Project 075 Improved Engine Fan Broadband Noise Prediction Capabilities

Boston University & Raytheon Technologies Research Center

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- Period of Performance: October 30, 2021 to November 1, 2022
- Tasks:
    1. Fan-wake surrogate model creation
    2. Improvement of the low-order model
    3. Rig test preparation

Project Funding Level
Year 2 funding:
FAA: $300,000: $115,000 to Boston University (BU), $185,000 to Raytheon Technologies Research Center (RTRC)
Match:$300,000: $115,000 from BU (data sets, faculty time, graduate student stipend)
$185,000 from RTRC (personnel time)

Investigation Team
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Michael Joly, RTRC: Staff scientist. Task 1

Project Overview
The noise signature of contemporary turbofan engines is dominated by fan noise, both tonal and broadband. Accepted methods for predicting the tone noise have existed for many years. Furthermore, engine designers have methods for controlling or treating tonal noise. However, this is not the case for broadband noise. Thus, it is clear that further reductions in engine noise will require accurate prediction methods for broadband noise to enable design decisions. Interaction noise

from the fan stage is a dominant broadband mechanism in modern high-bypass engines and is created by the interaction of turbulence in the fan wakes with the fan exit guide vanes. This project will leverage prior development of low-order models for the prediction of fan broadband interaction noise. Gaps in the low-order approach will be addressed based on knowledge gained from computation and experimentation. In particular, a method for determining the inflow into the stator via a machine learning (ML) algorithm will be developed. The low-order method will also be validated against full-scale rig data, and appropriate development will be undertaken based on the findings.

Task 1 - Fan-Wake Surrogate Model Creation

BU & RTRC

Objective

The goal of this task is to build a surrogate model using performance-level unsteady Reynolds-averaged Navier–Stokes data to specify the mean flow, turbulent kinetic energy, and turbulent length scale at locations along the helical fan-wake path.

Research Approach

Subtasks 1.1 and 1.2: Autoencoder and decoder development

The development of a multi-output ML method was the main focus of Year 2. Specifically, the decoder part of a convolution neural network (CNN) is now being used for learning the wake flow parameters of interest. Only the decoder is being used because of the mismatch between the input data type and the desired output. The input data consist of rotor geometry information from hub to tip, fan speed, engine mass flow, and basic performance-level flow information such as flow angles into and out of the fan. The output data consist of the flow variable of interest on a passage at an axial position downstream of the fan, as shown in the lower half of Figure 1.

Several findings led to the current state of the ML algorithm. First, the team determined that in order to gain high accuracy for the mean flow, it is necessary to learn the full averaged value from hub to tip and the wake deficit separately. The full average is simply a single data set from hub to tip and, as such, lends itself to a single-output type of analysis. Therefore, a deep neural network is used for learning the average value of the mean flow. A CNN is then used to learn the deficit. Second, it was found that learning the turbulence kinetic energy and turbulence dissipation parameter (k and e or w, from the computational fluid dynamics [CFD] turbulence model) separately and then creating the length scale from the learned values produced errors that led to inaccurate acoustic predictions. Hence, a new method for obtaining the length scale was devised. This method defines the length scale at every value on the CFD grid and interpolates the length scale directly onto the ML grid; then, the length scale is learned directly via a CNN.

TensorFlow is used for the CNN. In Year 2, the original R codes were ported to Python. The use of Python makes these codes more accessible to mechanical engineering students, who are often familiar with Python but not R. All of the results associated with ML performed via the method described above were reported in a conference paper (Li, 2022; Huang, 2022) and in an extended abstract submitted for Aeroacoustics 2022. These papers are attached as an appendix to this report.

