Project 059(D) Physics-based Analyses and Modeling for Supersonic Aircraft Exhaust Noise

Stanford University

Project Lead Investigator

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- PI(s): Dr. Sanjiva K. Lele, Dr. Juan J. Alonso
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- Period of Performance: October 1, 2021 to December 10, 2021
- Tasks: (for a 3-year effort)
    1. Develop and refine research plans in coordination with ASCENT Project 59 partners
    2. Conduct large eddy simulation (LES)-based simulation, modeling, and validation of jet noise predictions
    3. Perform Reynolds-averaged Navier–Stokes (RANS)-based simulation, modeling, and validation of jet noise predictions

Project Funding Level

$200,000 per year from FAA, with in-kind matching from Stanford. Matching from industry is being arranged.

Investigation Team

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Project Overview

Improved methods for predicting and reducing noise from civil supersonic aircraft would be highly valuable for the research and technology development community engaged in civil supersonic aircraft development. In addition to aircraft and engine companies, organizations such as NASA, FAA, and the DoD research and technology community would also benefit from improved methods and tools. Ultimately, supersonic jet noise tools with predictive capabilities can be used to design better noise mitigation systems and to provide estimates of noise for certification studies.

This project involves a coordinated development of both low- and high-fidelity approaches for jet noise predictions for civil supersonic aircraft being considered in ASCENT and includes the tasks listed above. High-fidelity simulations of jet exhaust flow and noise will be developed for a carefully selected subset of configurations and operating points being tested by the Georgia Institute of Technology (Georgia Tech) team. In parallel, Reynolds-averaged Navier-Stokes (RANS) computations of a broader range of configurations and operating conditions relevant for civil supersonic aircraft will be performed and used to develop improved jet noise source models and more accurate far-field noise propagation kernels. This noise source and noise propagation modeling will leverage high-fidelity simulation data and ongoing Georgia Tech experiments, as well as other noise and flow measurements available in the archival literature. Our goal is to understand the predictive quality of RANS-based noise prediction approaches with improved source and/or propagation models to enable designers to better capture tradeoffs typical in the development of full civil supersonic aircraft configurations.

Task 1 – Develop and Refine Research Plans in Coordination with ASCENT Project 59 Partners

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Objectives

We aim to design a simulation study that covers the range of operating conditions and possible nozzle configurations relevant for civil supersonic jet exhaust. This plan must include the current test plan from our experimental partners at Georgia Tech.

Research Approach

The planning involved discussions with Project 59 partners and communications with external advisors at NASA and elsewhere in academia and industry. Based on these efforts, it was determined that the project should focus on axisymmetric dual-stream nozzles with an internal mixer and with the possibility of an internal and/or external nozzle plug. We have also searched for nozzle configurations and flow and noise measurement data in the archival literature that would be relevant for civil supersonic aircraft and could be used in the development of noise prediction methods. Comprehensive exploration indicated that the bulk of jet noise data, including studies of noise reduction concepts, falls within the regime of a moderate to high bypass ratio (BPR) and is thus not particularly relevant for civil supersonic aircraft. While this finding affirmed the need for the planned laboratory measurement campaign by Project 59 partners at Georgia Tech, it also highlighted the need to use the most relevant data from the published literature to kickstart the modeling and simulation effort. Thus, two specific datasets associated with jet noise tests at NASA Glenn were identified.

Georgia Tech Dual-stream Nozzle

A co-annular nozzle geometry with a variable-length mixing duct was designed and is being extensively tested by the Georgia Tech team. Following discussions among project collaborators and key stakeholders, a test matrix has been determined for experimental efforts in years 1–2. Each jet Mach number for the two streams varies between $M_j = 0.4$ and $M_j = 1.0$, and the length of the nozzle mixing duct can be adjusted to be 0.7, 1.0, 2.0, or 3.0 times the length of the nozzle diameter, $D_e = 1.7''$.

Bridges and Wernet Internal Mixer

In 2004, Bridges and Wernet (NASA Glenn) reported flow and noise measurements for internally mixed two-stream nozzles with variations in the mixer duct length and mixer geometry. The operating conditions involve transonic and low supersonic jet exhaust velocity and moderate BPR. This configuration has also been used in previous RANS-based noise prediction studies by Rolls Royce and Purdue University, along with a more recent large eddy simulation (LES) study. We have been in touch with Rolls Royce and NASA regarding the nozzle geometry and measurement data. It is hoped that the geometry and data will become available in the future. This configuration is of interest to us, as it is unique in providing both jet flow measurements and far-field noise for conditions relevant to civil supersonic flights.

Recent Jet Noise Measurements at NASA Glenn

As part of NASA's Commercial Supersonic Technology (CST) Project, under the Advanced Aero Vehicle Program (AAVP), Dr. James Bridges at NASA Glenn (personal communication, 2020) recently completed jet noise measurements on specially designed modular nozzle configurations at operating points selected to be relevant for commercial supersonic aircraft. He plans to make the nozzle geometry and measurement data available in the future. NASA's plans include noise predictions using a variety of computational tools. We are interested in exploring a select subset of NASA's test matrix in our Project 59 studies. We have obtained the CAD geometry for the nozzle and have initiated early efforts in geometry cleaning and mesh generation. The mesh generation for this case is fairly challenging due to the steep curvature and sharp edges in the mixer lobes.

Milestone(s)

The simulation plan for years 1–2 has been determined and followed. Our plan for year 3, which focuses on nozzles with noise mitigation concepts, is yet to be finalized, pending discussions with our partners from Project 59.

Major Accomplishments

A research plan regarding the nozzle geometry and flow conditions to be studied has been developed. The plan includes both the experimental study by our partners at Georgia Tech and other relevant works from NASA Glenn.

Publications

None

Outreach Efforts

Communication with researchers at NASA Glenn has been established, and ideas for possible collaboration have been exchanged.

