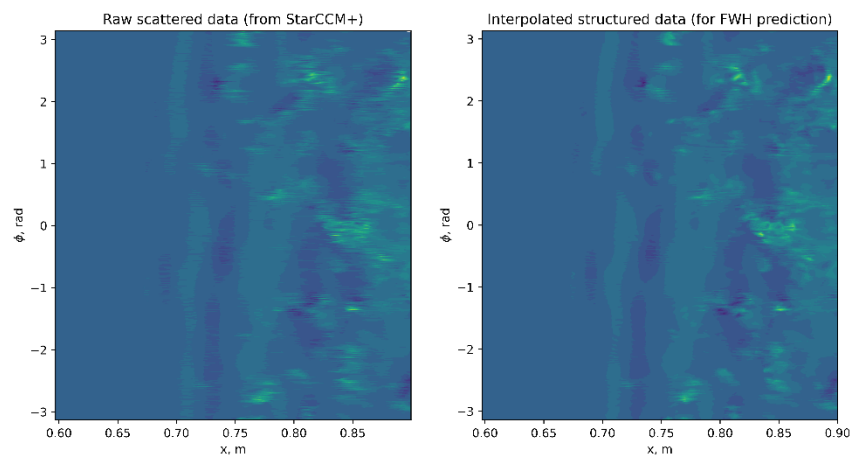
### FW-H Data Extraction and Verification

A Python code was written for the FW-H calculations. The code performs two tasks. First, given the scattered spatiotemporal data extracted from the FW-H surface in STARCCM+, the code interpolates the data onto a multi-block structured grid, which consists of a conic surface surrounding the jet flow and a circular plane closing the cone in the downstream direction (Figure 6). To accurately interpolate the data on a curved surface, the 3D conic unstructured surface is first mapped to a 2D structured surface. The data are interpolated by cubic splines on the 2D surface, then mapped back to a 3D structure conic surface (Figure 7). Furthermore, the grid can be refined in regions where spatial variation is strong, e.g., near the nozzle.





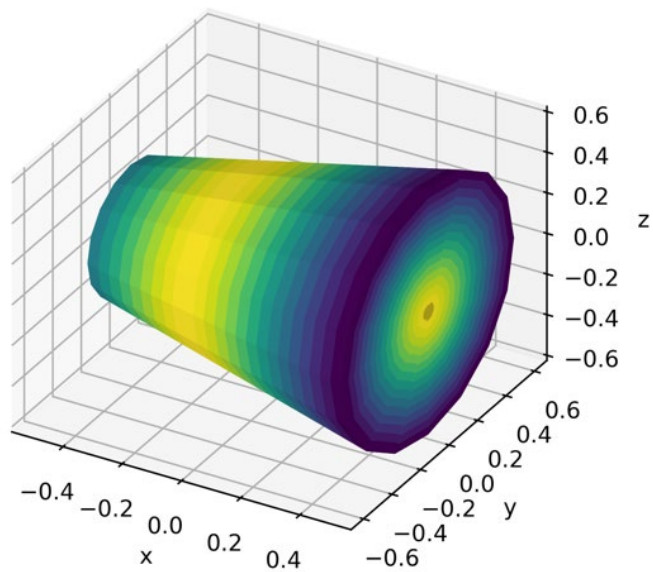
**Figure 6.** Illustration of the 3D FW-H surface at one time step, visualizing the density variation.



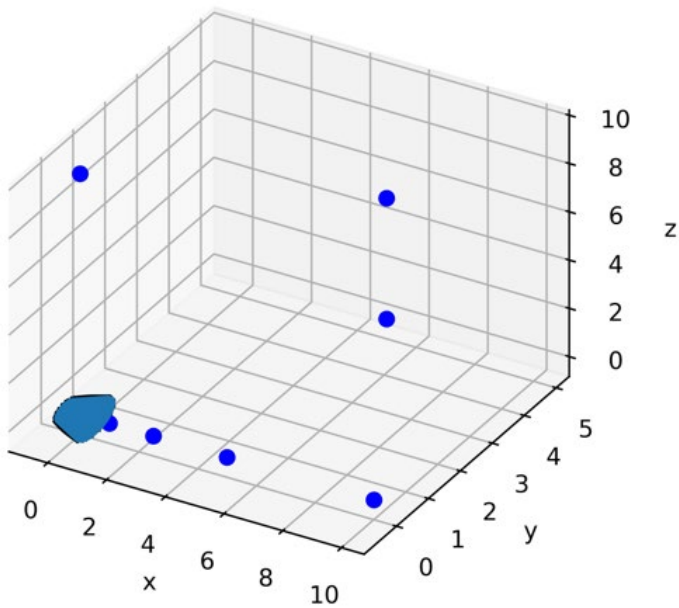
**Figure 7.** Illustration of the cubic interpolation on the mapped 2D structured surface.