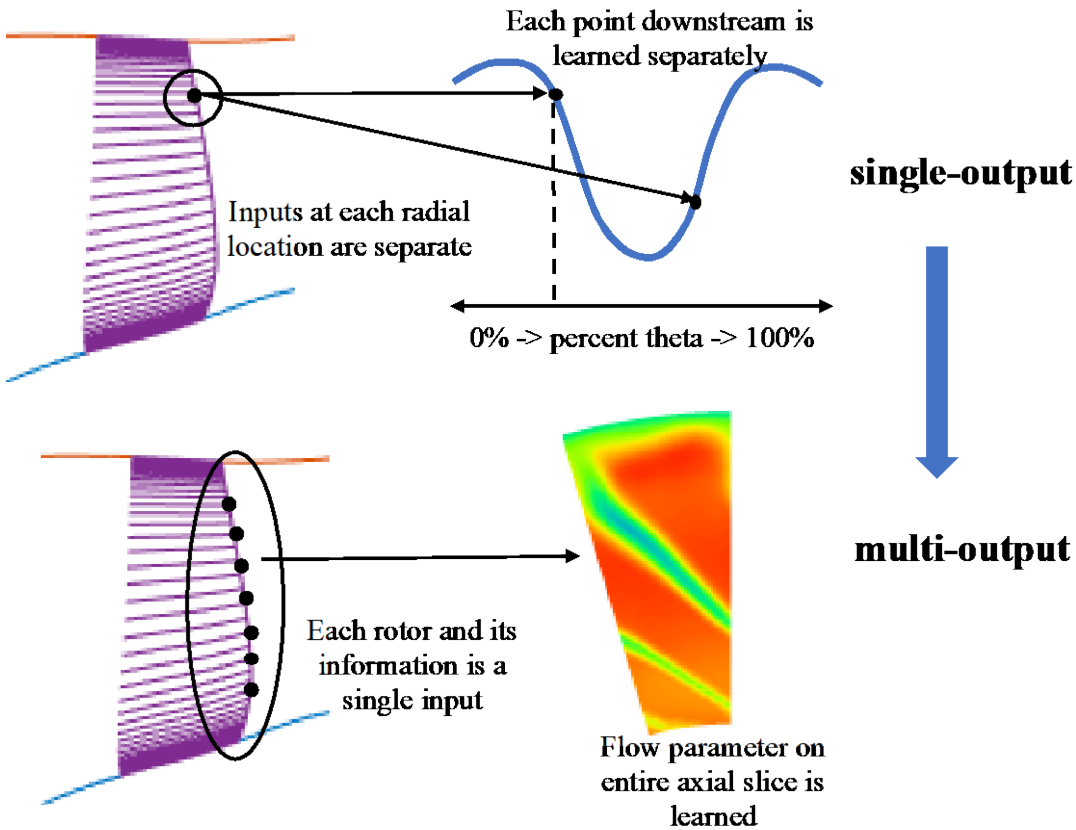

Figure 1. Single- vs. multi-output machine learning concept. The multi-output method does not require rectification of the wakes (centering) before the wakes are learned.

Subtask 1.3: Identification and creation of training data

Subtask 1.3a: Collection of existing training data: BU and RTRC worked to collect relevant existing fan-wake data sets.

Subtask 1.3b: Creation of additional training data: RTRC took the lead on developing new fans, and BU provided analyses in order to determine whether the fans were acceptable.

Throughout Year 2, a 264-case database derived from the four geometries related to the source diagnostic test (SDT) fan blade (i.e., cold [CAD], approach hot, cutback hot, and takeoff hot) was updated and improved. Closer analysis of the wake flow led to improvements in the setup of the CFD simulation.

During Year 2, much effort was spent in iterating on a method to create new fan geometries. RTRC used AxStream to create a derivative of the SDT fan blade that provided smoother variations of the geometry parameters from hub to tip. The performance metrics were similar to those of the SDT, with the new fan achieving a similar efficiency but being slightly more loaded, as shown in Figures 2 and 3. Once the baseline case was fully analyzed, slight modifications to the trailing edge thickness were made to create other geometries. It was expected that a four-fold increase in trailing edge thickness would change the wake, but it did not. Hence, for Year 3, other modifications such as increased lean, change in stagger, etc. will be pursued.