Awards

None

Student Involvement

Three graduate students are involved in this part of the project. G. Wu and K. Matsuno have conducted literature research on relevant jet experiments and simulations that involve similar flow conditions and nozzle mixing devices. T. Shanbhag has performed literature reviews on acoustic modeling of jet noise.

Plans for Next Period

We will continue to refine our research plan according to ongoing discussions among the teams of Project 59. In particular, we will select nozzle geometries with noise mitigation concepts that are of interest to industrial partners for the development of next-generation supersonic civil transport aircraft.

Task 2 – Conduct LES-based Simulation, Modeling, and Validation of Jet Noise Predictions

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Objectives

In collaboration with ASCENT partners in Project 59, we plan to develop physics-based analyses for supersonic aircraft exhaust noise. The main goals of these analyses are to develop improved jet noise prediction methods using a multi-fidelity approach. As part of the high-fidelity approach, LES will be conducted for a carefully selected set of configurations and operating points corresponding to tests conducted by the experimental team at Georgia Tech. The LES data will provide turbulence flow statistics and will be leveraged for acoustic source modeling.

Research Approach

Over the past project year, we have focused on numerical investigations of the co-annular nozzle geometry designed and tested by Georgia Tech. The operating conditions include subsonic and sonic jet exhaust velocity and low to moderate bypass ratio (BPR). A co-annular nozzle geometry with a variable-length mixing duct has been designed and is being extensively tested by the Georgia Tech team. Following discussions among project collaborators and key stakeholders, a test matrix has been determined for the experimental efforts of years 1–2. Each jet Mach number for the two streams varies between $M_j = 0.4$ and $M_j = 1.0$, and the length of the nozzle mixing duct can be adjusted to 0.7, 1.0, 2.0, or 3.0 times the length of the nozzle diameter, $D_e = 1.7''$. Our numerical study has focused on simulations of this co-annular nozzle at select test points.

Progress in Jet Noise Modeling and Simulations

LES and far-field acoustic calculations with the FW-H method have been conducted for the co-annular nozzle configuration with the shortest mixing duct using a compressible solver, CharLES, developed by Cascade Technologies. This work has been published in detail in a recent conference paper (Wu et al., 2022). Below is a summary of the key results.

The nozzle geometry (shown in Figure 1) was designed and tested by Project 59 partners at Georgia Tech. The area ratio of the secondary to primary nozzle is 2.25. An exhaust mixing duct is attached to the end of the co-annular nozzle, and the length of the mixing duct is 0.7 times the exit diameter. LESs of the jet exhaust flow and noise were conducted at $M_j = 0.8$ and 9 for both the primary conical nozzle alone and the co-annular nozzle. For the simulation of turbulent boundary layers on the nozzle interior walls, the strategy of numerical tripping via artificial geometric features in the CAD model was explored. The modification is a fixed-depth groove shortly upstream of the nozzle exit, as shown in Figure 2. Figure 3 shows the Voronoi mesh for the cases. The flow conditions and mesh size of each test case are summarized in Table 1.

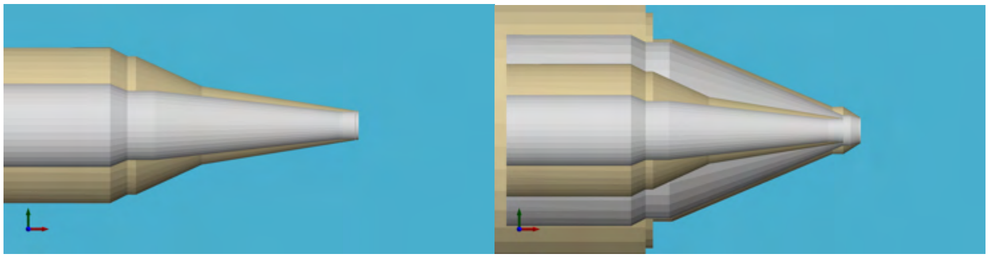


Figure 1. (Left) Primary nozzle. (Right) Co-annular nozzle designed by Georgia Tech.

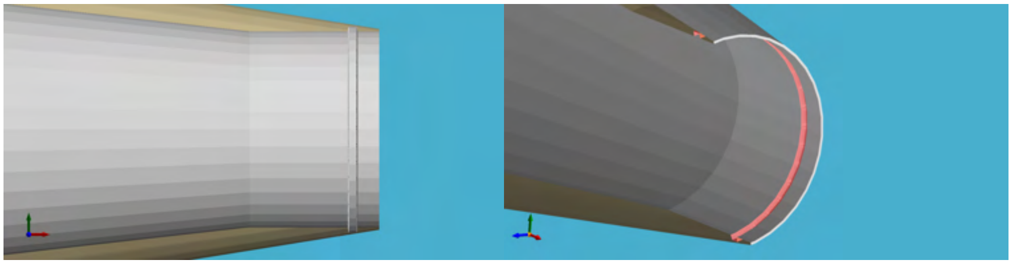


Figure 2. (Left) Cross-sectional view of the tripped primary nozzle. (Right) Isometric view of the tripping location highlighted in pink.

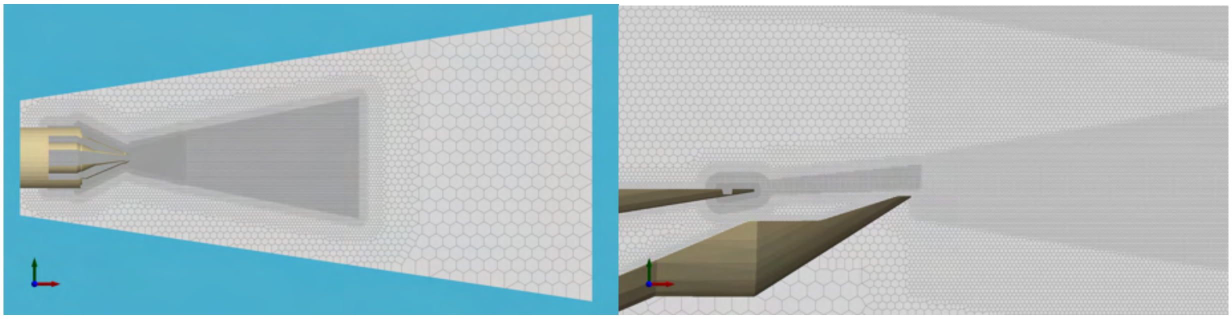


Figure 3. (Left) Overview of the Voronoi unstructured mesh. (Right) Magnified view of the Voronoi mesh near the co-annular nozzle exit.

