Project 059(C) Modeling Supersonic Jet Noise Reduction with Global Resolvent Modes

University of Illinois Urbana-Champaign

Project Lead Investigator

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University Participants

University of Illinois Urbana-Champaign (UIUC)

- P.I.: Dr. Daniel J. Bodony
- FAA Award Number: 13-C-AJFE-UI-031
- Period of Performance: October 1, 2023, to September 30, 2026
- Tasks:
  1. Establishment of industry-relevant low bypass ratio (BPR) engine parameters and acoustic assessment workflow with cost-sharing partner (completed)
  2. Automated Reynolds-averaged Navier–Stokes equation (RANS) predictions of jet exhaust (completed)
  3. Resolvent mode computation—primary and sensitivity (completed)
  4. Python® resolvent mode interpolation tool (completed)
  5. Python optimization tool for jet noise reduction (JNR) (version 1) (completed)
  6. Application of version 1 optimization tool on Georgia Institute of Technology Research Institute (GTRI) dual-stream nozzle (completed)
  7. Reformulation of resolvent modes by using local turbulent kinetic energy (in progress)
  8. Development and implementation of design parameter gradient direction for JNR (in progress)
  9. Application of version 2 optimization tool on GTRI dual-stream nozzle (paused)
  10. Application of version 1 optimization tool on Gulfstream®- and Boom®-relevant geometry (in progress)
  11. Collaboration with P.I.s for ASCENT Projects 010 and 047 (not yet started)

Project Funding Level

The Federal Aviation Administration (FAA) provided $199,999 in funding. In-kind cost-matching agreements were established with Gulfstream ($100,000; contact person: Dr. Brian Krupp [brian.krupp@gulfstream.com]) and with Boom ($50,000; contact person: Dr. Joe Salamone [joe.salamone@boom.aero]).

Investigation Team

University of Illinois Urbana-Champaign

Dr. Daniel Bodony (P.I.), Tasks 1, 3, and 11
Mr. Jay Woo (PhD student), Tasks 2, 3, 4, 5, 6, 8, and 9

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® Gulfstream is a registered trademark of Gulfstream Aerospace Corporation, Savannah, Georgia
® Boom is a registered trademark of Boom Technology, Inc., Centennial, Colorado.

California Institute of Technology (Caltech)
Dr. Tim Colonius (subaward), Tasks 3, 7, and 11
Mr. Ethan Eichberger (PhD student), Tasks 3 and 7

Project Overview

This ASCENT project leverages recent research in global-resolvent-mode-based descriptions of jet turbulence and its associated noise to develop a physics-based tool for estimating the impact of JNR strategies on the takeoff noise of civil supersonic transports. The software tool will efficiently identify promising JNR technologies and will more precisely evaluate the noise impact of parametric variation in a specific JNR approach. The tool will be compatible with the fleet-scale evaluation codes Global and Regional Environmental Analysis Tool (GREAT; Georgia Institute of Technology) and Fleet Level Environmental Evaluation Tool (FLEET; Purdue University) developed in ASCENT Project 010 and integrated into the ASCENT Project 047 clean-sheet evaluation tool targeting civil supersonic transport.

The proposed research will create a multi-fidelity JNR tool that can operate in two modes: one mode for specific engine estimates and one mode for fleet-scale estimates, as discussed below.

JNR Evaluation for an Engine Mode
According to the RANS-provided mean flow for a specific engine, the global resolvent description of wavepackets and their sensitivity to mean flow variations will be computed. The solutions will provide estimates of the low-frequency radiated noise, and the sensitivity derivatives will estimate how the noise changes as a result of changes in the engine design, thus enabling JNR optimization.

Fleet-level Estimation Mode
The resolvent modes and their sensitivity derivatives for existing JNR strategies (e.g., chevrons or internal mixers) will be pre-computed for canonical jet exhaust profiles and flow conditions, compressed, and stored within an efficient data layout that can be quickly evaluated within FLEET, GREAT, and/or National Aeronautics and Space Administration (NASA) Aircraft Noise Prediction Program.

The Year 3 proposal was approved for funding with a period of performance of October 1, 2022, through December 31, 2023 (after a no-cost extension), and a budget of $199,999. The Year 2 statement of work included five tasks, listed above as Tasks 7–11, and rephrased from the prior year's annual report. The status of each task is indicated in parentheses. A Year 4 proposal was funded for $199,999 with a period of performance of January 1, 2024, through September 30, 2026 (after a no-cost extension).

