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

Stanford University

Project Lead Investigator

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- FAA Award Number: 13-C-AJFE-SU-024
- Period of Performance: September 30, 2023, to October 1, 2024
- Tasks:
  1. Develop and refine research plans in coordination with ASCENT Project 059 partners
  2. Perform large eddy simulation (LES)-based simulation, modeling, and validation of jet noise predictions
  3. Conduct Reynolds-averaged Navier–Stokes (RANS)-based simulation, modeling, and validation of jet noise predictions

Project Funding Level

This project receives $200,000 per year from the Federal Aviation Administration (FAA), in-kind matching from Stanford, and cost-share matching from Gulfstream Aerospace Corporation.

Investigation Team

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Project Overview

Improved methods for predicting and reducing noise for civil supersonic aircraft would be highly valued by the research and technology development community engaged in civil supersonic aircraft development. In addition to aircraft and engine companies, organizations such as the National Aeronautics and Space Administration (NASA), FAA, and the U.S. Department of Defense, and the research and technology community would also benefit from improved methods and tools. Supersonic jet noise tools with predictive capabilities can be used to design improved noise mitigation systems and to provide estimates of noise for certification studies.

This project involves the coordinated development of both low- and high-fidelity approaches for jet noise predictions for civil supersonic aircraft being considered in ASCENT and involves the tasks listed above. High-fidelity simulations of the jet exhaust flow and noise will be developed for a carefully selected subset of configurations and operating points being evaluated by the Georgia Institute of Technology (Georgia Tech) team. In parallel, 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. The 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 so that designers can 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 059 Partners

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Objectives

The objective of this task is to design a simulation study that covers the range of operating conditions and nozzle configurations relevant for civil supersonic jet exhaust. The research plan must be inclusive of the current test plan from our experimental partner at Georgia Tech.

Research Approach

Planning involved discussions with ASCENT Project 059 partners and reaching out to 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. Our team has also searched for nozzle configurations and flow and noise measurement data in the archival literature that would be deemed relevant for civil supersonic aircraft and that could be used in the development of noise prediction methods. A comprehensive exploration indicated that the bulk of jet noise data including studies of noise reduction concepts were in the regime of moderate to high bypass ratios and were thus not particularly relevant for civil supersonic aircraft. While this affirmed the need for the planned laboratory measurement campaign by ASCENT Project 059 partner Georgia Tech, it also highlighted the need to use the most relevant data from the published literature to kickstart the modeling and simulation effort. Two specific datasets associated with jet noise tests at NASA Glenn Research Center were thus identified.

Georgia Tech Dual-Stream Nozzle

A coannular nozzle geometry with a variable-length mixing duct has been designed and is being evaluated extensively by the team at Georgia Tech. Following discussions among project collaborators and key stakeholders, a test matrix has been determined for the Year 1–2 experimental efforts. The jet Mach numbers for the two streams each vary 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, and 3.0 times the length of the nozzle diameter, $D_e = 1.7''$.

Bridges and Wernet Internal Mixer

Bridges and Wernet (2004) (at the NASA Glenn Research Center) 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 with a moderate bypass ratio. This configuration has also been used in previous RANS-based noise prediction studies by Rolls Royce® and Purdue University, along with a more recent LES study. Our team has 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 because 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 Research Center

As part of NASA's Commercial Supersonic Technology Project, under the Advanced Aero Vehicle Program, Dr. Bridges at NASA Glenn Research Center (Bridges, 2020) completed jet noise measurements on specially designed modular nozzle configurations at operating points selected to be relevant for commercial supersonic aircraft. Far-field acoustic measurements have been made available (Bridges et al., 2021), and particle image velocimetry (PIV) measurements of the jet have also been made available for select operating conditions (Bridges & Wernet, 2023). Our team is interested in

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exploring a selected subset of NASA's test matrix in our ASCENT Project 059 studies. Our team has obtained the computer-aided design (CAD) geometry for the nozzle and began early efforts in geometry cleaning and mesh generation.

Milestones

- Determined and followed the simulation plan (Years 1–2, complete).
- Studied the effects of mixing enhancement devices under heated jet conditions (Year 3, complete).
- Finalized and focused on trying to understand and improve noise discrepancies between the LES predictions and experimental measurements (Year 4).

Major Accomplishments

- Developed a research plan regarding the nozzle geometry and flow conditions to be studied. The plan includes both the experimental study by our partner at Georgia Tech and other relevant works from NASA Glenn Research Center.

Publications

None.

Outreach Efforts

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

Awards

None.

Student Involvement

Four graduate students have been involved in this part of ASCENT Project 059. 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. K. Matsuno recently completed her Ph.D. O. Martin has joined the project and is helping with the simulations of the mixer nozzle.

Plans for Next Period

- Continue to refine our research plan according to ongoing discussions among teams of ASCENT Project 059.
- Select nozzle geometries with noise mitigation concepts that are of interest to industrial partners for the development of next-generation supersonic civil transport aircraft.

References

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

Stanford University

Objectives

In collaboration with ASCENT partners in ASCENT Project 059, the objective of this task is to develop physics-based analyses for supersonic aircraft exhaust noise. The main goal of these analyses is 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

In the past project year, efforts have been dedicated to high-fidelity modeling of the NASA Plug20 dual-stream nozzle with an internal plug and lobed mixer (configuration 122Am5pInt) and an internal plug and axisymmetric splitter (configuration 122Am0pInt), shown in Figure 1. LES and far-field acoustics modeling by the permeable Ffowcs Williams–Hawkings (FWH) formulation were performed using a compressible solver, CharLES, developed by Cascade Technologies (now part of Cadence Design Systems).

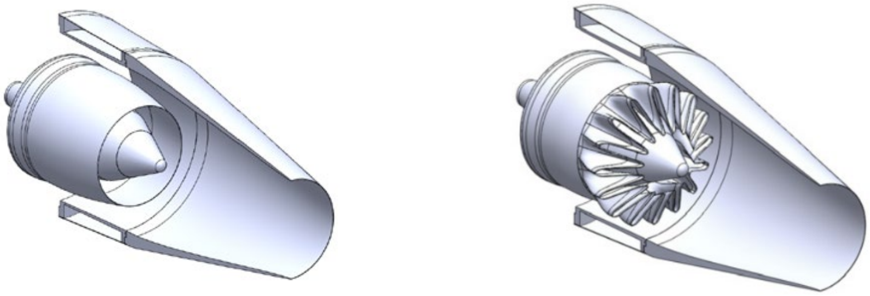


Figure 1. Detailed nozzle geometries. 122Am0pInt, confluent nozzle with an internal plug (left), 122Am5Int, confluent nozzle with an internal plug plus lobed mixer (right). Images obtained from Bridges et al. (2021).

In previous project years, configuration 122Am0pInt was tested at Setpoints 7 and 1183, and configuration 122Am5pInt was tested at Setpoint 1183. The LES-FWH far-field acoustic predictions for the 122Am0pInt nozzle showed good agreement with experimental measurements at Setpoint 7 across all polar angles. At Setpoint 1183, the LES–FWH results predicted downstream noise propagation accurately, but noise levels at upstream and sideline angles were substantially underpredicted. The 122Am5pInt nozzle LES-FWH results showed similar underprediction in the upstream and sideline angles, though the downstream noise was captured very well. In the current project year, we have run simulations at four new operating conditions in order to better diagnose these issues and understand where the LES-FWH method is performing well and where it is struggling. Table 1 summarizes the setpoints tested for nozzles 122Am0pInt and 122Am5pInt in the previous project years and the current project year (highlighted in gray). In the right-most columns of Table 1, the types of experimental measurements available at each operating condition (far-field acoustics/PIV) are listed. In the following, we examine the new simulation results and consider how they inform our understanding of the discrepancies between the LES and experimental data.

Table 1. Summary of the operating conditions (gray rows = current project year). FF: far-field, Nozzle Pressure Ratio (NPR):, PIV: particle image velocimetry.

