FAA CLEEN II – Low Pressure Ratio Fan Advanced Acoustics

Final Report – Public Version

GE Aviation

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Nomenclature

CAA: Computational Aero-Acoustics
CDR: Conceptual Design Review
CLEEN: Continuous Lower Energy, Emissions, and Noise
CMM: Coordinate Measuring Machine
DDOF: Double Degree Of Freedom
DDR: Detailed Design Review
EPNL: Effective Perceived Noise Level (EPNdB)
GFIT: Grazing Flow Impedance Tube
MDOF: Multi-Degree Of-Freedom
MRL: Manufacturing Readiness Level
NASA: National Aeronautics and Space Administration
NIT: Normal Incidence Tube
OGV: Outlet Guide Vane
PDR: Preliminary Design Review
PWL: Power Level (dB)
SDOF: Single Degree Of Freedom
TRL: Technology Readiness Level
UPS: Universal Propulsion Simulator

Section 1 Summary

1.1 Introduction

The CLEEN II Program, like the prior CLEEN Program, is focused on reducing current levels of aircraft noise, greenhouse gas emissions, and energy use, and advancing alternative fuels for aviation use. The Advanced Acoustics project was initiated at GE Aviation and focuses on the CLEEN objective to:

> "Mature previously conceived noise…reduction technologies for civil subsonic airplanes from Technology Readiness Levels (TRLs) of 3-5 to TRLs of 6-7 to enable industry to expedite introduction of these technologies into current and future aircraft and engines."

Ducted fan systems are trending toward shorter and slimmer inlets/nacelles and compact fan-outlet guide vane (OGV) systems which reduce the weight and drag of such systems but also have less available area for acoustic treatment. Reduced length nacelles require the acoustic efficiency, i.e., noise reduction per unit acoustic treatment area, to increase compared to current technology. Shorter fan-OGV spacings require fan noise source strength reduction concepts to reduce fan wake-OGV noise response. Also, shorter inlets may result in increased amount of in-flow distortion into the fan, increasing the fan source tonal and broadband noise content.

This project aimed at designing, optimizing, and maturing novel acoustic liner and fan source strength technologies. When implemented in future engine designs, these concepts provide superior noise benefit without compromising on fuel burn and performance of the aircraft system. The Advanced Acoustic CLEEN II program is split into two noise reduction subtasks focused on the addressing the important features of next generation architecture trends:

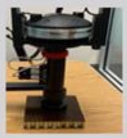
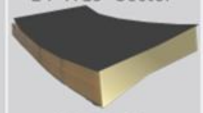
Task 1: Novel acoustic liners to increase acoustic efficiency of liners

Task 2: Fan noise source strength reduction technology

1.2 Goals and Timeline

The Advanced Acoustic CLEEN II project aimed at enabling future lower fuel burn engines while making progress toward the CLEEN II program goal of, "Certifiable aircraft technology that reduces noise levels by 32 EPNdB cumulative, relative to the FAA Part 36 Stage 4 limits, and/or reduces the noise contour area in absolute terms." The innovative acoustic liners subtask had a goal of demonstrating 2+ EPNdB cumulative noise reduction relative to current Single Degree Of Freedom (SDOF) acoustic liners when introduced throughout an engine and nacelle. The fan noise source strength reduction task had a goal of reducing cumulative noise by 1 EPNdB cumulative on an engine without measurably impacting fan performance efficiency.

The TRL/MRL maturation timeline for the technologies is summarized in Figure 1. The novel liner task consisted of modeling and testing activities that resulted in maturation of the technology from TRL/MRL 3 to TRL/MRL 4 through CLEEN II. The fan source strength reduction tasks progressed through design reviews to TRL 3 with the subscale test hardware manufactured and ready for a TRL 4 wind tunnel test. Plans are also developed to continue the technology maturation to TRL 6. The next major step is to test the source strength reduction hardware in a sub-scale wind tunnel test. Following that test, a static engine test would bring these technologies to TRL6.

	Prior to CLEEN II	CLEEN II Project			Future Projects
Task	**Earlier**	**FY 2018**	**FY 2019**	**FY 2020**	**FY 2021+**
1. Novel Acoustic Liner Technology	Concepts Developed and Tested in Normal Impedance Tube	Grazing Flow Test Rig Rd 1	Grazing Flow Test Rig Rd 2	MRL Focus Manufacturability, Joints, Curvature	Engine Test 360° Joints, Curvature
Test					
Part Geometry	5" X 5" Flat 	2.5" X 21" Flat 		24" X 13" Sector 	Full scale 360° 
TRL/MRL	2/2	3/3	4/3	4/4	6/5

	Prior to CLEEN II	CLEEN II Project			Future Projects
Task	**Earlier**	**FY 2018**	**FY 2019**	**FY 2020**	**FY 2021+**
2. Fan Noise Source Strength Reduction	Identify Source Strength Reduction Concepts and Down Select	Aeroacoustic Design	Detailed Design Reviews, Drawings & Pre-test Predictions	Subscale Test Hardware Fabrication	Wind Tunnel Test and Engine Test 
TRL		3	3	3	6

Figure 1: Project Timeline and TRL Levels

Product designs involve significant trades and must balance many conflicting requirements such as customer requirements for noise, fuel burn, cost, TRL, MRL, producibility, maintainability, repairability etc. Maturing these technologies through the CLEEN II program supports engine trade studies and provides a significant opportunity for future product incorporation.

