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Project 075 Improved Engine Fan Broadband Noise Prediction Capabilities

Boston University & Raytheon Technologies Research Center

Project Lead Investigator

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University Participants

Boston University (BU)

- P.I.: Sheryl Grace – Associate Professor, Mechanical Engineering
- FAA Award Number: 13-C-AJFE-BU Amendment 022
- Period of Performance: November 1, 2023, to October 30, 2024
- Tasks:
    1. Fan-wake surrogate model creation
    2. Improved low-order model
    3. Rig test planning

Project Funding Level

Year 4 Funding (March 18, 2024, to September 30, 2025):
Federal Aviation Administration (FAA): $201,044 total ($105,286 to BU, $95,758 to Raytheon Technologies Research Center [RTRC])
Matching Funds: $201,044 from BU (datasets, AeroAcoustics Research Consortium [AARC] previous funding, faculty time)

Year 5 Funding (December 3, 2024, to July 31, 2026):
FAA:$219,979 total ($25,000 to BU, $194,980 to RTRC)
Matching Funds: $110,161 from BU (datasets, AARC previous funding, faculty time), $109,819 from RTRC (Pratt & Whitney [P&W] effort)

Investigation Team

Boston University
Sheryl Grace (PD/P.I.), Tasks 1, 2 & 3
Nuo Li, graduate researcher (PhD), Tasks 1 & 2
Ronald Chambergo, undergraduate researcher, Tasks 2
Oliver Zajac, undergraduate researcher, Task 2

Raytheon Technologies Research Center
Jeff Mendoza (Co-PD/P.I.), Tasks 1, 2 & 3
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Dustin Frohnapfel, Task 3
Matt Kennedy, Task 3

Project Overview

The noise signature of contemporary turbofan engines is dominated by fan noise, both tonal and broadband. Accepted methods for predicting the tonal noise have existed for many years. Furthermore, engine designers have methods for controlling or treating tonal noise. This is much more challenging for broadband noise. Thus, it is clear that further reductions in engine noise will require accurate prediction methods for the broadband noise to enable design decisions. Interaction noise from the fan-stage is a dominant broadband mechanism in a modern high bypass engine and is created by the interaction of the turbulence in the fan wakes with the fan exit guide vanes (FEGV). This project leverages prior development of low-order models for the prediction of fan broadband interaction noise. Gaps in the low-order approach are 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 is being developed. The low-order method will also be validated against full- and rig-scale data and appropriate development undertaken based on the findings.

Task 1 - Fan-wake Surrogate Model Creation

Boston University

Objective

The objective of this task is to build a surrogate model using ML that will work with performance level unsteady Reynolds-Averaged Navier-Stokes (URANS) to specify the mean flow, turbulent kinetic energy, and turbulent length scale at locations along the helical fan-wake path.

Research Approach

Subtask 1.1&2: Development of Autoencoder & Development of Decoder

The ML was applied to this problem in Years 4 & 5 of the ASCENT Project 075 and our team continued to use the decoder part of a neural network. Four wake flow parameters are learned in the region downstream of the fan. The mean flow axial and circumferential velocities and the turbulent kinetic energy and turbulence length scale are learned using a two-dimensional (2D) Convolution Neural Network (CNN). In the 2D method, the data are made of axial slices of the wake flow.

TensorFlow® is used for the ML and is integrated into a Python® wrapper. In Years 4 & 5, the CNN method was further tested. The large fan dataset obtained previously from collaborators at the Institut Supérieur de l'Aéronautique et de l'Espace (ISAE-Supaero) in Toulouse, France was the basis for these studies. Initial results for the ML outcomes for this set of fans were presented at the 2025 American Institute of Aeronautics and Astronautics (AIAA) Aviation conference.

Next, the ISAE database was used to determine how the number of fans included in the database and the number of axial slices used downstream of each fan affects the ML. The different variations for the number of slices are shown in Figure 1. For each of the flow variables learned, the error between the ML prediction of three target fans not included in the database and the Reynolds-Averaged Navier-Stokes (RANS) determined wake for each of the three test fans were computed. Figure 2 shows the results for the prediction error of the slice at x = 0.129m. Not surprisingly, the error decreases as more fans are used in the database. However, at around 40 fans, the error is acceptable. It is also noted that one of the test fans is an outlier in terms of its geometry. This makes the prediction of it based on the fans in the database, an extrapolation, which is not expected to work well. When the predicted results are used in the low-order method to obtain the noise prediction, the results for the extrapolated cases are not good (see Figure 3). In terms of the number of axial slices, 1, 2, or 30 perform very similarly, except that the error bars are much smaller when more slices are used. As such, at this time, we still use a large number of axial slices to create the database.

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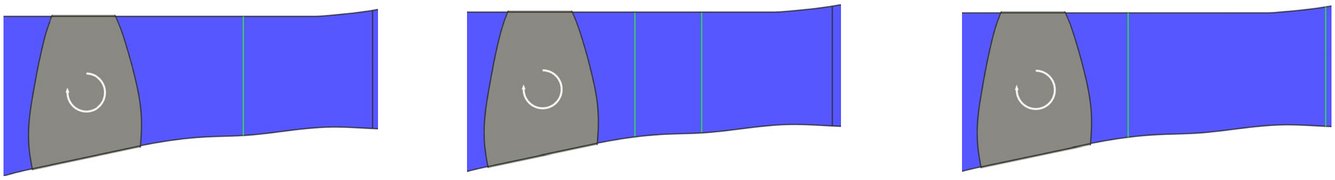
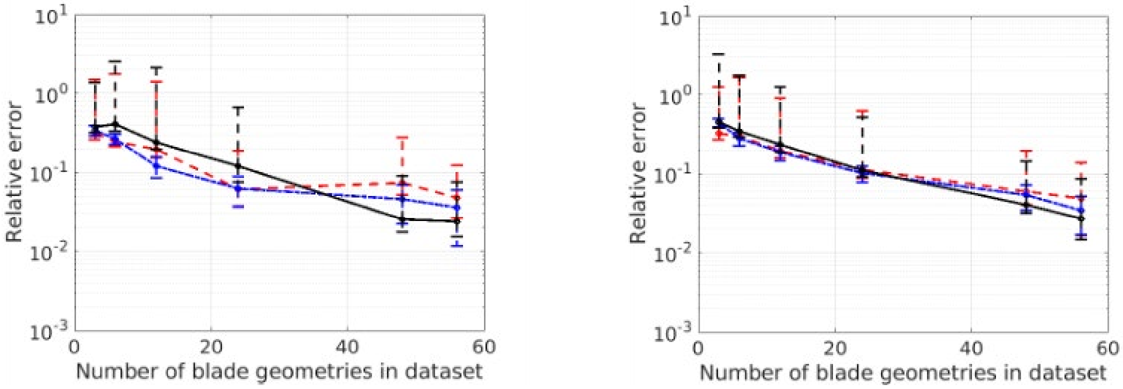
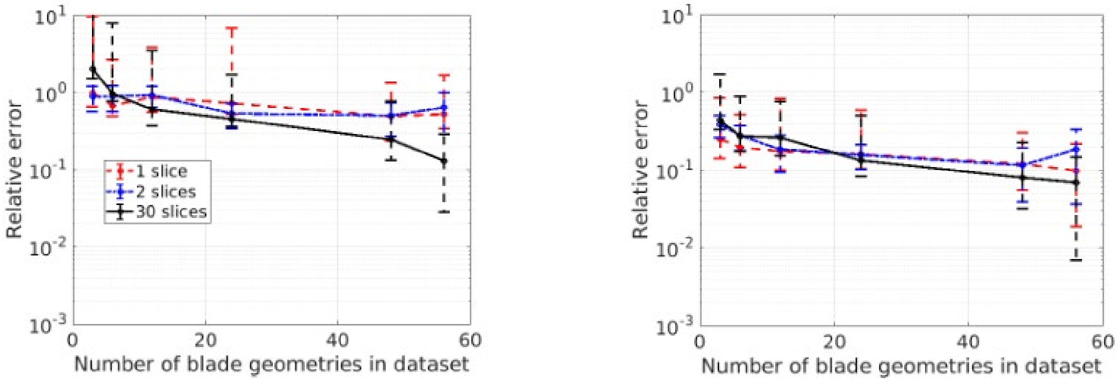


