

NASA's Quiet Electric ENgines (QUEEN): Summary of the Acoustic Tests of the QUEEN V1

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Noise produced by an electric ducted fan system was measured in tests at the NASA Glenn Research Center Acoustical Testing Laboratory. Main components of the system include a Commercial-Off-the-Shelf fan, shroud, motor, and Electronic Speed Controller, plus a custom-designed inlet bellmouth, and four experimental inlet duct acoustic liners. Fan speed and noise were measured in this static ground test of the propulsor. This propulsor prototype is one of NASA's Quiet Electric ENgines (QUEENs) and is designated the 'QUEEN V1.' The Quiet Electric ENgines are being developed for the 25% scale model of the Subsonic Aft Engine (SUSAN) Flight Research Vehicle and are intended to explore the potential of distributed electric propulsion for large single-aisle aircraft. Results indicated that inlet duct acoustic liners reduced tone and broadband noise as compared to a hardwall inlet duct. Predicted performance of the Perforate-Over-Honeycomb liner compared well with measurements from an array of far field microphones. Inlet acoustic liners are just one method for mitigating noise for electric ducted fans for aircraft propulsion systems. Lessons learned will be used to guide development of future QUEEN prototypes. Results of a thermal test of the Electronic Speed Controller are presented in a separate report.

I. Introduction

Air and noise pollution from large single-aisle aircraft engines is a widespread problem. Pollution from aircraft contributes to climate change, is associated with serious health problems, raises social justice questions, and is linked to reductions in biodiversity. Because noise pollution from our transportation system is widespread, the health and wellness of millions of people is affected. The World Health Organization (WHO) has attempted to study correlations between noise pollution from the transportation system and human health problems. WHO studies suggest that when humans experience long-term exposure to transportation noise that they face an elevated risk of a variety of cardiovascular diseases.[1] Other organizations have studied the disparate impacts of noise on different socioeconomic groups, which raises social justice questions.[2–4] Researchers for the U.S. National Park Service (NPS) have quantified the soundscapes in the national parks and note that the extensive transportation network in the United States has practically eliminated natural quiet conditions for most of the country.[5,6] Biologists for the NPS have observed changes in animal behavior with exposure to anthropogenic noise, which threatens the survival of wildlife.[7]

Innovation is needed to develop a more sustainable air transportation system accessible to a growing world population and NASA is exploring the electrification of aircraft propulsion. Developing hybrid/electric engines for large single-aisle aircraft (~180 passengers) and integrating these engines onto novel airframes is a formidable challenge. New design and optimization tools are needed, and data to validate these tools will be needed, too. New aircraft will need to prove flightworthiness, and certification requirements are not yet established for these new configurations, posing financial and technical risks to manufacturers.

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It is the combination of social, technological, and organizational complexity that makes research on electric propulsion for large aircraft a focus of international attention. Intricate cooperation between technologists within government, industry, and academia will be needed. Since there are international regulations on aircraft noise and emissions safer, cleaner, and quieter aircraft have a competitive advantage in the global market. NASA's research reported here is aligned with a variety of goals, policies, and plans such as those written by the International Civil Aviation Organization's (ICAO) Committee Aviation Environmental Protection (CAEP) Working Group [8] the U. S. Federal Aviation Administration.[9]

The Subsonic Single Aft eNginE (SUSAN) concept aircraft is guiding the experiment described in this report and is notionally depicted in Figure 1. This concept aircraft is being used to explore the potential of distributed electric propulsion for large single-aisle aircraft. Quiet electric engines (QUEENS) are envisioned as wing-mounted propulsors for the SUSAN 25% Flight Research Vehicle (FRV). Research supporting the development of the propulsion system for the SUSAN aircraft is multifaceted, and collaborations across different NASA centers is ongoing.

This is not the first time that NASA has studied distributed wing-mounted propulsors for aircraft. Researchers at the NASA Glenn Research Center (GRC), which was formerly known as the NASA Lewis Research Center (LeRC) explored distributed propulsion for aircraft at least as early as 1970.[10,11] Figures 2-5 show photographs from a series of experiments exploring Short Take Off and Landing (STOL) and vertical Short Take Off and Landing (vSTOL). Literature searches revealed at least eleven NASA Technical Memoranda associated with "Blown Flap Noise" research [12–22] and seventeen NASA Technical Memoranda associated with "STOL acoustics" research [14,15,19,23–36]

More recently, researchers at NASA GRC have also studied the acoustic performance of several 0.56 m (22 in) diameter fans models in the NASA GRC 9-by 15-Ft Low Speed Wind Tunnel: the Source Diagnostic Test Fan (SDT), the Advanced Ducted Propulsor (ADP) and the Quiet High Speed Fan (QHSF).[37] While these experiments were intended to help understand and improve the performance of turbofan engines installed on tube-and-wing airframes, the results may inform the design of similar-sized motor-driven wing-mounted considered as propulsors for futuristic airframes.

In 2023, NASA GRC tested a prototype designated the QUEEN V2 propulsor that featured a Commercial-Off-the-Shelf (COTS) Electric Ducted Fan (EDF) with a custom-built square-to-round inlet and heat exchanger around the motor.[38] The square-to-round inlet was chosen to mimic the rectangular inlet suggested by the SUSAN concept aircraft. The custom-built heat exchanger around the motor was integrated into the system since thermal management of large hybrid/electric aircraft is a concern for NASA and the aviation industry.[39,40] The test of the QUEEN V2 performed in the NASA GRC Thermal Laboratory demonstrated the basic functionality of the experimental fan system and began to characterize the aerodynamic, mechanical, electrical, and thermal performance of the prototype system.

Several recommendations were made after the QUEEN V2 test was finished. The first recommendation was to perform acoustic tests in the NASA GRC Acoustical Testing Laboratory (ATL), since including acoustics early in the development of these propulsors is essential as these prototypes and regulations on hybrid/electric aircraft evolve. The second recommendation was to redesign the fan system without the square-to-round inlet and without the heat exchanger around the motor. The second recommendation was made since the rotor of the QUEEN V2 experiment failed at the end of the experiment in 2023. While the root cause of the rotor failure is not well understood because the prototype was sparsely instrumented, unsteady loads on the rotor caused by the custom-built inlet and heat exchanger were a concern. Unsteady loads on the rotor would result from ingesting non-uniform flow through the square-to-round inlet. Fittings from the cooling system also protruded into the inlet duct and disturbed the flow entering the fan and contributed to the unsteady loads on the rotor.

Taking those recommendations into consideration, a new prototype was developed in 2024, shown in the illustration of Figure 6. The new prototype was designated the "QUEEN V1," since the team was notionally taking a step back from the ambitious square-to-round inlet design with the liquid-cooled motor to shift focus to the fan acoustics with a simpler fan system. There were two objectives of the test of the QUEEN V1 in the NASA GRC ATL. The first objective was to measure noise of the QUEEN V1 and quantify the effectiveness of four inlet-duct acoustic liner prototypes at different rotor speeds. The second objective was to characterize the thermal performance of the Electronic Speed Controller (ESC) mounted on a cold plate at different rotor speeds. The following sections will present details of the QUEEN V1 more thoroughly. Features of the test facility, the experimental apparatus, and testing procedure will be explained. Results of the acoustic tests of the QUEEN V1 in the NASA GRC ATL are presented and discussed in this report. Results of the thermal test of the ESC are presented in a separate report. Finally, recommendations for future investigations are offered.

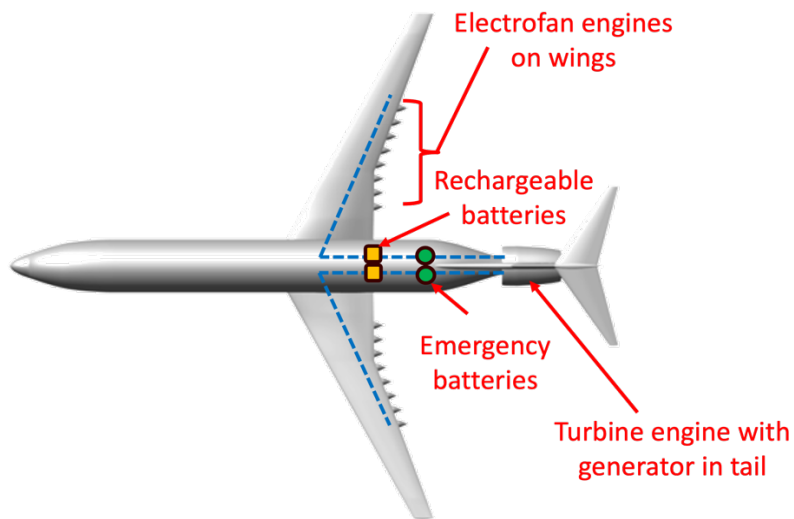


Figure 1: NASA's SUBsonic Single Aft eNginE (SUSAN) Concept Aircraft.