Nozzle	Setpoint	NPR core	NPR bypass	NTR core	NTR bypass	flight stream M_f	Exp. FF acoustics Yes/No	Exp. PIV Yes/No
122Am0pInt	7	1.856	1.856	1	1	0.002	Y	Y
122Am0pInt	1183	1.8	1.8	2.9	1.20	0.3	Y	N
122Am0pInt	1183-FMESJ	1.8491	1.8491	1.606	1.606	0.3	N	N
122Am0pInt	4200	2.0	2.0	1.31	1.31	0.002	Y	Y
122Am0pInt	1200	2.0	2.0	3.25	1.2	0.002	Y	Y
122Am5pInt	1183	1.8	1.8	2.9	1.20	0.3	Y	N
122Am5pInt	1203	2.0	2.0	3.25	1.20	0.3	Y	Y
122Am5pInt	1233	2.3	2.3	3.25	1.25	0.3	Y	N

122Am0pInt – Dual-Stream Nozzle with Axisymmetric Splitter

For nozzle 122Am0pInt, additional simulations were run at Setpoint 4200 and 1200. Setpoint 4200 is similar to Setpoint 7 but introduces equal heating in the core and bypass streams. Setpoint 1200 has mismatched heating between streams similar to Setpoint 1183, but Setpoint 1183 has a Mach 0.3 flight stream and Setpoint 1200 does not have a flight stream. Figure 2 shows the far-field acoustic results from LES compared to experimental measurements for Setpoint 7 and Setpoint 4200. The LES results generally agree very well with the experiments across all polar angles, though there is slight overprediction of high-frequency noise at downstream angles and underprediction of broadband shock-associated noise (BBSAN) at upstream angles. The comparable outcomes at Setpoints 7 and 4200 indicate that equal heating of the streams does not introduce new physics that the LES is unable to capture. Figure 3 shows the far-field acoustics predicted at Setpoint 1200 compared to Setpoint 1183. At downstream angles, the LES predictions agree very well with the experimental measurements. However, at upstream and sideline angles, the LES underpredicts noise systematically across frequencies. The consistent underprediction in both operating conditions suggests that discrepancies between the LES and the experiments are unlikely to be caused by the Mach 0.3 flight stream. If we consider all operation conditions together (Sp7, Sp4200, Sp1200, Sp1183), we observe that the upstream and sideline discrepancies stem from the unequal heating of core/bypass streams, rather than heating more generally or the presence of the Mach 0.3 flight stream. These underpredictions are consistent in polar angle, frequency, and magnitude for the Setpoints 1183 and 1200.

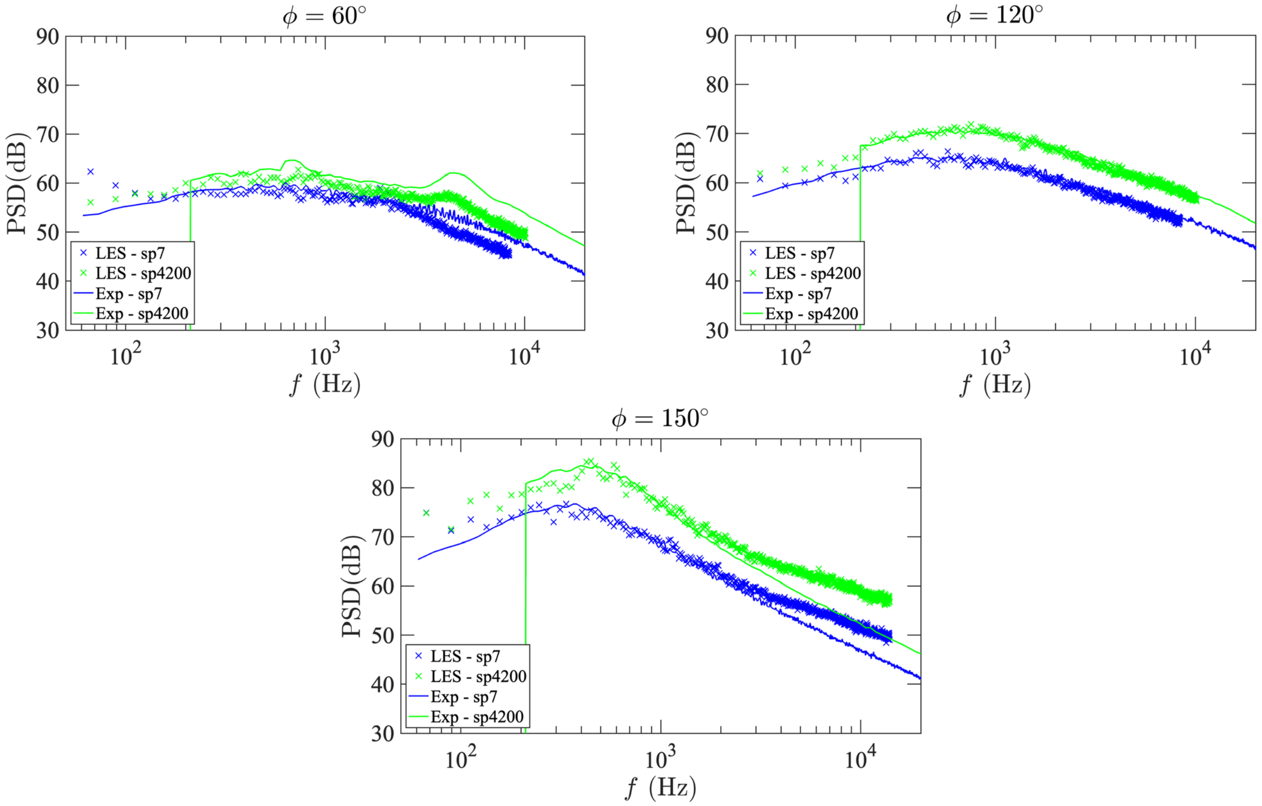


Figure 2. Far-field acoustics predictions for nozzle 122Am0pInt at Setpoint 7 (blue) and Setpoint 4200 (green) at polar angles $\phi = 60°, 120°, 150°$. Experimental data from Bridges et al. (2021). PSD: Power Spectral Density.