Section 2 Advanced Acoustic Liners

2.1 Background and Previous Studies

Figure 2 shows the basic parts of an acoustic liner. The advanced acoustic liner project focused on developing novel liner cores in combination with the facesheet that could provide an acoustic benefit versus traditional SDOF liners. GE has experience designing, fabricating, and testing acoustic liners in many of its turbofan engine products. Liners are typically located throughout an engine and nacelle. An example of the typical areas of an engine that have acoustic liners is shown in Figure 3.

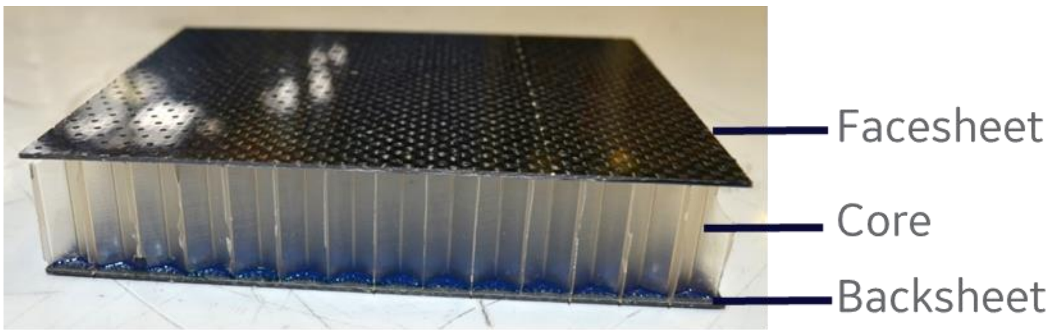


Figure 2: Single Degree of Freedom Acoustic Liner Parts

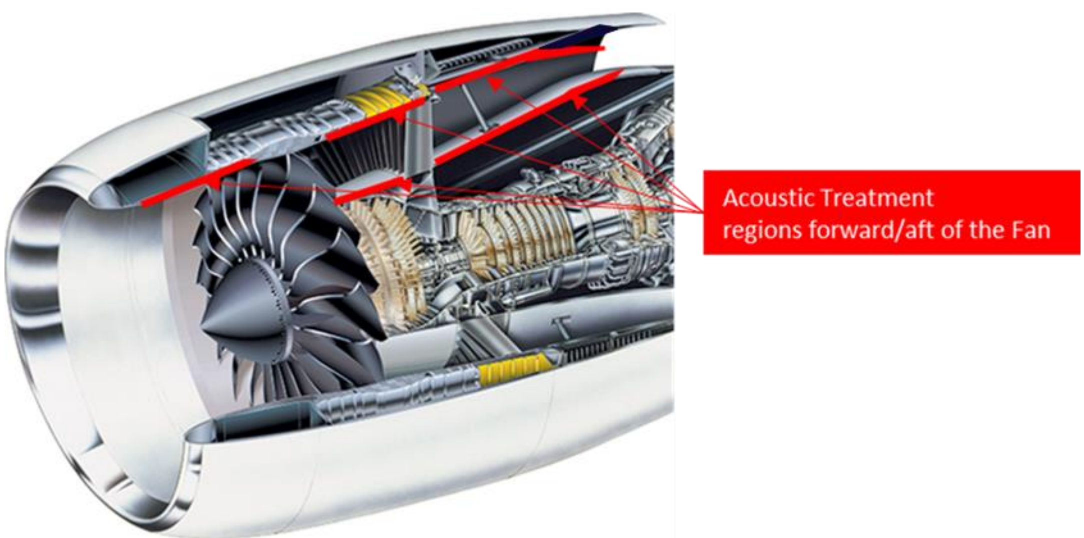


Figure 3: Typical Acoustic Liner Locations on an Engine and Nacelle

Double Degree Of Freedom (DDOF) acoustic liners are also used to reduce fan noise in turbofan engines. When optimized, these liners typically require a deeper depth, cost more, and weigh more than SDOF liners. The benefit for these liners is that they provide enhanced attenuation bandwidth that typically results in greater cumulative EPNdB noise reduction when implemented. Integration, space, and weight constraints can limit the usability of DDOF liners through the engine/nacelle.

This project focused on developing a liner that provided acoustic benefit over an SDOF without the drawbacks of a DDOF.

2.2 Initial Novel Liner Ideas and Impedance Tube Testing

The core of SDOF liners is typically a simple honeycomb structure that is relatively easy to manufacture and structurally efficient. Advances in additive technology's availability and speed have removed some of the roadblocks for advancing the simple honeycomb core shape into something more complex and acoustically advantageous. This project studied several different core shapes to discover which could provide significant acoustic benefit relative to the standard honeycomb core.

The Normal Incidence Tube (NIT) is a closed tube used to measure the normal incidence impedance of liners in static, no-flow conditions. It has drivers to generate acoustic waves that impinge on the liner sample and superimpose with reflections from the sample to create a standing wave pattern. Two microphones at prescribed distances from the sample are used to measure the complex acoustic pressures. The two microphone method is then used to compute the no-flow acoustic impedance as a function of frequency. A schematic of the NIT is described in Figure 4. Several initial concepts for novel core shapes were tested with a portable NIT. It is a relatively simple test performed on small panels (5" x 5" x 1" depth) that allows for measuring the bandwidth potential of novel acoustic cores concepts. All the measurements were carried out with a broadband source of noise. The measurements were in the frequency range 500Hz to 6000Hz.