Second, given the locations of observers, the FW-H code calculates the far-field acoustic pressure. The FW-H formulation is simplified, owing to the stationarity of the FW-H surface and the observers. Because the full LES data are currently being extracted from STARCCM+, the FW-H prediction was tested by using data synthesized from a monopole source placed at the origin (Figure 8), with multiple observer locations (Figure 9).

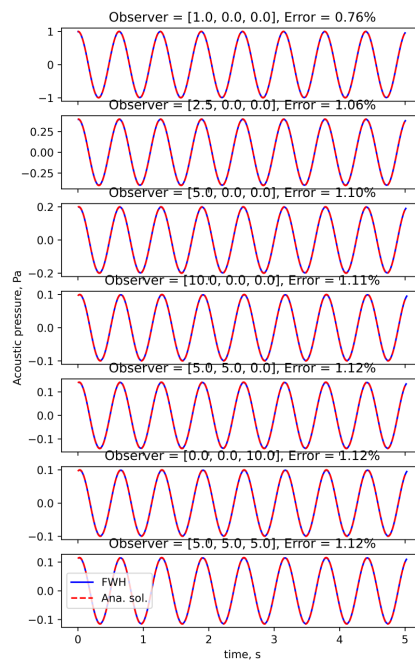
The FW-H prediction matches well with the analytical solutions at all observer locations, with errors less than 1.5% (Figure 10), and the error decreases as the grid is further refined. The test case verifies the correctness of FW-H code.



**Figure 8.** Pressure contours on the FW-H surface for a monopole source placed at the origin.



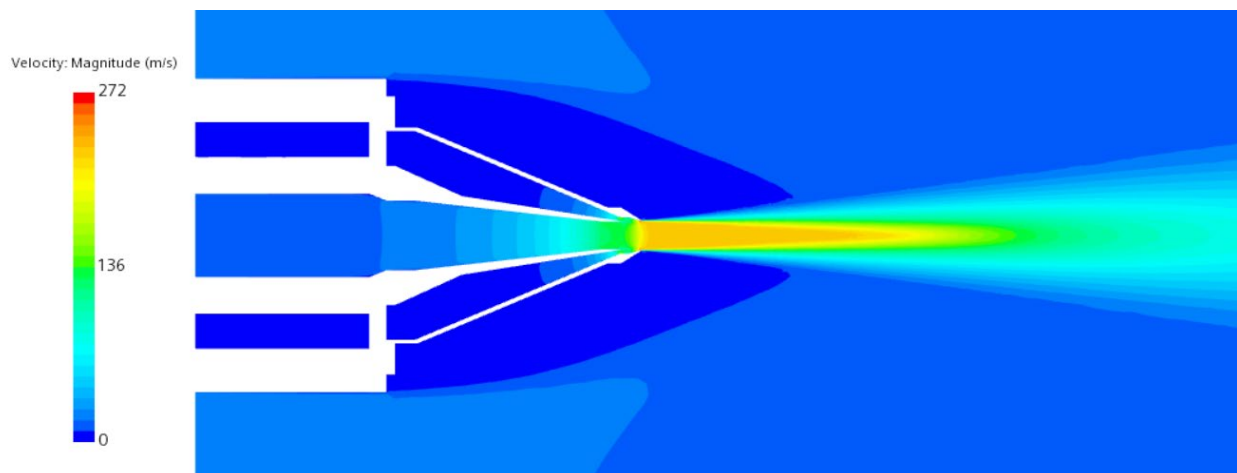
**Figure 9.** Observer locations (blue dots) with respect to the FW-H surface (cyan).