Table 1. Summary of the test cases. All flow conditions are non-heated.

M_{j1}	M_{j1}	Mesh Size (million cells)	LES Simulation Time $t_{sim}\, c_\infty/D_{e1}$	Note
0.5	N/A	25	700	RANS and LES
0.8	N/A	18	900	LES
0.9	N/A	14, 18, 27	700-900	RANS and LES
0.8	0.8	15, 28	690 - 720	LES
0.9	0.9	28	720	LES

This tripping approach produces noticeable differences in the jet boundary layer near the nozzle exit, but no significant variability is found in the overall jet spreading or far-field jet acoustics. Simulations were conducted using an identical mesh resolution for the same duration, $t_{sim}\, c_\infty/D_{e1} = 900$. Figures 4 and 5 show the mean streamwise velocity and Reynolds shear stress near the nozzle interior wall. Compared with the clean geometry, the tripped geometry causes the boundary to detach and reattach to the nozzle surface. Through this unsteady motion, the turbulence level of the exit boundary layer is increased. Figure 6 compares the velocity statistics just before the nozzle exit, at x/De_1=-0.02. The figure shows that the tripped geometry significantly increases the Reynolds normal and shear stress in the boundary layer. Profiles from the tripped case exhibit features similar to those of a turbulent boundary layer. The effects of turbulence tripping were further investigated by taking mean velocity and mean turbulent kinetic energy profiles at various streamwise locations in the jet plume. No significant differences were observed in the mean velocity or turbulent kinetic energy profiles between the tripped and non-tripped case.

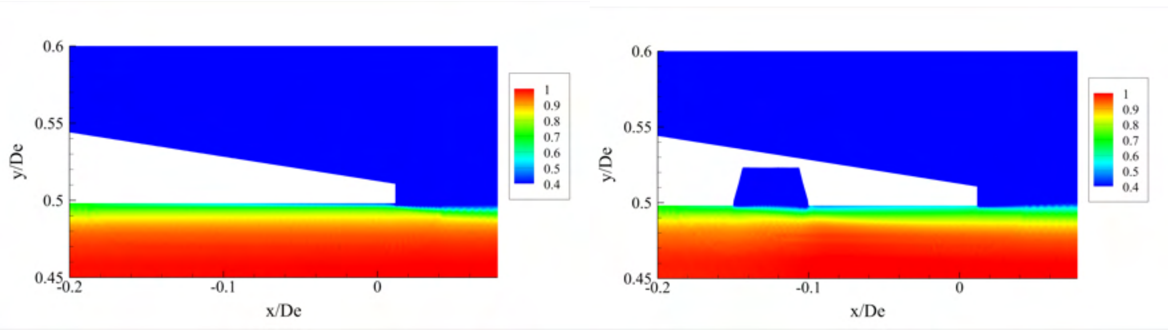


Figure 4. Mean streamwise velocity U/U_j contours for the non-tripped primary nozzle (left) and the tripped nozzle (right), M_j=0.8.

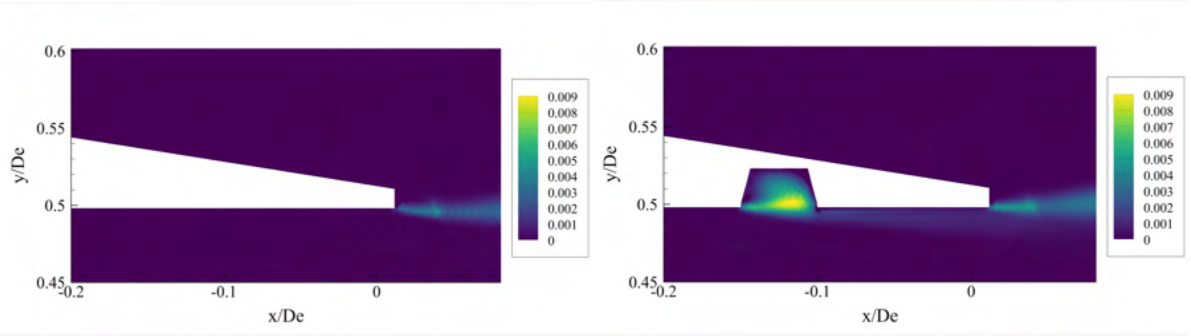


Figure 5. Reynolds shear stress $\underline{u'v'}/{c_\infty}^2$ contours for the non-tripped primary nozzle (left) and the tripped nozzle (right), M_j=0.8.

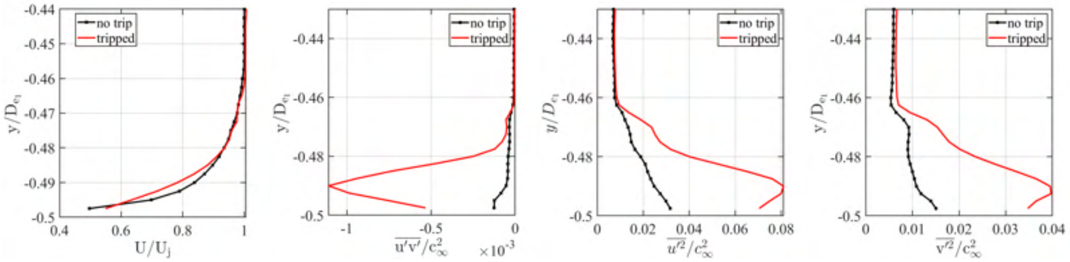


Figure 6. Velocity statistics of the exit boundary layer, M_j=0.8.