(a) 1 slice at x = 0.129m (b) 2 slices at x = 0.08 & 0.129 m (c) 30 slices between x = 0.08 & 0.2449m

Figure 1. Different axial slice numbers for testing the machine learning.



(a) Axial velocity (b) Tangential velocity



(c) TKE (d) Lengthscale

Figure 2. Effect of number of fans and number of axial flow slices included in the machine learning (ML) database, on the accuracy of the prediction: (a) axial velocity, (b) tangential velocity, (c) turbulent kinetic energy (TKE), and (d) lengthscale.

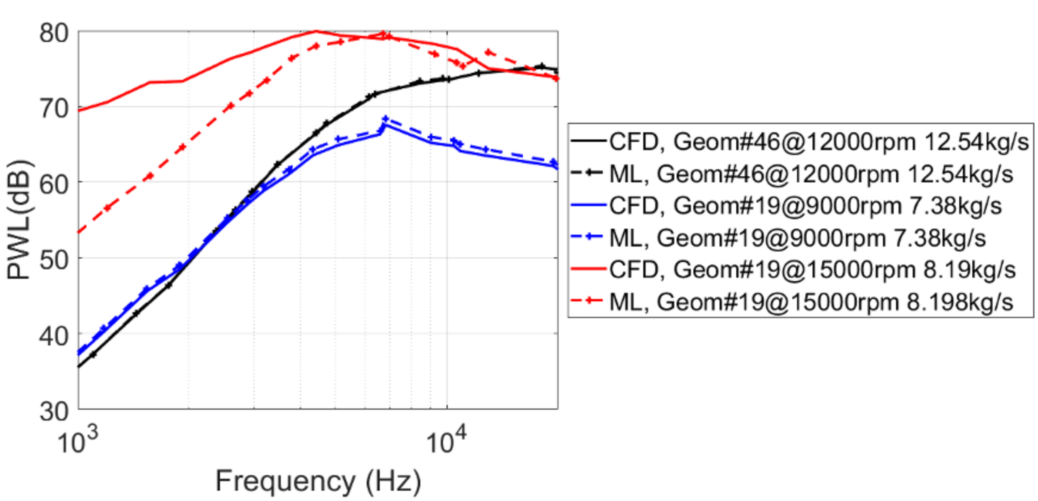


Figure 3. Exhaust power level for three different test fan geometries (from the Institut Supérieur de l'Aéronautique et de l'Espace [ISAE] cases) that were not used in the database. The same stator is used to complete the fan stage for each case. The low order acoustic method has been used with fan wake parameters from Reynolds-Averaged Navier-Stokes (RANS) (solid line) & fan wake parameters from machine learning (ML) prediction (dashed). CFD: computational fluid dynamics. PWL: sound power level.

Another modification to the ML method was also tested. A data wrapping method was tested. The goal was to allow the database to have arbitrary fan blade position and potentially improve inclusion of different fan blade counts. It was determined that the method did not improve the ML. It underscored that it is important to set up the axial slices such that the fans are positioned in their passage similarly. This often requires rotation (addition of a set angle) which does not impede the initial database setup greatly.

Subtask 1.3: Identification & Creation of Training Data

The focus of Years 4 & 5 was *Subtask 1.3b: Creation of additional training data*. The large dataset obtained from collaborators at ISAE-Supaero in Toulouse, France, continued to be a focus as discussed in the previous section. Two other geometries were also identified: the advanced ducted propulsor (ADP) whose geometry and accompanying rig test data are available from the National Aeronautics and Space Administration (NASA), and the ECL5 fan stage which has a very recent large eddy simulation (LES) completed on it. RANS simulations for both geometries are currently being developed so that they can be included in the database. These geometries were sought because they have differing blade counts than the fans in our current databases. The ability to predict fan wakes for a wide variety of fans with different blade counts has not been demonstrated yet.

The BU PhD student Nuo Li learned and thoroughly tested the Cadence® Fidelity® Fine Turbo[1] software. Multiple discoveries for best practices when running this code for the simulation of a fan and its wake as well as a full fan-stage were made. In particular, best practice for creating the grid (wake aligned) and turbulence model choice (Mentor's shear stress transport - SST) were discerned. Unfortunately, there was no turbulence model that gave as good as results as the United Technologies Computational Fluid Dynamics (UTCFD) code did for the approach case. Still, if the database is developed consistently the ML can still be assessed. Hence, currently, UTCFD and Cadence computed cases are not mixed in the database. Also, it was determined that because ISAE was not interested in the wake evolution when they performed the RANS for the fans in their database, the results did not match those obtained using our best practices. Therefore, the PhD student reran the RANS for all of the ISAE cases using the new best practices and then performed the ML.

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[1] Cadence Fidelity Fine Turbo is a computational fluid dynamics (CFD) platform specifically designed to optimize the power and efficiency of turbomachinery designs.

Subtask 1.4: Application of Surrogate Model to Relevant Fan Geometries

As discussed above, the CNN ML predictions were applied to the ISAE database of 59 fans. These fans were created by morphing aspects of several existing fans. In this sense, they have relevant features. The two newly acquired fan geometries: ADP and ECL5 will next be used to determine how well ML can predict these relevant fan geometries.

Milestones

- Validated and refined the ML surrogate model.
- Improved the ML model and applied the model to a new database with success.

Major Accomplishments

- Tested modifications to the 2D CNN models for fan wake parameter prediction.
- Fully tested and created a workflow for using the Cadence Fine Turbo software to provide a method for creating and analyzing additional fans in the future. Used it to rerun all of the ISAE cases.
- Demonstrated fast, downstream broadband noise prediction for a fan stage.

Publications

Li, N., & Grace, S. M. (2025). Low-Order, Data-Driven Method for Analysis of Impact of Fan Design on Fan Stage Broadband Interaction Noise (AIAA 2025-3650). *AIAA AVIATION 2025 Forum*, Las Vegas, Nevada.