Task 1 – Establish Industry-Relevant Low-BPR Engine Parameters and Acoustic Assessment Workflow with Cost-Sharing Partner [Completed]

University of Illinois at Urbana-Champaign

Objective

The objective of this task is to work with our cost-sharing partners to identify the anticipated range of characteristics of the low-BPR engines being considered for business-class civil supersonic transport. These parameters include, but are not limited to, diameter, BPR, mass flow rate, core and fan stream pressure ratios, core stream temperature ratio, thrust, nozzle configuration, plug designs, chevron designs, internal mixer designs, and afterburner design.

Research Approach

The research approach involves conducting face-to-face meetings and document exchange to obtain industry-relevant low-BPR engine parameters and acoustic assessment workflows.

Milestones

- Find a new candidate cost-sharing partner.
- Establish a nondisclosure agreement to initiate discussions.
- Exchange low-BPR engine parameters and acoustic assessment workflow.

Major Accomplishments

All milestones have been completed. A nondisclosure agreement between UIUC and Boom was signed in Year 2, and subsequent discussions led to Boom's partnership with $50,000 in-kind cost sharing for Year 3. The Boom commitment letter is attached. A cost-sharing agreement with Gulfstream was also established for $100,000 in-kind cost sharing. The Gulfstream letter is attached. In consultation with Dr. James Bridges at NASA Glenn Research Center, the "Plug20" family of nozzles (NASA TM-20210010291) was identified as relevant to industry. Downselecting the available nozzles will be the focus of the Year 4 effort, provided that it is funded.

Publications

None.

Outreach Efforts

None.

Awards

None.

Student Involvement

None.

Plans for Next Period

- Continued communication between UIUC and the principal contacts at Boom and Gulfstream, with focus on exchanging results, sharing data, and evaluating the UIUC-developed JNR workflow within each company's design process on the Plug20 nozzles. Of note, Dr. Joe Salamone left Boom and attempts to reconnect with Boom engineers have not yet been successful.

Task 2 – Automated RANS Predictions of Jet Exhaust [Completed]

University of Illinois at Urbana-Champaign

Objective

The objective of this task is to develop and verify an automated tool chain for using RANS methods to predict the jet exhaust plume from candidate near-sonic multi-stream jet nozzles.

Research Approach

Achieving JNR will require changes to the engine cycle and nozzle geometries. A Python-based software infrastructure is to be developed that takes parametrically defined computer-aided-design-based descriptions of nozzle geometries, automatically generates meshes and boundary conditions for the nozzle internal flow path and the external nozzle plume, initiates an open-source RANS solver, and curates the data.

Milestones

- Completed additional developments in computational fluid dynamics flow path.
- Verified RANS simulation results.
- Automated Python infrastructure.

Major Accomplishments

Milestone 1 has been completed and included subtasks such as adjusting the boundary conditions and increasing the computational domain of the mesh grid for each nozzle model. Post-processing calculations have also been developed to monitor properties of the nozzle exhaust and thereby characterize steady flow behavior. Milestone 2 has been completed, and included results obtained from post-processing that have been verified through comparison with a numerical solution based on quasi one-dimensional flow theory for mixed exhaust jet nozzles. Milestone 3 has been completed and included full automation of individual computational fluid dynamics processes.

Publications

Conference Proceedings

Woo, J., Murthy, S. R., & Bodony, D. J. (2024, January 8-12). Resolvent-based framework for jet noise reduction of a low-bypass ratio coannular nozzle (AIAA Paper 2024-2805). *AIAA SciTech 2024 Forum*. https://arc.aiaa.org/doi/10.2514/6.2024-2805

Dissertations and Theses

Woo, J. (2023). *Resolvent-based framework for jet noise reduction of a low-bypass ratio coannular nozzle* [Master's thesis, University of Illinois at Urbana-Champaign]. University of Illinois at Urbana-Champaign.

Outreach Efforts

None.

Awards

None.

Student Involvement

Jay Woo was responsible for developing the Python tool chain.

Plans for Next Period

None. This task is complete.

Task 3 – Resolvent Mode Computation—Primary and Sensitivity [Completed]

University of Illinois at Urbana-Champaign (lead) and California Institute of Technology

Objective

The objective of this task is to develop and verify a resolvent mode computation tool suitable for evaluating the JNR potential of candidate near-sonic multi-stream jet nozzles.

