Project 059D 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: June 5, 2020 to September 30, 2020
- Tasks: (for three year effort)
    1. Develop and refine research plan in coordination with ASCENT Project 59 partners.
    2. Reynolds-averaged Navier–Stokes- (RANS)-based modeling, simulation, and validation of jet noise predictions for baseline configuration.
    3. Large eddy simulation- (LES)-based modeling, simulation, and validation of jet noise predictions for baseline configuration.
    4. RANS-based modeling, simulation, and validation of jet noise predictions with noise reduction concept.
    5. LES-based modeling, simulation, and validation of jet noise predictions with noise reduction concept.
    6. Improved LES-based modeling and jet noise predictions.
    7. Improved RANS-based jet noise source modeling and predictions.

Project Funding Level

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

Investigation Team

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Project Overview

Improved methods for prediction and reduction of noise for civil supersonic aircraft would be highly valued by the research and technology (R&T) development community engaged in civil supersonic aircraft development. Besides the aircraft and engine companies, organizations such as NASA, FAA, and DoD R&T community would also benefit from the 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.

The project involves coordinated development of both low- and high-fidelity approaches for jet noise predictions for civil supersonic aircraft being considered in ASCENT and involves the seven Tasks listed above.

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 and better understand the uncertainty associated with the noise predictions for a range of engine cycle parameters and operating conditions relevant for civil supersonic aircraft.

The Stanford team will develop a multi-fidelity analysis approach. High-fidelity simulations of the 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 carried out 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.

Research Approach

1) Project Planning

The project began with a project planning exercise to define the range of operating conditions and possible nozzle configurations relevant for civil supersonic jet exhaust. These involved discussions with Project 59 partners and reaching out to external advisors at NASA and elsewhere in academia and industry. Based on this exercise, it was determined that the project should focus on axisymmetric dual-stream nozzles with internal mixer and with the possibility of internal and/or external nozzle plug. The operating conditions would include subsonic through low supersonic jet exhaust velocity and low-to-moderate bypass ratio (BPR). Research efforts were next focused on finding nozzle configurations and flow and noise measurement data in archival literature, which would be deemed 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 was in the regime of moderate-to-high BPR and thus not particularly relevant for civil supersonic aircraft. While this affirmed the need for the planned laboratory measurement campaign by Project 59 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 were thus identified.

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, shown schematically in Figure 1, 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 the measurement data. It is hoped that the geometry and data will become available in the future. This configuration is of interest to us since it is unique in providing both jet flow measurements and far-field noise at conditions relevant to civil supersonic

Recent Jet Noise Measurement 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 (see Figure 2) 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. Included in NASA's plans are noise predictions using a variety of computational tools. We are interested in exploring a selected subset of NASA's test matrix in our Project 59 studies.

2) Progress in Jet Noise Modeling and Simulations

Georgia Tech Dual Stream Nozzle

The co-annular nozzle designed by Project 59 partner Georgia Tech is of special interest in our work. Figure 3 shows one of the four co-annular nozzles proposed for the first stage of the study, each with a different length of internal mixing region. For the geometry with the shortest mixing zone, a preliminary unstructured Voronoi mesh for LES is generated using the grid generation tool developed by Cascade Technologies. The numerical domain spans from -20De to 80De in axial direction (x) and flares from 20De to 50De in the radial direction (r), where De is the nozzle exit diameter and the origin is located at the geometric center of the nozzle exit. As suggested in the literature (Brès et al. 2018a, 2018b), near-wall mesh refinement is needed inside the nozzle in order to properly capture the development of the internal boundary layers. Near the internal walls of both primary and secondary nozzles starting from x = -3De, the target length scale is set to Δx = 0.005De, and then further reduced to Δx = 0.0025De between x= -1De and the nozzle exit. The current near-wall grid sizing is based on Bres et al. (2018a), in which LES for a conical nozzle of similar size were conducted at Mj = 0.9. Readjustment of the near-wall grid resolution will be applied once more information about the boundary layers is obtained from experiments and preliminary LES calculations. Immediately downstream the exit up to x = 1De, the grids near the liplines are set to Δx = 0.005De and then doubled in size between x = 1De and x= 2De. Further downstream, between x = 2De and x = 20De, the grids near the jet shear layers are set to be 0.02De. Finally, the jet plume up to x = 40De is fully enclosed in a conical refinement zone with Δx = 0.04De. The rest of the domain is filled with successively coarser grids up to the boundaries. The resulting LES mesh contains around 64 million control volumes. Figure 4 (left) shows a schematic picture of the grid refinement near the nozzle surface and the jet shear layers in grayscale, with lighter color indicating a finer grid size. Figure 4 (right) shows a zoomed-in view of the Voronoi mesh near the nozzle exit, highlighting the fine isotropic grids placed near the nozzle wall and the exit shear layer.