Outreach Efforts

- Presented (undergraduate student) at the BU Undergraduate Research Symposium, October 17, 2025.
- Presented at the 2025 AIAA Aviation Forum, July 20, 2025, Las Vegas, Nevada.

Awards

None.

Student Involvement

Nuo Li, graduate researcher (PhD) developed the ML and adopted and fully tested the Cadence Fine Turbo solver. He also modified and tested the new ML input strategies. Ronald Chambergo and Oliver Zajac, the undergraduate researchers, worked with the Cadence software to perform some of the fan RANS simulations and they worked with a fan blade design tool, parablade, to support the creation of new fan blades for inclusion in the database.

Plans for Next Period

- Continue refinement and validation of the ML surrogate model.
- Develop and add additional fans to the database.

Task 2 - Improvement of Low-order Model

Boston University
Raytheon Technologies Research Center

Objective

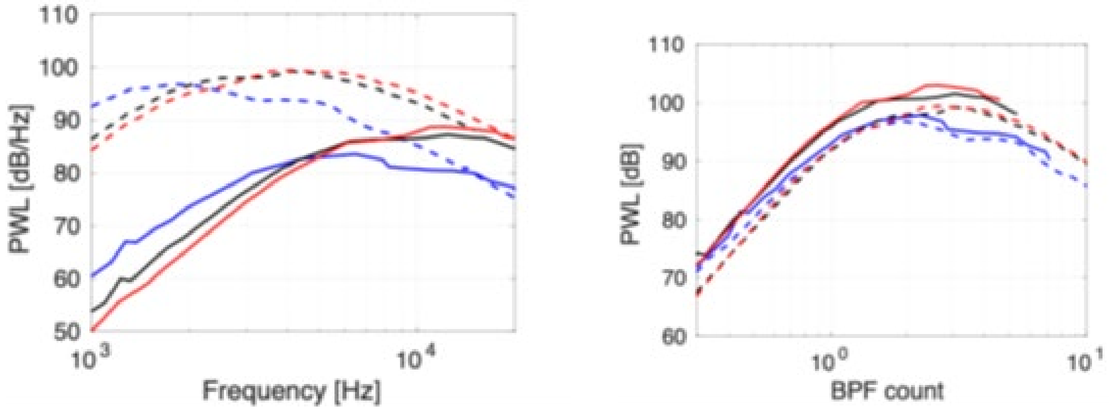
The objective of this task is to validate the low-order method against full-scale test data and adjust the low-order method as needed. The existing low-order methods are regularly applied to the source diagnostics test (SDT) cases and as such have been well validated against this test, which represents one scaled fan and multiple FEGV configurations.

Research Approach

Subtask 2.1: Ability to Predict Full-Scale Results

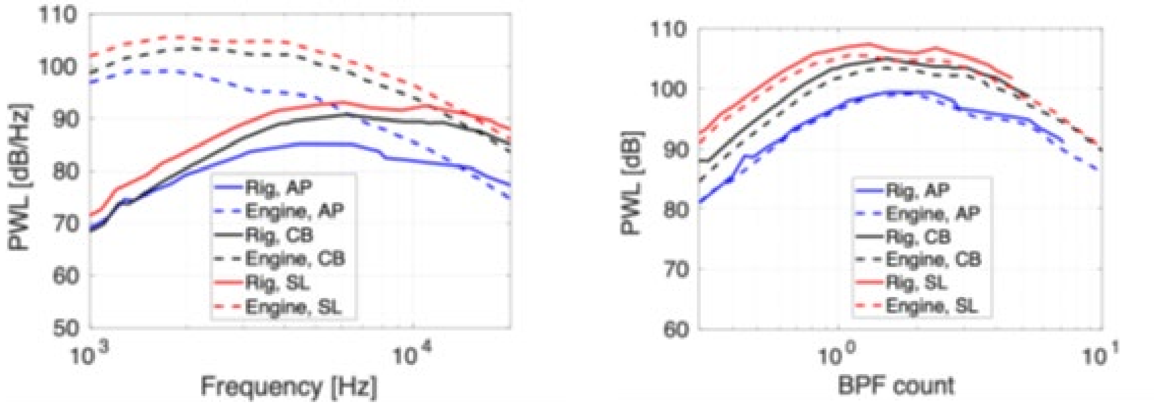
Great progress was made in Years 4 and 5 on this subtask. An initial check had been run previously using RTRC-generated RANS data for the FAA Continuous Lower Energy, Emission and Noise (CLEEN) Program I rig and full-scale rotor geometries. To perform the full-scale predictions, the Boston University Rotor-Stator Interaction (BU-RSI) code was updated so that the integrals carried out during the simulation had appropriate limits still as these do change with frequency and the frequency range of interest for the full-scale engine is different than for the rig. Once the low-order method was shown to converge properly, we used the normal method for extracting the low-order method inputs from the RANS data and created the predictions. RTRC made comparisons with the expected results and noted that the results were not acceptable. Over this past year, we revisited this issue.

First, we created our own full scale SDT geometry. We performed our own RANS simulations for the rig and full scale SDT geometries and explored how the fan wake flow parameters varied from rig to full scale. We compared this variation to the variation seen in the CLEEN I RANS results and realized that the CLEEN I RANS results were not correct. Using the SDT case, we verified that there is a scaling of the acoustic power with the geometry change. That is, if the geometry from rig to full scale increases by a factor of X, then the acoustic power scales with an exponent of X. This scaling is not perfect because the boundary layer on the fan plays a large role in creating the fan wake parameters of interest changes as the Reynolds number changes. This affects the turbulence intensity and length scale in the wake slightly altering what would otherwise be a perfect geometric scaling. Figure 4 shows the relevant results for the SDT case. The predictions were obtained using two different methods for determining the turbulence length scale. First, Pope's method which combines the turbulence parameters via : $\Lambda_k = \frac{0.043}{0.09}\frac{\sqrt{TKE}}{\omega}$. Second, the wake width, L_w, at half depth is determined and then the length scale is set to: $\Lambda_w = 0.21\, L_w$. We note that, near the hub and tip of the FEGV, the flow is not wake like. In these regions, one cannot fit a Gaussian to the wake profile in order to define the wake width. Therefore, a Gaussian fit error is defined and when it is more than 7% no value is computed. Currently, the radial locations where the wake is well defined are simply stretched onto the entire hub-to-tip extent in order to have a length scale value at every radial location. The predictions vary slightly when the different methods are applied to obtain the input to the low-order calculation. However, they are consistent in their application to the rig and full-scale cases.



(a) Pope k-w based lengthscale; actual

(b) Pope k-w based lengthscale; scaled



(c) Wake based length scale: actual

(d) Wake-based length scale; scaled

Figure 4. Exhaust sound power for source diagnostics test (SDT) rig and full scale (three times larger) at three operating points as predicted using the low-order method using input computed with Cadence Fine Turbo. Left: actual sound pressure level (PWL) spectra. Right: full scale fan stage results scaled by geometry factor and plotted against blade passage frequency. Top: length scale computed from turbulence parameters using Pope's method. Bottom: length scale computed based on wake width.