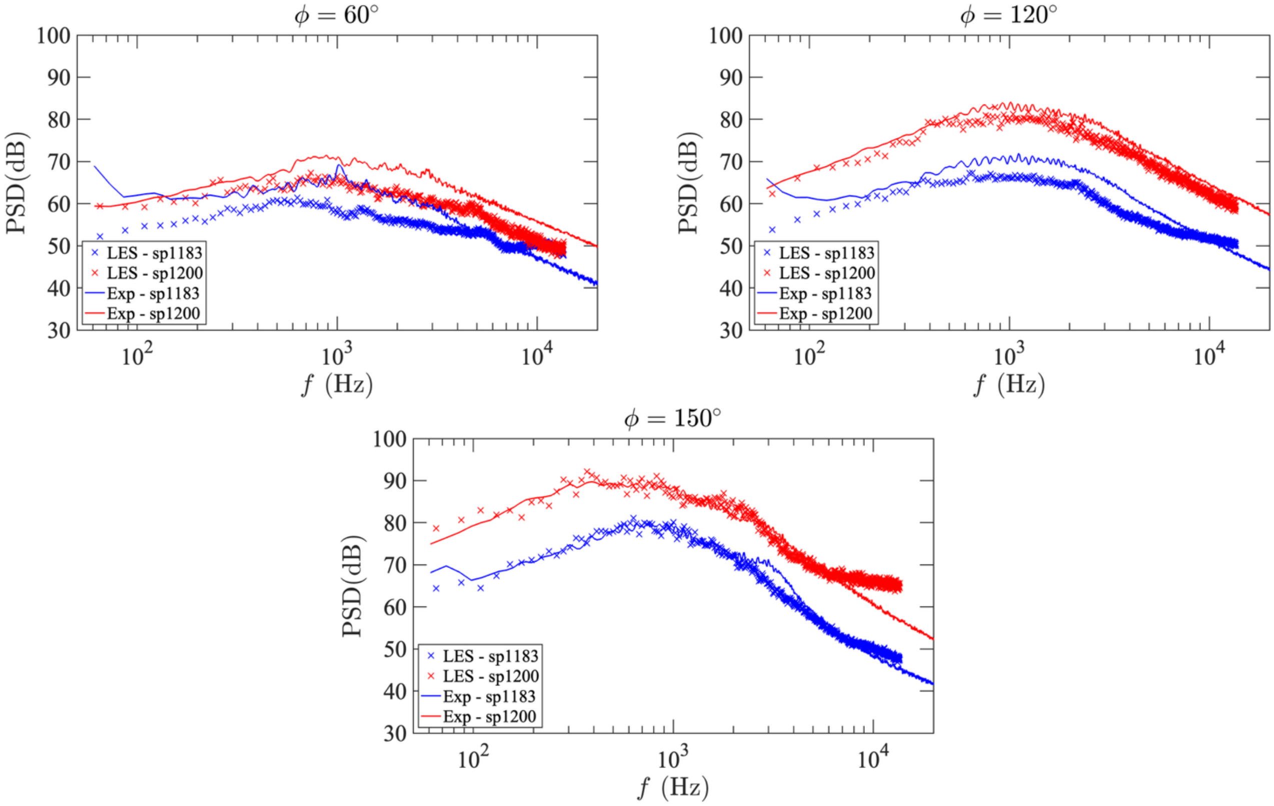
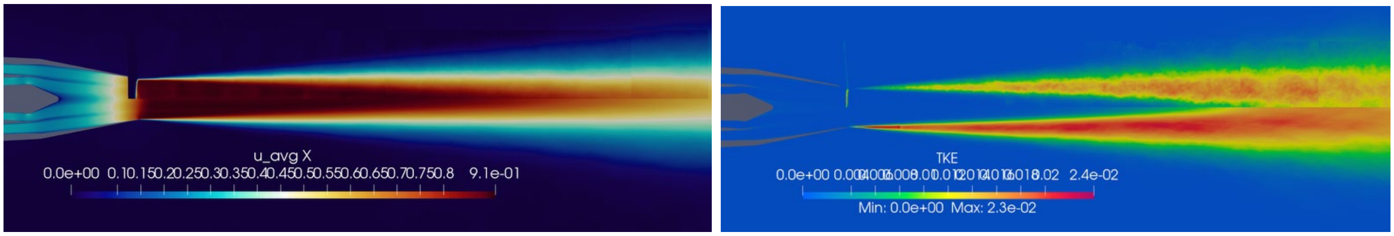
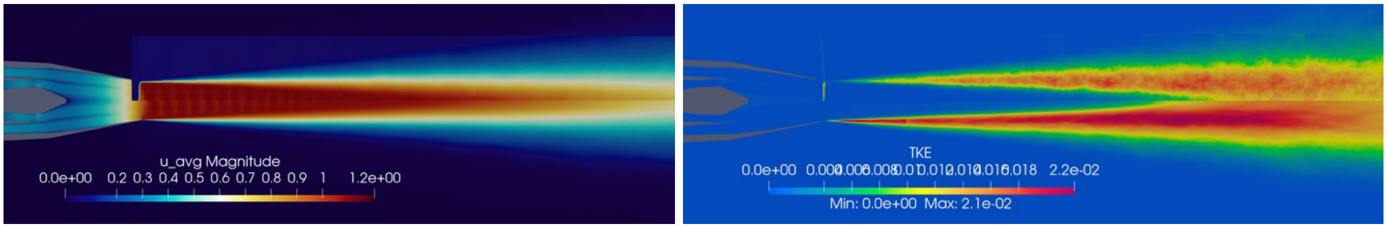


Figure 3. Far-field acoustics predictions for nozzle 122Am0pInt at Setpoint 1183 (blue) and Setpoint 1200 (red) at polar angles $\phi = 60°, 120°, 150°$. Experimental data from Bridges et al. (2021). PSD: Power Spectral Density.

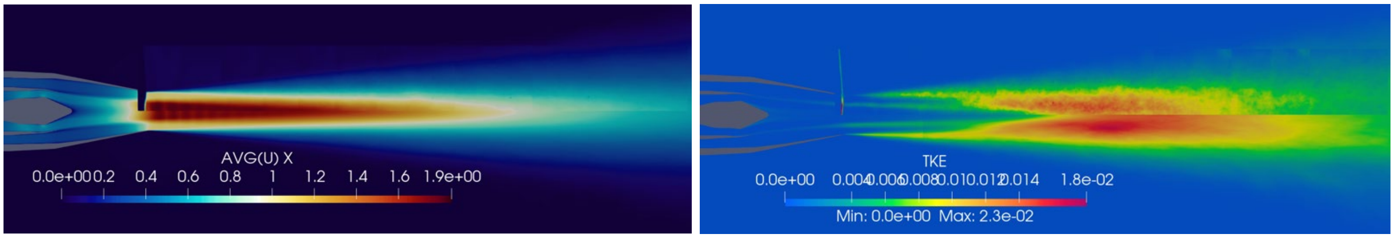
In Figure 4, mean streamwise velocity and turbulence kinetic energy (TKE) are compared between LES and PIV measurements at Setpoint 7, Setpoint 4200, and Setpoint 1200. The upper half of each figure outside the nozzle is the PIV field, and the bottom half of each figure is the LES. Across all three operating conditions, the mean velocity profiles agree very well between the LES and PIV. The flow exiting the nozzle and its development downstream is captured accurately in the LES. A weak shock-cell structure is observed at Setpoints 4200 and 1200 in both the LES and PIV measurements. The accurate representation of the base flow in the LES is consistent with our ability to capture the dominant downstream-radiated noise. TKE in the shear layer is overpredicted in the LES compared to the PIV, particularly in the upstream close to the nozzle exit. This suggests that the boundary layers inside the nozzle may be more turbulent in experiments than in the LES. For Setpoints 7 and 4200, this excess TKE in the shear layer may be linked to the high-frequency noise overprediction at downstream angles.



(a) Setpoint 7



(b) Setpoint 4200



(c) Setpoint 1200

Figure 4. Comparison of mean streamwise velocity (left column) and turbulence kinetic energy (TKE) (right column) from LES and experimental PIV measurements. For each figure, the upper portion downstream of the nozzle exit corresponds to the PIV field, and the lower portion corresponds to the LES.

122Am5pInt – Dual-Stream Nozzle with Lobed Mixer

For nozzle 122Am5pInt, additional simulations were run at Setpoint 1203 and Setpoint 1233. Setpoint 1203 was run in order to compare with available PIV measurements and assess whether underpredictions at Setpoint 1183 persistent across operating conditions. Setpoint 1233 was run to assess how the LES performs at much higher Mach numbers where BBSAN noise is significant. Figure 5 shows the far-field acoustics at Setpoint 1203 compared to Setpoint 1183. Very similar trends are observed as for nozzle 122Am0pInt at conditions with unequal heating between streams. The far-field noise is accurately captured by LES at downstream angles. However, at upstream and sideline angles, there is a systematic underprediction that is consistent across Setpoints 1183 and 1203. Figure 6 shows comparison between LES and PIV measurements at Setpoint 1203. Very good agreement is observed in both the mean streamwise velocity and TKE fields for this case. Figure 7 shows the far-field acoustic predictions at Setpoint 1233. Strong BBSAN is present for this case in the upstream direction. The LES captures the far-field acoustics well at downstream angles but underpredicts the broadband noise signal at upstream and sideline directions. The magnitude of the BBSAN hump is captured well in the LES, but it is shifted to lower a frequency range than experiments.