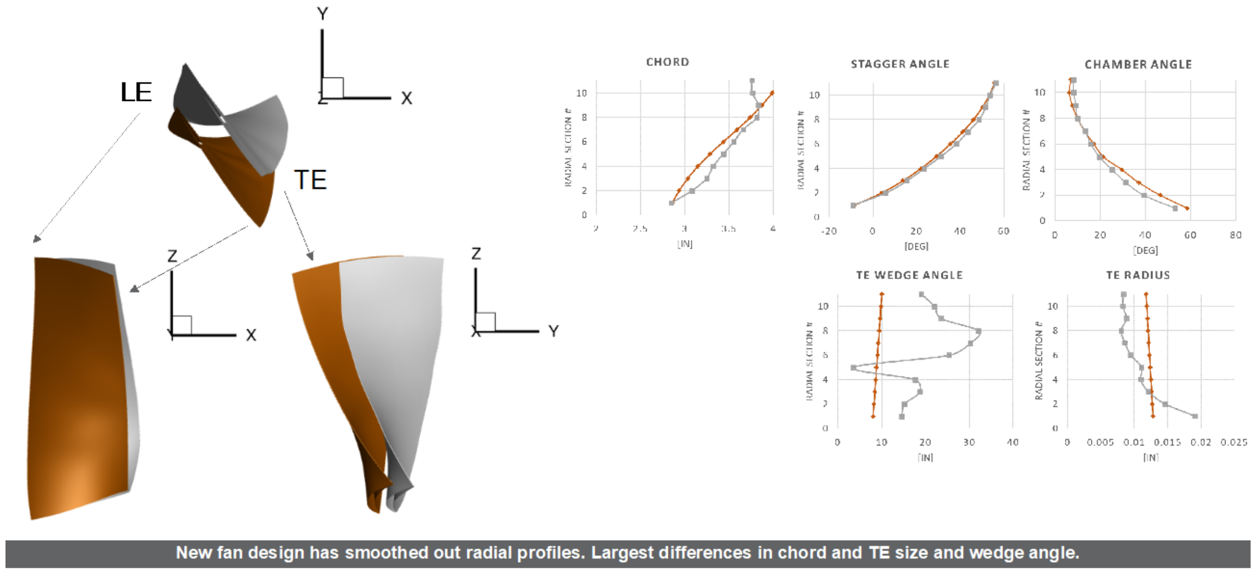

Figure 2. New baseline fan blade vs. the source diagnostic test fan blade. LE: leading edge; TE: trailing edge.