By scaling the grids in the 64 million mesh by a factor of two, a coarse mesh containing around 15 million control volumes is generated. A preliminary test run using the coarse mesh is conducted at M = 0.9 for the primary nozzle and M = 0.7 for the secondary nozzle. This test run is done to further verify the numerical setup in preparation for the upcoming simulation plan. Figure 5 shows a contour plot of the instantaneous jet axial velocity near the nozzle exit, highlighting the interactions of the boundary layers inside the internal mixing region and the growth of the jet initial shear layers. Once the exact operating conditions of the nozzle are provided by the Georgia Tech experimental team, higher-fidelity simulations will be conducted on a finer mesh and validated with experimental data.

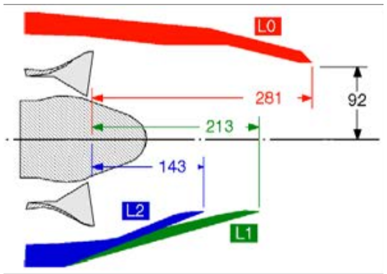

Figure 1. Internally mixed nozzle studied by Bridges and Wernet (AIAA 2004-2896).

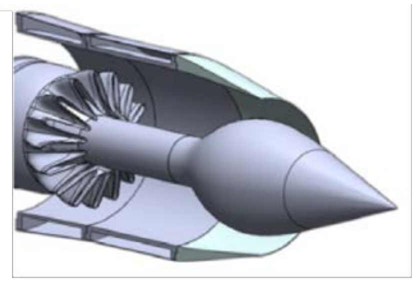

Figure 2. Dual stream internally mixed nozzle with external plug designed by Dr. Bridges at NASA.

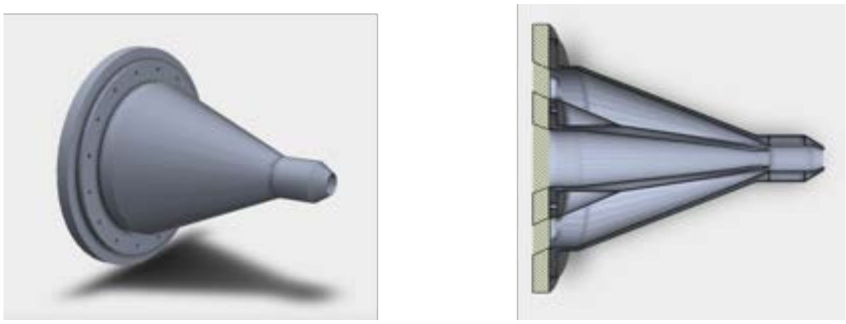

Figure 3. Coannular geometry provided by Georgia Tech team

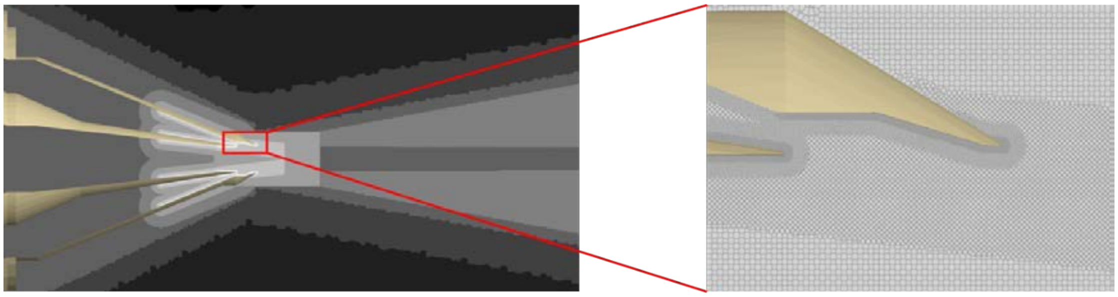

Figure 4. (Left) Preliminary LES mesh with refinement regions around the nozzle and the jet plume shear layers highlighted in grayscale; lighter color indicates finer grids. (Right) Zoomed-in view of the Voronoi mesh near the nozzle exit.

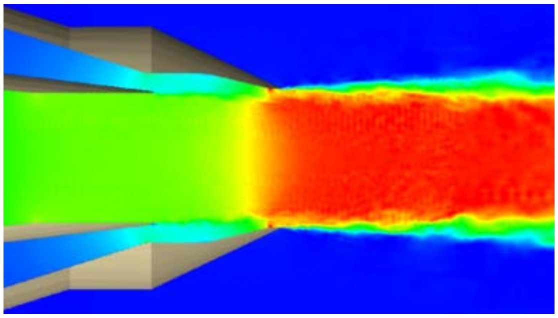

Figure 5. Instantaneous axial velocity from a test run using the Georgia Tech geometry on a coarse mesh.

Jet Noise Propagation Modeling

A number of methods have been applied to predict jet noise from RANS (mean flow) calculations alone. Several of these build upon Lighthill's original acoustic analogy (Lighthill), 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) similarly rearranges the full flow equations, into a linear left-hand side representing the spatially developing mean flow and a non-linear 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.).