Research Approach

Achieving JNR will require changes to the engine cycle and nozzle geometries. Estimation of the JNR potential of candidate cycles and geometries will use resolvent mode descriptions of the coherent wavepacket-associated jet noise of the loudest sound sources. We denote the resolvent calculations that provide the input–gain–output modes of the resolvent operator $(i\omega - A)^{-1}$ as "primary," and we denote the changes in those modes due to changes in the jet nozzle geometry and engine cycle as "sensitivity." The resolvent operator requires knowledge of the linearized Navier–Stokes operator A generated for each nozzle and its exhaust plume, and a global mode computational infrastructure. The sensitivity of the resolvent input–gain–output modes requires knowledge of the change in A, e.g., δA, resulting from changes in the nozzle design and/or engine cycle.

Milestones

- Developed primary resolvent mode computation capability.
- Performed resolvent mode training data and fitting.
- Developed resolvent mode sensitivity computation capability.

Major Accomplishments

Milestone 1 has been completed and tested on single-stream subsonic and supersonic jets. Milestone 2 has been completed by using GTRI dual-stream jet data. Milestone 3 has been completed and validated by using GTRI dual-stream jet data.

Publications

Conference Proceedings

Woo, J., Murthy, S. R., & Bodony, D. J. (2024, January 8-12). Resolvent-based framework for jet noise reduction of a low-bypass ratio coannular nozzle (AIAA Paper 2024-2805). *AIAA SciTech 2024 Forum*. https://arc.aiaa.org/doi/10.2514/6.2024-2805

Dissertations and Theses

Pickering, E. (2021). *Resolvent Modeling of Turbulent Jets* [Doctoral dissertation, California Institute of University]. California Institute of University. doi:10.7907/szxb-f168. https://resolver.caltech.edu/CaltechTHESIS:03022021-005902351

Woo, J. (2023). *Resolvent-based framework for jet noise reduction of a low-bypass ratio coannular nozzle* [Master's thesis, University of Illinois at Urbana-Champaign]. University of Illinois at Urbana-Champaign.

Outreach Efforts

None.

Awards

None.

Student Involvement

Jay Woo is primarily responsible for running and applying the resolvent calculation and its sensitivity. Ethan Pickering was responsible for calibrating the primary resolvent mode computation and the preliminary training data and fitting tasks; he graduated and left Caltech. Ethan Eichberger is the current student, who learned from Liam Heidt and now leads global mode data-driven alignment.

Plans for Next Period

None. This task is complete.

Task 4 – Python Resolvent Mode Interpolation Tool [Completed]

University of Illinois at Urbana-Champaign (lead) and California Institute of Technology

Objective

The objective of this task is to develop and verify a Python-based interpolation tool for computing resolvent input–gain–output modes at nozzle geometry and/or engine cycles for which RANS data are unavailable but are near previously known input–gain–output modes from nearby nozzle geometries and/or engine cycles.

Research Approach

By using Kriging interpolation methods, a response surface-based interpolation approach will be developed to estimate resolvent input–gain–output modes for estimating the radiated noise from an engine geometry/engine cycle for which previously computed RANS data, linearized operators, and resolvent data are unavailable.

Milestones

- Identify candidate interpolation methods and downselect.
- Develop a Python tool to implement the interpolation method.
- Verify the Python tool.

Major Accomplishments

Milestones 1–3 have been completed: a Kriging method has been chosen, and an interpolation code has been developed and verified. Performance and accuracy comparisons between the interpolation tool and re-running the computational fluid dynamics and mode calculations suggest that the interpolation method is inferior.

Publications

Dissertations and Theses

Woo, J. (2023). *Resolvent-based framework for jet noise reduction of a low-bypass ratio coannular nozzle* [Master's thesis, University of Illinois at Urbana-Champaign]. University of Illinois at Urbana-Champaign.

Outreach Efforts

None.

Awards

None.

Student Involvement

Jay Woo was responsible for developing the Python tool chain.

Plans for Next Period

None. The resolvent-based interpolation tool will no longer be a focus of the work.

Task 5 – Python Optimization Tool for JNR [Completed]

University of Illinois at Urbana-Champaign (lead) and California Institute of Technology

Objective

The objective of this task is to develop and verify a Python-based optimization tool that searches the optimization space of the engine geometry/cycle, to identify design choices that improve JNR.

Research Approach

With gradient-informed optimization methods, an optimization approach will be developed for estimating JNR potential from a class of candidate engine geometries/cycles by using resolvent mode predictions of jet noise based on linearized operators described by RANS predictions of the jet exhaust plume.

Milestones

- Identify candidate optimization methods and downselect.
- Develop a Python tool to implement the optimization method.
- Verify the Python tool.