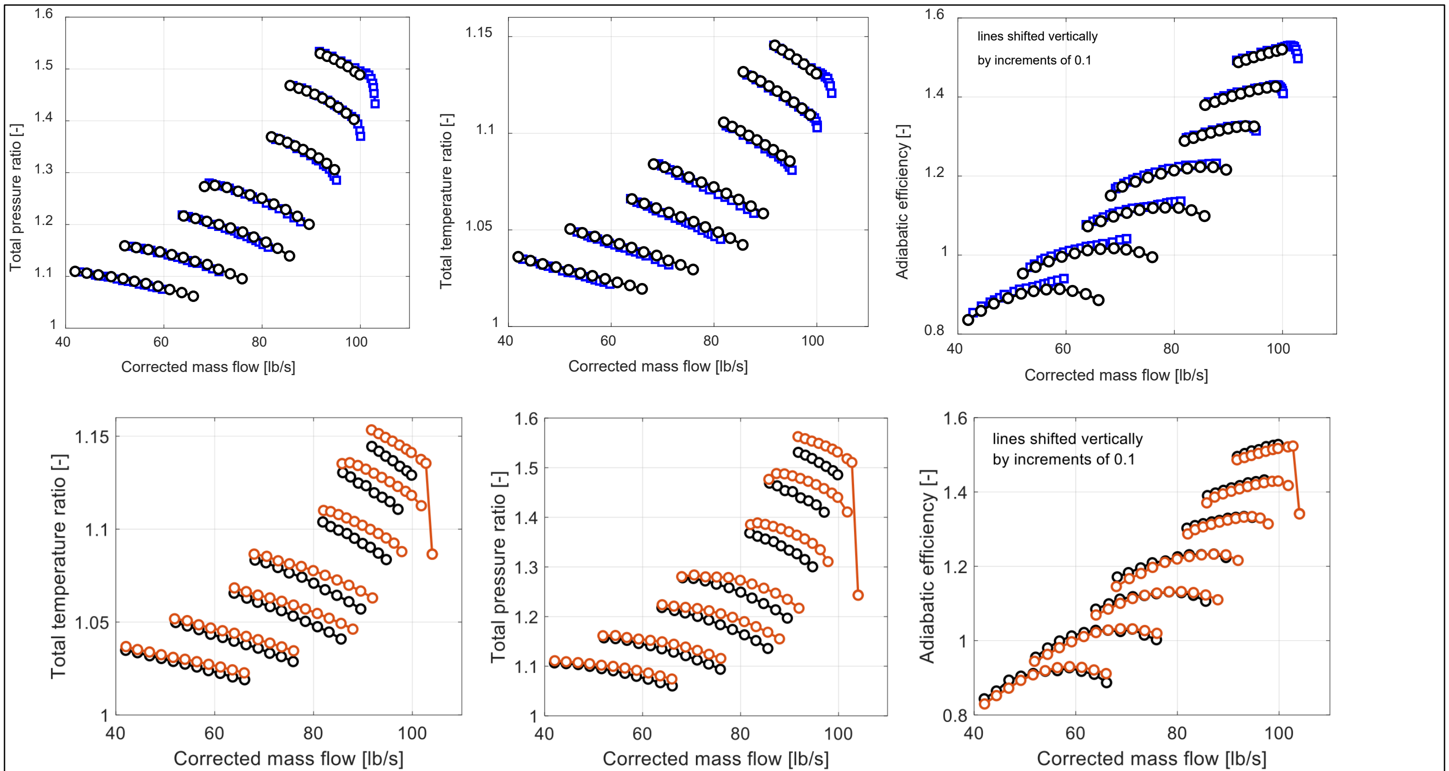

Figure 3. (Top) Performance curves for the source diagnostic test (SDT) cold (CAD) geometry. Blue: experimental data digitized from NASA TM 2013-214029. Black: computational fluid dynamics results. (Bottom) Performance curves for the new fan (orange) and SDT cutback hot geometry (black).

Subtask 1.4: Application of the surrogate model to relevant fan geometries

The deep neural network/CNN ML predictions were tested in many ways. First, the learning results were adjusted to test for robustness of the method given the original 264 fan cases. Typical 80% training and 20% test runs were performed. Next, full fan speeds were excluded from the training data and used only for testing. In all cases, the method was found to be robust. In Year 2, the ML parameters were used with the low-order acoustic method to predict the final expected power level in the bypass duct for the SDT cases. The results are described in the submitted extended abstract (Li, 2022) and show that the method is viable. A more demanding test for the method will be performed in Year 3, when very different fan geometries are introduced into the database.

Milestones

The milestones set out for Task 1 in Year 2 included the following:

- ML surrogate model refinement and validation
    - As described above, the ML model was modified and tested.
- Validation of the full cycle of ML for wake parameters
- Use of wake parameters as input to the low-order model
- Comparison of predicted sound power level against experimental results and predictions when the input is taken directly from CFD data

Major Accomplishments

- Creation of a CNN decoder method for multi-output learning
- Finalization of the CFD simulation method; 264 cases recomputed using a new grid, etc.