It was determined that using Pope's method for determining the length scale from the turbulence model parameters in the RANS, does not work when the UTCFD is applied to the CLEEN I rig and full-scale cases. We wrote a brief summary report about the length scale issue (included as Appendix A). Even though the full-scale case was rerun using different turbulent parameter inputs, which improved the RANS result, it still does not give the expected length scale. As such, we switched to using the wake width method for defining the length scale. We showed that this method is far more robust for defining the length scale from the UTCFD results. The predicted sound pressure level (PWL) spectra with the rig values scaled by the geometric multiplier are shown in Figure 5 plotted against the blade passing frequency count. The geometric scaling is a bit less accurate for the CLEEN I, implying that the Reynolds number effects are stronger. This is still being investigated. A full scaling formula that includes both the geometric and Reynolds number effects is being sought.

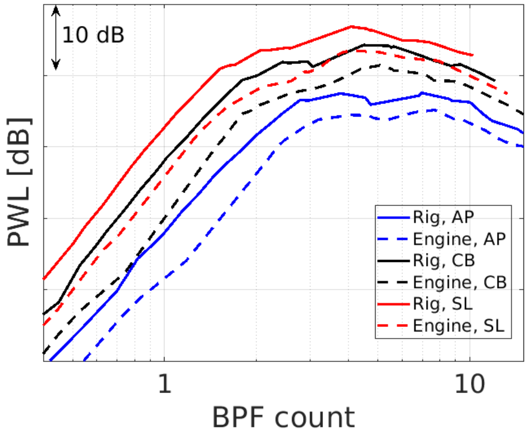


Figure 5. Exhaust sound power for Continuous Lower Energy, Emission and Noise (CLEEN) I rig results scaled up three times and full-scale results both plotted against blade passage frequency at three operating points as predicted using the low-order method with input computed via United Technologies Computational Fluid Dynamics (UTCFD). Wake width-based length scale. BPF: blade passage frequency, PWL: sound power level.

After a journal article submission came back from review. There were some comments that led to further investigation concerning the results reported last year about the effect of moving the FEGV in fan-stage broadband interaction noise. Further studies were run that indeed solidified the low-order prediction results. Moving the FEGV does not significantly affect the performance of the fan-stage for the cases considered and only changes the broadband noise by 1-2 dB. The differences between the predictions using BU-RSI and Hanson's method, which differ on whether the noise is increasing or staying the same is still not completely understood.

The low-order method was used to perform a preliminary assessment of the effect of having a bifurcation and a pylon downstream of the fan-stage. The new rig is similar to the CLEEN I rig but slightly larger. The first question that was addressed was whether the pylon and bifurcation add significant noise to the full-stage geometry. The wake information downstream of the FEGV was estimated and used as input to a BU-RSI type simulation where the mean flow has no tangential component and the flow interacts with only one vane – either the pylon or the bifurcation. This is more like the reaction of a single airfoil to unsteady disturbances versus a cascade. The response was still based on flat plate theory even though the pylon's cross section is a very thick airfoil. The acoustic propagation downstream still assumes propagation in a full annulus whereas the pylon splits the annulus. Previous studies showed that whether the annulus is split or not does not change the total power, it just shifted the modes a bit. Therefore, we believed this assumption was reasonable to get a first look at the effect on sound power. The results when adding the contributions from both the pylon and bifurcation show that their effect will be small as shown in Figure 6. The pylon and bifurcation raise the level of the broadband by up to 5 dB in the low frequency range. The change is expected to be negligible beyond the second blade pass frequency.

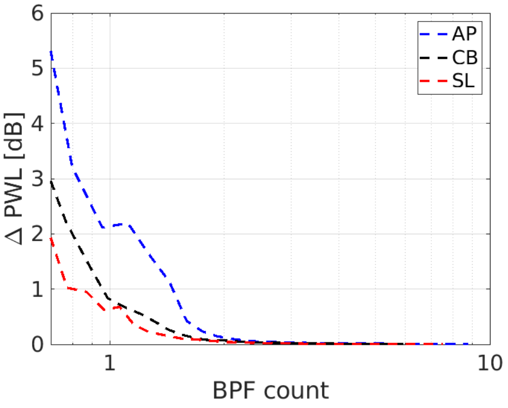


Figure 6. Difference in exhaust sound pressure level (PWL) for the Continuous Lower Energy, Emission and Noise (CLEEN) I fan stage without and with downstream pylon and bifurcation. BFP: blade passage frequency.

The second analysis was done in support of a fan alone test that was originally being planned. The question again was how fan-alone broadband noise would change with the presence of the bifurcation and pylon. However, it was discerned that because for the fan-alone case, the flow will not be well aligned with the pylon. The separation that will occur on the pylon will give rise to broadband self-noise which may be on the same order as the interaction broadband noise. Without more information about the actual geometry and ability to estimate the separation, this calculation could not be completed.

Subtask 2.2: Inclusion of Tip Flow Impact on the Low-Order Model and *Subtask 2.3: Inclusion of Inflow Distortion Impact on the Low-Order Model* were discussed previously (in Year 2).

Milestones

- Validate the low-order model for rig and full-scale applicability.
- Improve low-order model.

Major Accomplishments

- Developed best practices for using Cadence Fine Turbo for these simulations.
- Acquired enough information and developed full-scale SDT fan in order to validate that the low-order model works well for full scale as well as rig size fan stages.
- Analyzed some cases that will be of interest for the upcoming rig test.

Publications

Li, N., Winkler, J., Reinmann, C. A., Mendoza, J., & Grace, S. M. (2024). On the Use of a Low-Order Model for Rig and Full-Scale Turbofan Broadband Noise Predictions. *Being developed for the AIAA/CEAS Aeroacoustics Conference (2026).*

Outreach Efforts

None.

Awards

None.

Student Involvement

Nuo Li, graduate researcher (PhD), worked on the low-order model.

Plans for Next Period

- Further validation of the full-scale broadband noise predictions.
- Package the BU-RSI code and ML for distribution.

Task 3 - Rig Test Preparation

Raytheon Technologies Research Center

Objectives

The objectives of this task are to perform experiments in the RTRC Acoustic Research Tunnel (ART) to: (a) acquire key aerodynamic and acoustic data to support the validation of low-order and mid- (RANS) to high- (VLES, LBM Very Large Eddy Simulation, Lattice Boltzmann Method) fidelity computational fluid dynamics (CFD) models, and (b) assess the noise trends and scaling laws of different fan stages.

Research Approach

The rig being designed is a scaled version of the P&W fan rig from the FAA CLEEN I program. Thus, the rig will include a modern fan, but the flow path will focus solely on the bypass, thus eliminating the need for a core. The configurations that are planned include the P&W baseline design, as was previously evaluated at NASA. While it was anticipated that either a rotor-alone (no FEGV) configuration or a shifted FEGV configuration might be part of this test, the available funding will only cover testing of the baseline configuration.

The rig and measurement methods are fully designed as shown in Figure 7. The flow measurement probe setup was designed to capture radial length scale, which has not been measured previously in the fan-stage gap. The two-probe setup is novel and can be deployed at two different locations axially in the gap.