**Figure 10.** Comparison of FW-H predictions and analytical solutions at all observer locations.

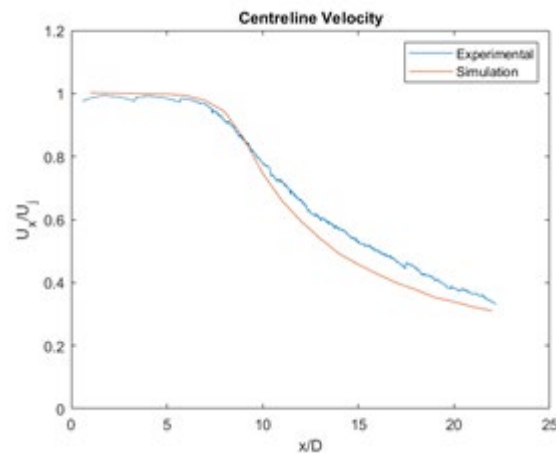
### RANS Solution for Dual-Stream Nozzle

A RANS simulation was conducted for the full dual-stream Georgia Tech nozzle geometry for an NPR of 1.39. Velocity magnitude contours are shown in Figure 11.

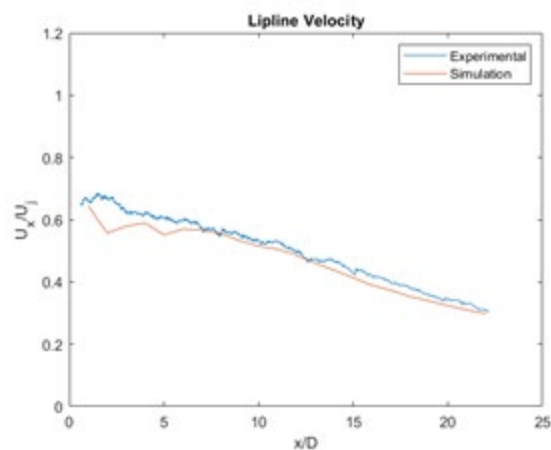


**Figure 11.** Velocity contours for the co-annular nozzle at NPR = 1.39 and TTR = 1.

The extracted centerline axial velocity (Figure 12) and the axial lipline velocity (Figure 13) showed good agreement with the experimental data provided by Georgia Tech for the same nozzle geometry.



**Figure 12.** Comparison of centerline axial velocity at NPR = 1.39 and TTR = 1 from experiments provided by Georgia Tech and RANS simulations using STARCCM+.



**Figure 13.** Comparison of lipline axial velocity at NPR = 1.39 and TTR = 1 from experiments provided by Georgia Tech and RANS simulations using STARCCM+.

#### Acoustic Analogy for High-Strouhal-Number Predictions

The frequency range of interest for aircraft certification is 50 Hz to 10000 Hz. For full-scale engines, Strouhal numbers from 0.1 to 100 are included (Viswanathan, 2018). Quite recent LESs of subsonic jet noise by Brès et al. (2018) have indicated that LESs with 69-M control volumes and nozzle interior turbulence modeling can achieve an upper-Strouhal-number limit of 4 (additional information in Brs, et al. (2019)). This value remains well below the upper-Strouhal-number limit required for aircraft certification.

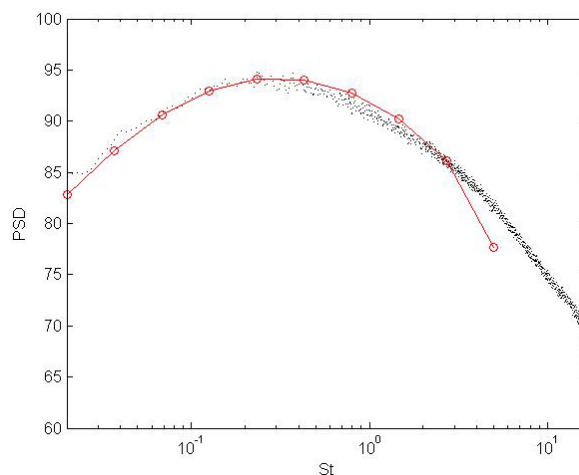


In principle, methods based on acoustic analogies have no Strouhal-number-range limit, but their accuracy depends on correct modeling of the statistical properties of the equivalent noise sources and the accurate evaluation of the sound propagation through the non-uniform jet flow. Many methods have successfully made predictions of the radiated noise at 90° to the jet axis.

The widely used MGBK method (for example, Khavaran, et al. (1994) and many subsequent references) uses steady CFD to provide a model for the mean flow and the turbulence scales. In a departure from the usual approach based on an acoustic analogy, Tam and Auriault (1999) have provided a physics-based model for the noise from the fine-scale turbulence. A generalized acoustic analogy was developed by Goldstein (2003), and Goldstein and Lieb (2008) have demonstrated good agreement with noise measurements for convectively subsonic flows. Subsequent extensions of Goldstein's generalized acoustic analogy (for example, by Karabasov et al. (2010)) have used complementary LESs to indicate the relative strengths of the quadrupole equivalent source terms that appear in the acoustic analogy. This last approach prompts the question of why an acoustic analogy is needed for an LES of the unsteady jet flow. In addition, if LES is used to describe source characteristic noise, both fine-scale and large-scale turbulence are included.

