

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 (COTS) fan and motor, an Electronic Speed Controller, a custom-designed inlet bellmouth, and several experimental inlet duct acoustic liners. Fan speed, thrust, 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 regional single-aisle aircraft. Lessons learned will be used to guide development of future QUEEN prototypes. Results of a thermal test of the Electronic Speed Controller measured during this test 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. Innovation and intricate cooperation will be needed to develop a more sustainable air transportation system accessible to a growing world population.

Noise pollution from transportation vehicles is pervasive. For example, 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. Biologists for the NPS have observed changes in animal behavior with exposure to anthropogenic noise, which threatens the survival of wildlife.[1–3]

Because noise pollution is widespread, millions of people are 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.[4] Other organizations have studied the disparate impacts of noise on different socioeconomic groups, which raises social justice questions. [5–7]

The electrification of engines for large single-aisle aircraft (~180 passengers) and integration of these engines onto novel airframes, such as the Subsonic Aft Engine (SUSAN) concept aircraft is a formidable engineering challenge. To realize predicted performance benefits, these engines are more tightly integrated into the fuselages than in the past which implies more cooperation between engine and airframe manufacturers. New design and optimization tools are needed, as well as the data to validate these tools. 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. Since there are international regulations on aircraft noise and emissions, formulated by the International Civil Aviation Organization (ICAO) Committee Aviation Environmental Protection (CAEP) Working Group and adopted by the U. S. Federal Aviation Administration, cleaner and quieter aircraft have a competitive advantage in the global market. [8]

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The Subsonic Single Aft eNginE (SUSAN) concept aircraft is guiding this effort described in this report, notionally depicted in Figure 1. Quiet electric engines (QUEENS) are envisioned as wing-mounted propulsors for the SUSAN 25% Flight Research Vehicle (FRV). Research on the SUSAN aircraft is ongoing, and recent publications are given here.[9–13]

Researchers at the NASA Glenn Research Center (NASA GRC), which was formerly known as the NASA Lewis Research Center (NASA LeRC) explored distributed electric propulsion at least as early as 1970. 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 11 NASA Technical Memoranda associated with “Blown Flap Noise” research [14–24] and 17 NASA Technical Memoranda associated with “STOL acoustics” research [16,17,21,25–38]

Researcher at NASA GRC have also studied the acoustic performance of several 22” fans models in the NASA GRC. The Source Diagnostic Test Fan (SDT), the Advanced Ducted Propulsor (ADP) and the Quiet High Speed Fan (QHSF) [39] These fan models tested in the NASA GRC 9-by 15-Ft Low Speed Wind Tunnel may be similar in size to the wing mounted propulsors featured in the full-size SUSAN concept vehicle and could offer insight into low-noise fan designs.[40]

Recently, a Commercial-Off-the-Shelf electric ducted fan system was tested at the NASA Glenn Research Center Acoustical Testing Laboratory. It is designated the Quiet Electric Engine V1 (QUEEN V1). There were two objectives of this experiment. The first purpose of the experiment was to measure the noise, speed, and thrust from the QUEEN V1 with and without inlet duct acoustic liners. The second objective was to characterize the performance of the Electronic Speed Controller using three different methods of cooling: air cooling, a cold plate, and immersion cooling. Results of these tests of the QUEEN V1 at NASA GRC are presented and discussed in this report. Recommendations for future investigations are offered.

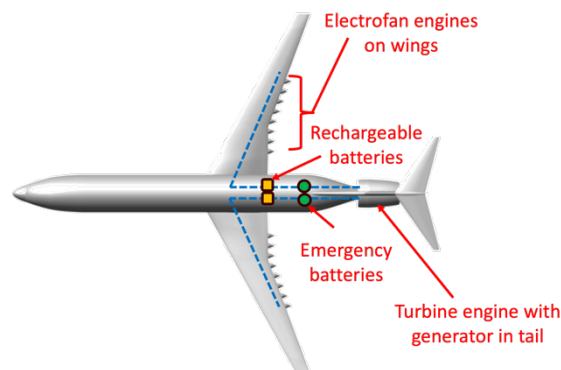


Figure 1: Illustration of one of NASA's Subsonic Single Aft ENginE (SUSAN) concepts with main components of the propulsion system indicated.



1970-01199

Figure 2: Blown Flap Model in NASA Lewis 9- by 15-Ft Low Speed Wind Tunnel.
Image: NASA 1970-C-01199



Figure 3: Fan-on-Flap Model in NASA Lewis 9- by 15-Ft Low Speed Wind Tunnel.
Image: NASA C-1970-02412



Figure 4: Blown Flap Model at NASA Lewis.
Image: NASA 1970-C-03034



Figure 5: Fan in Wing Model in the NASA Lewis 9- by 15-Ft Low Speed Wind Tunnel.
Image: NASA 1969-C-03531

II. Description of the QUEEN V1 Propulsor

The QUEEN V1 is an electric ducted fan that features a Commercial-Off-the-Shelf (COTS) fan and motor. Photograph of the fan assembly is shown in Figures x and x. Selected dimensions and features of the fan are given in Table 1. The QUEEN V1 fan consisted of ten rotor blades and seven Outlet Guide Vanes (OGVs) downstream of the rotor. The maximum design speed of the QUEEN V1 motor was 45,000 rpm and maximum thrust was projected to be approximately 30 lbf. based on test of the QUEEN V1 that were performed at NASA Langley Research Center (LaRC). The rotor tip diameter is 5.113 inches at the rotor blade leading edge.