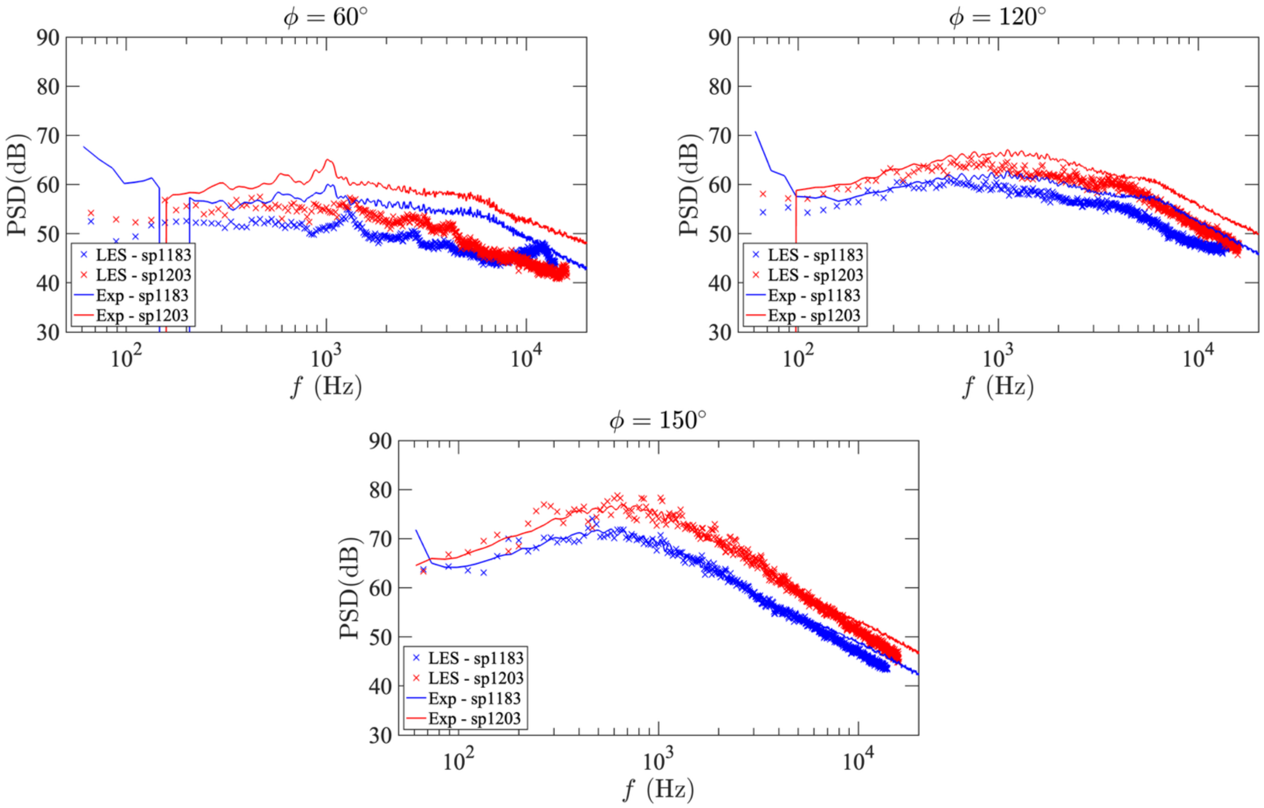


Figure 5. Far-field acoustics predictions for nozzle 122Am5pInt at Setpoint 1183 (blue) and Setpoint 1203 (red) at polar angles $\phi = 60°, 120°, 150°$. Experimental data from Bridges et al. (2021). PSD: Power Spectral Density.

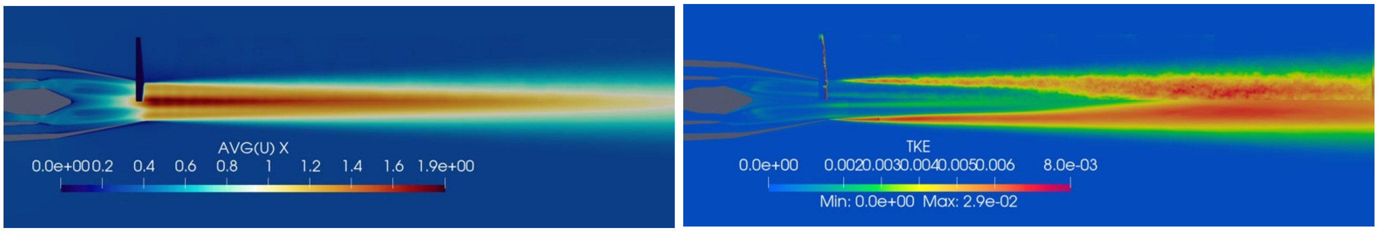


Figure 6. Comparison of mean streamwise velocity (left column) and turbulence kinetic energy (TKE) (right column) from LES and experimental PIV measurements at Setpoint 1203. For each figure, the upper portion downstream of the nozzle exit corresponds to the PIV field, and the lower portion corresponds to the LES.

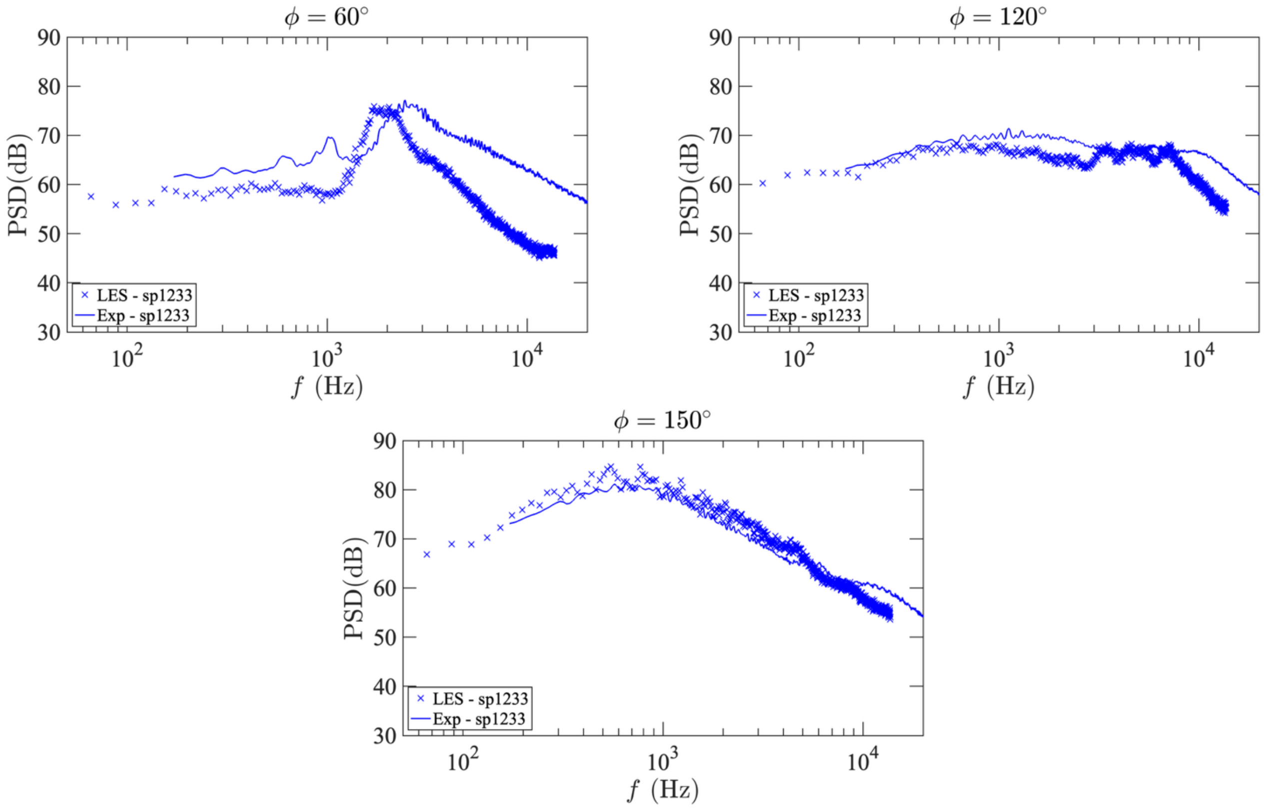


Figure 7. Far-field acoustics predictions for nozzle 122Am5pInt at Setpoint 1233 at polar angles $\phi = 60°, 120°, 150°$. Experimental data from Bridges et al. (2021). PSD: Power Spectral Density.

Conclusions from New Simulations

The new simulations performed for nozzles 122Am0pInt and 122Am5pInt show that the dominant downstream noise is accurately captured by LES across a wide variety of operating conditions (subsonic & supersonic, Mach 0.3 flight stream & no flight stream, equal heating and unequal heating between streams). These results also show that the noise underpredictions at upstream and sideline angles are consistent across all setpoints where there is unequal heating of core/bypass streams. Through comparison with PIV measurements, we confirm that the mean flow outside the nozzle is accurately captured in the LES for all setpoints. All of these results indicate that the missing noise sources contributing to upstream/sideline acoustics originate in the mixing region inside the nozzle.

In order to test the sensitivity of the upstream/sideline acoustics to the mesh resolution inside the nozzle, an additional simulation was run at Setpoint 1203 for the 122Am5pInt nozzle with 2x mesh coarsening throughout the inside of the nozzle ($\Delta x = 0.01D$ compared to $\Delta x = 0.005D$). Figure 8 shows the original mesh compared to the new coarsened mesh. The coarse mesh contained 150M cells, compared to 198M cells for the original mesh. Despite this large reduction in mesh count, no significant changes were observed in the far-field acoustics for the coarsened mesh compared to the original mesh at Setpoint 1203. This finding indicates that mesh resolution in the mixing region inside the nozzle is unlikely to be the source of the issue, and we can coarsen the mesh inside the nozzle by 50M cells without impacting the acoustic predictions. In future work, we plan to explore more modifications to model the flow inside the nozzle, such as the boundary layer treatment on the nozzle wall, the mixer, and the plug.