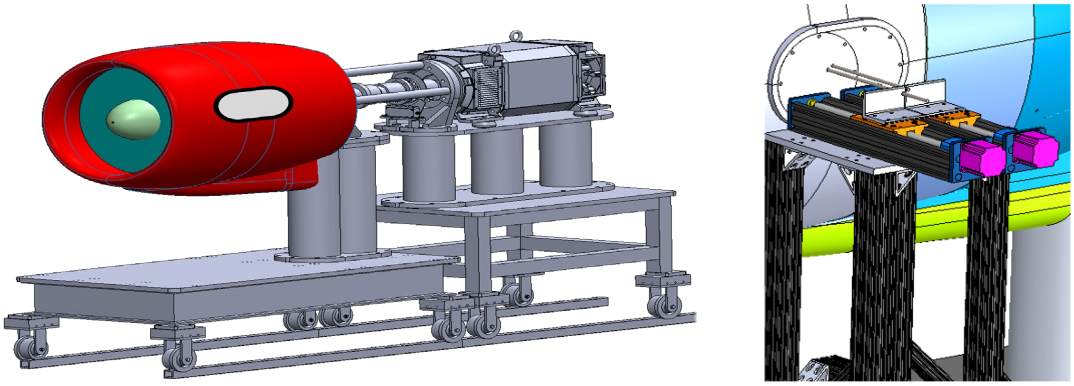


Figure 7. Raytheon Technologies Research Center (RTRC) rig design (left) and two hot-wire probe design (right).

As Year 5 concludes, the rig should be complete and ready for testing. The Gantt chart for the project in Figure 8 shows the best estimate for completion of the tests. The tests will now take place in early 2026.

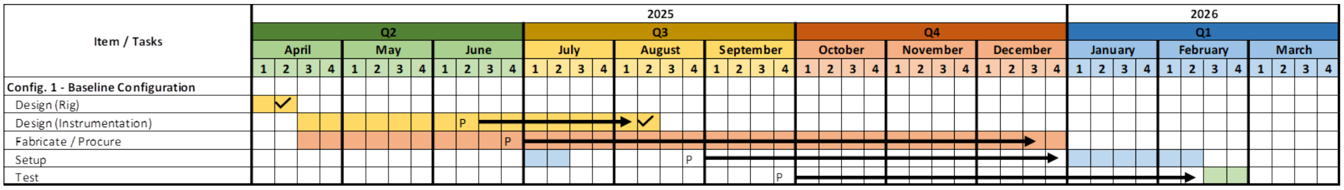


Figure 8. Raytheon Technologies Research Center (RTRC) rig development and test schedule.

Milestone

Design the rig test.

Major Accomplishments

- Participated in multiple meetings between RTRC/BU and P&W to determine the exact test capabilities.
- Completion of the probe design.

- Sourced all of the parts.
- Initial set up of the rig – parts that have arrived.

Publications

None.

Outreach Efforts

None.

Awards

None.

Student Involvement

None.

Plans for Next Period

- Test rig shakedown.
- Complete rig testing.

Appendix A

A Study in Why Lengthscale is a Difficulty in Broadband Modeling

Boston University
Authors: Sheryl Grace and Nuo Li
September 9, 2025

Introduction

This report details salient points related to length scale estimation applied to the flow solutions obtained from two computational fluid dynamics (CFD) solvers: United Technologies Computational Fluid Dynamics (UTCFD) and Cadence® Fidelity® Turbo. UTCFD utilizes the Ni-scheme based on Lax-Wendroff (Lax & Wendroff, 1960). A turbulence model based on Wilcox's $k-\omega$ with a vorticity source term is applied (Wilcox, 1988, 2006). Fidelity Turbo uses the Jameson–Schmidt–Turkel (JST) scheme (Jameson, et al., 1981). The Wilcox k–ω model is implemented but it has numerical instability issues and does not perform well. The Menter Shear Stress Transport (SST) model (Menter, 2003) was suggested by the developers. As such, the Fidelity Turbo simulations currently utilize the SST turbulence model. Table A-1 shows which solvers have been applied to which fan geometries in this study.

Table A-1. Solver applied to the fan geometry. CLEEN: Continuous Lower Energy, Emission and Noise, SDT: Source Diagnostics Test, UTCFD: United Technologies Computational Fluid Dynamics.

Solver	Fan Geometry
SDT rig scale	UTCFD, Fidelity Turbo
SDT full size	Fidelity Turbo
CLEEN rig scale	UTCFD
CLEEN full size	UTCFD

The UTCFD simulations were run by Julian Winkler (Raytheon Technologies Research Center [RTRC]), and the solution files were transmitted to Boston University (BU). We only have the flow values downstream of the fan. We do not have the Continuous Lower Energy, Emission and Noise (CLEEN) geometry and cannot repeat any of the simulations using Fidelity Turbo to check for consistency.

Length Scale Estimation

There are two main methods that have been considered for estimating the turbulent length scale in this work.

Pope's method: $\Lambda_k = \frac{0.043}{0.09}\frac{\sqrt{TKE}}{\omega}$ (Eq. A-1)

Wake width based: $\Lambda_w = 0.21 L_w$ (Eq. A-2)

L_w is obtained by fitting the turbulent kinetic energy (TKE) on the passage with a Gaussian function as shown in Figure A-1.

$$TKE(r,\theta) = TKE_b(r) + TKE_\omega(r)e^{-(\frac{\theta}{2\sigma})^2} \quad \text{(Eq. A-3)}$$

and then $L_w = 2\sqrt{2ln2\sigma}$

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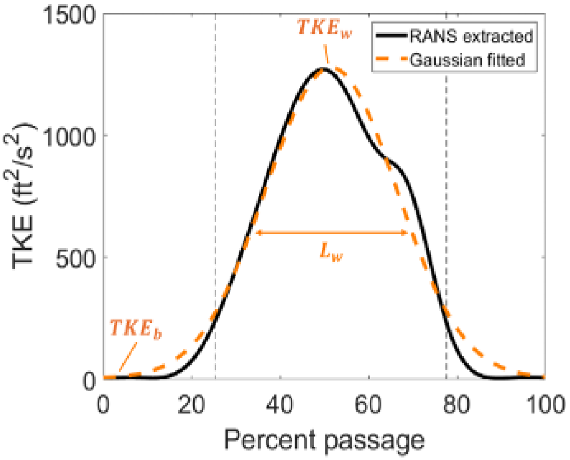


Figure A-**1.** Typical Gaussian fit to turbulent kinetic energy (TKE) on passage at given spanwise location. RANS: Reynolds-Averaged Navier-Stokes.

Pope's method requires a decision on how the averaging on the passage will be conducted. The averaging can be done in many ways. Two methods are compared here: (1) identify average values of turbulence kinetic energy *(TKE)* and ω separately on the passage at each radial location and then form Λ_k, this is denoted by "Λ_k avg *k*,ω" in Figure A-2, or (2) identify a value of $\Lambda_{k\vartheta}$ at every point on the passage and then average to get Λ_k, this method is denoted by "Λ_k" in Figure A-2. These methods give different outcomes depending on the wake shape of k and ω. When the source diagnostics test (SDT) cases were originally run using the flow solution from UTCFD, it was determined that a best match to the experimentally calculated integral length scale was obtained when the latter method of computing $\Lambda_{k\vartheta}$ at every point and then averaging to get Λ_k provided the better prediction. Hence, this method has been used moving forward.