Figure 6: Photo of the QUEEN V1, forward looking aft, without the COTS inlet installed.

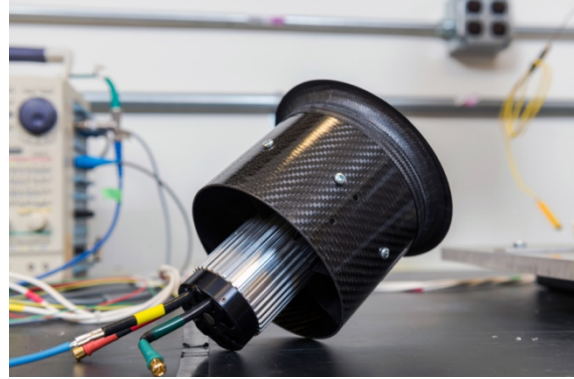


Figure 7: Photo of the QUEEN V1, with motor, duct, and COTS inlet installed.

Table 1: Selected Dimensions and Features of the QUEEN V1

Rotor tip diameter	13.0 cm (5.11 in)
Duct 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)
Overall axial length	

III. Description of the Experiment

The QUEEN V1 propulsor was tested in the NASA Glenn Research Center (GRC) Acoustical Testing Laboratory ATL. The NASA GRC ATL is a reconfigurable anechoic/hemi-anechoic chamber. For this experiment, the ATL was in the fully anechoic configuration, with fiberglass wedges 0.86 m (34 in) deep covering the walls and the floor which are used to absorb 99% of all sound above 100 Hz. The fiberglass wedges are protected by perforates and steel grating is mounted over the floor wedges for personnel access. To minimize recirculation inside the chamber during this test, the chamber ventilation fan was turned on and the large bay doors were opened. Barricades were placed on either side of the chamber to prevent entry into the chamber during test. The test operators could control and monitor test equipment remotely from a separate control room located adjacent to the anechoic chamber. The ATL was chosen for this test primarily since inlet and aft radiated noise measurements were desired. The experimental apparatus, the instrumentation installed on the QUEEN V1, the test objectives and procedure are discussed in more detail in the sections below.

A. Experimental apparatus

The main components of this experiment are indicated notionally in the schematic shown in Figure 8. Electrical power was supplied to the motor by a 10 kW DC power supply. Motor speed is controlled by an electronic speed controller (ESC) kept cool by a small fan or cold plate. A stand-alone portable cooling cart allows coolant to be pumped, regulated, and measured through the ESC cold plate. When running the ESC on the cold plate, to avoid condensation that could cause an electrical short or other hazard the chiller temperature was set to be equal to the ambient temperature. A plexiglass enclosure covered the apparatus to protect people and laboratory equipment from harm if an unplanned failure of the rotor were to occur. A photograph of the laboratory and test equipment is shown in Figure 9-10.

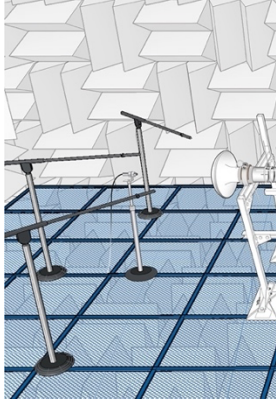


Figure 8: Illustration of the QUEEN V1 test set up in the NASA GRC Acoustical Testing Laboratory.

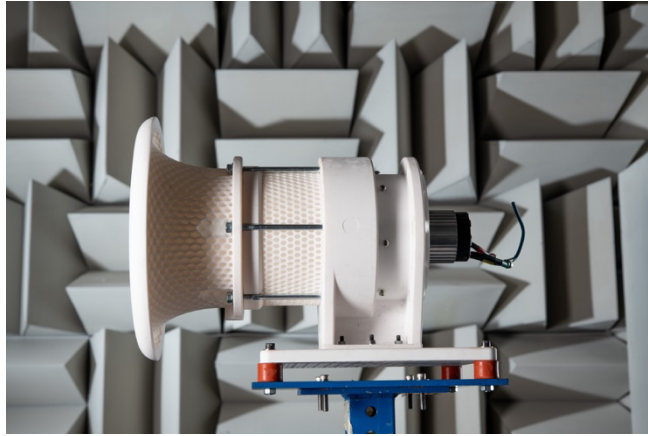


Figure 9: Photograph of the QUEEN V1 test set-up in the NASA GRC Acoustical Testing Laboratory, side view.



Figure 10: Photograph of the QUEEN V1 test set-up in the NASA GRC Acoustical Testing Laboratory, forward looking aft.