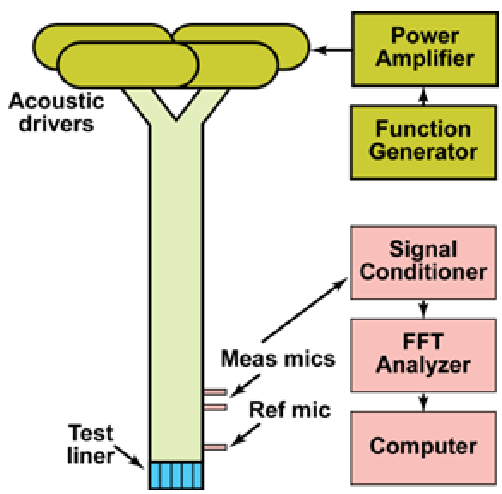


Figure 4: Schematic of the Normal Incidence Tube (NIT)

Early in the NIT testing phase there were several ideas that showed potential. In parallel to these initial measurements, the GE team was developing analytical and numerical models of novel liner cores. These models were used to mature understanding of the physics, guide design changes and new core ideas, and optimize the designs for product applications.

2.3 Modeling and Down-selection

In the liner analysis and design work that follows, GE considered Multi-Degree-Of-Freedom (MDOF) liners comprised of single cavity resonators arranged in parallel. Acoustic impedance is hence formed by linearly adding the individual cavity acoustic admittances (inverse of impedance) weighted by their treatment areas, i.e.,

$$Z_{\text{net}} = \Sigma A_i \left[\Sigma\left(\frac{A_i}{Z_i}\right)\right]^{-1}$$

The facesheets forming the flow-side surface of the liner cavities are modeled either as wiremesh or perforated sheet depending on the application and design intent. The acoustic resistance and mass reactance for perforated facesheets in grazing flow are modeled using [Syed 2002], whereas the acoustic resistance of wiremesh layers are simply specified (constant in frequency) with negligible mass reactance.

For each individual SDOF resonator in a parallel array of acoustic cavities, acoustic reactance modeling for expanding or contracting cavity cross-sectional area distributions between the facesheet and cavity floor is obtained by solving Webster's horn equation (below) analytically using the WKB method [Pastouchenko 2021].

$$\frac{\partial^2 \hat{p}}{\partial y^2} + \frac{\partial(\ln A)}{\partial y}\frac{\partial \hat{p}}{\partial y} + k^2\hat{p} = 0, \text{ where } k = \frac{\omega}{c},\ p = \hat{p}e^{-i\omega t},\ \hat{v} = \frac{1}{i\rho\omega}\frac{\partial \hat{p}}{\partial y}, \text{ and } Z_{\text{cavity}} = -\frac{\hat{p}(h)}{\hat{v}(h)}$$

Note for straight walled SDOF cavities with constant cross-sectional area, the 1D solution to the classical Helmholtz equation is simply $Z = -i\rho c\cot(ky)$.

Prediction validations for a representative MDOF design described in [Lin 2017] are shown in Figure 5 for normal impedance testing and Figure 6 for NASA's Grazing Flow Impedance Tube (GFIT) test rig. The results show the model predicts similar qualitative behavior, but the measured absorption peaks are scaled to higher frequencies than predicted. Some of this scaling could be from reduced cavity depths associated with the as-built parts but there is interesting behavior between the first antiresonance frequency and the 2^{nd} resonant mode, where the model singularity appears significantly damped. This could be the case because the prediction model does not include any mechanism for damping other than the resistance in the facesheet, nor does it include the potential for vibrational coupling between adjacent cavities.

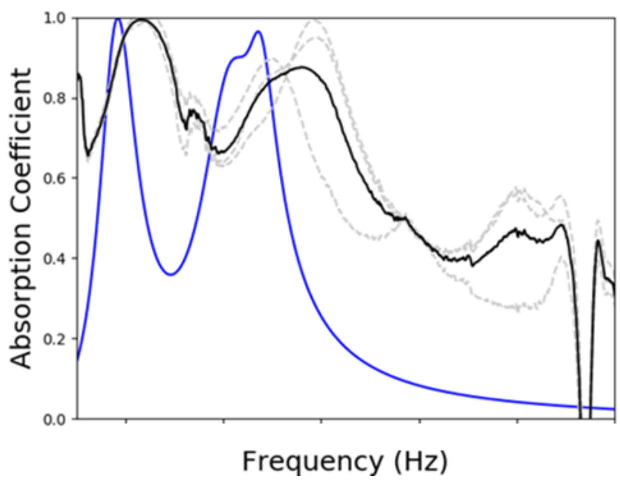


Figure 5: Measured normal impedance data

Individual repeats in grey, average result in black, compared to model prediction (blue).