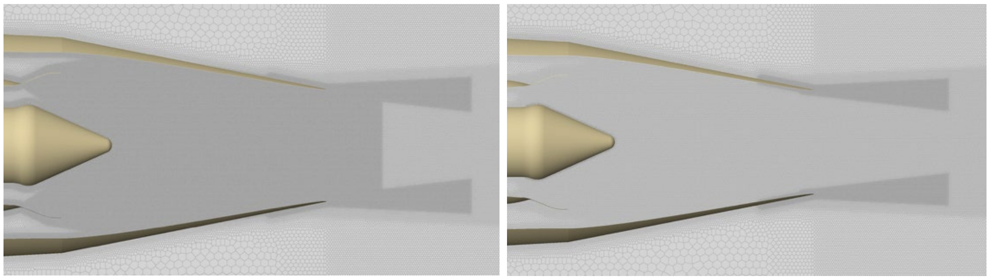


Figure 8. Original mesh inside the 122Am5pInt nozzle (left) and coarsened mesh (right). Dark gray regions indicate a mesh spacing of $\Delta x = 0.005D$.

Milestones

- Conducted LESs for test cases corresponding to the NASA Plug20 experiment for two different coaxial nozzles with an internal plug.
- Extended the LES database to include a variety of subsonic and supersonic operating conditions in order to more carefully identify where the LES is performing well and where it struggles to agree with experiments.
- Performed comparisons between LES flow fields and experimental PIV measurements for both NASA Plug20 nozzle configurations.

Major Accomplishments

- Made steady progress in the high-fidelity simulations of jet noise in accordance with the test plan established by our ASCENT Project 059 partners.
- Characterized discrepancies between LES and experimental far-field acoustics across a wide variety of operating conditions (subsonic & supersonic, flight stream & no flight stream, matched core/bypass heating & mismatched heating). Showed that the dominant downstream noise is predicted very well by the LES across all conditions tested.
- Identified that upstream and sideline noise underpredictions arise from mismatched heating between streams.
- Performed detailed comparison of LES flow fields to experimental PIV measurements. Confirmed that the LES accurately captures the mean flow fields across all operating conditions with available PIV.
- Examined sensitivity of far-field acoustics to mesh resolution inside the nozzle in the mixing region and identified potential for cost savings.

Publications

Doctoral Dissertation

Wu, G. J. (2024). *Towards quieter supersonic flight: a computational aeroacoustic study of high-speed jets* (Ch.4) [Doctoral dissertation, Stanford University]. Stanford University.

Conference Proceedings

Martin, O. G., Wu, G. J., & Lele, S. K. (2024, July 29-August 2). *Noise predictions of a dual-stream jet with forced internal mixing* [Conference paper]. AIAA Aviation Forum and ASCEND 2024, Las Vegas, Nevada.

Shanbhag, T. K., Zhou, B. Y., Ilario, C. R. S., & Alonso, J. J. (2024, January 8-12). *An AD framework for jet noise minimization using geometrical acoustics* [Conference paper]. AIAA SCITECH 2024 Forum, Orlando, Florida.

Shanbhag, T. K., Zhou, B. Y., Ilario, C. R. S., & Alonso, J. (2024, June 4-7). *Adjoint-based jet noise minimization using geometrical aeroacoustics* [Conference paper]. 30th AIAA/CEAS Aeroacoustics Conference, Rome Italy.

Shanbhang, T. K. (2024). *RANS-based methods for the prediction and reduction of jet noise* [Doctoral dissertation, Stanford University]. Stanford University.

Wu, G. J., Martin, O. G., & Lele, S. K. (2024, June 4-7). *Computational aeroacoustic study of coannular nozzles with internal mixing geometries at high transonic Mach numbers* [Conference paper]. 30th AIAA/CEAS Aeroacoustics Conference, Rome, Italy.

Outreach Efforts

Communication with ASCENT Project 059 partners and NASA scientists has been established. Deeper collaboration with the Georgia Tech experiments and with NASA scientists is expected as the project progresses further.

Awards

None.

Student Involvement

Two graduate students, G. Wu and O. Martin, participated in this task for Year 3. G. Wu has since graduated from Stanford.

Plans for Next Period

We plan to comprehensively explore the reasons for discrepancy between LES predictions and NASA data for the sideline and upstream observer locations. Grid refinement and coarsening and acoustic data-surface placement will be studied. We will also use more sophisticated data-decomposition methods to understand the role of upstream traveling modes in the generation of observed acoustic tones.

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Wu, G. J., Martin, O. G., & Lele, S. K. (2024, June 4-7). Computational aeroacoustic study of coannular nozzles with internal mixing geometries at high transonic Mach numbers [Conference paper]. *30th AIAA/CEAS Aeroacoustics Conference*, Rome, Italy. https://arc.aiaa.org/doi/10.2514/6.2024-3198

Task 3 – Conduct RANS-Based Simulation, Modeling, and Validation of Jet Noise Predictions

Stanford University

Objectives

The objective of this task is a 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

Turbulent Scales Modeling

The ASCENT Project 059D team is continuing work to model the turbulent length and time scales used in standard RANS-based acoustic source models. In previous work, our team studied the two-point fourth order velocity fluctuation correlation data extracted from LES databases of round jet simulations at Mach numbers of 0.5 and 0.9. In this research period, the same framework has been applied to extract the turbulent length and time scales at different points in the hydrodynamic source-containing region from this unsteady flow data on the basis of two common frameworks used in high frequency modeling, assuming that the spatial and temporal components of these correlation functions are separable. The validity of the widely applied assumption that these turbulent scales may be assumed universally proportional to the dimensionally derived dissipation scales arising from RANS-based turbulent quantities is investigated. Our team has found that this assumption breaks down over the potential core, where in the context of both the source models studied, the length and time scales appear to be relatively constant (see Figure 9). In the case of the time scale, we find that the constant of proportionality is not in fact constant over space but may be well approximated by a simple radial weight function. Our proposed 'weighted scales' model offers improved predictive capability as compared with the baseline Ribner source model for an unseen jet case (see Figure 10). The similarity of both the length and time scale distributions between the two Mach numbers studied, supported by the experimental and numerical observations of previous authors, suggest that this type of prediction framework could be widely applicable across jet operating conditions (see Figure 11 and Figure 12). However, this assumption will require further verification. This could take the form of either repeating the type of 'scale extraction' analysis performed in the present work on a more extensive set of unsteady simulations or experimental measurements or testing the far field predictions of similar weighted scales models against other jet noise experiments.

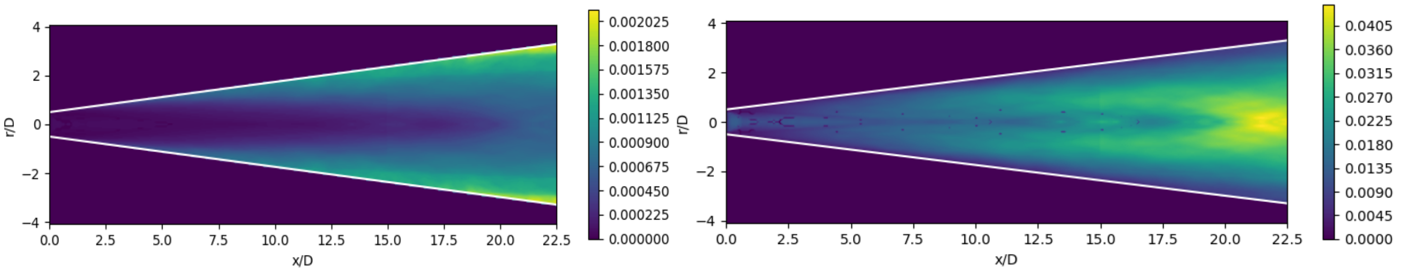

Figure 9. LES consistent scales for RANS modeling, time scale (left) and length scale (right).