Figure 2: A Blown Flap model in the NASA Lewis 9- by 15-Ft Low Speed Wind Tunnel; Image: NASA 1970-C-01199; see Reference 2.

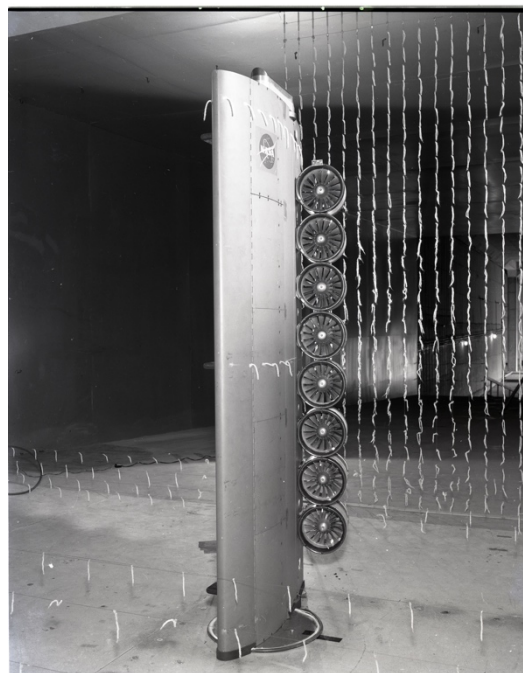


Figure 3: A Fan-on-Flap model in the NASA Lewis 9- by 15-Ft Low Speed Wind Tunnel; Image: NASA C-1970-02412; see Reference 11, Figure V-23, page 163.



Figure 4: A Blown Flap Model; Image: NASA 1970-C-03034; see Reference 11, Figure VI-32, page 201.



Figure 5: Fan in Wing Model in the NASA Lewis 9- by 15-Ft Low Speed Wind Tunnel; Image: NASA 1969-C-03531, see Reference 11, Figure VI-32, page 167.

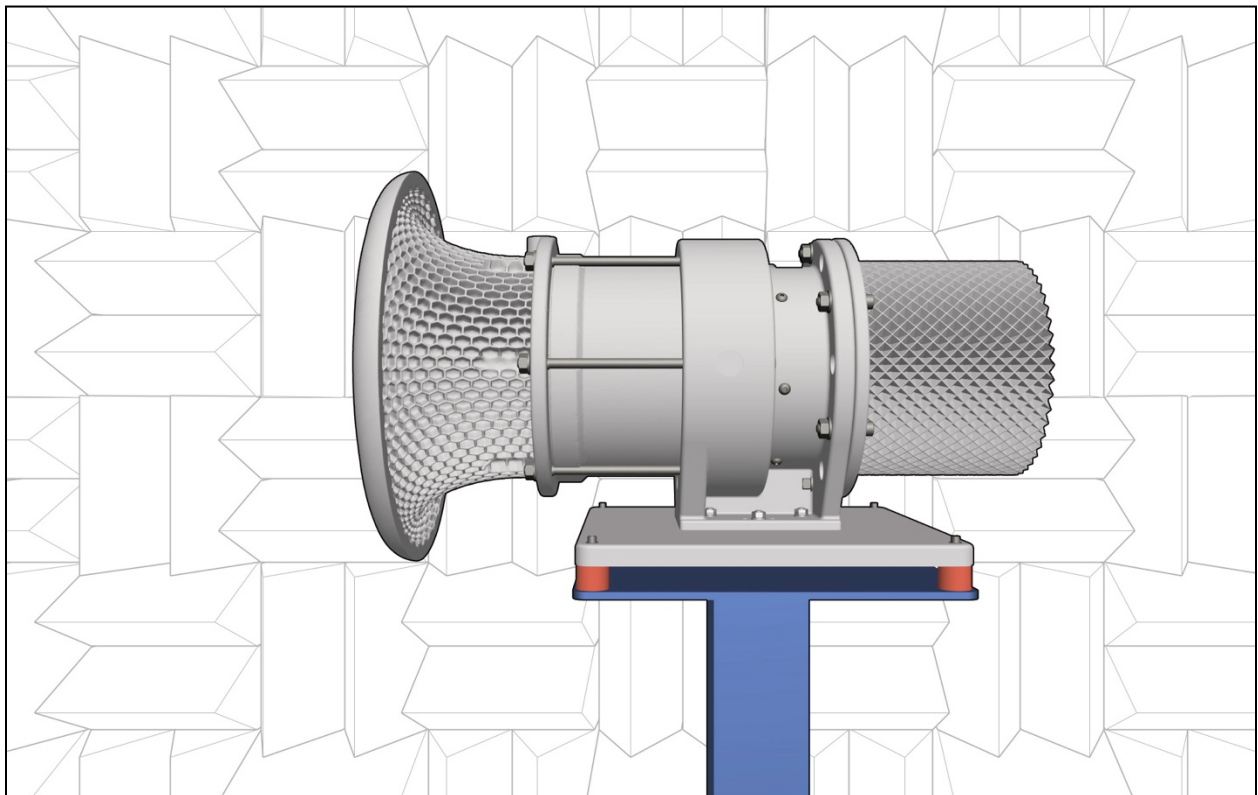


Figure 6: Illustration of the NASA QUEEN V1 prototype installed in the Acoustical Testing Laboratory.

II. Description of the QUEEN V1

The QUEEN V1 was designed, fabricated, and tested in 2024 included a Commercial-Off-the-Shelf Electric Ducted Fan, which is typically sold to remote-control airplane hobbyists. The COTS EDF featured a rotor, stator, carbon fiber rotor shroud, and motor. The COTS EDF had ten rotor blades and seven stationary Outlet Guide Vanes downstream of the rotor. The maximum rotor test speed was chosen to be 25,400 rpm, which was less than the speed at which the rotor failed during the 2023 test (29,000 rpm), and well below the maximum speed of the motor (45,000 rpm). The maximum thrust of the QUEEN was estimated to be 133 N (30 lbf) based on tests of the QUEEN V2 in 2023. The QUEEN V1 and the QUEEN V2 used the same type of COTS EDF. Selected specifications are given in Table 1 and photographs of the COTS EDF are shown in Figures 7 and 8.

In the QUEEN V1, the thin black COTS carbon fiber shroud fit inside the thicker white a NASA custom-designed containment shroud, as shown in Figure 9. The NASA containment shroud was 3D-printed at NASA GRC from a glass-filled photopolymer resin (Formlabs Rigid 10K material) using a stereolithography additive manufacturing process. The glass increases the stiffness of the polymer. The NASA containment shroud provided additional protection since it fit over the carbon fiber shroud that was part of the COTS EDF. The 3D printed fan shroud was chosen to be 5.71 cm (2.25 in) long and 2.20 cm (0.865 in) thick, intended to contain a rotor blade failure at maximum test speed using NASA design guides for rotor containment shields.

Additionally, to help avoid the need for a bulky rotor containment system which would have significantly impacted the acoustic results, a “soft” emergency stop was put into place. The system was able to bring the propulsor to a pre-set safe speed without stopping the rotor entirely. Previous experiments like the QUEEN V2 have shown that abruptly stopping the rotor during a static ground test results in a loss of cooling air, which can subsequently melt the enamel on the motor windings leading to a loss of the motor. The inclusion of this soft stop allowed a rapid but safe shutdown of the propulsor should the model deviate from expected performance.

The QUEEN V1 also featured a NASA-designed and 3D-printed bellmouth and aft duct section, shown in the cross-sectional illustration of Figure 10. The inlet bellmouth conditioned the flow entering the fan. The aft duct section was added mostly to redirect the noise in the aft section of the fan and not for aerodynamic purposes. The aft duct did not feature any struts, so the cables connecting the motor to the controller were exposed to the exhaust flow.