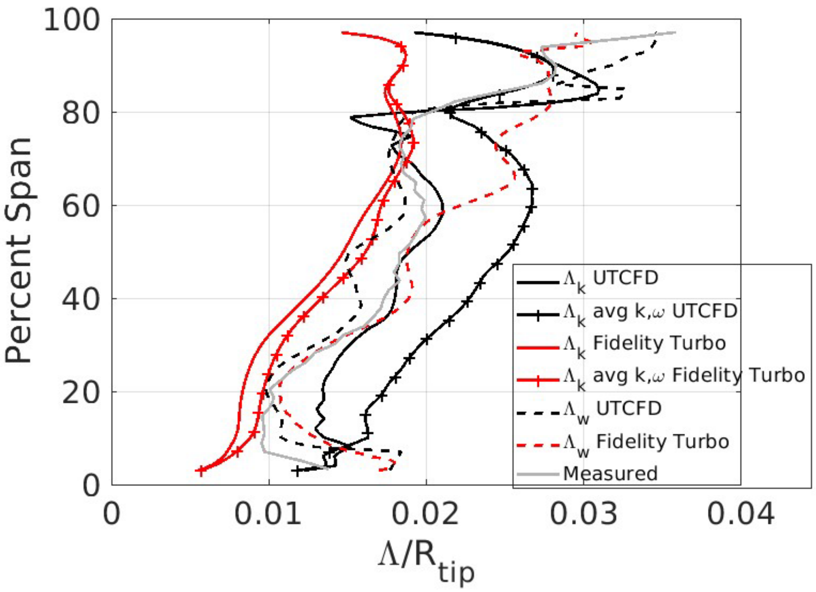


Figure A-2. Source diagnostics test (SDT) approach. Comparison of different methods for obtaining length scale applied to the flow solutions from the two solvers. UTCFD: United Technologies Computational Fluid Dynamics.

Results from the simulation of the SDT approach case show that the wake width method gives much more similar results between the UTCFD and Fidelity Turbo outcomes (dashed lines in Figure A-2) than the length scale based on Pope's method (i.e., the $k - \omega$ enhance and SST model outcomes).

It is noted from the ACAT1 report (Kissner et al., 2020) that many others have shown that the Pope-based length scale predictions can vary greatly depending on the solver and turbulence model. Many others have reported that the SST turbulence model leads to low Pope-based length scale values compared to Wilcox and this is clearly seen here.

Length Scale for Rig and Full-scale Engines

We created our own SDT full size engine by scaling the SDT geometry uniformly in every direction by a factor of 3. The rotations per minute (RPM) and mass flow are scaled in a way that $\frac{RPM_{Rig}}{RPM_{Engine}} = 3$ and $\frac{\dot{m}_{Engine}}{\dot{m}_{Rig}} = 3^2$.

We used the Fidelity Turbo solver to compute the flow field for both the rig and engine scaled fans. The length scale computed using the two methods are different, but both behave similarly. The length scale for the rig is smaller than the engine length scale by a factor equal to ~3 for both the Pope and wake width methods. This can be seen in Figure A-3.

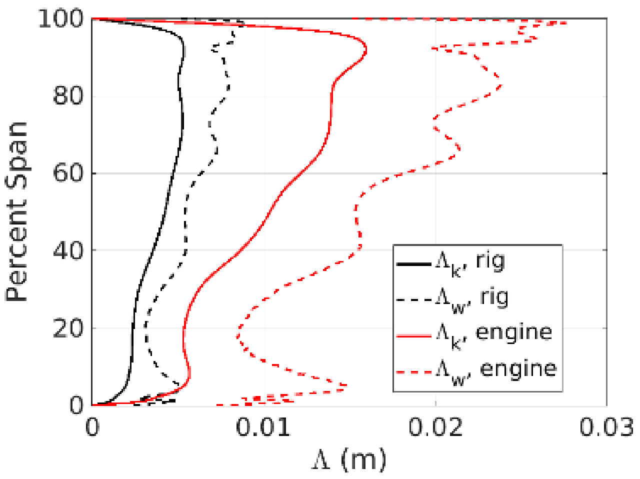
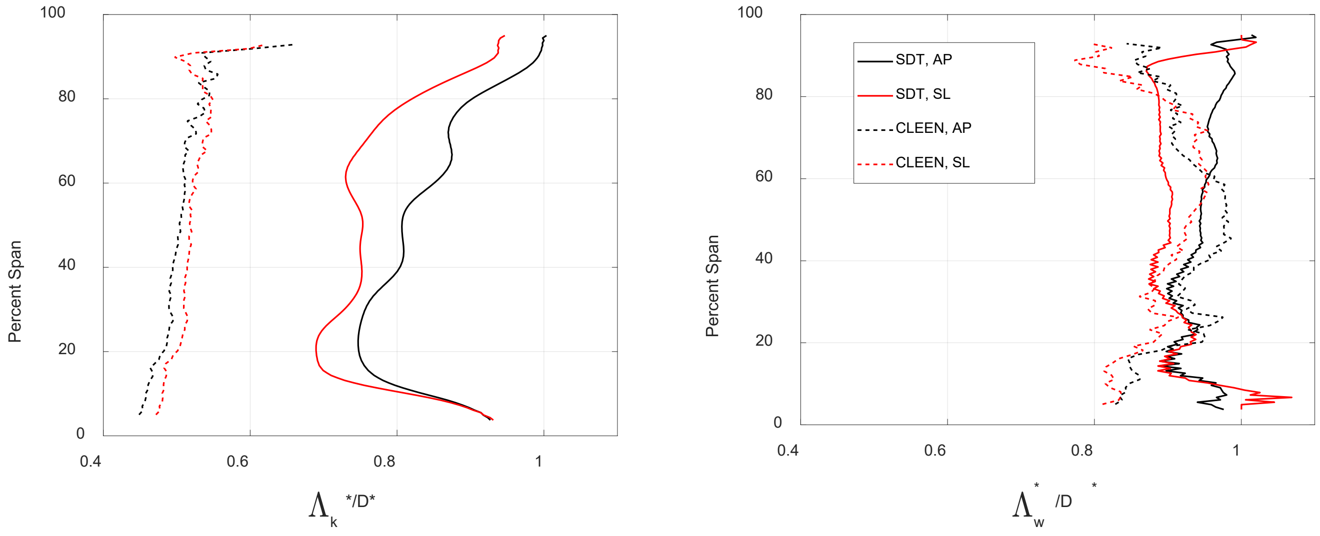


Figure A-3. Source Diagnostic Test (SDT) at approach speed. Comparison of two different methods for obtaining length scale. Based on Fidelity Turbo inputs.

The UTCFD results that were provided to us for the CLEEN rig and full-scale engines were used to compute the length scale. The outcomes indicate that the Pope method may be no longer valid, as we expect that the length scale for the full-size engine to be roughly proportional to the size of the fan. This is not true when Pope's method is used to obtain the length scale from the CLEEN UTCFD results. However, they are true when the wake-width method is used. To show this, we defined a decay coefficient for both Pope-based length scale and wake-width-based length scale. This is shown in Figure A-4, where the superscript * indicates ratio between engine and rig (i.e., $\Lambda^*_\omega = \Lambda^*_{\omega,Engine}/\Lambda^*_{\omega,Rig}$, note that $\Lambda^*_\omega = L^*_\omega$), and D is the diameter. This plot shows how turbulence length scale changes with respect to geometry.