Figures 7 and 8 show the mean jet velocity and Reynolds shear stress for a co-annular case at M_j =0.8. The initial shear layer from the primary nozzle is contained inside the mixing duct and is deflected toward the centerline of the jet due to the secondary stream, as shown in Figure 8. The presence of the convergent mixing duct and the shear layer entrainment from the primary nozzle cause the secondary stream to be accelerated slightly beyond the core stream between $x/De = 0$ and $x/De = 0.7$. This trend is akin to the behavior observed in a jet ejector and generates an additional peak in the mean velocity profile near the nozzle exit. Figure 9 shows that the peaks increase the velocity gradient across the initial jet shear layer, which leads to an increase in the jet spreading rate between $\tilde{d} = 2$ and $\tilde{d} = 10$, where $\tilde{d}$ is the normalized streamwise distance over which each jet has expanded beyond the nozzle exit. Beyond $\tilde{d}$ =10, the enhanced mixing effect diminishes and the velocity profiles between the primary and co-annular cases are quite similar.

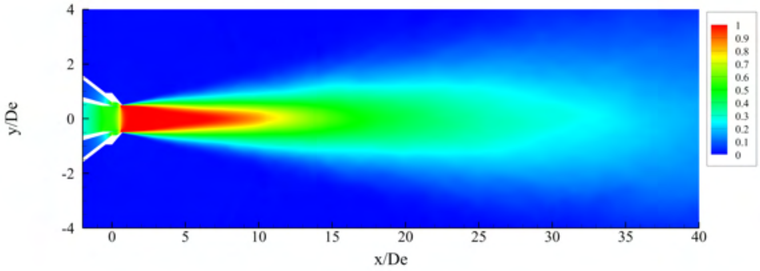


Figure 7. Mean streamwise velocity contours for the co-annular nozzle with $L/D_e = 0.7$ at $M_j = 0.8$.

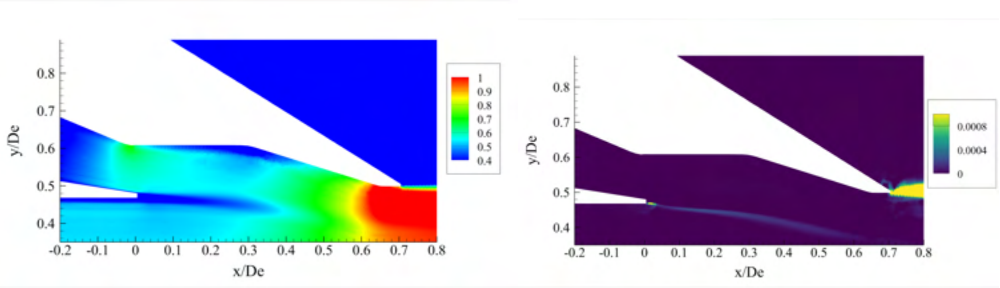


Figure 8. Magnified view of the mean streamwise velocity contours (left) and Reynolds shear stress (right) for a co-annular nozzle with $L/D_e = 0.7$ at $M_j = 0.8$.

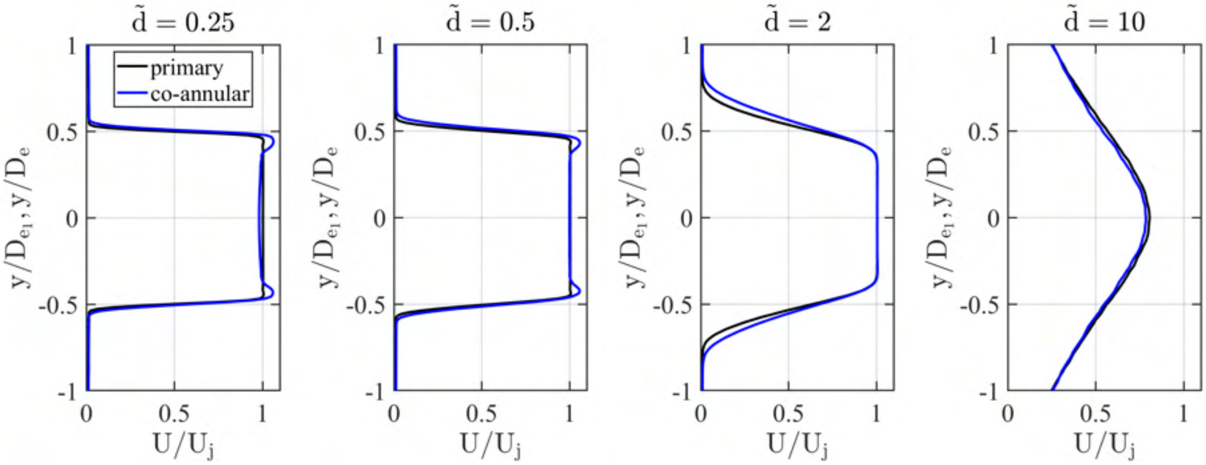
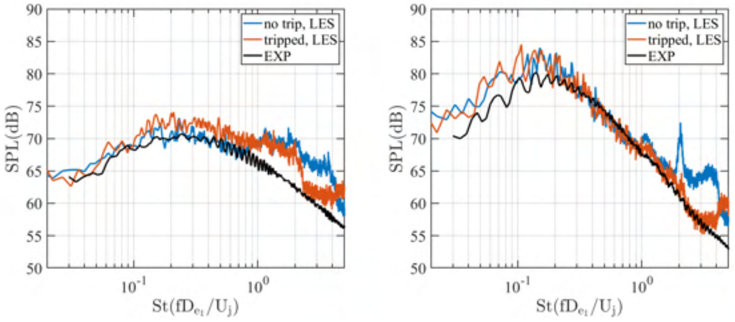
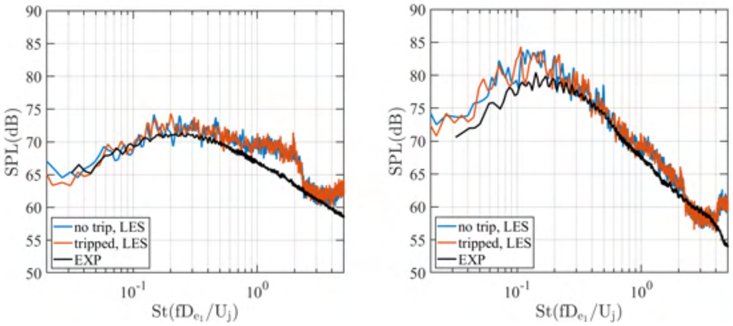


Figure 9. Comparison of mean streamwise velocity profiles between the primary nozzle and the co-annular nozzle test cases, $M_j = 0.8$.