A modal analysis of the fan blades was conducted with ANSYS Workbench 2021 R1 for a range of speeds, and results were compared to potential excitation sources using a Campbell diagram shown in Figure 11. The analysis assumed the fan blades were composed of a 40% carbon fiber filled nylon, approximated by the mechanical properties of Complet® LCF4-PA66. Results from the analysis showed that the most critical source of excitation caused by potential imbalances in the fan system, also known as the first-engine-order sources, would not excite blade modes within the testing speed range (0 to 25,400 rpm). Other potential vibration sources were also evaluated, including a sixth-engine-order (6EO) excitation associated with the electric motor's six-pole configuration and a seventh-engine-order (7EO) excitation related to interactions with the seven stator blades. This is shown in the Campbell diagram by the 6EO and 7EO lines intersecting the first blade bending mode frequency. Both the 6EO and 7EO cases were deemed unlikely to induce significant blade excitations. No other vibration sources of concern were identified. Accelerometers were mounted on the rotor and shroud section to detect vibrations from any unexpected blade excitations at specific rotor speeds so that the test operators could avoid these speeds if vibrations were excessive.

Finally, the QUEEN V1 included four inlet duct acoustic liners, shown in Figures 12 to 15. Each liner was 6.60 cm (2.60 in) long and was installed between the EDF and the bellmouth that NASA custom-designed and 3D-printed. The Hardwall Liner shown in Figure 12 was used as a baseline, since it was not intended to absorb any sound produced by the EDF. The Perforate-Over-Honeycomb liner shown in Figure 13 was designed to absorb sounds in the 4000 Hz to 10 kHz range. The Perforate-Over-Honeycomb Liner had a perforated face sheet that was 1.02 mm (0.04 in) thick and each hole in the perforate had a diameter of 1.52 mm (0.06 in), so that the Percent-Open-Area (POA) of the face sheet was 16%. Each honeycomb cell behind the perforated face sheet was 0.76 cm (0.30 in) deep and the hexagonal cell flat-to-flat distance was 0.635 cm (0.25 in). The facesheet dimensions and the depth of the cavity were the same for each of the acoustic liner prototypes, determined by the design of the honeycomb liner.

The Bulk Absorber Liner shown in Figure 14 featured the same perforated face sheet design but used a 1.10 cm (0.43 in) layer of PrimaLoft One synthetic microfiber insulation material slightly compressed to fill the 0.76 cm (0.30 in) thick empty cavity behind the perforated face sheet. A removeable end cap held the bulk absorber inside the liner.

Finally, the bio-inspired Broadband Acoustic Absorber liner shown in Figure 15 featured the same perforated face sheet design but used a 0.30 in thick layer of loose hollow biomimetic reeds to fill the empty cavity behind the perforated face sheet. A removeable endcap was used as a retainer to hold the reeds in place. These biomimetic reeds were like the ASA-2.0 reeds described in Reference [41]. However, unlike the ASA-2.0 prototype, the reeds in the QUEEN V1 bio-inspired Broadband Acoustic Absorber liner were printed using stereolithography from the Formlabs Rigid 10k material and were 65.5 mm (2.58 in) long.

Table 1: Selected specifications of the QUEEN V1

Rotor tip diameter	13.0 cm (5.11 in)
Duct inner diameter	13.3 cm (5.23 in)
Number of rotor blades	10
Number of outlet guide vanes	7
Maximum motor rotational speed	45,000 rpm
Tip clearance	1.5 mm (0.060 in)
Maximum rotor speed during the test in ATL	25,400 rpm
Maximum tested power during the test in ATL	6.33 kW



Figure 7: The COTS EDF with rotor and carbon fiber shroud visible, forward looking aft.

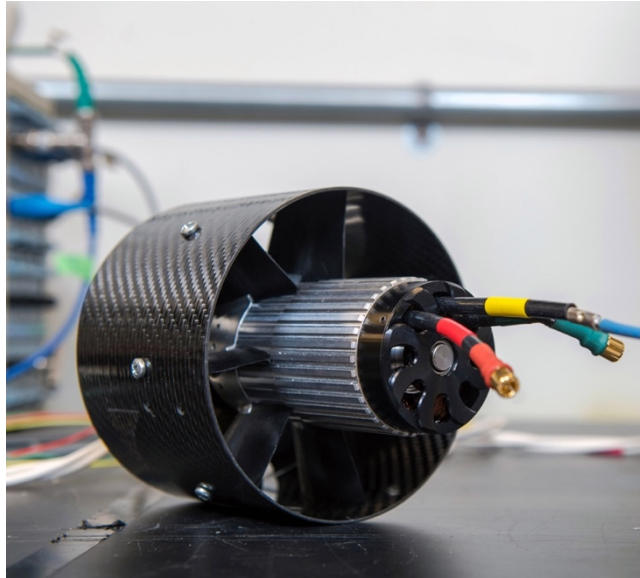


Figure 8: The COTS EDF with the carbon fiber shroud, outlet guide vanes, and motor visible, aft looking forward

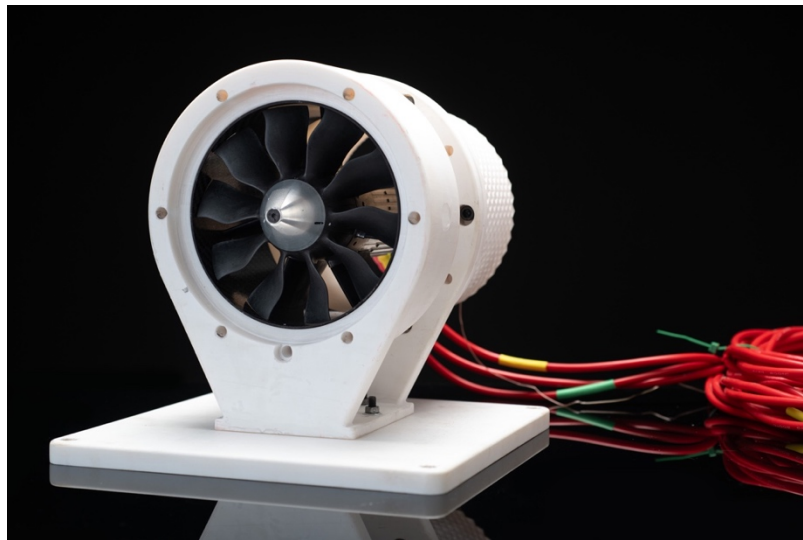


Figure 9: The COTS EDF installed in the NASA custom-designed 3D printed containment shroud and aft duct and pedestal mounting plate visible. The bellmouth and inlet duct acoustic liner sections were not installed in this photograph.

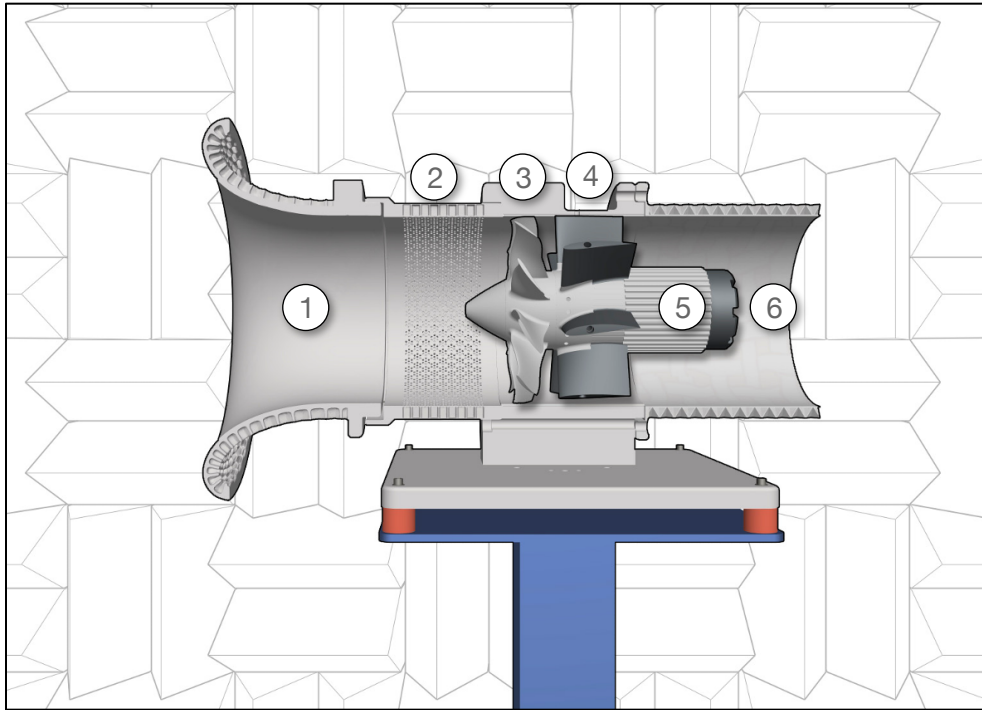


Figure 10: A cross-sectional illustration of the QUEEN V1 in the ATL. Main components of the system include: 1) bellmouth, 2) inlet duct acoustic liner, 3) rotor and shroud section, 4) outlet guide vane section, 5) motor, 6) aft duct.

