

# 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.s: Dr. Daniel J. Bodony and Dr. Tim Colonius
- FAA Award Number: 13-C-AJFE-UI-031
- Period of Performance: October 1, 2021 to September 30, 2022
- 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 (paused)
  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 (in progress)
  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 (not yet started)
  10. Application of version 1 optimization tool on Gulfstream- and Boom-relevant geometry (in progress)
  11. Collaborate with P.I.s for ASCENT Projects 10 and 47 (not yet started)

### Project Funding Level

The 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](mailto:brian.krupp@gulfstream.com)]) and with Boom (\$50,000; contact person Dr. Joe Salamone [[joe.salamone@boom.aero](mailto:joe.salamone@boom.aero)]).

### Investigation Team

- Dr. Daniel Bodony, UIUC, P.I. (Task 1, 3, 11)
- Mr. Jay Woo, UIUC, MS (Task 2, 3, 4, 5, 6, 8, 9)
- Dr. Tim Colonius, California Institute of Technology (Caltech), co-P.I. (Task 3, 7, 11)
- Mr. Liam Heidt, Caltech, PhD student (Task 3, 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 10 and integrated into the ASCENT Project 47 “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:

### **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 NASA's Aircraft Noise Prediction Program.

The Year 2 proposal was approved for funding with a period of performance of October 1, 2021 through September 30, 2022, 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 given in parentheses.

## 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 partner 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 new cost-sharing partner candidate
- 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, and subsequent discussions led to Boom's partnership with \$50,000 in-kind cost sharing. 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.

### **Publications**

None.

### **Outreach Efforts**

None.

### **Awards**

None.

### **Student Involvement**

None.

### **Plans for Next Period**

Communication between UIUC and the principal contacts at Boom and Gulfstream will continue, and will focus on exchanging results, sharing data, and evaluating the UIUC-developed JNR workflow within each company's design process.

## **Task 2 - Automated RANS Predictions of Jet Exhaust**

University of Illinois at Urbana-Champaign

### **Objective**

The objective of this task is to develop and verify an automated toolchain 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**

- Additional developments in computational fluid dynamics flow path
- Verification of RANS simulation results
- Automation of 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-1D flow theory for mixed exhaust jet nozzles. Milestone 3 has been completed and included full automation of individual computational fluid dynamics processes.

### **Publications**

None.

### **Outreach Efforts**

None.

### **Awards**

None.

### **Student Involvement**

Jay Woo was responsible for developing the Python toolchain.

### **Plans for Next Period**

None. Task is complete.

## **Task 3 - Resolvent Mode Computation—Primary and Sensitivity**

Caltech (lead) and University of Illinois at Urbana-Champaign

### **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.,  $\delta A$ , resulting from changes in the nozzle design and/or engine cycle.

### **Milestones**

- Primary resolvent mode computation capability
- Resolvent mode training data and fitting
- 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**

Pickering, E.(2021). *Resolvent Modeling of Turbulent Jets* [Doctoral thesis, California Institute of University].

doi:10.7907/szxb-f168. <https://resolver.caltech.edu/CaltechTHESIS:03022021-005902351>

### **Outreach Efforts**

None.

### **Awards**

None.

### **Student Involvement**

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

### **Plans for Next Period**

None. Task is completed.

## Task 4 - Python Resolvent Mode Interpolation Tool

University of Illinois at Urbana-Champaign (lead) and Caltech

### 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 down-select
- Develop a Python tool to implement the interpolation method
- Verify the Python tool

### Major Accomplishments

Milestone 1 has been completed: a kriging method has been chosen. Milestones 2 and 3 have not yet started.

### Publications

None.

### Outreach Efforts

None.

### Awards

None.

### Student Involvement

Jay Woo is responsible for developing the Python toolchain.

### Plans for Next Period

We will begin Milestone 2.

## Task 5 - Python Optimization Tool for JNR

University of Illinois at Urbana-Champaign (lead) and Caltech

### 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

Using 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 down-select
- 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**

None.

### **Outreach Efforts**

None.

### **Awards**

None.

### **Student Involvement**

Jay Woo was responsible for implementing the optimization tool.

### **Plans for Next Period**

None. Task is complete.