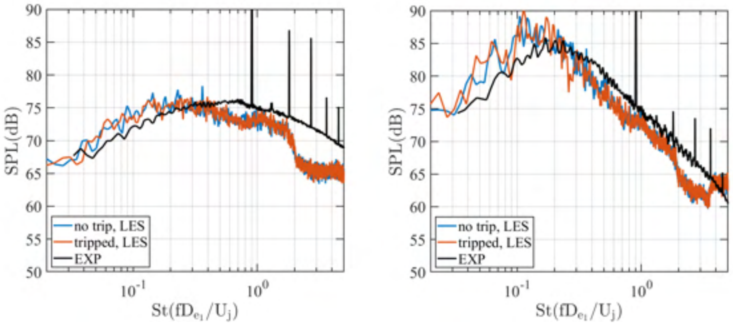
Sound pressure level (SPL) spectra for the primary nozzle alone and the co-annular nozzle are shown in Figure 10. The radial distance of the observer location is about 12 feet away from the nozzle exit, and the jet polar angle ϕ is defined with respect to the jet upstream direction. Experimental data were obtained via private communications with Georgia Tech. Over the range of $0.02 \leq St \leq 1$, the LES results agree reasonably well with the experimental data. However, for $St > 1$, a spurious hump is present in the LES SPL spectra. The cause for such discrepancy in the noise spectra is unknown at the moment. One possible cause is the difference in the exterior nozzle surfaces. These surfaces are treated with noise absorption materials to avoid acoustic reflections in the experiments, but these noise reduction features are not included in the CAD geometry of the LES. Another possibility is that the spurious hump is generated by insufficient grid resolution in the aft portion of the jet plume. Recall that the present results were obtained using modest resolution grids. We expect to improve these results in the future. For both the tripped and non-tripped cases, the noise spectra show little difference in Figure 10, except near the spurious hump.



(a) Primary nozzle only, $M_j = 0.8$, $\phi = 120^\circ$(left) and $\phi = 150^\circ$(right).



(b) Co-annular nozzle, $M_{j1} = M_{j2} = 0.8$, $\phi = 120^\circ$(left) and $\phi = 150^\circ$(right).



(c) Co-annular nozzle, $M_{j1} = M_{j2} = 0.9$, $\phi = 120^\circ$(left) and $\phi = 150^\circ$(right).

Figure 10. Comparison of far-field SPL spectra between LES and experiments. Experimental data were shared by Georgia Tech via private communication.

Analyses of the most energetic coherent structures in the jet plume were conducted with spectral proper orthogonal decomposition (SPOD). Figure 11 shows the first two leading SPOD modes of p' for the primary nozzle test case at $M_j = 0.9$ for the zeroth azimuthal wavenumber. Kelvin–Helmholtz and Orr-type instability waves are observed. We plan to study, in detail, the changes in growth of these coherent structures introduced by numerical tripping and the co-annular mixing device. These results will be used for acoustic source modeling in our future work.

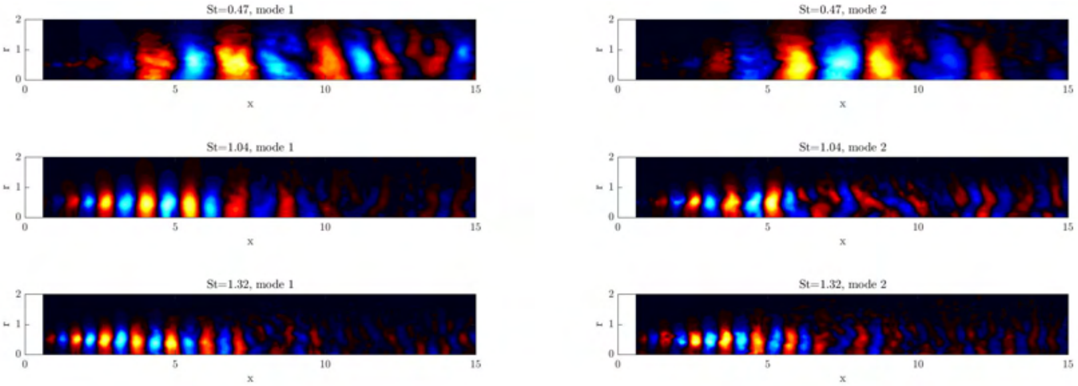


Figure 11. First two leading SPOD modes of p' at select St values for the zeroth-order azimuthal wavenumber in the primary nozzle, $M_j = 0.9$.

Milestones

LESs corresponding to the year 1 test matrix have been conducted at select test points. The numerical results are being validated with experimental data, and further numerical improvements are required.

Major Accomplishments

Over the past project year, we have made steady progress in the high-fidelity simulations of jet noise, in accordance with the test plan established by our Project 59 partners. LESs have been conducted for the Georgia Tech co-annular nozzle using the compressible solver CharLES, developed by Cascade Technologies. The nozzle configuration with the shortest mixing duct, $L/D_e = 0.7$, was considered for two Mach numbers, $M_j = 0.8$ and $M_j = 0.9$. For the simulation of turbulent boundary layers on the nozzle interior walls, the strategy of numerical tripping via artificial geometric features in the CAD model was explored. This tripping approach produces noticeable differences in the jet boundary layer near the nozzle exit, but no significant variability is found in the overall jet spreading or far-field jet acoustics. Compared with simulations involving only the primary nozzle geometry, LES data indicate that the secondary stream and mixing duct introduce faster-moving flow on the inner periphery of the jet initial shear layer, leading to faster jet spreading rate further downstream. The agreement between numerical results and experimental data is satisfactory, but discrepancies are observed in the far-field acoustics at high frequencies. Further investigation of the causes for such discrepancies is needed. Analyses of the most energetic coherent structures in the jet plume have been conducted via SPOD, and a more in-depth analysis of the SPOD modes is underway.