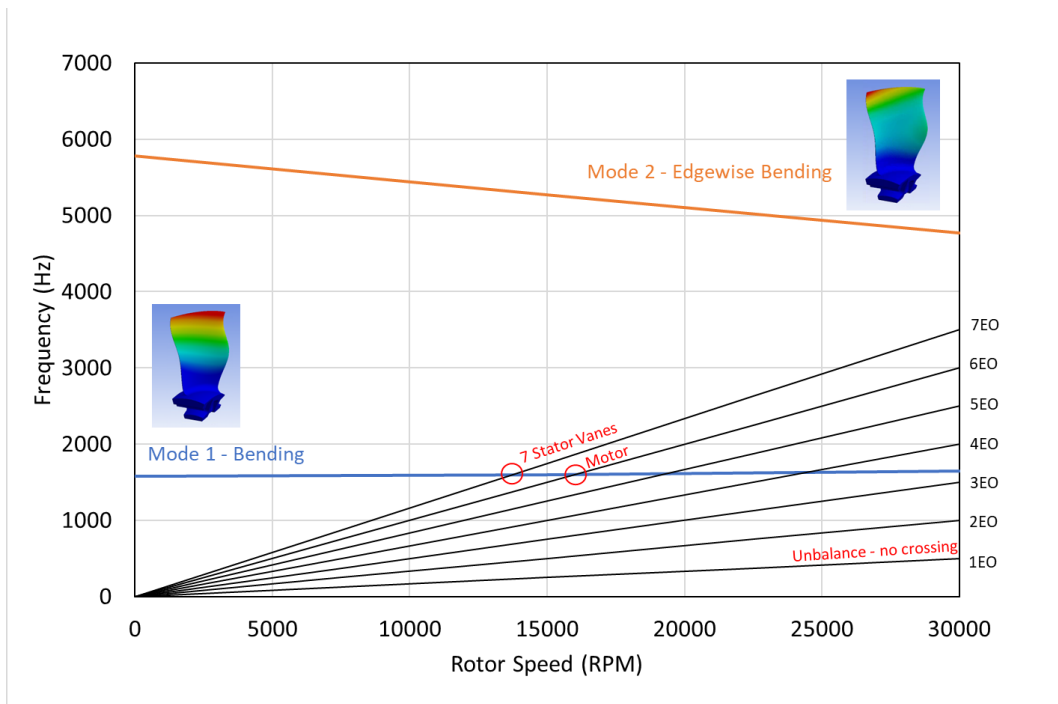


Figure 11: Campbell Diagram for the QUEEN V1 for the ATL experiment, blade-alone modes.



Figure 12: The QUEEN V1 Hardwall Inlet Duct

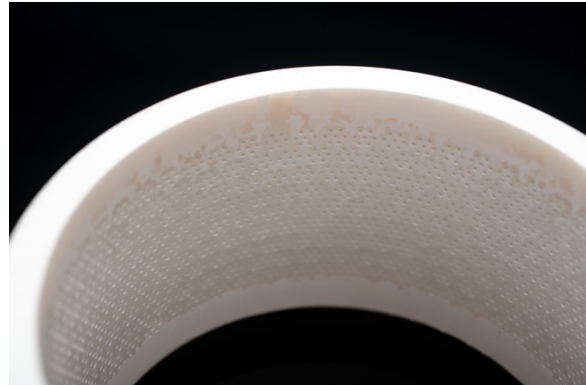


Figure 13: The QUEEN V1 Perforate-Over-Honeycomb Inlet Duct Acoustic Liner



Figure 14: The QUEEN V1 Bulk Absorber Inlet Duct Acoustic Liner



Figure 15: The QUEEN V1 bio-inspired Broadband Acoustic Absorber Inlet Duct Acoustic Liner

III. Description of the Experiment

In 2024 the QUEEN V1 was tested in the NASA Glenn Research Center (GRC) Acoustical Testing Laboratory (ATL). The ATL was chosen since this facility was available at the time of the scheduled test and would allow the team to check out the equipment needed to measure the relative effectiveness of different inlet duct acoustic liner prototypes. The test operators controlled and monitored test equipment remotely from a separate control room located adjacent to the anechoic chamber, which was a safety and comfort benefit.

The NASA GRC ATL is a reconfigurable anechoic/hemi-anechoic chamber. The internal dimensions of the chamber are 6.4 m (21 ft) x 5.2 m (17 ft) x 5.2 m (17 ft). For this experiment, the ATL chamber was initially set up in the fully anechoic configuration, with fiberglass wedges 0.86 m (34 in) deep completely covering the walls and the floor. Steel grating was mounted over the floor wedges for personnel access while the ATL is in the anechoic configuration. However, to reduce recirculation inside the chamber during this test, the two sets of large bay doors were opened (each door is 2.7 m (9.0 ft) x 3.1 m (10.0 ft)).[42] Since the doors were open, barricades were installed on either side of the chamber to prevent people working in the building from inadvertently entering the ATL during testing where they would be exposed noise and the various hazards of testing experimental fan systems. Noise levels were measured at the barrier to verify that hearing protection was not needed in areas outside of the barrier per the usual occupational health and safety protocols at NASA GRC. The experimental apparatus, the instrumentation installed on the QUEEN V1, the test objectives and procedure are discussed in more detail in the sections below. An illustration of the equipment installed in the chamber and in the control room is shown in Figure 16.

A. Experimental apparatus

The main components of this experiment are indicated notionally in the schematic shown in Figure 16. Electrical power was supplied to the QUEEN motor by a 10 kW DC power supply. Motor speed was controlled by a COTS Electronic Speed Controller that was kept cool by a cold plate. A stand-alone portable cooling cart allowed deionized water to be pumped, regulated, and measured as it flowed through the ESC cold plate. When running the ESC on the cold plate, the chiller temperature was set to be equal to the ambient temperature in the control room to avoid condensation that could cause an electrical short. The fan assembly was placed near the center of the ATL chamber, mounted to a pedestal attached to the concrete floor accessed by removing one of the floor acoustic wedges. Vibration dampers, shown in red in Figure 6, were installed between the base of the sleeve holding the fan and the pedestal.

B. QUEEN V2 instrumentation

A variety of measurements were recorded to characterize the noise produced by the fan at different operating speeds and the thermal performance of the Electronic Speed Controller. The set of instrumentation included microphones, thermocouples, a pressure transducer, accelerometers, an optical speed sensor, current probes, voltmeters, oscilloscopes, a power analyzer, and a data acquisition system. The QUEEN V1 motor was exposed to the air flow in the exhaust duct. The motor surface temperatures were measured for both the motor and housing as and the motor windings. The ESC temperatures were measured separately using embedded probes from the supplier. For the electrical data, current probes and voltmeters were used to directly measure the current and voltage at the DC supply side as well as the AC motor side. A power analyzer was used to obtain efficiencies across the ESC.

Eleven 0.64 cm (0.25 in) microphones (PCB Piezoelectronics Model 378C01) were used to measure noise on a 1.22 m (4.00 ft) radius from a center point located at the fan centerline at the rotor blade leading edge, as shown in Figure 17. There were nine microphones spaced 22.5° apart around the inlet and two microphones spaced +/- 45° apart around the fan exhaust. The microphones were mounted on poles at the height of the fan centerline which was 2.58 m (101.5 in) above the anechoic chamber floor, or 1.6 m (64.0 in) above the grating covering the sound absorbing wedges that covered the floor. Microphone measurements were recorded using an HBM Gen3i data acquisition system.