(a) Pope’s $k - \omega$ method (b) Wake-width method

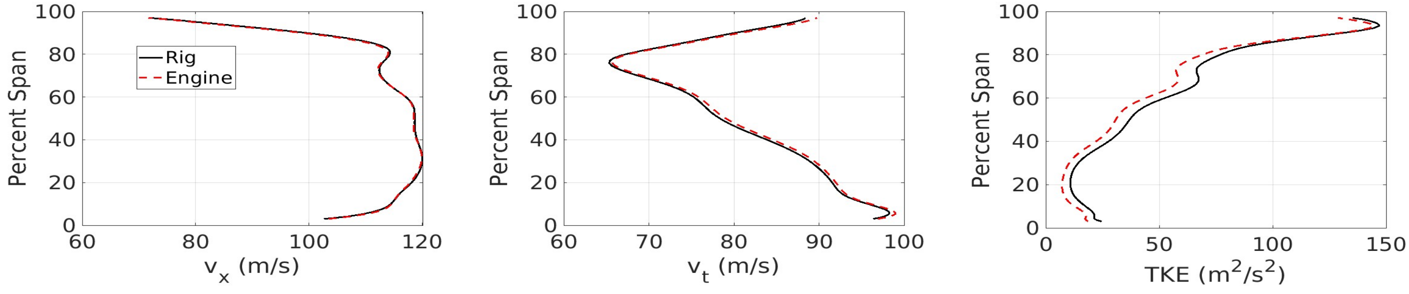
Figure A-4. Influence of engine scale on mean flow extracted near fan exit guide vanes (FEGV) leading edge. CLEEN: Continuous Lower Energy, Emission and Noise, SDT: Source Diagnostics Test.

In Figure A-4, the solid lines compare the SDT length scales, which show rather similar trends for Λ_k and Λ_w, with coefficients slightly less than 1 and decrease at higher speed. The CLEEN geometry denoted by dashed lines on the other hand, shows much smaller values for Λ_k^* , while Λ_ω^* show similar aforementioned trend.

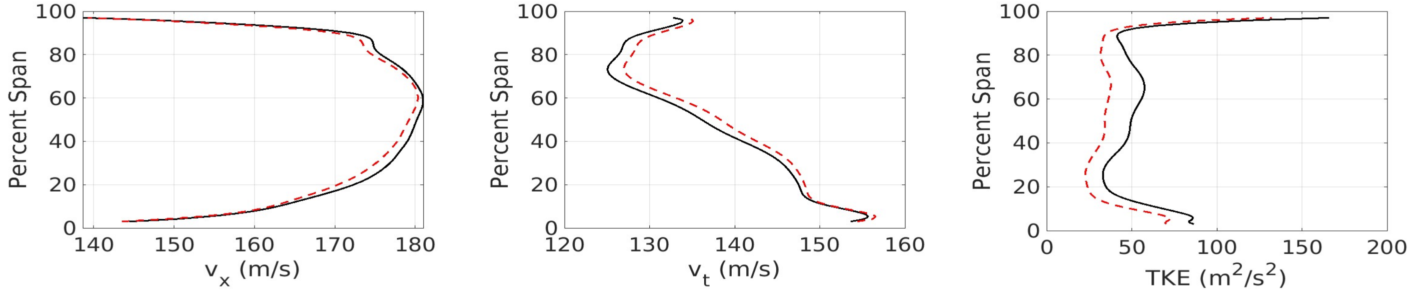
The exact reason behind the unreliable Pope-based length scale is unclear. However, we noted that the difference is mainly driven by the background values, where the specific turbulence dissipation rate does not scale proportionally to the geometry.

Other Input Parameters

The low-order broadband noise method relies on other input parameters besides the length scale. These include the axial and tangential mean flow values and TKE. Figure A-5 shows the results for the SDT at approach and sideline. Again, the larger fan was obtained by simply multiplying the original geometry by 3.0. Importantly, the TKE for the full engine is slightly less than the TKE for the rig and this is more pronounced for the sideline case. The mean axial and tangential flows are very closely aligned because the operating points were chosen to be identically scaled as the geometry scaled, which leads to identical relative flow at the blade leading edge.



(a) v_x, AP (b) v_ϑ, AP (c) *TKE*, AP



(d) v_x, SL (e) v_ϑ, SL (f) *TKE*, SL

Figure A-5. SDT rig and full-scale engine flow inputs. Based on Fidelity Turbo inputs. TKE: turbulence kinetic energy.

Figure A-6 shows the difference in mean flow between engine and rig. The CLEEN cases show similar trends to the SDT cases, except at the approach speed which operating point does not scale exactly with geometry. The biggest differences between the behavior of these flow parameters as the engine size changes from rig to full for the CLEEN occurs in the axial velocity at approach which is much lower for the full engine. The turbulence intensity (TI) for u'/U behaves similarly to what we see in TKE from the Fidelity Turbo run of the SDT engine at two scales. The full-engine TKE is lower than the rig and this is more pronounced for the sideline case.

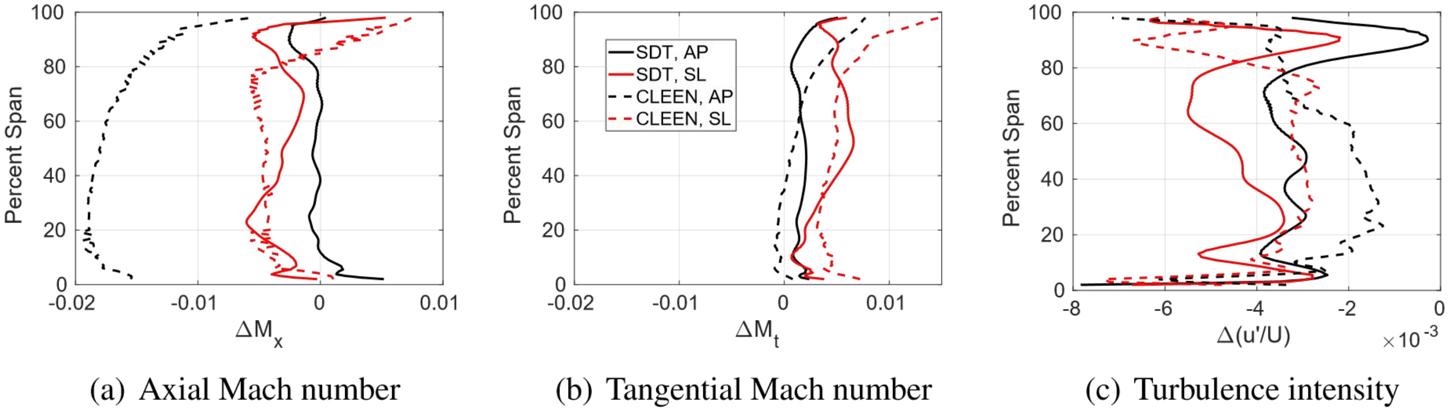
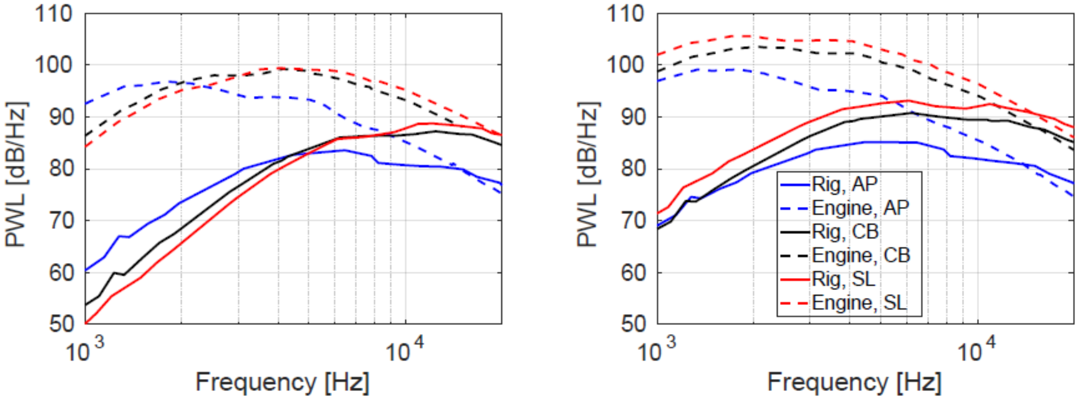