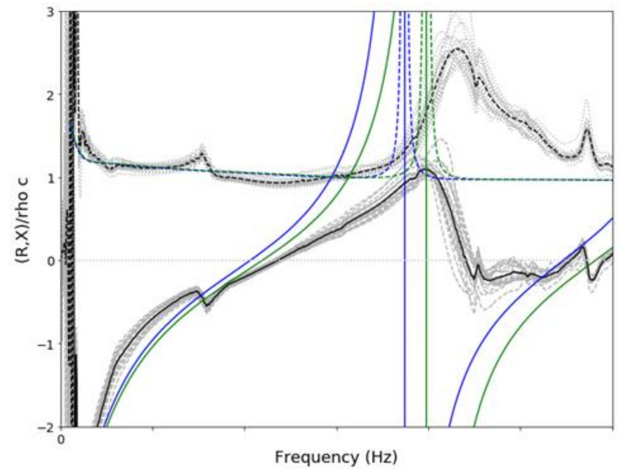


Figure 6: GFIT test data comparison at Mach 0.3.

Average of test results in black (individual tests are grey dashed/dotted curves); nominal prediction in blue, reduced depth (accounting for finite wall thickness of as-built geometry) in green. Specific reactance spectra are denoted by solid curves, whereas resistance is shown by dashed curves.

The key features of the liner impedance and absorption characteristics are clearly visible, leading to this model providing a useful means to enable design optimization studies.

A number of optimization studies were performed on this liner concept using different styles of objective functions. First, the acoustic energy absorbed in a frequency range of interest to the application was used to guide the choice of favorable designs, as denoted by the circled designs in the left panel of Figure 7.

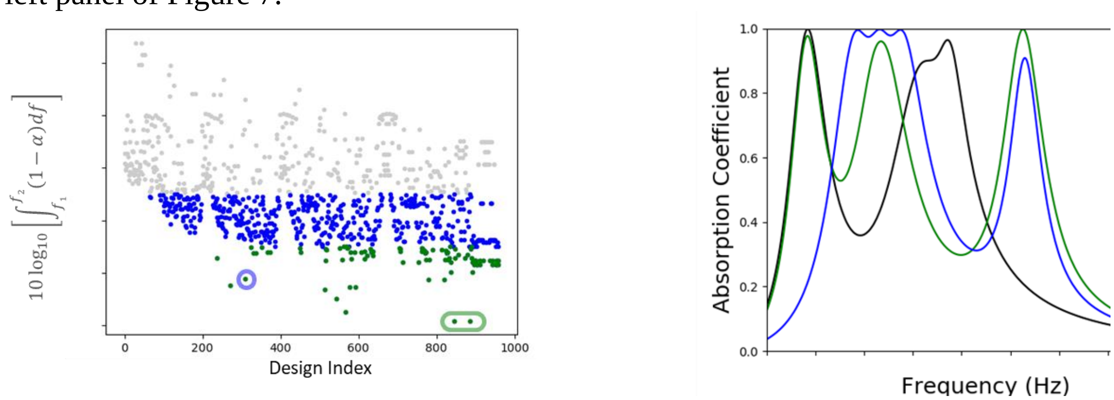


Figure 7: MDOF tapered cavity liner design parametric sweep guided by selected frequency band integration absorption benefit.

Next, absorption of the fan tone levels weighted by their tone PWL sensitivities to system EPNL was used to guide the optimal design (green absorption curve in Figure 8). The black curve corresponds to a straight SDOF cavity at the same depth for reference so as to show the improved bandwidth and low frequency coverage of the novel MDOF liners.

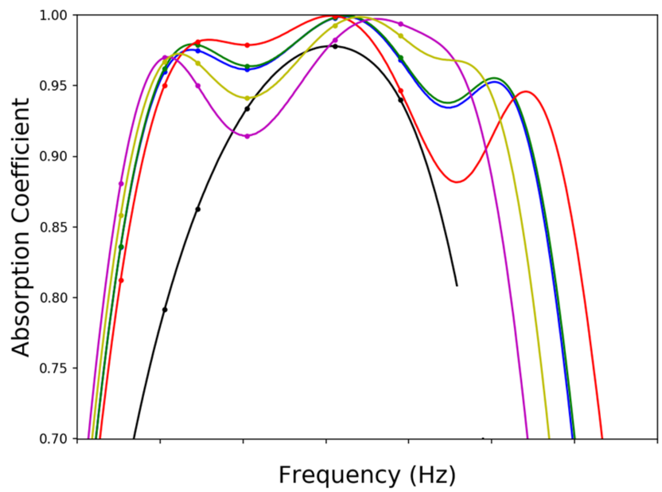


Figure 8: Sample impedance results from the MDOF cavity liner design optimization guided by tone level benefits

Different representative acoustic conditions shown versus an SDOF (black). Note the change in absorption axis scale, while the frequency axis matches that of Figure 7.

Validation of the design study summarized in Figure 9 shows qualitatively similar behavior to the predicted results with the frequency scaling issues observed in Figure 5 and Figure 6. The wideband absorption in the mid-frequency range of the design denoted by the blue curve is observed in the test data, further improving confidence that although there remain quantitative differences in the predicted impedance, the model can suitably be used to guide the liner design.