Publications

Conference Proceedings

Wu, G. J., Shanbhag, T. K., Matsuno, K., Lele, S. K. & Alonso, J. J. (2022). *Numerical simulations and acoustic modeling of a co-annular nozzle with an internal mixing duct*. Conference paper accepted for presentation.

Outreach Efforts

Communication with Project 59 partners in ASCENT and with NASA scientists has been established. Deeper collaboration with the Georgia Tech experiments and with NASA scientists is expected as the project progresses.

Awards

None

Student Involvement

Two graduate students are involved in this project task. G. Wu has taken the lead on single-nozzle LES computations and turbulence-tripping efforts to better match experimental acoustic data. K. Matsuno has compared co-annular nozzle LES calculations with available experimental data.

Plans for Next Period

We plan to further refine the current LES results and achieve better agreement with experimental data. SPOD analyses with LES data will be conducted to analyze the large-scale coherent structures associated with low-frequency acoustics. LES under additional flow conditions and geometries corresponding to the latest experimental study at Georgia Tech and NASA Glenn will be performed.

Task 3 – Perform RANS-based Simulation, Modeling, and Validation of Jet Noise Predictions

Stanford University

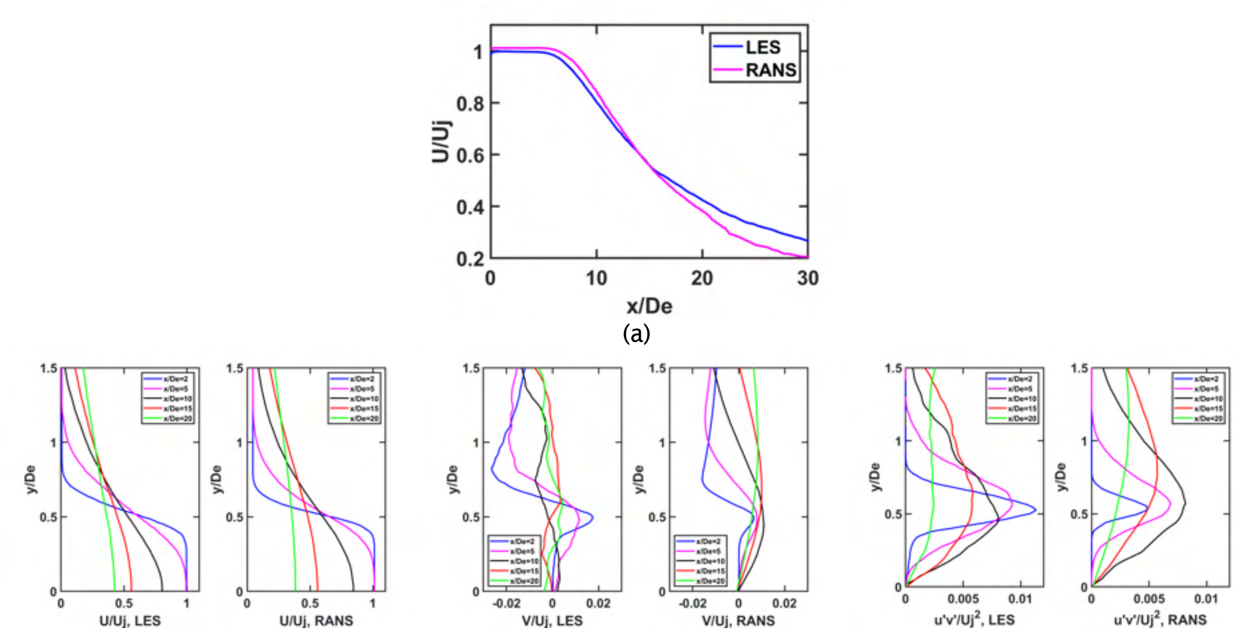
Objectives

This project involves the coordinated development of both low- and high-fidelity approaches for jet noise predictions. For the low-fidelity approach, RANS computations of a broader range of configurations and operating conditions relevant for civil supersonic aircraft will be performed and used to develop improved jet noise source models and more accurate far-field noise propagation kernels.

Research Approach

Using the open-source RANS solver SU2, simulations for the primary conical nozzle designed and tested by Georgia Tech have been performed at two jet Mach numbers, $M_j = 0.5$ and $M_j = 0.9$. The results have been compared with LES results. For acoustic modeling, models based on Goldstein's generalized acoustic analogy that are available in the literature have been tested on a benchmark problem.

The mesh resolutions are similar to the resolution used in the LES cases. Figure 12 compares the mean velocity and Reynolds stress between the LES and RANS results. The agreement is fairly good, demonstrating the validity of using low-cost RANS simulations for obtaining the mean states of a turbulent jet under a wide range of engine operating conditions for acoustic modeling.



(a)

(b)

Figure 12. Comparison of the mean velocity and Reynolds shear stress between RANS and LES results. Profiles are shown along (a) the jet centerline and (b) various streamwise stations for the primary nozzle test case at $M_j = 0.9$

A number of methods have been applied to predict jet noise from RANS (mean flow) calculations alone. Several of these methods build upon Lighthill's original acoustic analogy (Lighthill, 1952), where the Navier-Stokes equations are rearranged into the form of an acoustic wave equation with a distribution of quadrupole source terms arising from local Reynolds stresses. Goldstein's generalized acoustic analogy (Goldstein, 2003) similarly rearranges the full flow equations into a linear left-hand side representing the spatially developing mean flow and a nonlinear right-hand side representing the acoustic sources. This framework allows for the effects of convection and refraction to be accounted for correctly and has been shown to be more robust to numerical errors in the jet mean flow than other commonly used acoustic analogy formulations (Samanta et al., 2006).