- Development of a new baseline fan geometry and two associated blades with larger trailing edge thickness
- Full analysis of the new fan geometry
- Creation of speed line data for the new fan geometry
- Development of a method for extracting necessary ML input data from AxStream
- First attempt to add new fan cases to the database and perform ML

Publications

Published conference proceedings

Li, N., Watchmann, B., Ramsarran, T., Winkler, J., Reimann, A., Voytovych, D., Mendoza, J., & Grace, S. M. (2022, June 14). Fan-stage broadband interaction noise trends. *28th AIAA/CEAS Aeroacoustics 2022 Conference*. 28th AIAA/CEAS Aeroacoustics 2022 Conference, Southampton, UK. https://doi.org/10.2514/6.2022-2884

Huang, Z., Shen, H., Kung, K., Carvalho, L., Thai, A., Watchmann, B., Ramsarran, T., Winkler, J., Reimann, A., Joly, M., Lore, K. G., Mendoza, J., & Grace, S. M. (2022, June 14). Fan wake prediction via machine learning. *28th AIAA/CEAS Aeroacoustics 2022 Conference*. 28th AIAA/CEAS Aeroacoustics 2022 Conference, Southampton, UK. https://doi.org/10.2514/6.2022-2883

Li, N., Zhang, Y., Winkler, C., Reimann, A., Voytovych, D., Mendoza, J., & Grace, S. (2022). Development of fully low-order prediction of fan broadband interaction noise via integration of machine learning. Submitted to 2023 AIAA Aviation-Aeroacoustics Conference.

Outreach Efforts

None.

Awards

None.

Student Involvement

In Year 2, two undergraduate students, one PhD student, and one MS student contributed to this project.

Plans for Next Period

The milestone that has been set for Year 3 of this project is ML surrogate model refinement and validation. In Year 3, the ML development focus will involve exercising the ML on a much larger database that includes more varied fan geometries. Necessary adjustments will be made to the method depending on the outcomes.

Task 2 - Improvement of the Low-Order Model

BU & RTRC

Objectives

The existing low-order methods are regularly applied to the SDT cases and, as such, have been well validated against this test, which represents one scaled fan and multiple fan exit guide vanes. The newly developed low-order method must now be validated against full-scale test data. The low-order method might also require reformulation to account for other real-flow effects.

Research Approach

Subtask 2.1: Ability to predict full-scale results

The low-order method will be applied to a full-scale geometry with available validation data. Due to the difference in the frequency range of interest for the full-scale case compared with the scaled fans, it is expected that the low-order method will require grid adjustments and integral extent adjustments. Such improvements to the low-order method will be completed as part of this task.

A non-disclosure agreement between BU, RTRC, and P&W to transfer data and information from the Continuous Lower Energy, Emissions, and Noise (CLEEN) I project is now in place. RTRC has organized the rig-scale information for CLEEN I and has begun CFD simulations to determine the type of input that is required for the low-order model. Further analyses of available data for the full rig validation are being completed by RTRC.

The low-order method has been scrutinized, and some slight modifications have been made. These modifications primarily pertain to methods for estimating duct parameters that may not be readily available if a fan-alone simulation (or ML) is used to obtain the inputs. The definition of the length scale based of Reynolds-averaged Navier–Stokes data was adjusted after much investigation into options in the literature and tests for how/when averaging should be applied during the process of preparing the CFD data as usable input data. The graduate student involved in this project is now very adept at utilizing the low-order code.

Subtask: 2.2: Inclusion of tip flow impact on the low-order model

RTRC produced CFD data for the SDT geometries with varying tip gaps, and a total of 48 cases were run. The data were used to obtain acoustic outcomes, and comparisons were made with past acoustic measurements. The low-order model shows slightly higher sensitivity to the tip flow compared with experimental measurements. However, the influence of realistic tip gaps on the broadband noise is quite small overall, and as such, it appears as though the method is basically robust to this parameter. Some related results are shown in Figures 4 and 5. Three speeds close to the original SDT values were considered, and the tip gap was varied from the nominal value of 0.002" to 0.001" and 0.003". The input quantities measured just upstream of the exit guide vane are shown in Figure 4 for the three cases: approach (61.7% speed), 59 lbm/s; cutback (87.5% speed), 83.7 lbm/s; takeoff (100% speed), 96.9 lbm/s.