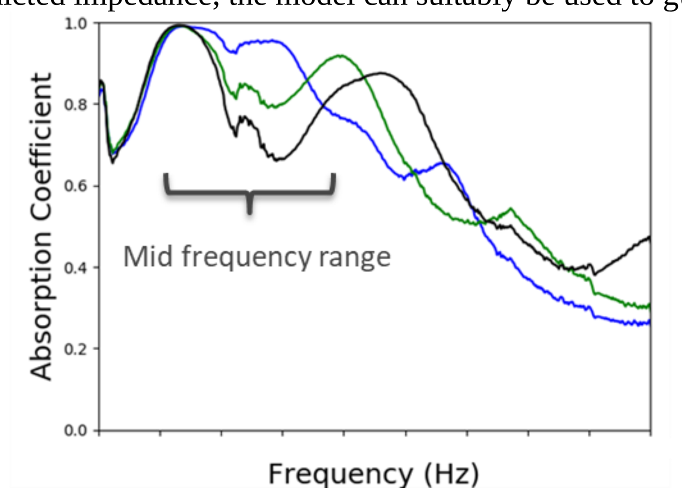


Figure 9: Normal impedance test data validation corresponding to Figure 7.

One consideration in using these tapered cavity liners comprised of parallel expanding and contracting resonators is that the expanding cavity used for low frequency attenuation is outnumbered by its neighboring high frequency contracting cavities. For the sample MDOF results presented here, one low frequency cavity is partnered with three higher frequency cavities, which can reduce the effective treatment area associated with the lower frequency resonators if one aims for higher frequency scaling relative to a straight SDOF resonant frequency.

When combined with a facesheet of low porosity, grazing flow effects result in an acoustic resistance behavior that varies nonlinearly with frequency (higher acoustic resistance at low frequencies). This results in a biasing high absorption towards higher frequencies at appreciable grazing flow velocity. Thus the core and facesheet designs must be modeled together during optimizations at the appropriate grazing flow conditions. An example of this effect is modeled using experimentally measured facesheet resistance curves over our model of the parallel MDOF liner of Figure 5 is presented in Figure 10 below:

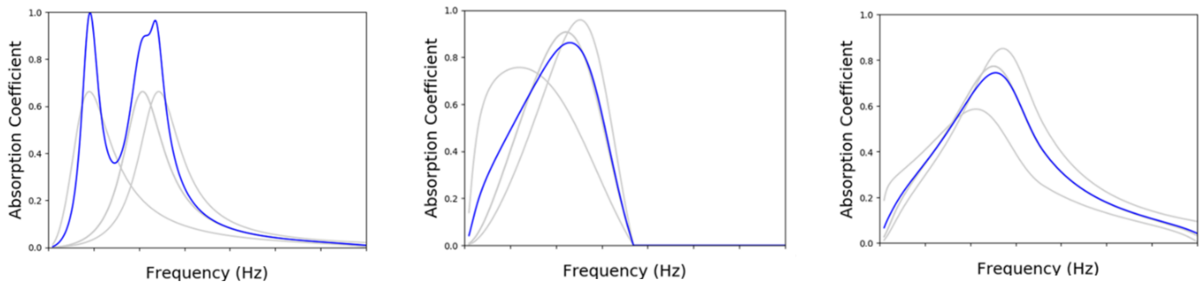


Figure 10: Predicted net absorption spectra

Blue (individual cavities responses in gray prior to parallel impedance summation) for Mach 0 (left), 0.3 (center) and 0.5 (right).

Additional parallel, MDOF liners designs were considered which widened the design space that is used for optimization [Wood, 2019]. Similar modeling techniques were used to estimate the impedance of these liners. To assess the potential benefits of the additional liner concepts, the previous design study summarized in Figure 8 was repeated. Traditional 1-3DOF liners in series (using 0-2 septa) and the additional MDOF design were considered, and the results are summarized in Figure 11. The key finding was that the MDOF could attain nearly the maximum tone noise benefits of the other optimal configurations. Furthermore, additional degrees-of-freedom were not necessary to significantly improve the overall benefit.

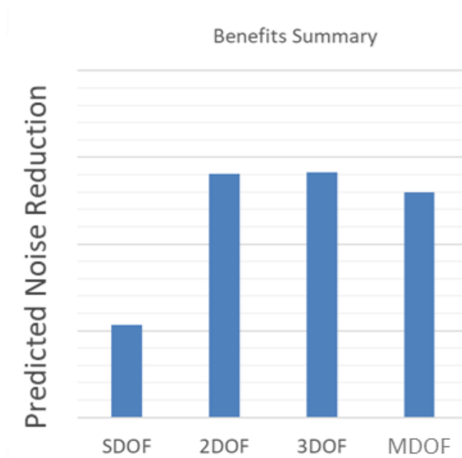


Figure 11: Summary of optimal designs

Used EPNL weighted tone scaling sensitivities for various cavity configurations: 1-3DOF in series vs. MDOF resonators were considered.

The modeling and analysis described in this section was used to determine which liner concepts had the highest potential for acoustic benefit.

2.4 Grazing Flow Impedance Tube Testing and Results

A grazing flow facility is used to measure the acoustic impedance with the influence of airflow over the facesheet of the liner, as well as with the noise source propagating over the liner (grazing) instead of normal to it as in the NIT tests. The method of source application and grazing flow influence are more representative of engine-like conditions and can significantly impact the impedance of the liner.

GE collaborated with NASA Langley under a Space Act Agreement to test the CLEEN II acoustic liner coupons at their grazing flow impedance tube facility. The facility layout is shown in Figure 12. 22” x 1.5” coupons were manufactured and tested at several conditions including Mach 0, 0.3, and 0.5 grazing flow conditions. Source sound pressure levels varied from 120 dB to 140 dB from 400 to 3000 Hz.