B. QUEEN V2 instrumentation

An illustration of the QUEEN V1 with bellmouth and inlet liner spool piece is shown in Figures 11-12. Instrumentation included a load cell, thermocouples, pressure transducers, accelerometers, current probes, voltmeters, oscilloscopes, a power analyzer, and a data acquisition system. The QUEEN V1 motor was air-cooled and motor surface temperatures were measured for both the motor and housing as well as the motor windings. The Electronic Speed Controller (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. There were six microphones placed 3 feet from the inlet and six microphones placed 3 feet from the edge of the exhaust duct of the fan. The microphones were spaced 18° apart, -45° to 45° from the fan centerline. Vibration dampers were installed between the base of the sleeve holding the fan and the pedestal.

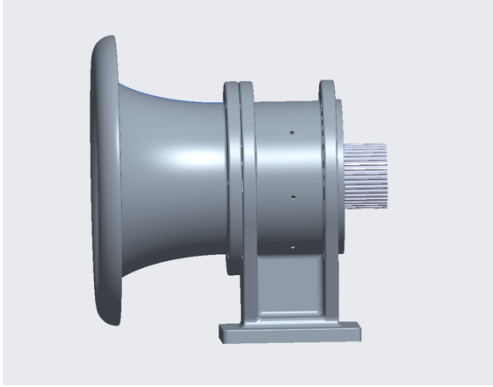


Figure 11: Test Configuration 1—QUEEN V1 installed in NASA sleeve to mount to a pedestal inside the anechoic chamber. A 3D printed bellmouth guides the flow into the fan.

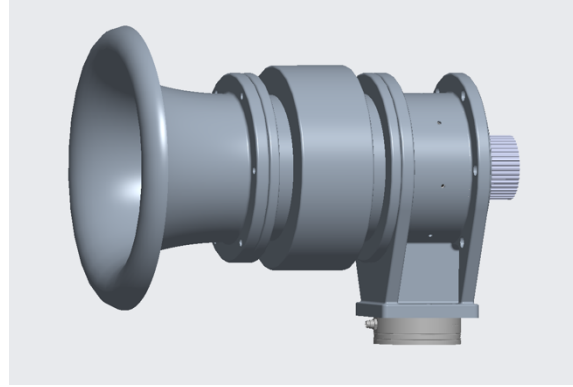


Figure 12: Test Configuration 2--QUEEN V1 installed in a NASA 3D printed sleeve, with bellmouth and inlet duct acoustic liner. Six axis load cell shown installed under the sleeve.

C. Test objective and procedure

As mentioned earlier, there were several objectives. The first purpose of the experiment was to measure the noise, speed, and thrust from the QUEEN V1 with and without inlet duct acoustic liners. The second objective was to characterize the performance of the Electronic Speed Controller using three different methods of cooling: air cooling, a cold plate, and immersion cooling. This report describes the acoustic results, and a separate report describes the thermal results.

For each test, motor voltage (80 V) was set first. Then the fan speed was increased from 0 to 25,000 rpm in increments of 1,000 rpm. Temperatures, pressures, vibrations, current, and voltage measurements were recorded at each speed. Thermocouples were used to directly measure temperatures at multiple angles along the axial length of the motor, adjacent housing surface, motor winding. Thrust was measured by the six-axis load cell as shown in Figure 12. Voltages and currents on both the AC and DC side of the ESC were measured and a power analyzer was used to directly calculate the electrical efficiency as well as the heat load produced by the ESC.

Acoustic measurements were recorded at 12,500 rpm, 23,000 rpm, 24,000 rpm and 25,000 rpm. Sound was measured using a total of twelve 0.5 inch microphones arranged in two arcs. The microphones were mounted on poles at the height of the fan centerline which was 101.5 inches above the anechoic chamber floor, and 64.0 inches above the grating covering the sound absorbing wedges that covered the floor. The six microphones measuring the inlet radiated noise were 3.0 feet upstream and 3.0 feet downstream of inlet duct lip and the microphones faces were oriented towards the inlet and placed at regular intervals from -45° to 45° . The six microphones measuring the aft radiated noise were 3.0 feet downstream of the aft duct lip and placed at regular intervals from -45° to 45° .

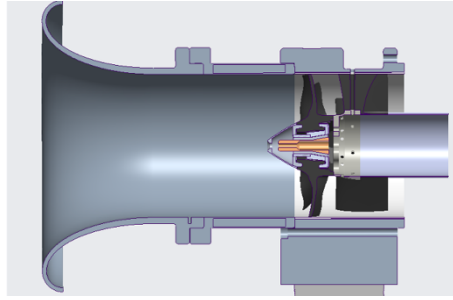


Figure 13: Test Configuration 2--QUEEN V1 cross section with hardwall inlet duct liner.

IV. Discussion of Results

The test is underway and the aerodynamic and acoustic results from the experiment will be discussed here.

Recommendations

Tone noise predictions using the method described by Koch [41] indicate that it may be possible to reduce noise produced by the fan by redesigning the stator.

V. 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 fan with an Outlet Guide Vane. Several inlet duct acoustic liners were tested. Measurements of the ESC temperature were recorded for three different cooling methods: air cooling, cold plate, and immersion cooling. Results of the thermal test are described in a separate report. Far field noise measurements were recorded in the inlet and aft region of the QUEEN V1.

Acknowledgments

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