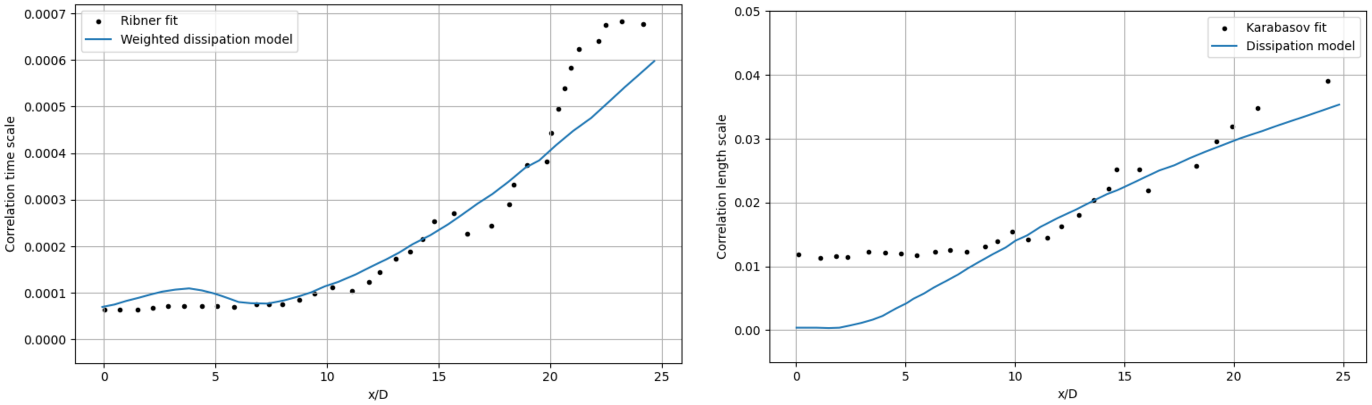

Figure 10. Comparison of fitted LES scales (symbols) and weighted dissipation model scales (line) along jet centerline based on Ribner fit (left) and Karabasov fit (right).

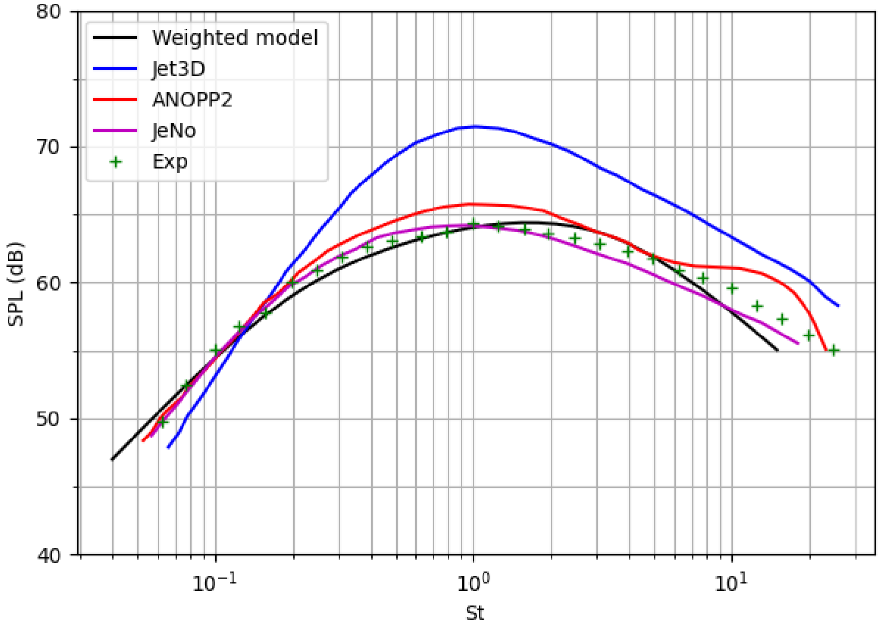

Figure 11. Convergent straight nozzle, M = 0.5: far field spectrum at r = 50.8D, θ = 90 deg.

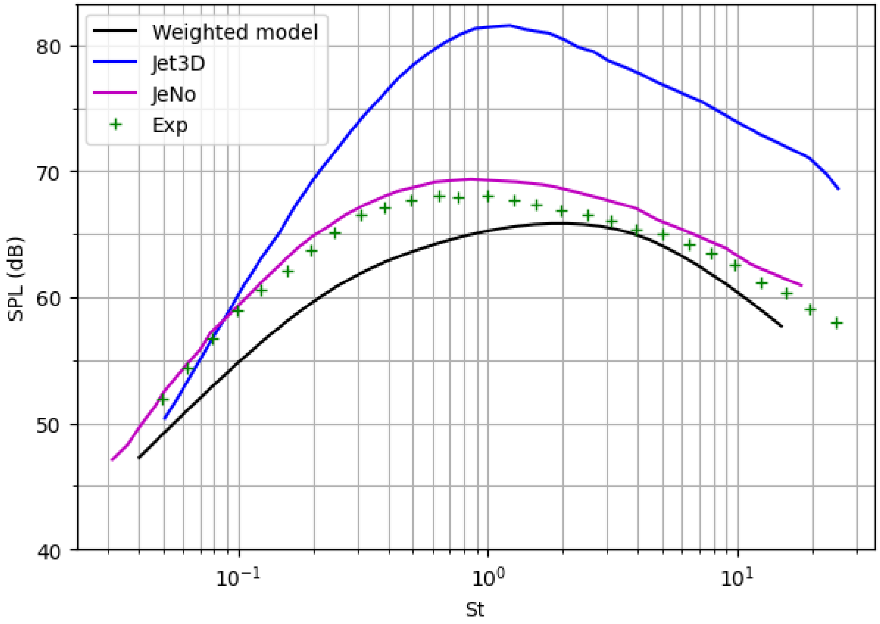

Figure 12. Convergent straight nozzle, M = 0.5: far field spectrum at r = 50.8D, θ = 50 deg.

Wavepacket Jitter Modeling

The ASCENT Project 059D team continued our effort towards modeling far field noise associated with the large-scale coherent structures in the jet flow. Our team proposed a predictive model form of the near field turbulent velocity fluctuation cross spectral density, based on a line source representation building upon the previous works of Crow, Mollo-

Christensen (1967), Cavalieri and Agarwal (2014). Resolvent analysis was used, augmented by a RANS-based eddy viscosity model, to deduce properties of the wavepacket spatial structure. This information was then used to reconstruct the cross-spectral density matrix (CSD), which is augmented with an explicit model of axial coherence decay along the wavepacket structure, observed experimentally as jitter. The coherence function used to represent the stochastic effects of jitter in the frequency domain is chosen to require minimal model parameter tuning, while offering an improved representation of the true CSD. The values of these parameters are selected, both based on LES conical nozzle round jet data at Mach number 0.5 and 0.9, and experimental measurements of far field acoustic directivity for round jets at subsonic Mach numbers between 0.4 and 0.9. In both cases, there is an observed linear scaling of the coherence length scale with wavelength (see Figure 13), supporting the hypothesis of this and previous works, that the wavepacket sources considered exhibit self-similar properties, not only in their spatial growth and decay but also in their streamwise coherence. However, while the LES-consistent parameters show this linearity between the coherence length and the acoustic wavelength, the experiment-consistent parameters suggest that the hydrodynamic wavelength is more relevant. The resulting global source model is demonstrated to be capable of low frequency noise prediction on a round jet test case at M = 0.9, and a promising degree of agreement with experimentally measured far field directivity profiles is obtained (see Figure 14 and Figure 15). With an unchanged parameter set, the model also has some preliminary applicability to supersonic jet cases, with minor modifications to the CSD construction methodology. Additional details on this work can be found in Shanbhag (2024).