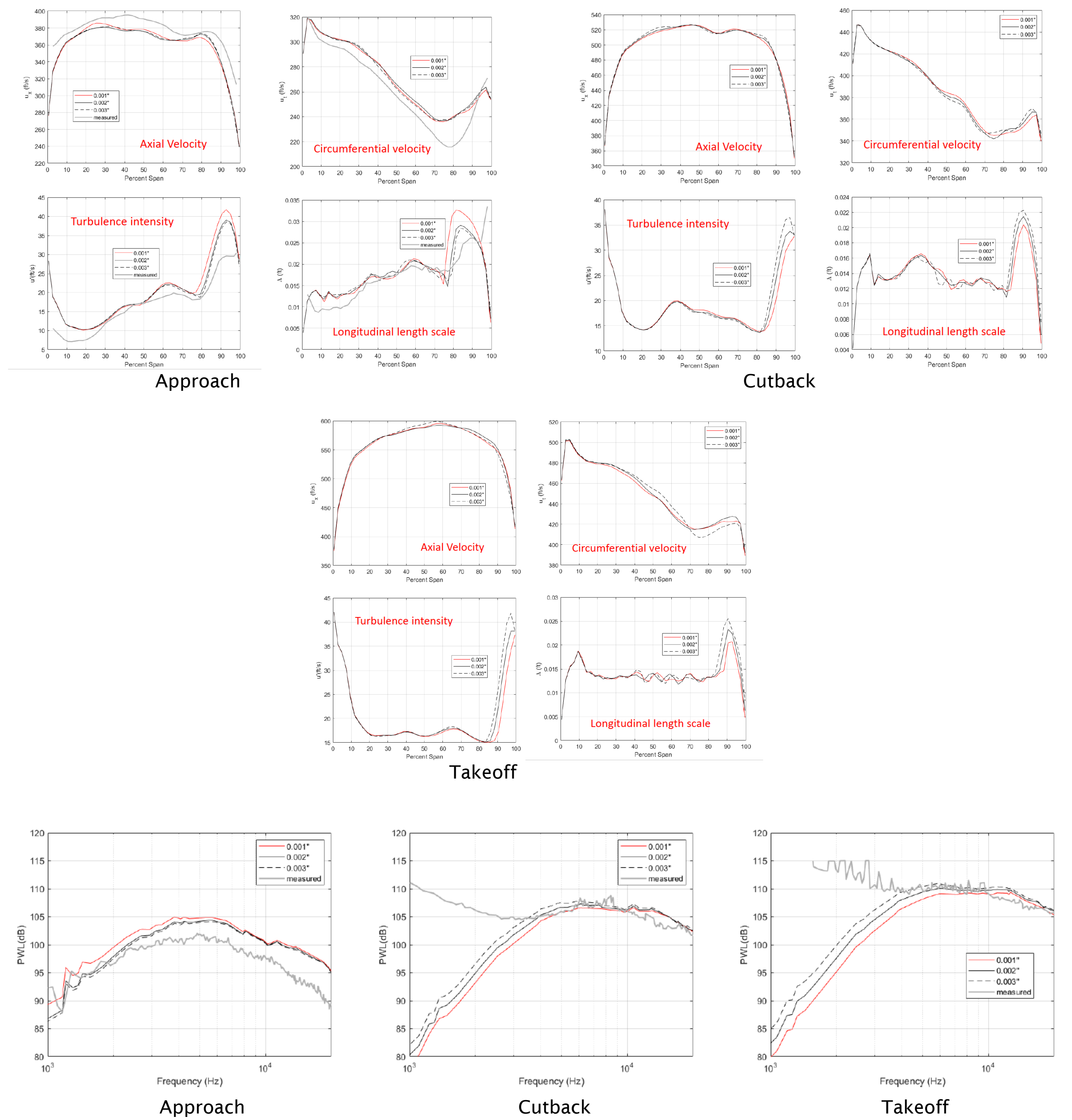

Figure 4. (Top) Comparison of low-order acoustic model input values from computational fluid dynamics Reynolds-averaged Navier–Stokes results for different fan geometries with different tip gaps. Experimental results are shown as a gray solid line when available. (Bottom) Acoustic predictions based on the different inputs.