C. Test objective and procedure

As mentioned earlier, there were several objectives. The first purpose of the experiment was to measure the noise and speed from the QUEEN V1 with and without inlet duct acoustic liners. The second objective was to characterize the performance of the Electronic Speed Controller a cold plate to keep the circuitry within an acceptable thermal operating range. This report describes the acoustic results, and a separate report describes the ESC thermal test.

For each test, motor voltage (80 V) was set first. The ESC was then commanded to different throttle setting using a Pulse Width Modulated (PWM) signal created by a signal generator. For the acoustic test, microphone measurements were recorded at rotor speeds of 0%, 10%, 80%, 90% and 100%, (0 rpm, 2,700 rpm, 20,320 rpm, 22,860 rpm, 25,400 rpm, respectively).

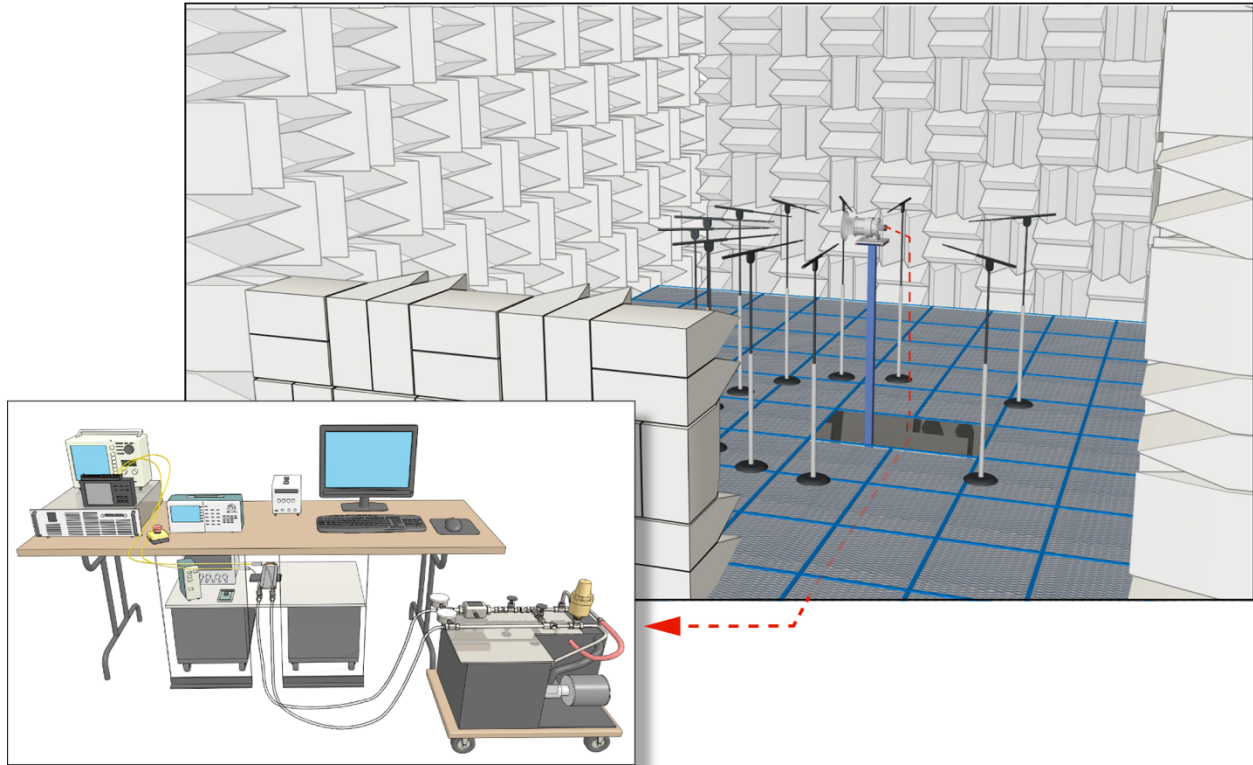


Figure 16: Illustration of the QUEEN V1 experimental apparatus installed in the NASA GRC Acoustical Testing Laboratory. The inset illustrates the equipment that was installed in the ATL control room.

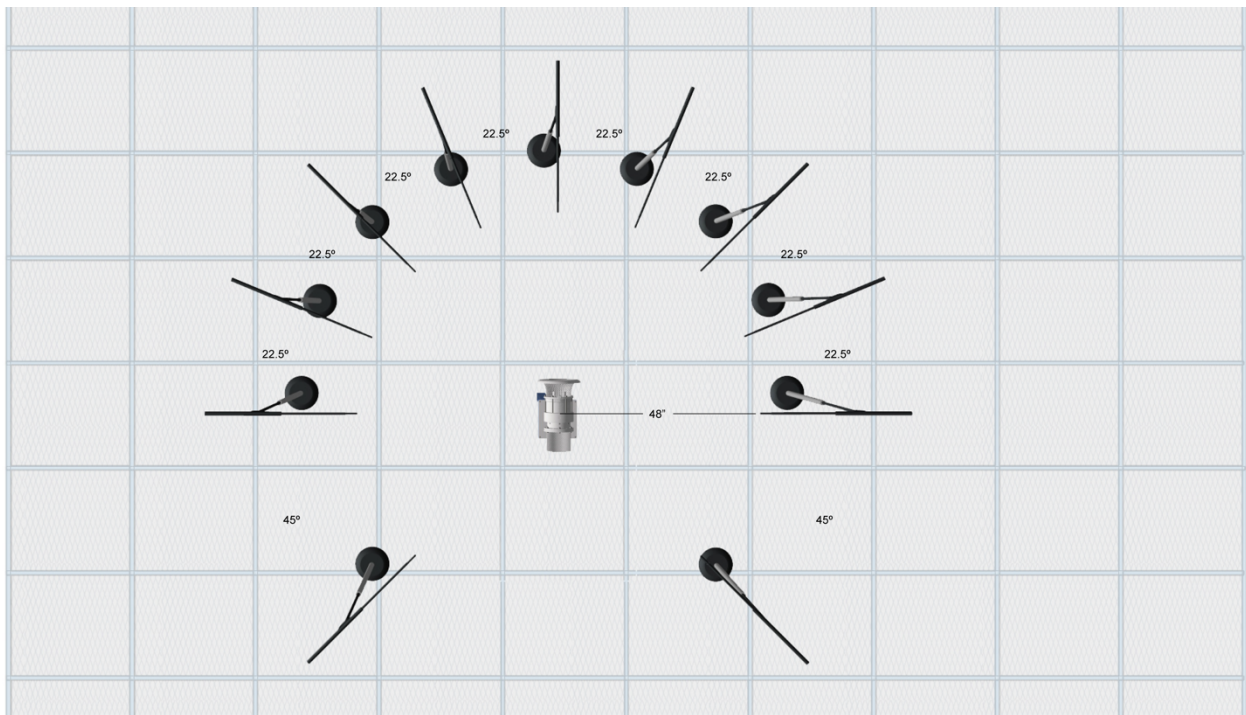


Figure 17: Illustration of the microphone array used to quantify the performance of the QUEEN V1 inlet duct acoustic liner prototypes.

IV. Discussion of Acoustic Results

An array of microphones was used to quantify the performance of four inlet duct acoustic liners installed between the bellmouth and the rotor of the QUEEN V1. One hypothesis was that a Perforate-Over-Honeycomb (POHC) liner could be designed to be effective at reducing tone and broadband noise for the QUEEN V1. The team was also curious about POHC liner would compare to the acoustic performance of a Bulk Absorber and a bio-inspired Broadband Acoustic Absorber with the same cavity depth and facesheet design as the POHC liner. Bulk absorbers could be used for noise reduction in ventilation fans rather than aircraft propulsion systems, since aircraft engines are exposed to the weather and fibrous bulk absorbers are often not suited for that application since they can absorb water and may not be durable enough. Proof of concept tests of NASA's bio-inspired Broadband Acoustic Absorber in normal incidence impedance tubes demonstrated that 50.80 mm (2.00 in) thick prototypes absorbed sound below 1000 Hz better than Bulk Absorber and POHC prototypes of similar thicknesses. While the QUEEN V1 inlet duct acoustic liners were only 0.76 cm (0.30 in) thick, this experiment was also a manufacturability experiment for the bio-inspired broadband acoustic absorber. This was the first example of annular bio-inspired Broadband Acoustic Absorber installed in a fan system.