Major Accomplishments

Milestone 1 has been completed, and the conjugate gradient method was selected for the optimization. Milestones 2 and 3 are also complete.

Publications

Conference Proceedings

Woo, J., Murthy, S. R., & Bodony, D. J. (2024, January 8-12). Resolvent-based framework for jet noise reduction of a low-bypass ratio coannular nozzle (AIAA Paper 2024-2805). *AIAA SciTech 2024 Forum*. https://arc.aiaa.org/doi/10.2514/6.2024-2805

Dissertations and Theses

Woo, J. (2023). *Resolvent-based framework for jet noise reduction of a low-bypass ratio coannular nozzle* [Master's thesis, University of Illinois at Urbana-Champaign]. University of Illinois at Urbana-Champaign.

Outreach Efforts

None.

Awards
None.

Student Involvement
Jay Woo was responsible for implementing the optimization tool.

Plans for Next Period
None. This task is complete.

Task 6 – Application of Version 1 Optimization Tool on GTRI Dual-Stream Nozzle [Completed]
University of Illinois at Urbana-Champaign (lead) with California Institute of Technology

Objective
The objective of this task is to apply the Python-based tool developed in Tasks 2–5 to the GTRI dual-stream nozzle with extensible mixer duct lengths, to predict the quietest configuration.

Research Approach
The automated Python toolchain, starting with the moderate mixer duct length, will be applied to predict the mixer duct length that yields the quietest configuration. The predictions will be compared with the GTRI-measured acoustic field.

Milestones
- Select the GTRI operating condition of interest.
- Apply the optimization tool.
- Compare the predicted quiet configuration to the measured quiet configuration.

Major Accomplishments
Milestone 1 has been completed and was based on the conditions for which GTRI jet velocity particle image velocimetry (PIV) data and acoustic data are available. Milestone 2 has been applied, and optimization has been performed. Milestone 3 has been completed. Qualitative trends from the resolvent modes have been found to be consistent with the measured acoustic field.

Publications
Conference Proceedings

Woo, J., Murthy, S. R., & Bodony, D. J. (2024, January 8-12). Resolvent-based framework for jet noise reduction of a low-bypass ratio coannular nozzle (AIAA Paper 2024-2805). *AIAA SciTech 2024 Forum*. https://arc.aiaa.org/doi/10.2514/6.2024-2805

Dissertations and Theses

Woo, J. (2023). *Resolvent-based framework for jet noise reduction of a low-bypass ratio coannular nozzle* [Master's thesis, University of Illinois at Urbana-Champaign]. University of Illinois at Urbana-Champaign.

Outreach Efforts
None.

Awards
None.

Student Involvement
Jay Woo was responsible for applying version 1 of the optimization tool to the GTRI nozzle.

Plans for Next Period
None. This task is complete.

Task 7 – Reformulation of Resolvent Modes by Using Local Turbulent Kinetic Energy
California Institute of Technology

Objective
The objective of this task is to develop a means for the resolvent gain predictions to be internally calibrated by using information from the RANS-predicted flow-fields.

Research Approach
A calibrated reconstruction of the input–output modes from the resolvent formulation is used to estimate the jet's turbulent kinetic energy, as predicted by the RANS model.

Milestones
- Finalize the calibration formulation.
- Implement the calibration procedure.
- Verify the calibration procedure.

Major Accomplishments
Task 7 has been started. Initial results from Caltech showed a significant improvement in reconstructing the far-field acoustics using localized resolvent modes. The team is working on producing consistent resolvent responses which is essential for the training of the machine learning model. A wall-modeled large eddy simulation framework has been developed to produce high fidelity flow data for Milestones 1 and 3. Complete verification of the framework is ongoing with preliminary calculations showing promising performance.

Publications
None.

Outreach Efforts
None.

Awards
None.

Student Involvement
Ethan Eichberger and Jay Woo will be jointly responsible.

Plans for Next Period
Develop the new self-calibration formulation and apply it to Plug20 flow field data.

Task 8 – Development and Implementation of Design Parameter Gradient Direction for JNR
University of Illinois at Urbana-Champaign (lead) with California Institute of Technology

Objective
The objective of this task is to develop and verify an updated Python-based optimization tool based on version 1 that searches the optimization space of the engine geometry/cycle, to identify design choices that improve JNR.

Research Approach
Using gradient-informed optimization methods, we will develop an optimization approach for estimating JNR potential from a class of candidate engine geometries/cycles by using resolvent mode predictions of jet noise, on the basis of linearized operators described by RANS predictions of the jet exhaust plume.