Many previous works have developed methods based on GAA, wherein a statistically stationary RANS realization of the flow field based on a k-epsilon turbulence model forms the basis for characterizing the acoustic sources. In these frameworks, a form is proposed for the two-point space-time correlation function of the sources, in which the amplitude and integral length and time scales are deduced from the turbulent kinetic energy and dissipation fields via empirically determined relationships. Tam and Auriault (1999) proposed one such framework based on kinetic theory, arguing an analogy between molecular pressure and turbulent pressure. Morris and Farassat (2002) later showed an equivalence between this model and the standard acoustic analogy, provided that a consistent representation is used for the source term and Green's function. Models of this type largely rely upon the assumption of isotropic turbulent Reynolds stresses. While this approach is expected to result in good sound predictions at high frequencies, where the dominant noise generation mechanisms arise from fine-scale turbulence, it is also expected that the low-frequency part of the spectrum, where the larger-scale coherent structures recovered in SPOD are of much greater importance, will be largely inaccurate. Previous authors have attempted to resolve this issue by applying a more sophisticated representation of the acoustic sources that account for anisotropy. For example, Karabasov et al. (2010) proposed a Gaussian form for the two-point correlation, in which the different components of the fourth-order correlation tensor take different relative magnitudes based on parameter fitting to an LES.

We have applied three different acoustic modeling methods based on the generalized acoustic analogy to the time average of an unsteady jet realization taken from a DDES simulation of a subsonic jet. The spectra obtained from the three methods were compared, and the limitations of this analysis approach studied in the context of SPOD results from the same jet simulation.

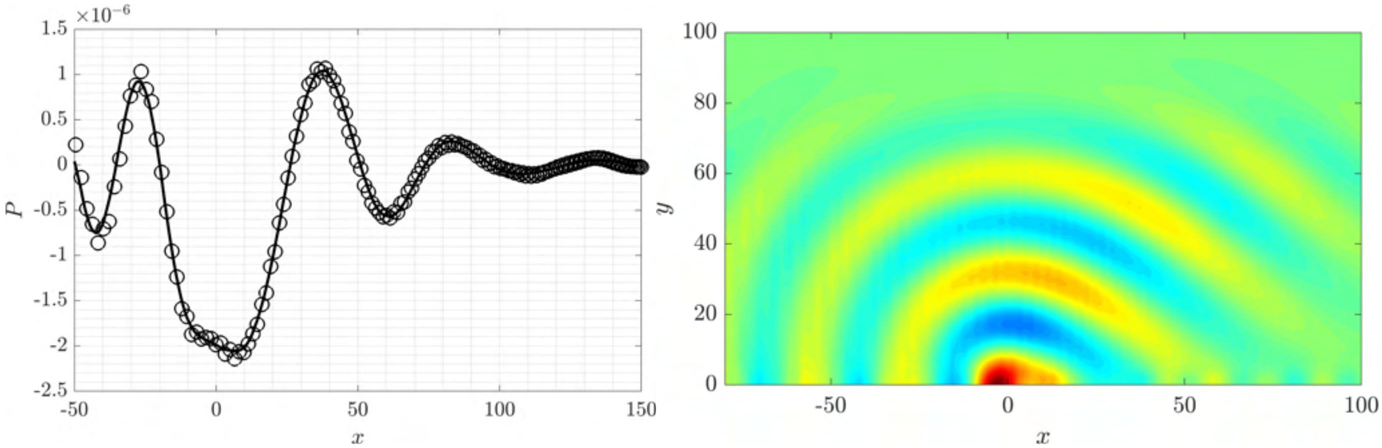


Figure 13. Numerical LEE solution to the benchmark problem (Agarwal et al.) of sound propagation from a point source through a 2D shear-layer, pressure fluctuation amplitude: (Left) Comparison of the numerical field (markers) with the analytic solution (solid line). (Right) Contours of the converged LEE solution.

In these methods, flow variables are decomposed into steady and fluctuating components using a Favre decomposition, resulting in a linearized form of the compressible flow governing equations with nonlinear source terms arising from Reynolds and shear stresses. Separate perturbation variables are defined for the momentum and stagnation enthalpy. The wave propagation problem is then efficiently solved in the frequency domain using an adjoint Green's function method (Karabasov et al., 2010). The Fourier transform of the adjoint Green's function solution satisfies the adjoint PDE system for the linearized equations already obtained. Each adjoint variable corresponds to one of the base flow state variables (density, momentum, and temperature) and represents the sensitivity of this system to a point source placed at a given location in the domain. The adjoint equations are solved iteratively in a pseudo-time-stepping scheme. Given that this linearized Euler system governs shear layer instabilities in addition to acoustic propagation, it is important to adjust the numerical scheme accordingly, such that the Green's function solution obtained is not contaminated by the instability solution. To verify this, the adjoint LEE frequency domain solver was tested against a benchmark problem presented by Agarwal et al. at the fourth Computational Aeroacoustics Workshop, in which a two-dimensional parallel shear flow immerses a monopole Gaussian source placed at the origin. The aim of this benchmark problem is to extract only the acoustic solution, which is known analytically for this setup, from the full LEE solution, which contains both the acoustic wave and a Kelvin–Helmholtz instability. Figure 13 shows the numerical solution of the LEE system along the line y=15, together with the analytic solution and the spatial distribution of the solution containing only the acoustic component. The adjoint solver converges to the required bounded solution component with reasonably good accuracy, as shown.