Figure 12: Grazing Flow Impedance Tube Duct (NASA LaRC)

More than 8 liner designs were designed, fabricated and tested in the GFIT. These included two baseline SDOF liners to establish baseline suppression levels and facility calibration. Figure 13 shows an example of the liner coupons that were used for testing.

Figure 13: Novel Liner 21.5” x 2.5” Coupons for the GFIT

Through the grazing flow testing and associated modeling, a novel core design shape was selected as the final design. Once the core shape was selected, additional GFIT tests on 4 more coupons were performed to study the novel core with different facesheet properties. The facesheet resistance in these tests varied to cover the approximate optimal range of resistances for typical engine liners.

With the test data from the GFIT and the basic novel liner definition complete, the focus of the project shifted to optimizing a design for a future full-scale demo static engine test.

2.5 Final Design

A full-scale demo application for this technology was identified based on an existing engine product. A noise prediction for the product was used to estimate the benefit of replacing SDOF liners with the novel liner studied in this product. The prediction estimated that the novel liner can achieve the goal of providing 2+ EPNdB cumulative noise benefit when the acoustic liners are changed from SDOF to the novel liner.

2.6 Manufacturing Maturation

2.6.1 Core Manufacturing

Additive manufacturing is the enabling technology to open the design space for acoustic liners away from standard honeycomb cores used over the last 30 years. With additive manufacturing, complex walls, wall features, and core geometry can be introduced into the design almost without bounds.

The team assessed various additive manufacturing modality and materials to manufacture the cores. For a good summary of polymer additive modalities, see article from Sirrus, "Picking the most suitable additive manufacturing technology" (https://www.sirris.be/picking-most-suitable-additive-manufacturing-technology). Some key criteria for down-select of the method and materials are the maturity level of the process, speed, build size, availability of service temperature capable materials, and adhesion capability.

A challenge for manufacturing cores is the low wall thickness. The wall thickness determines the core density and total core weight. With the widespread application of acoustic liners in the engine, there can be significant weight associated with the acoustic cores. Any trade-off with associated weight increase will be negotiated with system design and may limit application. Multiple manufacturing techniques for the final core design are still considered to widen the potential for use.

2.6.2 Manufacturing and Assembly

Facesheet structure and assembly of the sandwich structure liner can be changeable. Several manufacturing methods and trials on small coupons were performed as part of this project. A large two-foot circumference panel was manufactured as the final demo panel for the project. This panel, shown in Figure 14, represents a portion of a full-scale acoustic liner. Acoustic impedance measurements were taken on this demo panel that showed excellent quality and correlation to the prediction models.

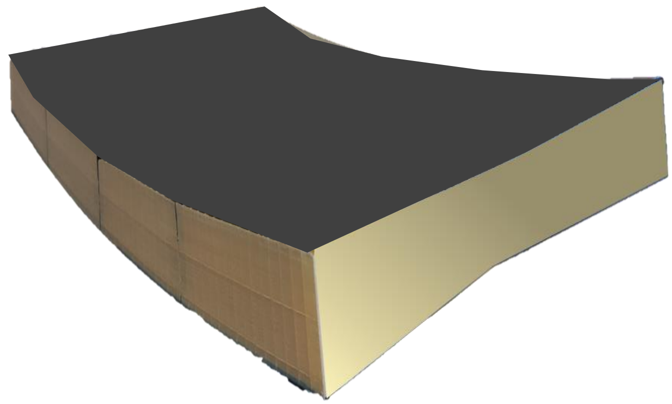


Figure 14 Novel acoustic liner demo panel

2.7 Test Plans and Future Studies

The novel liner design has progressed to a TRL/MRL of 4 through testing in the GFIT and manufacturing of a demo liner panel which represents a portion of a full-scale acoustic liner. The next step in the maturation process is to test the design on a full-scale engine static acoustic test. As community noise remains an important aspect of aircraft and engine design, this technology will remain in GE's technology pipeline.

Section 3 Fan Source Strength Reduction

3.1 Background

The interaction between fan wakes and stationary Outlet Guide Vanes (OGVs) is an important noise source for modern high bypass ratio turbofan engines. Traditional methods to reduce the interaction noise include spacing the guide vanes further from the fan and specifically designing the geometry of the guide vanes to produce a time lag for the arrival of the wake on different part of the vane (i.e. vane sweep and lean). Vane sweep and lean have been employed by GE to accomplish this phase lag and noise reduction in production engines. However, as OGVs become more optimized in engines, sweep and lean have become less ideal from a structural efficiency standpoint due to the weight and engine length implications to a simple swept or leaned design. For this reason, GE has been researching alternate fan and OGV designs that reduce fan-OGV interaction aero-acoustic sources without the system level drawbacks.

3.2 Advanced Fan Design

The goal of the CLEEN II Fan Noise Source Strength Reduction Task is to achieve a total of 1.0 EPNdB noise reduction relative to a baseline Fan-OGV design with negligible performance penalty. First, a sensitivity study was performed to identify the dominant component sources (i.e. tones vs. broadband) driving system level noise. The results of this study were used to establish weighting factors that drove the optimization and design approach for the fan and OGV system.