Milestones
- Incorporated lessons-learned updates from version 1 of the Python toolchain into version 2.
- Verified implementation.

Major Accomplishments
Milestone 1 has been completed. Milestone 2 has been completed for a supersonic jet. The automated Python optimization tool is being applied to the GTRI dual-stream nozzle data.

Publications
Conference Proceedings

Murthy, S., & Bodony, D. J. (2023, June 12-16). Resolvent analysis based jet-noise-reduction of a biconical tactical jet nozzle (AIAA 2023-4518). *2023 AIAA Aviation Forum*. https://doi.org/10.2514/6.2023-4518

Dissertations and Theses

Woo, J. (2023). *Resolvent-based framework for jet noise reduction of a low-bypass ratio coannular nozzle* [Master's thesis, University of Illinois at Urbana-Champaign]. University of Illinois at Urbana-Champaign.

Outreach Efforts
None.

Awards
None.

Student Involvement
Jay Woo and Ethan Eichberger will be jointly responsible.

Plans for Next Period
Complete Milestone 2 on the Plug20 nozzle.

Task 9 – Application of Version 2 Optimization Tool on GTRI Dual-Stream Nozzle
University of Illinois at Urbana-Champaign (lead) with California Institute of Technology

Objective
The objective of this task is to apply version 2 of the Python-based tool developed in Tasks 2–5 to the GTRI dual-stream nozzle with extensible mixer duct lengths and predict the quietest configuration.

Research Approach
We will apply the automated Python toolchain, starting with the moderate mixer duct length, to predict the mixer duct length that yields the quietest configuration, then compare predictions with the GTRI-measured acoustic field.

Milestones
- Apply the optimization tool.
- Compare the predicted quiet configuration to the measured quiet configuration.

Major Accomplishments
Task 9 has been completed on the GTRI dual-stream nozzle but yielded null results because the nozzle design parameters (e.g., mixer length) were found not to change the far-field sound.

Publications
None.

Outreach Efforts
None.

Awards
None.

Student Involvement
Jay Woo will be responsible for applying version 2 of the optimization tool.

Plans for Next Period
Re-apply Task 9 to the Plug20 nozzles.

Task 10 – Application of Version 1 Optimization Tool on Gulfstream- and Boom-Relevant Geometry
University of Illinois at Urbana-Champaign

Objective
The objective of this task is to work with Gulfstream and Boom to apply version 1 of our optimization tool to a supersonic nozzle design relevant to Gulfstream and Boom. Performance, successes, and failures will be documented.

Research Approach
The results of version 1 of the Python optimization tool will be transitioned to Gulfstream and Boom for internal evaluation of the tool.

Milestones
- Developed and implemented a cost-sharing agreement with appropriate intellectual-property safeguards.
- Worked with Gulfstream and Boom engineers to identify cases of interest.
- Apply optimization code to Gulfstream and Boom cases of interest.

Major Accomplishments
Milestone 1 has been completed, and the letters of support from Gulfstream and Boom are included. Milestone 2 has been completed, and the NASA Plug20 configurations of Bridges et al. (NASA TM-20210010291) were selected. Milestone 3 has not yet been started.

Publications
None.

Outreach Efforts
None.

Awards
None.

Student Involvement
Jay Woo and P.I. Daniel Bodony will be jointly responsible.

Plans for Next Period
Begin Milestone 3.

Task 11 – Collaboration with P.I.s for ASCENT Projects 10 and 47
University of Illinois at Urbana-Champaign

Objective
The objective of this task is to collaborate with P.I.s on ASCENT Projects 010 and 047 to understand fleet-scale estimation needs and constraints and develop a prototype software interface that connects the engine-class tool from Task 3 to FLEET/GREAT.

Research Approach
We will discuss, document, and identify implementation possibilities for connecting version 1 (or version 2) of the JNR optimization tool within their project software tools.

Milestones
- Engage P.I.s on ASCENT Projects 10 and 47 to understand their goals, data, and software ecosystems.
- Identify possible means through which ASCENT Project 059C tools could be integrated ASCENT Projects 010 and 047 ecosystems.
- Re-engage ASCENT Projects 010 and 047 P.I.s to downselect the most promising integration path.

Major Accomplishments
This task has not yet been started.

Publications
None.

Outreach Efforts
None.

Awards
None.

Student Involvement
Jay Woo and P.I. Daniel Bodony will be jointly responsible.

Plans for Next Period
Begin Task 11.