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)

- PI(s): Dr. Daniel J. Bodony, Dr. Tim Colonius
- FAA Award Number: 13-C-AJFE-UI-031
- Period of Performance: June 5, 2020 to September 30, 2022
- Tasks:
    1. Establish industry-relevant low bypass ratio (BPR) engine parameters and acoustic assessment workflow with cost-sharing partner
    2. Automated Reynolds-averaged Navier–Stokes equations (RANS) predictions of jet exhaust
    3. Resolvent mode computation—primary and sensitivity
    4. Python resolvent mode interpolation tool
    5. Python optimization tool for jet noise reduction (JNR) (version 1)
    6. Application of version 1 optimization tool on Georgia Tech Research Institute (GTRI) dual-stream nozzle
    7. Self-calibrating resolvent formulation and implementation
    8. Python optimization tool update using self-calibrating resolvent formulation (version 2)
    9. Application of version 2 optimization tool on GTRI dual-stream nozzle
    10. Application of version 2 optimization tool on Boom-relevant geometry (if cost-sharing agreement is in place)

Project Funding Level

FAA provided $399,955 in funding. Proposed cost-matching with GE Aviation (contact person: Dr. Robert Babbitt) is no longer active. Negotiations with Boom (contact person: Dr. Joe Salamone) are in progress.

Investigation Team

- Dr. Daniel Bodony, UIUC, PI
- Mr. Jay Woo, UIUC, MS student (Previous student Mr. Omar Gutierrez was released from ASCENT Project 059C responsibilities in Q2 of 2021, and Jay Woo was brought on in Q3 of 2021.)
- Dr. Tim Colonius, California Institute of Technology (Caltech), Co-PI
- Mr. Liam Heidt, Caltech, PhD student (Previous student Mr. Ethan Pickering defended his PhD thesis and left Caltech.)

Project Overview

This ASCENT project will leverage recent research in global resolvent-mode-based descriptions of jet turbulence and associated noise to develop an efficient physics-based tool for estimating the impact of jet noise reduction (JNR) strategies on the takeoff noise of civil supersonic transports. The software tool will quickly identify promising JNR technologies and will more precisely evaluate the noise impact of parametric variation of 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:

1. *JNR evaluation for an engine* mode: Using 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 due to changes in the engine design, thus enabling JNR optimization.
2. *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 (ANOPP).

The original proposal outlined six tasks to be conducted. The project tasks have since been modified in response to changes in the ASCENT Project 59 objectives as well as changes regarding our cost-sharing partner. In particular, ASCENT Project 59 now includes a Georgia Tech Research Institute- (GTRI-) provided extensible dual-stream, internally mixed nozzle that is to be studied computationally and whose noise is to be measured for validation. Furthermore, our GE Aviation cost-sharing partner has been removed because of personnel changes at GE Aviation coupled with the financial impact of the COVID-19 pandemic.

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 as Tasks 6–10 above. The ordering of Tasks 6–10 above differs from the proposal to reflect available GTRI data and cost-sharing developments with Boom.

Task 1 - Establish Industry-relevant Low-BPR Engine Parameters and Acoustic Assessment Workflow with Cost-sharing Partner

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 exchanges to obtain industry-relevant low-BPR engine parameters and acoustic assessment workflows.

Milestone(s)

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

Major Accomplishments
Milestone 1 has been completed with the help of Donald Scata (FAA). An initial discussion was held on October 28, 2020, between UIUC (Daniel Bodony) and Boom Supersonics (Rachel Devine, Joe Salamone, and Lourdes Maurice) to connect and establish the overall goals of the ASCENT 59 Project. Milestone 2 has been completed, and an NDA between Boom and UIUC has been established. Milestone 3 has been completed through Zoom-based conversations with Joe Salamone and Daniel Bodony.

Publications
None

Outreach Efforts
None

Awards
None

Student Involvement
None

Plans for Next Period
In the next period, a cost-sharing agreement with Boom will be finalized. In Q1 of 2021, Boom requested an extension of time to accommodate Boom's internal demands on staff and resources. PI Daniel Bodony will reconnect with Boom in Q1 of 2022.

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 (CAD)-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
1. Additional developments to computational fluid dynamics flow path
2. Verification of RANS simulation results
3. Automation of Python infrastructure

Major Accomplishments
Milestone 1 progress included 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. For Milestone 2, results obtained from post-processing have been verified through comparison to a numerical solution based on quasi-1D flow theory for mixed exhaust jet nozzles. Milestone 3 is in progress; almost-complete automation of individual computational fluid dynamics processes has been achieved, with the necessary user interaction required to execute the processes in sequential order.

Publications
None

Outreach Efforts
None

Awards
None

Student Involvement
Jay Woo is responsible for developing the Python toolchain.