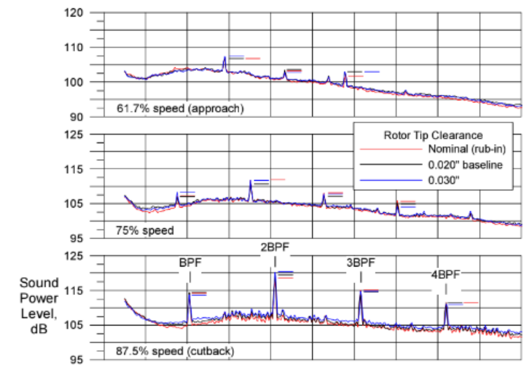

Figure 5. Measured results for the source diagnostic test fan with different tip clearances. From CITATION?

Subtask 2.3: Inclusion of inflow distortion impact on the low-order model
Two points of progress have been made on this subtask. First, some relevant data for benchmarking have been identified. Second, modification of the low-order method to make a very crude allowance for inflow asymmetry has been attempted.

A publication by Damiano's group at Delft describes the results of full fan-stage VLES lattice Boltzmann method simulations with and without inflow distortion (Romani, 2020). From this paper, examples of the flow values given for the region upstream of the exit guide vane that are relevant to application of the low-order method to the problem are shown in Figure 6.

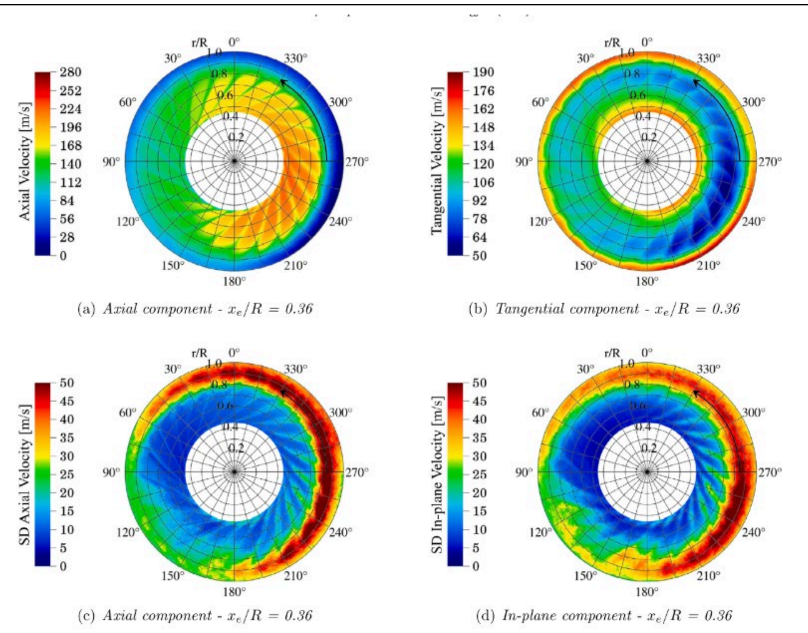

Figure 6. Interstage flow values from the source diagnostic test fan stage with distorted inflow (Romani et al., 2020).