The aim of the present research is to develop an efficient model describing the high-frequency behavior of the radiated noise. The approach uses an acoustic analogy to predict the noise from the fine-scale turbulence, and uses LES to predict the lower frequencies (Strouhal numbers). Initially, we are using Tam and Auriault's (1999) approach. Figure 14 shows a prediction of noise at 90° to the jet axis by using Tam and Auriault's model (1999). The agreement with measurements by Bridges and Brown (2005) is very good, except at high frequencies.

Ongoing work involves reassessing the modeling coefficients in the Tam and Auriault model, with a goal of matching the spectral density's high-frequency behavior at all angles. The purpose is to model the fluctuations responsible for the high-frequency noise rather than the noise generated by all scales.



**Figure 14.** Comparison of predictions (red) with experimental results (black) at 90° to the jet axis.  $M_j = 1.0$ ,  $TTR = 1.0$

## Major Accomplishments

The tasks for the second project year included continued RANS simulations as well as LES. The focus was initially on the Georgia Tech inner nozzle. Subsequent calculations used, or are using, a first internal mixer case. In addition, acoustic-analogy-based predictions are underway, and are aimed at predicting very high frequencies that are important for noise certification assessments. Finally, a code has been developed for far-field noise prediction using LES simulation data and verified with a synthetic benchmark problem.

## **Publications**

None.

## **Outreach Efforts**

ASCENT Advisory Board Meeting.

## **Awards**

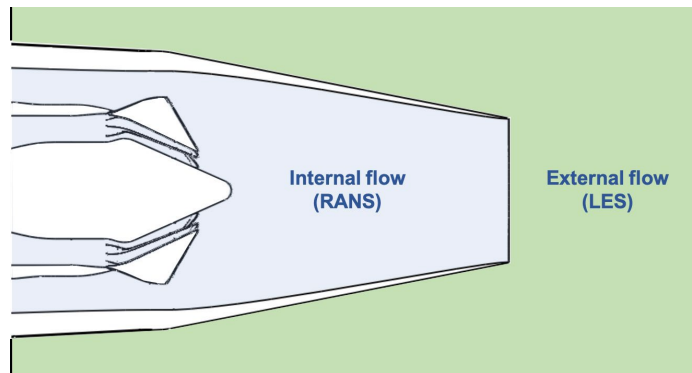
None.

## **Student Involvement**

For the second year, the Pennsylvania State University team included one graduate research assistant. 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.

## **Plans for Next Period**

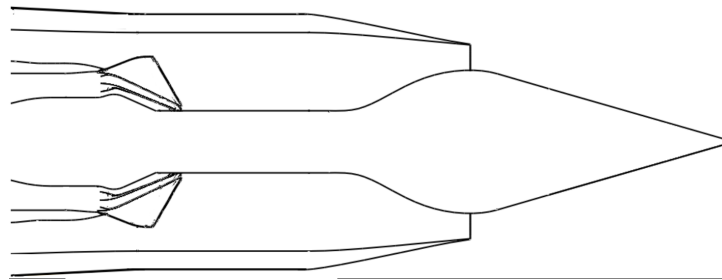
During the next research period, a RANS solution will be obtained for an internal mixer nozzle (Figure 15). This solution will be compared with experimental data and will provide a baseline characterization of the flow; it will then be used as a basis of comparison for subsequent moderate-fidelity simulations.



**Figure 15.** Sketch of the dual-stream, internally mixed plug nozzle with lobed mixer. 122Am5plnt (Bridges and Wernet, 2021).

A grid for an LES solution will then be developed, and a moderate-fidelity solution will be obtained by using the RANS solution as an initial condition at the jet exit. The LES solution will provide the unsteady flow information needed for the next task, in which the FW-H analogy will be used to calculate the far-field noise for the internal mixer nozzle.

The code detailed in an earlier section will be used to extract data from the FW-H surface in STARCCM+ and interpolate it onto a structured conical surface. The FW-H analogy will be used to calculate the far-field noise. The far-field predictions will be in the form of overall sound pressure level and power spectral densities, and these predictions will be compared with experimental data. Adjustments to parameters such as grid resolution may be made. These tasks will then be repeated for an external plug nozzle with an internal mixer (Figure 16).