Plans for Next Period
- Complete Milestone 3
- Compare simulation results with experimental data to validate and revise models as necessary

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., δA, resulting from changes in the nozzle design and/or engine cycle.

Milestones
1. Primary resolvent mode computation capability
2. Resolvent mode training data and fitting
3. Resolvent mode sensitivity computation capability

Major Accomplishments
Milestone 1 has been completed and tested on single-stream subsonic and supersonic jets. Milestone 2 continues to be in progress for the low-BPR, near-sonic jets anticipated for the supersonic aircraft of interest to ASCENT Project 59. Milestone 3 has been completed but not validated.

Publications
Resolvent modeling of turbulent jets, Ethan Pickering PhD thesis, Caltech, 2021.

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 has graduated and left Caltech. Liam Heidt is a new 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
- Complete Milestone 2 by using acquired but not yet available GTRI flow acoustic data and high-fidelity LES data from the Stanford University ASCENT Project 59 team
- Complete Milestone 3 by validating the sensitivities with GTRI data

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 to previously known input–gain–output modes from nearby nozzle geometries and/or engine cycles.

Research Approach
By using Kriging interpolation methods, develop a response surface-based interpolation approach for estimating 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
1. Identify candidate interpolation methods and down-select
2. Develop a Python tool to implement the interpolation method
3. 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.

Conclusion - ASCENT 59 Year 1 Summary
The following key tasks and activities have been completed under the ASCENT 59 year 1 performance period:
- Signed NDA between UIUC and targeted cost-sharing partner Boom
- Developed, implemented, verified, and validated a RANS-based dual-stream jet exhaust simulation tool
- Developed, implemented, and verified an automated jet nozzle CAD → RANS simulation workflow

- Developed, implemented, and verified a resolvent analysis tool
- Developed, implemented, and verified a resolvent sensitivity analysis tool
- Applied automated CAD → RANS simulation workflow to a GTRI dual-stream nozzle with variable mixer duct lengths
- Demonstrated resolvent gain sensitivity to the GTRI dual-stream nozzle with variable mixer duct lengths

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, develop an optimization approach 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.

Milestone(s)

1. Identify candidate optimization methods and down-select
2. Develop a Python tool to implement the optimization method
3. Verify the Python tool

Major Accomplishments

Work on this task has not yet begun.

Publications

None

Outreach Efforts

None

Awards

None

Student Involvement

Jay Woo will be responsible for implementing the optimization tool.

Plans for Next Period

We will begin Task 5.

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, is applied to predict the mixer duct length that yields the quietest configuration. The predictions will be compared with the GTRI-measured acoustic field.

Milestones

1. Select the GTRI operating condition of interest
2. Apply the optimization tool
3. Compare the predicted quiet configuration to the measured quiet configuration

Major Accomplishments

This task has not been started.

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 start Task 6.

Task 7 - Self-Calibrating Resolvent Formulation and Implementation

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.

Milestone(s)

1. Finalize the calibration formulation
2. Implement the calibration procedure
3. Verify the calibration procedure

Major Accomplishments
Task 7 has not yet been started.

Publications
None

Outreach Efforts
None

Awards
None

Student Involvement
Mr. Liam Heidt will be responsible.

Plans for Next Period
We will begin Task 7.

Task 8 - Python Optimization Tool Update Using Self-calibrating Resolvent Formulation (Version 2)
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, develop an optimization approach for estimating JNR potential from a class of candidate engine geometries/cycles using self-calibrated resolvent mode predictions of jet noise, based on linearized operators described by RANS predictions of the jet exhaust plume.

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

Major Accomplishments
Task 8 has not yet started.

Publications
None

Outreach Efforts
None

Awards
None

Student Involvement
Mr. Jay Woo and Mr. Liam Heidt will be jointly responsible.

Plans for Next Period
We will start Task 8.

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
1. Apply the optimization tool
2. 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

Task 10 - Application of Version 2 Optimization Tool on Boom-relevant Geometry (if cost-sharing agreement is in place)
University of Illinois at Urbana-Champaign

Objective
The objective of this task is to work with Boom to apply version 2 of our optimization tool to a supersonic nozzle design of relevance to Boom. Performance, successes, and failures will be documented.

Research Approach
Transition version 2 of Python optimization tool to Boom (if an agreement is in place) for Boom-internal application of the tool.

Milestones

1. Develop and implement a cost-sharing agreement with appropriate intellectual-property safeguards
2. Transition code to Boom
3. Work with Boom engineers to identify cases of interest
4. Apply optimization code to Boom cases of interest

Major Accomplishments

This task has not been started.

Publications

None

Outreach Efforts

None

Awards

None

Student Involvement

Jay Woo and PI Daniel Bodony will be jointly responsible.

Plans for Next Period

We will begin Task 10.