Several calculations were performed to optimize the POHC liner for the QUEEN. First, the normalized impedance for the QUEEN V1 POHC liner was predicted, as shown in Figure 18. The physics-based simulation tool COMSOL Multiphysics® [44] was used to iterate on various design concepts to compute the impedance. An interior impedance boundary condition was used that implements an iterative two parameter model, previously validated in [45]. Then predicted normalized impedance was used as input to a low-fidelity grazing flow simulation to estimate the expect level of noise attenuation at the rotor max testing speed. An assumption was made that the local duct Mach number would be low (<0.1), which allowed for a low-fidelity approach. A liner section corresponding to the length of the lined inlet resulted in an estimated 12 dB reduction was predicted at the first harmonic of the blade passing frequency and 4 dB for the second harmonic of the blade passing frequency at a rotor speed of 25,400 rpm.

The plot in Figure 19 shows power spectral density for frequencies ranging from 0 to 20 kHz for Microphone 3 in the array around the fan inlet and bellmouth for each of the four inlet liners: the Hardwall Liner, Perforate-Over-Honeycomb Liner, Bulk Absorber Liner, and the bio-inspired Broadband Acoustic Absorber. Data was taken with the fan at 25,400 rpm. The spectra show tones at blade passing frequency harmonics prominent above the broadband noise, typical of ducted axial fans used for aircraft propulsion. Tones may be obscured in part by the air recirculation in the ATL, and further testing in a larger facility may help discern this factor.

The plot in Figure 20 shows power spectral density for Microphone 3 in the array around the fan inlet and bellmouth for the Hardwall Liner compared to the Perforate-Over-Honeycomb Liner for the same frequency range, 0 to 20 kHz, at maximum test speed of 25,400 rpm. The plot in Figure 21 examines the first and second blade passing tones more closely. The Perforate-Over-Honeycomb liner reduced the first blade passing tone by approximately 11 dB, and reduced the second blade passing tone by approximately 3 dB.

The plot in Figure 22 shows power spectral density for Microphone 3 in the array around the fan inlet and bellmouth for the Hardwall Liner compared to the Bulk Absorber Liner for the same frequency range, 0 to 20 kHz, at maximum test speed of 25,400 rpm. The plot in Figure 23 examines the first and second blade passing tones more closely. The Bulk Absorber Liner reduced the first blade passing tone by approximately 10 dB, and reduced the second blade passing tone by approximately 7 dB.

The plot in Figure 24 shows power spectral density for Microphone 3 in the array around the fan inlet and bellmouth for the Hardwall Liner compared to the bio-inspired Broadband Acoustic Absorber Liner ('Bioliner') for the same frequency range, 0 to 20 kHz, at maximum test speed of 25,400 rpm. The plot in Figure 25 examines the first and second blade passing tones more closely. The Bioliner reduced the first blade passing tone by approximately 5 dB, and reduced the second blade passing tone by approximately 4 dB. In this plot, the Bioliner also appeared to reduce the sound pressure level at 1226 Hz compared the Hardwall liner, an observation that warrants further investigation.

The plot in Figure 26 shows is a directivity plot of Overall Sound Pressure Level (OASPL) for each of the four liners at 25,400 rpm. All the acoustic liners reduced the sound pressure level of the first blade passing frequency tone. Including acoustics early in the design of hybrid/electric aircraft like the SUSAN continues to be important.

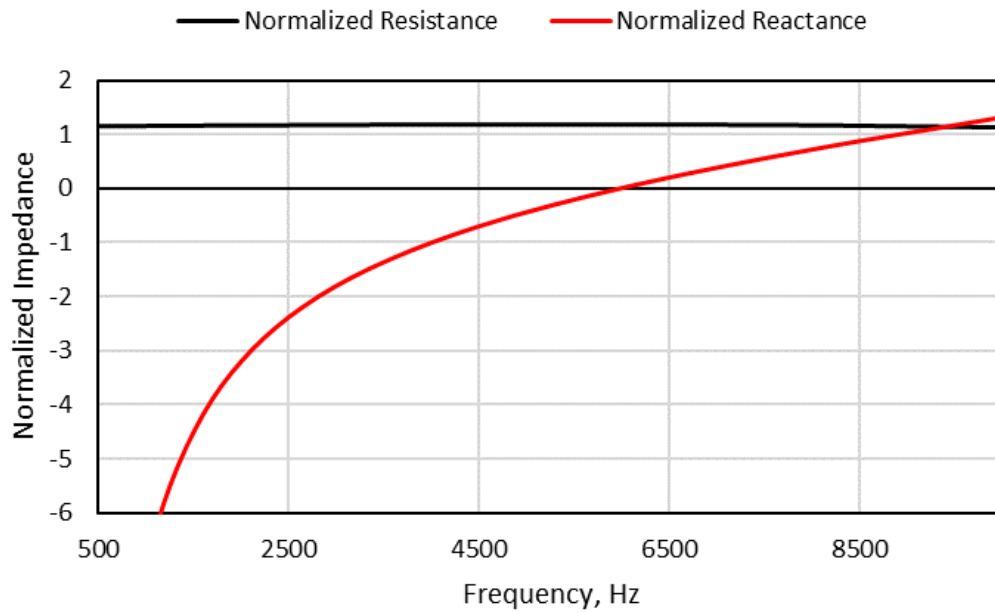


Figure 18: The predicted normalized impedance of the QUEEN V1 Perforate-Over-Honeycomb inlet duct acoustic liner versus frequency.

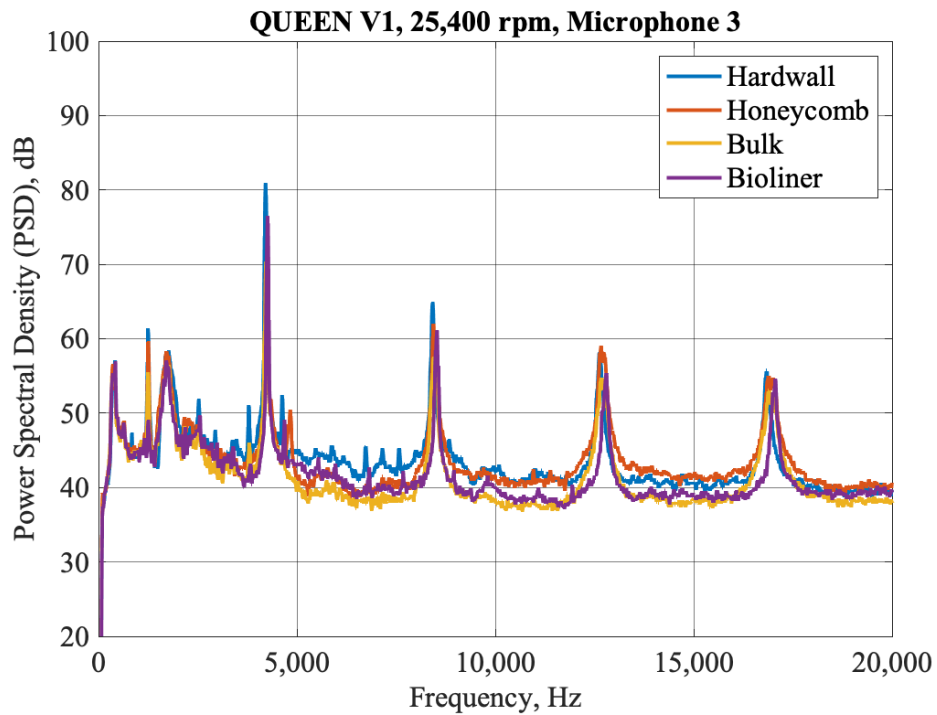


Figure 19: Spectra from Microphone 3 at -45° in the inlet array for each of the four inlet duct acoustic liners.