Having obtained the adjoint Green's function solution, the expressions for the far-field pressure and subsequently the power spectral density are computed by taking the convolution of the second-rank wave propagation tensor (calculated from the Green’s function) at each frequency with the modeled spatiotemporal cross-correlation of the turbulent source terms. The model is assumed to take the form of a multivariate Gaussian, with the imposed length and time scales being assumed to scale with standard turbulent length and time scales according to universal nondimensional constants. We have implemented three variants in the model based on assumptions suggested by Karabasov (2010), Tam and Auriault (1999), and Morris and Farassat (2002). The latter two models reduce the convolution to a single volume integral by invoking the compact eddy approximation. Our implementation has been tested on the time-averaged output of an SU2 (Molina) delayed detached-eddy simulation (DDES) calculation of a subsonic jet. This test case was previously studied in the framework of a European Union project, Go4Hybrid (G4H) (Fuchs et al., 2018), and the simulation results for this grid resolution have been validated against experimental data from Bridges and Wernet (Bridges & Wernet, 2010).

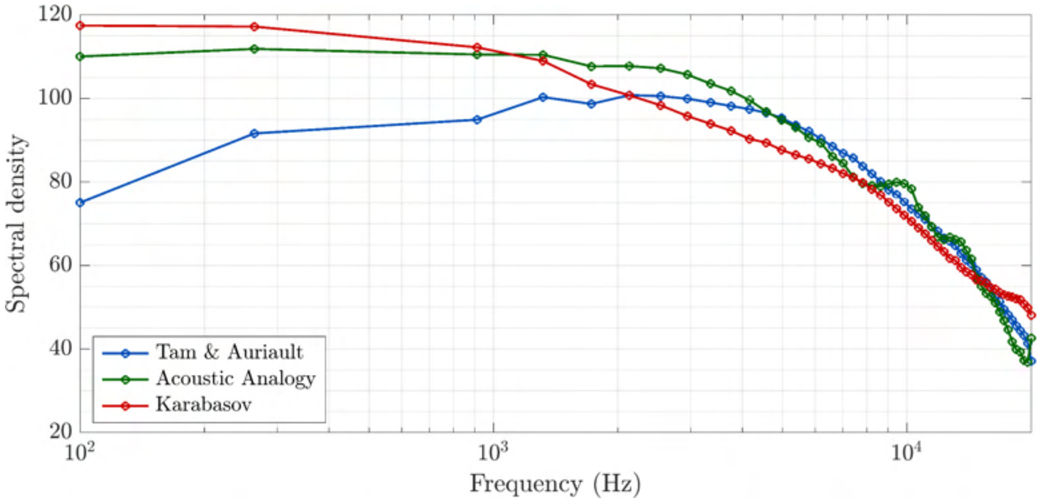


Figure 14. Spectral comparison between acoustic source models

Figure 14 shows the power spectral density calculated using each of the three RANS-based acoustic analogy methods at a 30° polar angle to the jet and a distance of r/D = 10000 from the jet origin. The spectra obtained by each of the three models capture the overall expected variation with frequency; in particular, the fall-offreduction at high frequencies is well captured in all cases. There are no significant disparities between the Tam and Auriault (1999) and acoustic analogy models, which both rely on the compact turbulent eddy approximation to simplify the convolution integral, and the Karabasov model, which does not rely on this assumption. This result suggests that the compact turbulent eddy approximation is appropriate for this type of source model. The expected fall-off at low frequencies is only observed for the Tam and Auriault model (Tam & Auriault 1999), with the other two models flattening out or rising in this frequency range. However, it is important to note that we expect this type of RANS-based modeling to be limited in this part of the spectrum. While the overall jet turbulent statistics captured in time-averaged flow modeling are sufficient to describe the sources of fine-scale noise, this type of modeling does not capture the large-scale wave-packet-type structures that dominate the more deterministic noise generation mechanisms at lower frequencies and smaller jet observation angles.

Having studied the strengths and limitations of a few GAA-based methods, we have begun to develop two additional method classes for RANS-based acoustic predictions, which we hope will enable accurate and computationally efficient calculations in both the low- and high-frequency portions of the spectrum. To improve accuracy at lower frequencies, we intend to extend the Karabasov source model (Karabasoy et al., 2010) with the present GAA implementation, incorporating a frequency dependency for the RANS-derived turbulent length and time scales. These functional dependencies have been previously studied in the context of LESs by Self and Azarpeyvand among others, and we intend to follow a similar approach by assessing these dependencies from LESs and determining the robustness with which they can be applied across different geometries and operating conditions. In addition, we are developing an alternative high-frequency acoustic code that relies on the methodology of ray tracing rather than solving for the adjoint Green's function in order to handle far-field propagation. This class of methods has been successfully applied by Ilario et al. to acoustic calculations for this type of jet flow, and we hope that by replacing the need to solve an additional coupled PDE system with a high-order ODE system, this propagation method will provide a significant reduction in computational cost while maintaining accuracy. Work on each of these methods is ongoing.

Milestone(s)

Early benchmark tests have been carried out for Task 3.

Major Accomplishments

For low-fidelity simulations, test cases with the primary nozzle at $M_j = 0.5$ and $M_j = 0.9$ have been conducted. A comparison between the RANS and LES results of mean velocity and Reynolds stress for various locations shows good agreement. Additional RANS test cases with the co-annular nozzle geometry are planned. Thus far, the agreement between RANS and LES has given us confidence in using RANS to obtain the mean states of the jet under a wide range of engine operating conditions for acoustic modeling. For acoustic modeling, models based on Goldstein's generalized acoustic analogy that are available from the literature have been tested on a benchmark problem (Goldstein, 2003).

Publications

Conference Proceedings

Shanbhag, T. K., Zhou B. Y., Eduardo, M., & Alonso, J. J. (2021, August). A comparison of jet acoustic analysis methods [Presentation]. AIAA Aviation 2021 Forum.

Outreach Efforts

None

Awards

None

Student Involvement

T. Shanbhag has led the modeling effort with the adjoint Green's function methods described in the previous sections and is developing RANS-based jet noise predictions.

Plans for Next Period

Additional RANS calculations involving co-annular nozzle geometries will be conducted and compared with LES and experimental data. RANS-based acoustic modeling with improved low-frequency predictions will be performed using the LES data.

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