3.2.1 Design Approach

The first step is to identify a geometry that provides more acoustic benefit than the reference design. An existing, recent GE fan system design was used as a starting point. A simple model of the acoustic radiation from the fan and OGVs was used to guide airfoil shaping changes. At low frequencies noise radiated from the OGV is directly proportional to the unsteady sectional lift which in turn is proportional to the unsteady incidence caused by the fan wakes or gusts, see Figure 15. These sectional lift dipoles vary in magnitude and phase over the span and project on to the duct acoustic modes to create in-duct noise (the equation in Figure 15 uses a circular duct mode as an example). The radial integration of these sources projected onto the dominant duct modes thus provides a surrogate for noise source levels which can be used to estimate the benefit of design changes.

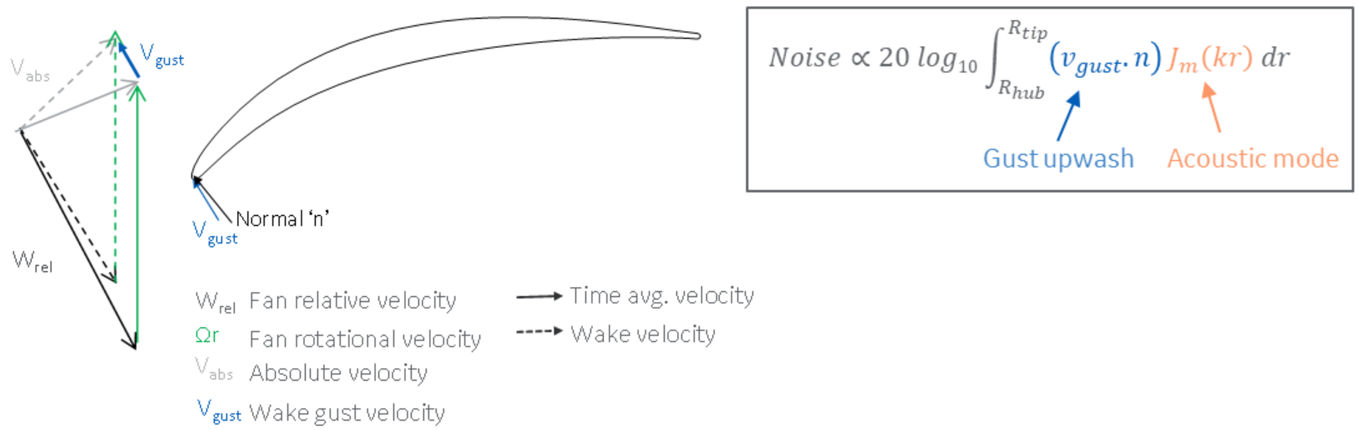


Figure 15: Reduced order model for design guidance.

Incoming velocity triangle from the fan shown where v_{gust} is the perturbation velocity due to the wake in the OGV frame of reference.

Design progression was guided by the reduced order model. Through the design stages of Conceptual Design Review (CDR), Preliminary Design Review (PDR), and Detailed Design Review (DDR) there were significant acoustic improvements as determined by GE calibrated Computational Aero-Acoustics (CAA) modeling as shown in Figure 16.

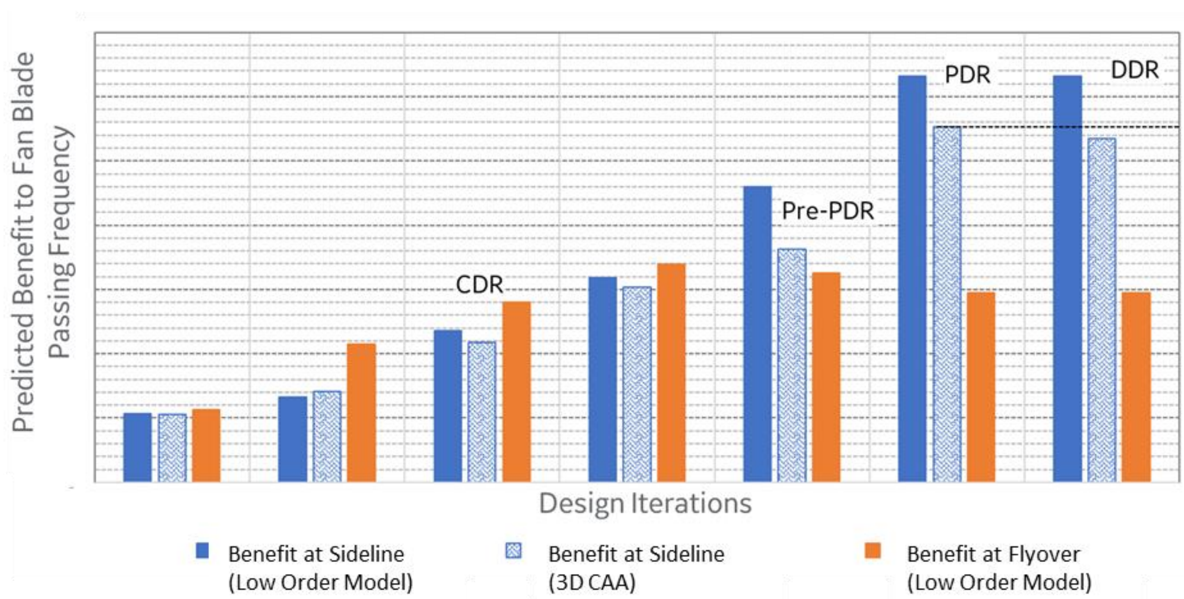


Figure 16: Fan Design Evolution Increasing Noise Benefit

From the optimal design for acoustics, detailed aerodynamic design changes were made to maximize smoothness and maintain similar efficiency as the baseline design. The trade between acoustic benefit and aerodynamic efficiency will be characterized in the next stages of the technology demonstration. Measured aerodynamic and acoustic data from a rig and/or full-scale test under a future project will be used to inform the appropriate aero vs. acoustic trades needed for eventual technology insertion into a product.