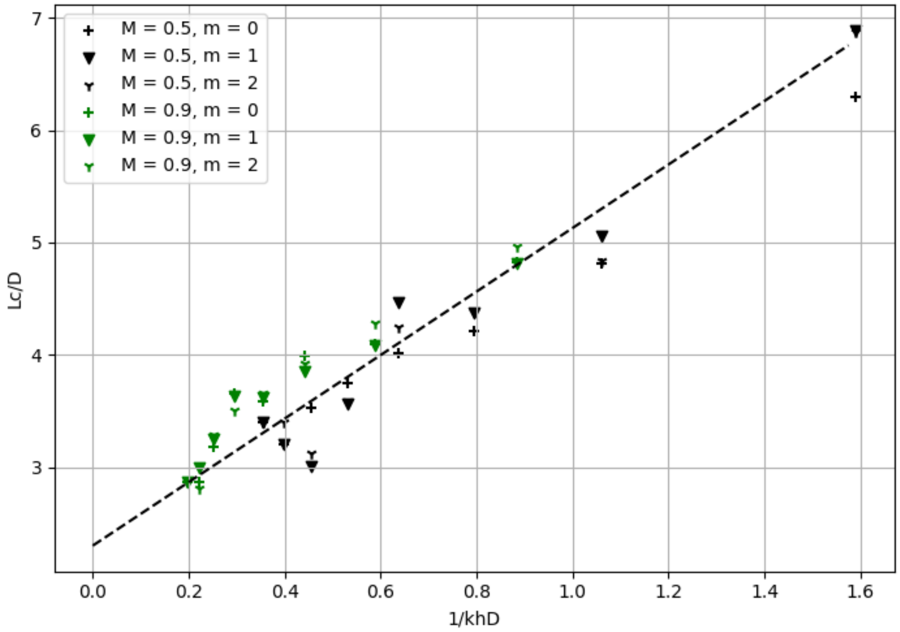

Figure 13. Optimal value of coherence length scale parameter Lc vs. acoustic wavelength 1/kh. Both length scales are normalized by nozzle diameter D

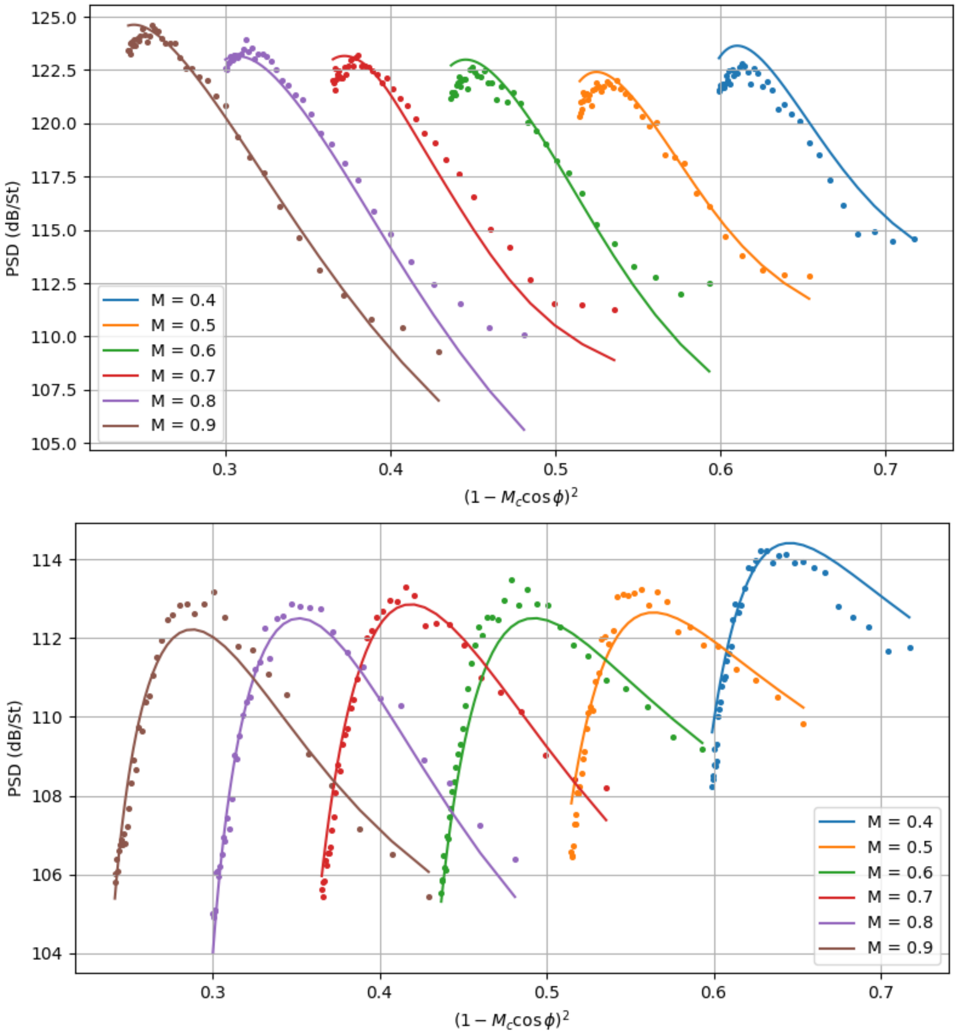

Figure 14. Predicted acoustic directivity for Poitiers jet compared against experimental measurements (Hasparyk et al., 2024) St = 0.2 (upper) and St = 0.6 (lower). PSD: Power Spectral Density. The polar angle ϕ is plotted on the horizontal axis in terms of the Doppler factor.

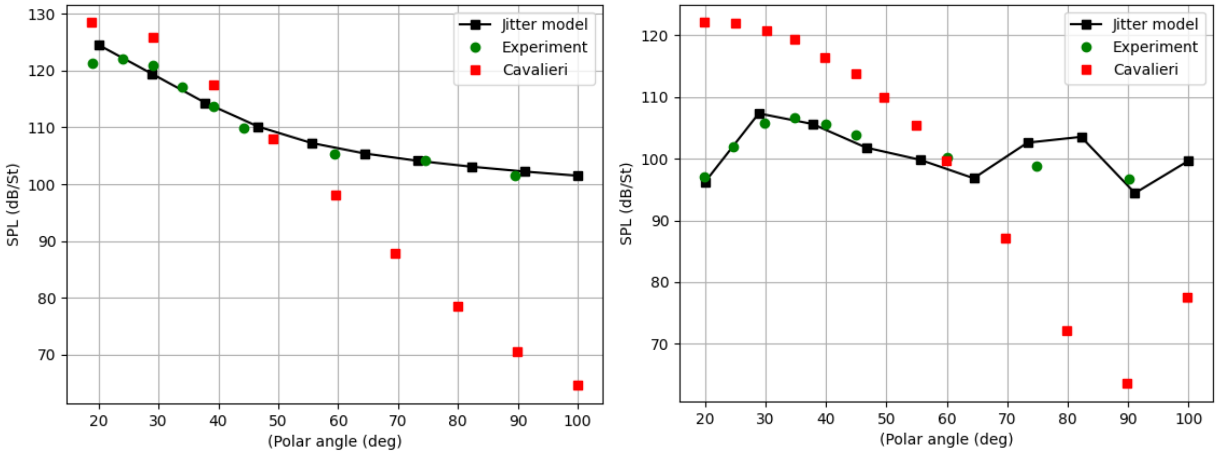

Figure 15. Comparison of M = 0.9 round jet directivity at St = 0.2 (left) and St = 0.75 (right). SPL: sound pressure level.

Given the relatively small amount of data used to select model parameters in this study, it will be important to repeat the model calibration in further work, using a greater variety of axisymmetric jet data across different Mach numbers and temperature ratios, to verify the trends that we observe. The recent experimental works of Hasparyk et al. (2024) have suggested that properly calibrated global source models proceeding along the lines in this work may be capable of shallow angle acoustic predictions accurate to within 1.5 dB of measured values, underlining the potential value of developing these methods further.

Adjoint (AD) Framework for Chevron Design Optimization

The ASCENT Project 059(D) team applied our previously developed framework for efficient adjoint-based design to the optimization of two baseline nozzle geometries. Our design framework allows the incorporation of realistic constraints on quantities such as thrust. The optimal designs produced show the capability of such a design framework to make significant noise reductions through minor geometric alterations. The alterations in geometry and flow field observed appear to be logically consistent with the conclusions drawn by the parametric design studies of previous authors looking to minimize jet noise through shear layer interference.

Figure 16 and Figure 17 show the results of a series of gradient-driven design iterations, beginning from the Poitiers round nozzle geometry. The results of two optimization problems are shown here: (1) the unconstrained problem, in which the computed nozzle thrust is allowed to vary freely, and (2) the constrained problem, in which thrust is maintained within 10% of the baseline value via incorporation of a penalty function. While this implementation does not guarantee satisfaction of the thrust constraint at every design iteration, the converged result of the optimization problem should satisfy the constraint exactly. The chosen design objective in both problems was the averaged SPL at St = 0.1, St = 0.3 and St = 1.0, computed over four equally azimuthally spaced sideline observers placed at r = 50D from the nozzle exit. It should also be noted that both problems were run under one additional constraint: the nozzle exit area was not permitted to increase beyond a certain point. This was found to be necessary during early design iterations, when the direction of the parameter gradient tended to open the nozzle exit - beyond a certain point this would result in the development of a choked throat and weak normal shock system. As an internal shock would be unacceptable to nozzle performance, this constraint was added to all design iterations and enforced via a backtracking line search along the computed gradient direction.