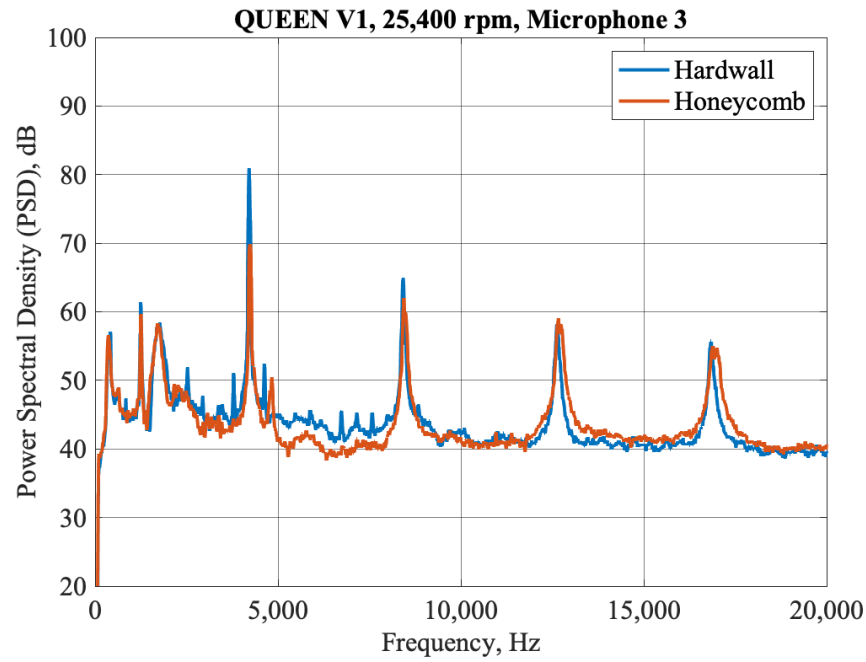


Figure 20: Spectra from Microphone 3 at -45° for the Hardwall Liner and the Perforate-Over-Honeycomb Liner.

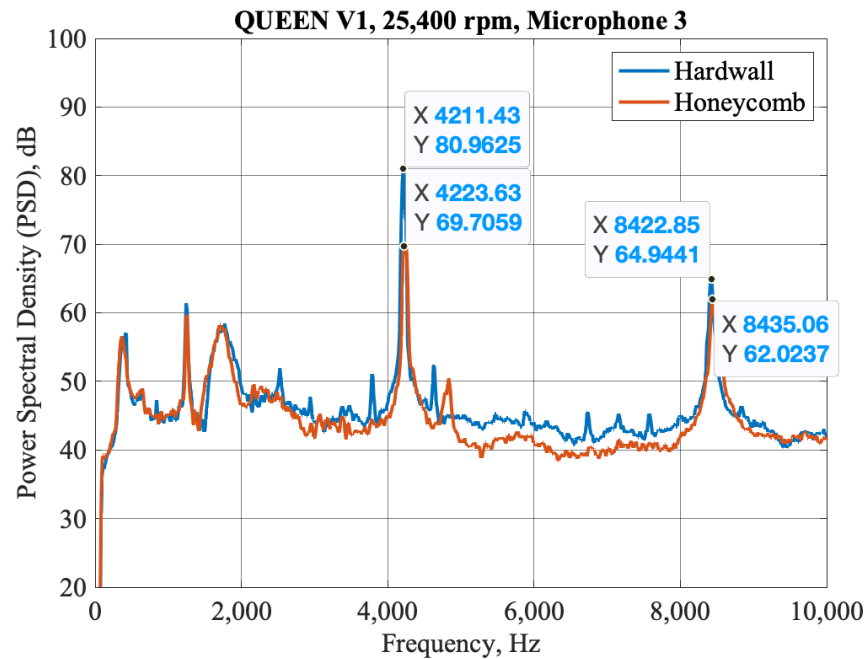


Figure 21: Spectra from Microphone 3 at -45° for Hardwall Liner and Perforate-Over-Honeycomb Liner examining noise reduction for the first two blade passing frequency tones.

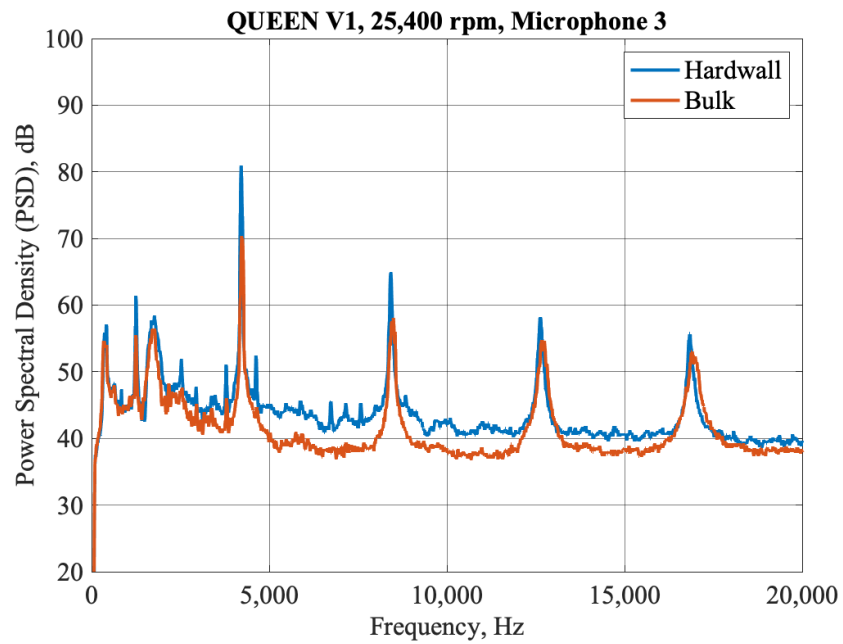


Figure 22: Spectra from Microphone 3 at -45° for the Hardwall Liner and the Bulk Absorber Liner.

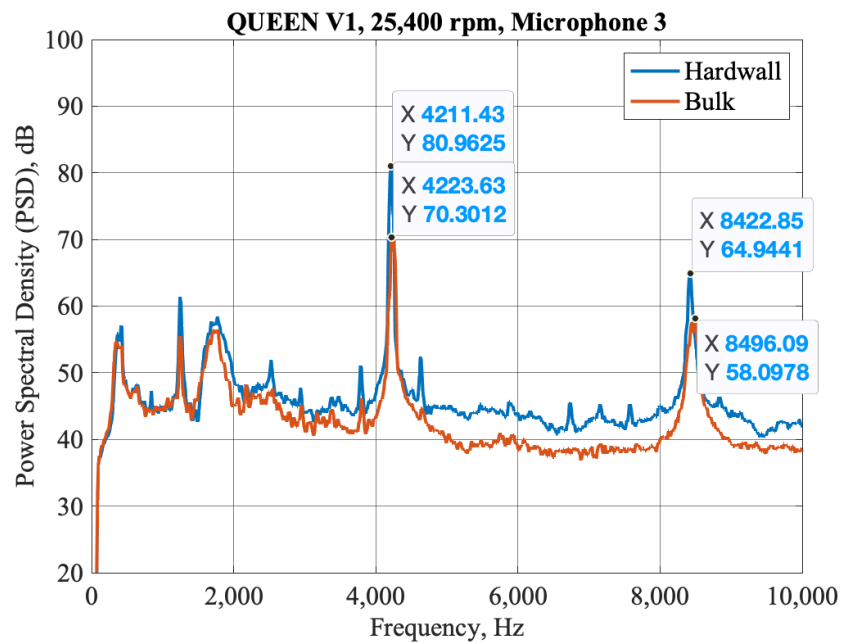


Figure 23: Spectra from Microphone 3 at -45° for the Hardwall Liner and the Bulk Absorber Liner examining trends at the first two harmonics of the blade passing frequency.