## **Task 6 - Application of Version 1 Optimization Tool on GTRI Dual-stream Nozzle**

University of Illinois at Urbana-Champaign (lead) with Caltech.

### **Objective**

The objective of this task is to apply the Python-based tool developed from 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 PIV data and acoustic data are available. Milestone 2 has been partially applied: a user-guided optimization has been performed but the fully automated design has not. Milestone 3 has not yet been attempted.

### **Publications**

None.

### **Outreach Efforts**

None.

### **Awards**

None.

### **Student Involvement**

Jay Woo will be responsible for applying version 1 of the optimization tool to the GTRI nozzle.

### **Plans for Next Period**

We will apply the automated Python optimization tool to Milestone 2 and compare its predictions with the GTRI data in Milestone 3.

## **Task 7 - Reformulation of Resolvent Modes by Using Local Turbulent Kinetic Energy**

Caltech

### **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. However, initial results from Caltech showed that the original formulation for calibrating the resolvent modes by using the local turbulent kinetic energy led to an ill-posed problem whose solutions were not suitable. A new formulation is being developed.

### **Publications**

None.

### **Outreach Efforts**

None.

### **Awards**

None.

### **Student Involvement**

Liam Heidt will continue to be responsible.

### **Plans for Next Period**

We will continue Task 7 by developing the new self-calibration formulation and applying it to GTRI flow field data.



## Task 8 - Development and Implementation of Design Parameter Gradient Direction for JNR

University of Illinois at Urbana-Champaign (lead) with Caltech

### Objective

The objective of this task is to develop and verify an updated Python-based optimization tool based on version 1 and the self-calibration procedure developed in Task 7 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 self-calibrated resolvent mode predictions of jet noise, on the basis of linearized operators described by RANS predictions of the jet exhaust plume.

### Milestones

- Incorporate self-calibrated resolved mode implementation into the Python toolchain
- Incorporate lessons-learned updates from version 1 of the Python toolchain into version 2
- Verify implementation

### Major Accomplishments

Milestone 1 will be completed pending the new formulation for self-calibration determined in Task 7. Milestone 2 is in progress; the automated Python optimization tool is being applied to the GTRI dual stream nozzle data. Milestone 3 has not yet been started.

### Publications

None.

### Outreach Efforts

None.

### Awards

None.

### Student Involvement

Jay Woo and Liam Heidt will be jointly responsible.

### Plans for Next Period

We will complete Milestone 2 early in Year 3. Milestone 1 development is paused while Task 7 is being completed. Milestone 3 will begin once Milestone 1 has been completed.

## Task 9 - Application of Version 2 Optimization Tool on GTRI Dual-stream Nozzle

University of Illinois at Urbana-Champaign (lead) with Caltech

### Objective

The objective of this task is to apply version 2 of the Python-based tool developed in Tasks 2-5, by using self-calibration from Task 7 and implementation in Task 8, to the GTRI dual-stream nozzle with extensible mixer duct lengths, and predict the quietest configuration.



### **Research Approach**

Apply the automated Python toolchain, starting with the moderate mixer duct length, to predict the mixer duct length that yields the quietest configuration. Predictions are compared with the GTRI-measured acoustic field.

### **Milestones**

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

### **Major Accomplishments**

Task 8 has not been started.

### **Publications**

None.

### **Outreach Efforts**

None.

### **Awards**

None.

### **Student Involvement**

Jay Woo will be responsible for applying version 2 of the optimization tool to the GTRI nozzle.

### **Plans for Next Period**

We will begin Task 9 once Tasks 7 and 8 are complete.

## **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 of relevance to Gulfstream and Boom. Performance, successes, and failures will be documented.

### **Research Approach**

Transition the results of version 1 of the Python optimization tool to Gulfstream and Boom for internal evaluation of the tool.

### **Milestones**

- Develop and implement a cost-sharing agreement with appropriate intellectual-property safeguards
- Work 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**

We will begin Milestone 3 when Gulfstream provides UIUC with the Plug20 flow data computed with their RANS code(s).

## **Task 11 - Collaborate 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 10 and 47 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**

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 59C tools could be integrated in Project 10 and 47 ecosystems.
- Re-engage project 10 and 47 P.I.s to down select 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**

We will begin Task 11 in the next year.