3.2.2 DDR Acoustic Status

Full wheel CAA was used to predict the noise benefits of the DDR design. The predicted reductions in unsteady pressures support the substantial noise reductions that are expected from this design. The predicted noise reductions are also consistent with the lower order model used to guide design improvements in the early design phases. At some conditions, the CAA predicts increased noise benefits beyond that of the initial model.

The predicted tone noise benefits were multiplied by the tone noise sensitivities to project an expected system level noise benefit with an expected technology realization factor consistent with previous fan noise technology programs. The resulting benefits are projected to meet/exceed the CLEEN II community noise goal for this technology for the Advanced Acoustics task, Figure 17.

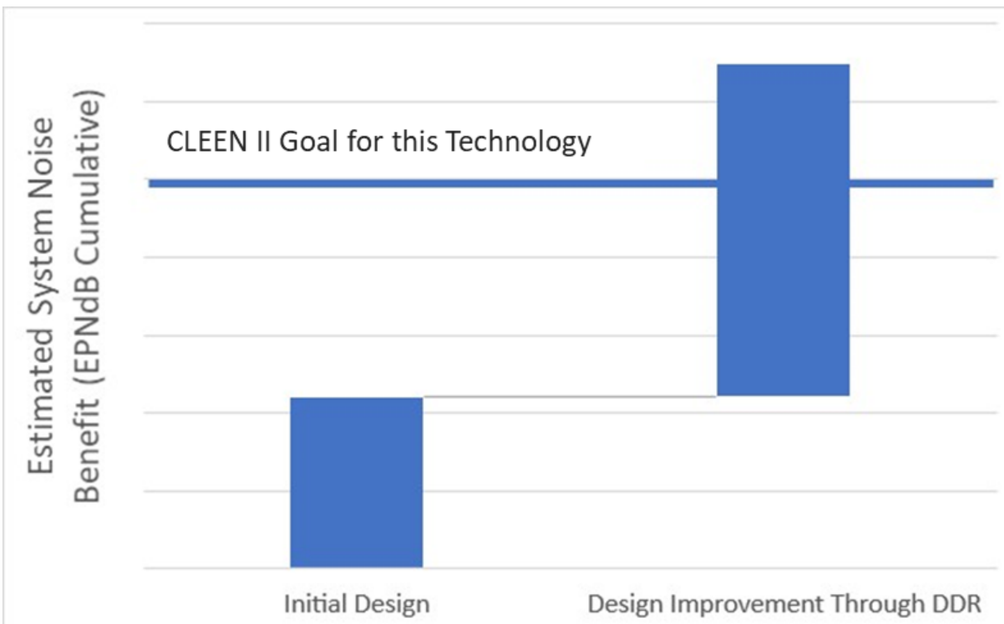


Figure 17: Predicted system level noise benefits for CLEEN II design derived from full wheel CAA

3.3 Mechanical and Manufacturing Assessments

After the aero-acoustic PDR, and in preparation for rig testing, more detailed mechanical and manufacturing assessments were performed. A summary of the mechanical risk assessments and actions is shown in Figure 18. No major mechanical risks are expected. Previous testing of the baseline design allows for aeromechanical responses to be scaled to the current design and the risk is projected to be low.

Criterion	Risk Level
Fan Blade Out Ultimate Loads	Low
Max Steady State Stress	Low
Mechanical responses in operating range	Low
High and Low Cycle Fatigue Capablity	Low
Flutter Risk	Low

Figure 18: Summary of mechanical risk assessment for rig scale aero design.

Finally, a manufacturing assessment taking into consideration the geometric complexity, tolerance requirements, cost and schedule was performed to determine the best method of manufacturing the part. Inspection with a Coordinate Measuring Machine (CMM) will be performed on the manufactured part to quantify deviations from design intent to accurately account for any debits to performance or acoustics.

3.4 Sub-scale Hardware Manufacture

Manufacturing of a sub-scale part began after the design reviews and planning were complete. In-process part inspection showed excellent quality. The reference design was already manufactured under a previous program. The new hardware fits into the same model rig as the reference design, allowing for a direct back-to-back noise comparison in a wind tunnel using a Universal Propulsion Simulator (UPS) rig.

3.5 Test Plans and Future Studies

The fan source strength reduction design has progressed to a TRL/MRL of 3 through detailed design and analysis of several concepts. The design is predicted to meet/exceed the initial CLEEN II goal for the project of 1 EPNdB cumulative noise reduction relative a baseline product design. The next step in the maturation process is to test the design on a sub-scale wind tunnel aero-acoustic test to achieve TRL 4. A full-scale static engine test will then be used to bring the technology to TRL 6. As community noise remains an important aspect of aircraft and engine design, this technology will remain in GE's technology pipeline.

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