**Figure 16.** Sketch of external plug nozzle with short mixing duct (Bridges and Wernet, 2021).

As noted above, the Tam and Auriault method for fine-scale noise prediction will be modified, and probably extended, to enable the prediction of the high-frequency noise radiation. This approach will be applied to all geometries considered.

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

**Table 1.** Anticipated tasks and milestones for the next research period.

| Task No. | Milestone  | Planned due date  |
|----------|--|-------------------|
| Task 1   | Internal mixer nozzle RANS solution and comparisons with measurements completed              | February 15, 2022 |
| Task 2   | Internal mixer nozzle moderate-fidelity solution completed                                   | April 30, 2022    |
| Task 3   | Internal mixer nozzle noise predictions and comparisons with measurements completed          | May 31, 2023      |
| Task 4   | Grids for moderate-fidelity simulation of external plug nozzle with internal mixer completed | June 30, 2023     |
| Task 5   | External plug nozzle moderate-fidelity solution completed                                    | August 31, 2023   |
| Task 6   | External plug nozzle noise predictions and comparisons with measurements completed           | October 31, 2023  |
| Task 7   | Extension of acoustic analogy to predict high Strouhal numbers                               | October 31, 2023  |
| Task 8   | Annual ASCENT report submitted   | November 30, 2023 |

## References

- Farrasat, F. & Succi, G.P. (1983). The prediction of helicopter rotor discrete frequency noise. *Vertica*, 7 (4), 497-507.
- J. E. Ffowcs Williams, & Hawkins, 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. <http://www.jstor.org/stable/73790>
- Bridges, J., & Wernet, M. (2010, June 7). Establishing consensus turbulence statistics for hot subsonic jets. *16th AIAA/CEAS Aeroacoustics Conference*. 16th AIAA/CEAS Aeroacoustics Conference, Stockholm, Sweden. <https://doi.org/10.2514/6.20>
- Viswanathan, K. (2018). Progress in prediction of jet noise and quantification of aircraft/engine noise components. *International Journal of Aeroacoustics*, 17(4-5), 339-379. <https://doi.org/10.1177/1475472X18778279>
- Brès, G., Jordan, P., Jaunet, V., Le Rallic, M., Cavalieri, A., Towne, A., . . . Schmidt, O. (2018). Importance of the nozzle-exit boundary-layer state in subsonic turbulent jets. *Journal of Fluid Mechanics*, 851, 83-124. doi:10.1017/jfm.2018.476
- Brès, G. A., & Lele, S. K. (2019). Modelling of jet noise: A perspective from large-eddy simulations. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 377(2159), 20190081. <https://doi.org/10.1098/rsta.2019.0081>
- Khavaran, A., Krejsa, E. A., & Kim, C. M. (1994). Computation of supersonic jet mixing noise for an axisymmetric convergent-



- divergent nozzle. *Journal of Aircraft*, 31(3), 603–609. <https://doi.org/10.2514/3.46537>
- Tam, C. K. W., & Auriault, L. (1999). Jet mixing noise from fine-scale turbulence. *AIAA Journal*, 37(2), 145–153. <https://doi.org/10.2514/2.691>
- Goldstein, M. E. (2003). A generalized acoustic analogy. *Journal of Fluid Mechanics*, 488, 315–333. <https://doi.org/10.1017/S0022112003004890>
- Goldstein, M. E., & Leib, S. J. (2008). The aeroacoustics of slowly diverging supersonic jets. *Journal of Fluid Mechanics*, 600, 291–337. <https://doi.org/10.1017/S0022112008000311>
- Karabasov, S. A., Afsar, M. Z., Hynes, T. P., Dowling, A. P., McMullan, W. A., Pokora, C. D., Page, G. J., & McGuirk, J. J. (2010). Jet noise: Acoustic analogy informed by large eddy simulation. *AIAA Journal*, 48(7), 1312–1325. <https://doi.org/10.2514/1.44689>
- Bridges, J., & Brown, C. (2005, May 23). Validation of the small hot jet acoustic rig for aeroacoustic research. *11th AIAA/CEAS Aeroacoustics Conference*. 11th AIAA/CEAS Aeroacoustics Conference, Monterey, California. <https://doi.org/10.2514/6.2005-2846>
- Bridges, J. E., & Wernet, M. P. (2021, August 2). Noise of internally mixed exhaust systems with external plug for supersonic transport applications. *AIAA AVIATION 2021 FORUM*. AIAA AVIATION 2021 FORUM, VIRTUAL EVENT. <https://doi.org/10.2514/6.2021-2218>