In Generalized Acoustic Analogy (GAA), 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 non-linear source terms arising from Reynolds and shear stresses. Separate perturbation variables are defined for momentum and stagnation enthalpy.

The wave propagation problem is then solved efficiently in the frequency domain using an adjoint Green's function method (Karabasov et al.). The Fourier transform of the adjoint Green's function solution satisfies the adjoint PDE system to 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 placing a point source at a given location in the domain. The adjoint equations are solved iteratively in a pseudo-time stepping scheme, controlling the step size in order to prevent inaccuracies arising from the shear layer instability. Our implementation of this adjoint solver has been tested on a time-averaged ensemble of unsteady jet realizations, taken from 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.), and the simulation results for this grid resolution have been validated against experimental data from Bridges and Wernet (Bridges and Wernet). Figure 6 shows an example calculation, the density sensitivity field obtained using the adjoint solver for the M = 0.9 test jet, placing a point source underneath the jet.

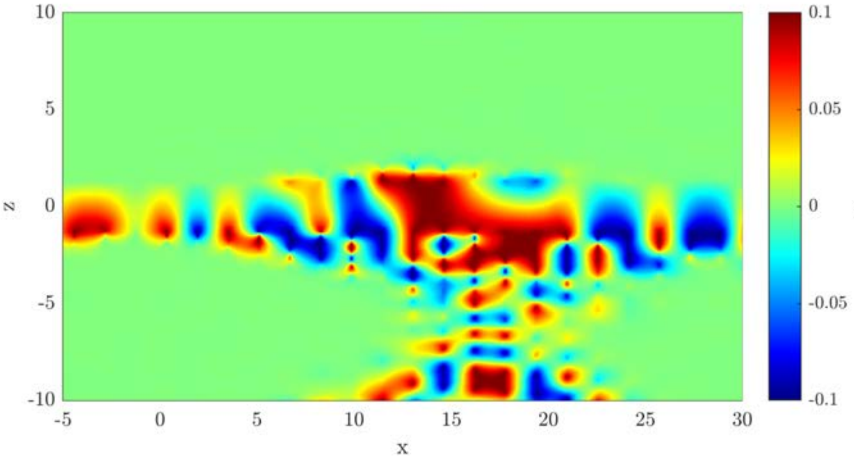

Figure 6. Adjoint density solution for point source placed in the x-z plane at y = -18.

The far-field acoustic pressure at a given observer location may then be calculated from a convolution integral over the domain volume of the adjoint fields with the non-linear sources obtained from the mean flow calculation. Calculating the power spectral density of the distant sound field in this way requires us to impose a model of the spatio-temporal cross-correlation of the source terms. This 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 non-dimensional constants (Karabasov et al.).

In addition to GAA, we have examined a number of other methods that could also be used to obtain far-field acoustic information from mean flow calculations alone. These include two lower order methods based on Lighthill's equations (Morris and Farassat) and the linearized Euler equations (Tam and Auriault), as well as resolvent analysis (Schmidt et al.), whereby the operator representing the transfer function between the base flow's forcing and response is decomposed to yield the most energetic acoustic modes present. These methods carry some advantages and drawbacks in comparison with GAA. The lower order methods carry the lowest computational cost while offering reasonable accuracy, and therefore appear to be well-suited for the purposes of design and optimization. However, this class of method requires significant tuning of empirical constants to provide the required accuracy. It is very difficult to attribute physical meaning to such parameters, and therefore difficult to come up with a universal tuning that would give sufficient predictive accuracy across the design space. Likewise, with resolvent analysis, the modes obtained are only indicative of the true energetic acoustic modes in the theoretical case of white noise forcing. In the true case, a model is required to account for non-forcing interactions within the flow. This model can range in complexity from simply including the eddy viscosity in the resolvent operator to more sophisticated solutions obtained from fitting to unsteady LES data. Work on each of these methods is ongoing.

Milestones

None

Major Accomplishments

To date, we have generated the preliminary grids for our RANS and LES studies. These preliminary grids serve as the starting point for quantifying the quality of our simulations. We expect the grid generation process to be an iterative process, especially as we receive more specifics on flow conditions from the experimental team.

We have also applied for and received some startup computer time on Extreme Science and Engineering Discovery Environment's (XSEDE) Stampede2 platform, on which we will begin running the preliminary simulations. This computer allocation and the anticipated preliminary runs will allow us to further refine our computational cost estimated in the future, larger allocation requests for production-sized runs.

Publications

None

Outreach Efforts

None

Awards

None

Student Involvement

Three graduate students are involved in this project. G. Wu has taken the lead on grid generation for the LES computations and computer time estimates for preliminary calculations. K. Matsuno has looked into previous literature relevant to this study and guided efforts to obtain more computer allocations. T. Shanbhag has led the modelling effort with the adjoint Green's function methods described in the previous sections and is in charge of running the RANS-level computations.

Plans for Next Period

Research will be focused on Tasks 1–3, as listed above, for the following project year.

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