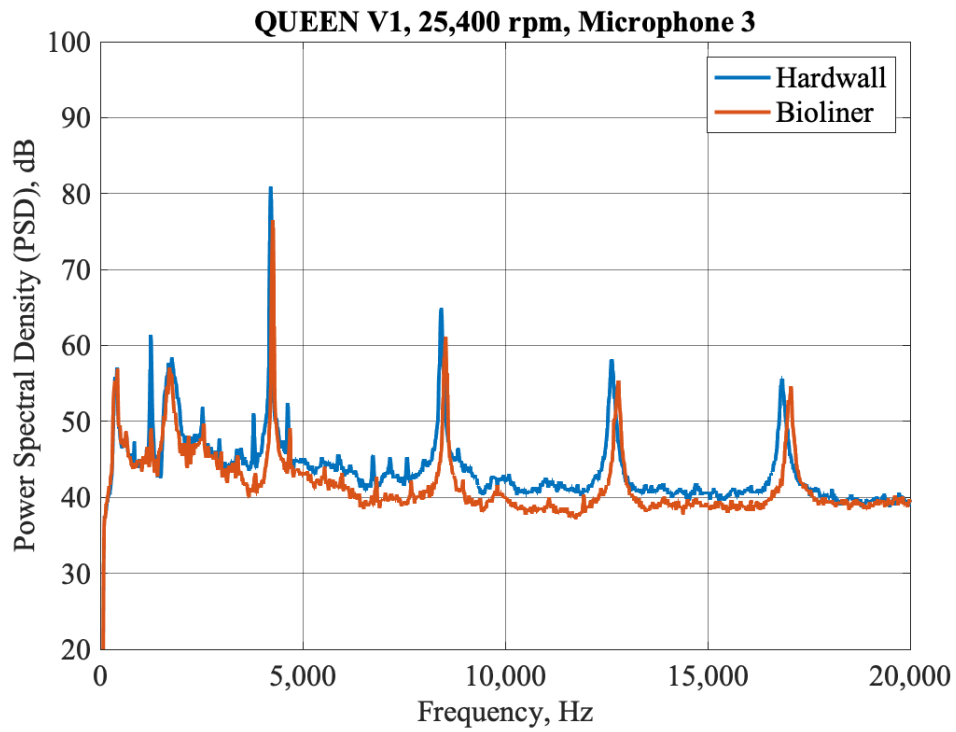


Figure 24: Spectra from Microphone 3 at -45° for the Hardwall Liner and the bio-inspired Broadband Acoustic Absorber ('Bioliner')

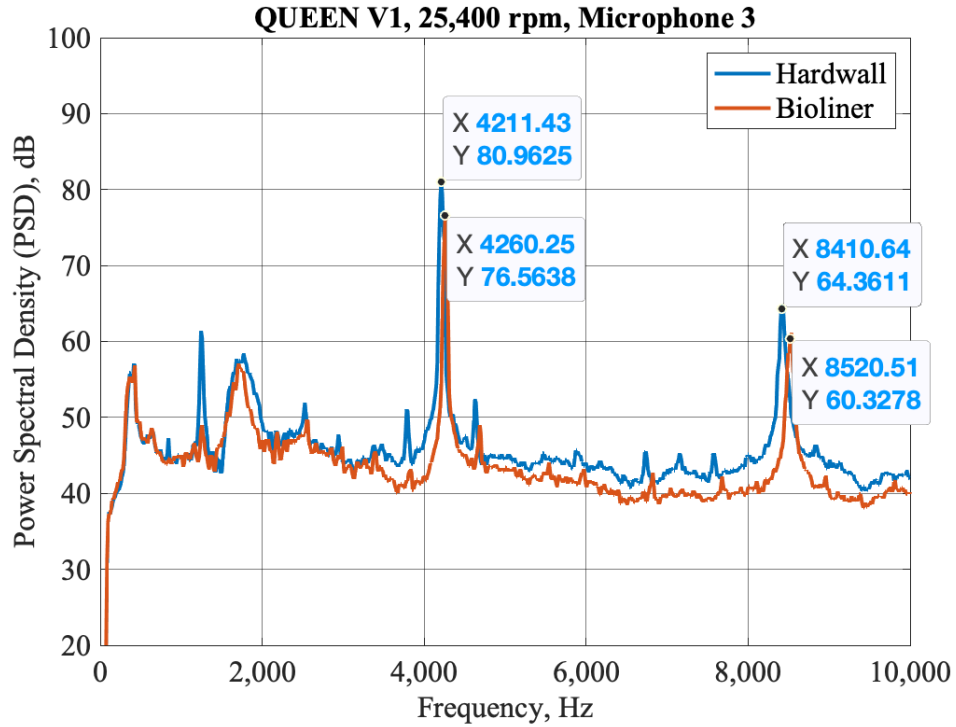


Figure 25: Spectra from Microphone 3 at -45° for the Hardwall Liner and the Bioliner examining trends at the first two harmonics of the blade passing frequency and noting some absorption benefits at 1200 Hz.

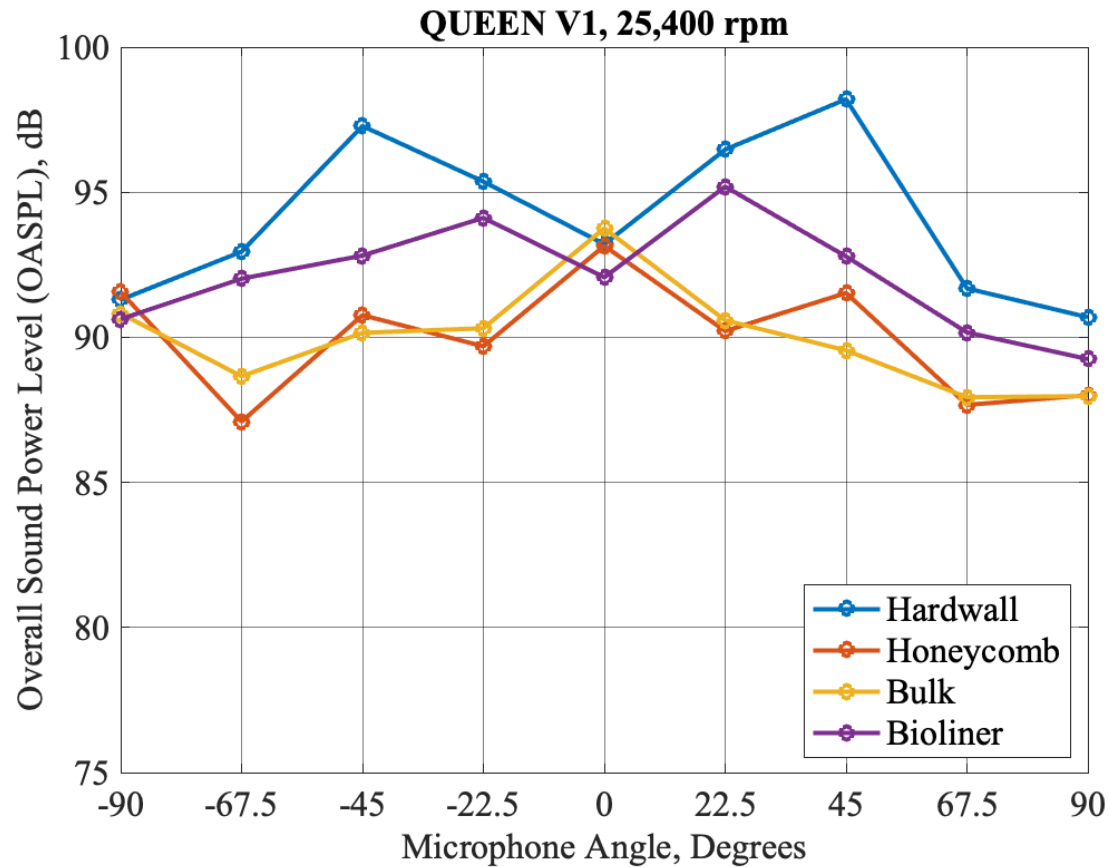


Figure 26: Directivity plot of the QUEEN V1 comparing data from all four liners.

V. Recommendations

This test was intended to be a short cost-effective exploration of aeroacoustics research supporting the development of distributed electric propulsion for large single-aisle aircraft, and several recommendations can be made. First, sound absorbing liners are not the only way to reduce noise from ducted fans like the QUEEN V1. Tone noise predictions using the method described by Koch [43] indicate that it may be possible to reduce noise produced by the fan by redesigning the stator and choosing a low noise blade/vane count. Second, since air recirculation was reduced but not eliminated by opening the ATL chamber doors, future tests in the much larger NASA GRC Aeroacoustic Propulsion Laboratory are recommended. Third, power cables to the motor could be routed through struts in the aft duct to reduce noise during static ground tests for acoustic research.

VI. Conclusion

The QUEEN V1 electric ducted fan was designed, built, instrumented, and tested at NASA GRC Acoustical Testing Laboratory. The QUEEN V1 features a single Commercial-Off-the-Shelf EDF with NASA custom-designed parts including several inlet duct acoustic liners. Results indicated that inlet duct acoustic liners reduced tone and broadband noise as compared to a hardwall inlet duct. Predicted performance of the Perforate-Over-Honeycomb liner compared well with measurements from an array of far field microphones, significantly reducing broadband noise and tones at the first and second harmonics of the blade passing frequency at the maximum tested rotor speed of 25,400 rpm. Results of the thermal test of the QUEEN V1 are presented in a separate report. [46]

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