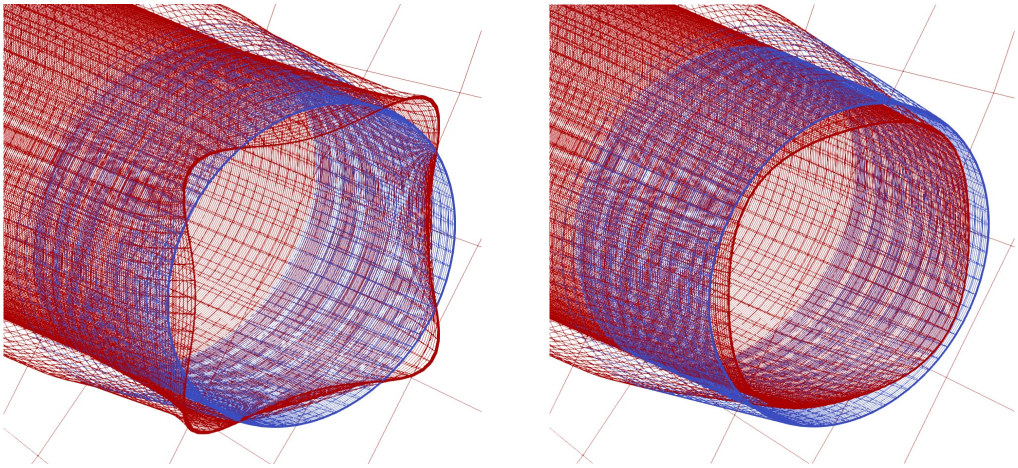

Figure 16. Poitiers jet optimization results: unconstrained (left) and constrained (right) cases.

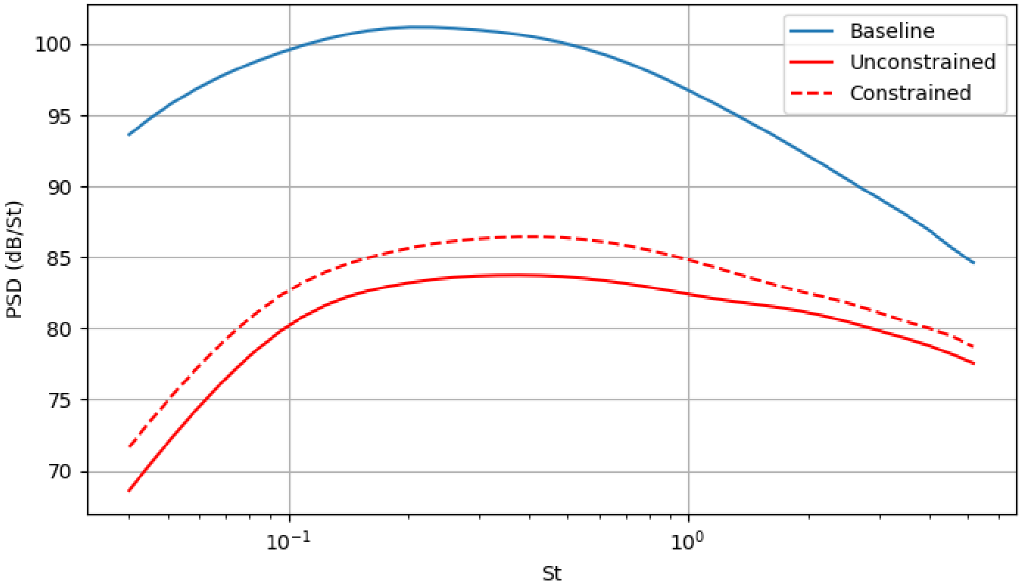

Figure 17. Baseline and optimized far field spectra for Poitiers optimization cases.

Comparing the two optimized geometries, both develop along similar lines. When prevented from simply expanding at the exit to reduce axial flow velocity, the nozzle instead develops an azimuthal radius asymmetry or 'waviness', similar to what is seen in a lobed mixer design. The amplitude of this waviness is significantly greater in the unconstrained case, whose geometry grows into something closer resembling lobes. The constrained case develops a squarer exit profile, whose final area is slightly contracted compared to the initial design point. Looking then at the relative performance of the two optimized geometries, the overall noise improvement in the constrained case is not much worse than that in the unconstrained case, with reductions of 12 dB and 15 dB, respectively. This suggests that while traversing this region of the design space, disruption of the shear layer, and the shape and amplitude of the associated turbulent kinetic energy field, via relatively small azimuthal variations has more impact on the far field noise than changes in the bulk axial velocity via exit area variations. It can also be seen that the single frequency noise objective monotonically reduces over both optimization problems, albeit to a lesser extent than the overall noise objective. This suggests that although the changes made during the design process have not resulted in crossover explicitly, they have resulted in an overall 'flattening' of the spectrum, with the higher frequency part of the spectrum being raised in comparison to the low frequency part. This is illustrated clearly by the optimized geometry spectra plotted in Figure 17. In both cases, however, the nozzle 'squaring' that results in noise reduction also results in significant thrust deviation, corresponding to a loss of approximately 7% even in the constrained case. In a realistic optimization scenario, this would represent a design trade-off skewed too far in favor of noise reduction at the expense of propulsive performance. Repeating these optimizations with significantly tighter aerodynamic constraints will be important to demonstrate the real-world applicability of the method.

Considering the observed geometry changes in the context of existing design studies, there have been a number of investigations into the performance of similarly 'squared' or rectangular exit nozzles as compared to the round jet baseline. The conclusions of these studies have varied. The work of Tam and Zaman (2000) pointed out that beyond an initial region of evolution, both the flow field and radiated sound field associated with a square or rectangular jet is, “quite axisymmetric and practically the same as that of a circular jet.” In contrast, the experimental studies of Massey, Ahuja and Gaeta (2004), which examined unheated subsonic jets issuing from rectangular nozzles of varying aspect ratio, found that sideline Overall Sound Pressure Level (OASPL) was lowered for the rectangular geometries compared with the round baseline. Furthermore, this noise reduction effect was found to be more pronounced in lower AR rectangular exits, suggesting that an optimal geometry closer to a square is not unreasonable. The subsequent experiments of Bridges (2012) corroborated these observations and further noted that the non-square rectangular geometries result in an azimuthally varying effect on OASPL, whereby a reduction in noise was observed on the narrow side of the nozzle, but noise on the wide side was increased. It is possible that repeating this optimization problem without azimuthal averaging of the noise objective may therefore result in larger aspect ratio, narrowing in the direction of the chosen observer. Further work on this topic would include application of the framework to a greater range of baseline geometries, and investigation in detail the effects of different parameterizations of the geometry, and the outcomes of optimizing for multiple objectives.

Milestones

- Applied our modular implementation of the low-fidelity (RANS-based) acoustic prediction tool and AD-enabled adjoint design framework to two simple nozzle optimization problems.
- Extended our predictive model for the shallow-angle low-frequency component of jet noise based on resolvent analysis.

Major Accomplishments

- Demonstrated a simple predictive model of the acoustic line source CSD, using an eddy viscosity-augmented resolvent analysis to deduce coherent wavepacket structures in the hydrodynamic region of a jet, coupled with an explicit modified exponential function to account for the effects of axial coherence decay and the corresponding jitter. Preliminary predictions of far field noise using this model have shown reasonable agreement with experimental measurements.
- Demonstrated our AD-enabled framework for RANS-based jet noise minimization via a set of gradient-driven optimization steps on round and chevron baseline nozzle geometries. The resulting geometry changes are physically consistent with the conclusions of previous parametric study into the variation of nozzle geometries and jet flow fields for the purpose of noise reduction.

Publications

Shanbhag, T. K. (2024). *RANS-based methods for the prediction and reduction of jet noise* [Doctoral dissertation, Stanford University], Stanford University.

Outreach Efforts

None.

Awards

None.

Student Involvement

T. Shanbhag has led the efforts with geometrical acoustics, AD-enabled nozzle optimization, and wavepacket jitter modeling described for Task 3.

Plans for Next Period

None.

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