Figure A-6. Difference in inflow extracted near FEGV leading edge, (a) axial Mach number, (b) tangential Mach number, and (c) turbulence intensity. CLEEN: Continuous Lower Energy, Emission and Noise, SDT: Source Diagnostics Test.

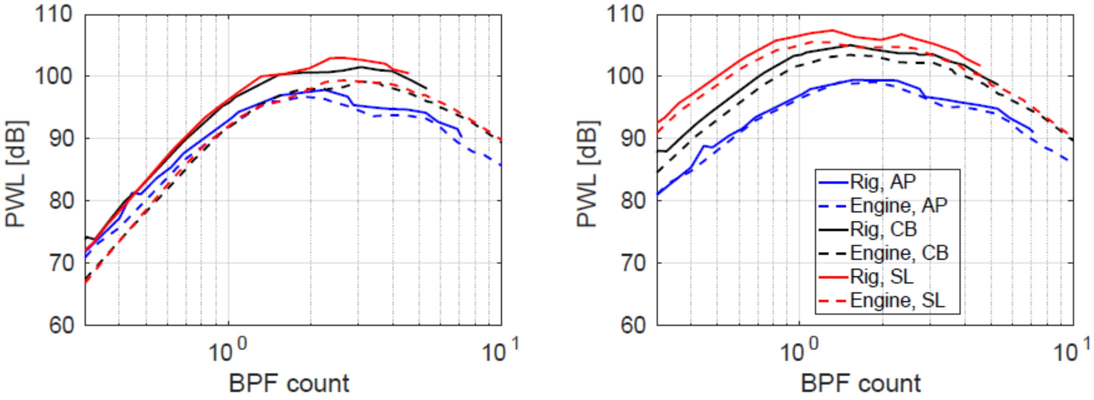
Noise outcomes

The results we presented originally for the CLEEN rig and engine used the Pope-based method for determining the length scale. As shown in the previous section, this method is not reliable. As such, new simulations were run using the wake width-based method for determining the length scale. This analysis was done also for the SDT rig and full engine that we created.

Starting with the SDT where the geometry and RPM are identically scaled, Figure A-7 shows the spectra for the three operating points for the rig and full-scale engines. The full-scale values are then scaled by a power of 3 and the frequency is scaled based on the blade passage frequency (BPF). The results using both the Pope and wake-width methods are shown. The scaling performs a bit better for the wake-based method; however, the power 3 scaling works for approach and not as well for cutback and sideline.



(a) Pope (b) Wake width

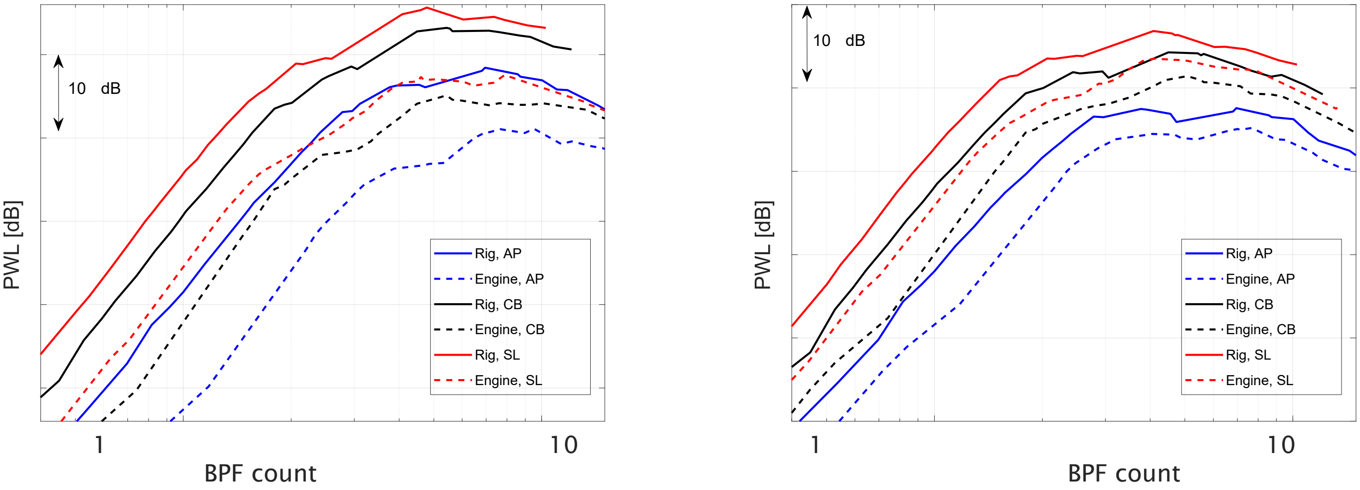


(c) Pope, scaled (d) Wake width, scaled

Figure A-7. SDT spectra rig and full scale. Based on Fidelity Turbo inputs. Pope length scale (left). wake width length scale (right). Based on Fidelity Turbo inputs. BPF: blade passage frequency, PWL: sound pressure level.

For the CLEEN, we will show the Pope based outcomes in Figure A-8 (a) but know these cannot be correct. They were our original results, and one can see how much the difference between engine and rig spectra amplitude changed (see

Figure A-8 [b]). The scaling of the spectra amplitude by the third power of the diameter ratio works better when the wake width method is used.



(a) Pope, scaled

(b) Wake width

Figure A-8. CLEEN spectra rig and full scale. Based on Fidelity Turbo inputs. (a) Pope length scale and (b) wake-width length scale. United Technologies Computational Fluid Dynamics (UTCFD). BPF: blade passage frequency, PWL: sound pressure level.

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