The low-order model has been modified so that the exit guide vane disk analysis can be performed in chunks. This effort requires the suspension of cascade assumptions of infinite repetition. For this reason, the method is only approximate. However, different regions of the fan are solved using different inflow specifications for the cascade response part of the model. The unsteady response on the full set of vanes is then stitched together. The Green's function method can be used to integrate the vane response and obtain the duct values. We are currently in discussion with Damiano Casalino to obtain the pertinent data shown in Figure 6. In Year 3, we will assess whether this simplified model can provide insight into the trend in acoustic modifications due to inflow distortion.

Milestones

The milestones set out for Task 2 in Year 2 included the following:

- Validate low-order model on the new geometry and test rig-scale vs. full-scale applicability (to be continued in Year 3)
- Assess the impact of tip flow on the low-order model
- Assess the impact of inflow distortion on the low-order model

As described above, the tip flow study indicated that the low-order method can provide insights into the influence of the tip gap on noise; however, the trends are slightly stronger than those observed experimentally. The effect of realistic tip-gap changes is so small that this has been deemed a negligible effect. Progress was made on the inclusion of inflow distortion in the low-order model, but no results have yet been benchmarked.

Major Accomplishments

- The low-order code and pre- and post-processing codes have been updated.
- A non-disclosure agreement is in place for the transfer of CLEEN 1 data required for low-order acoustic simulations.
- CFD analysis in support of the CLEEN 1 acoustic simulation has been started.
- The effect of tip-gap differences on SDT-related noise has been analyzed and deemed negligible.
- A relevant benchmark case for the effect of inflow asymmetry on noise has been identified.
- A very low-order method for potentially handling the asymmetry has been devised and will be tested in Year 3.

Publications

Published conference proceedings

Li, N., Watchmann, B., Ramsarran, T., Winkler, J., Reimann, A., Voytovych, D., Mendoza, J., & Grace, S. M. (2022, June 14). Fan-stage broadband interaction noise trends. *28th AIAA/CEAS Aeroacoustics 2022 Conference*. 28th AIAA/CEAS Aeroacoustics 2022 Conference, Southampton, UK. https://doi.org/10.2514/6.2022-2884

Outreach Efforts

None.

Awards

None.

Student Involvement

One BU PhD student has worked on the low-order model. He has updated the code, and the pre- and post-processing methods.

Plans for Next Period

The milestones that have been set out for Year 3 related to this task include final improvements to the low-order model. The milestone of completing a full-scale validation test of the low-order method will also be continued in Year 3.

References

Romani, G., Ye, Q., Avallone, F., Ragni, D., & Casalino, D. (2020). Numerical analysis of fan noise for the NOVA boundary-layer ingestion configuration. *Aerospace Science and Technology*, *96*, 105532. https://doi.org/10.1016/j.ast.2019.105532

Task 3 - Rig Test Preparation

BU & RTRC

Objective

Experiments in the RTRC Acoustic Research Tunnel will be used to (a) investigate the effect of the downstream pylon and (b) validate noise outcomes due to fan geometry changes predicted by the low-order method in this work.

Research Approach

In developing the Year 3 proposal, RTRC and BU established plans for experiments that will leverage an existing fan rig at RTRC. The team will ensure that at least the approach rotor speed will be obtainable based on the rig electric motor constraints, as mentioned above. The process for determining the basic fan rig and a basic test plan were developed. The initial rig will include pylons similar to the CLEEN 1 design. After obtaining aerodynamic and aeroacoustic measurements for the initial setup, the downstream pylon will be removed in order to assess its impact on noise. Then, at least two other fan designs informed by the differences seen in the computational predictions of the noise will be 3D-printed and tested. The fan design will be similar to that of CLEEN 1 but on a smaller scale.

Milestone

The milestones set out for Task 3 in Year 2 included the development of a Year 3 rig test plan. As described above, this milestone was completed in support of the Year 3 proposal.

Major Accomplishments

The rig test plan has been completed.

Publications

None.

Outreach Efforts

None.

Awards

None.

Student Involvement

None.

Plans for Next Period

The milestones that have been set out for Year 3 related to this task include the following:

- Establish a final rig design
- Test the rig shakedown
- Complete rig testing