Spacecraft Cabin Ventilation Fan Research at NASA

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NASA has recently made the geometry and solid model for a spacecraft cabin ventilation fan prototype available to the public via electronic file downloads from the NASA Technical Reports Server. This fan can be used for research and development by many organizations. The NASA Quiet Space Fan is 8.89 cm (3.50 in) in diameter, 22.9 cm (9.00 in) long, and the metal fan weighs 1.63 kg (3.6 lbm). The fan was designed to generate a system total pressure rise of 906 Pa (3.64 inches of water) at 0.0709 m^3/s (150.3 cfm) of airflow at 12,000 rpm (at 21.1ºC (70ºF) and 14.7 psia). Performance measured using standardized techniques showed good agreement with design and predicted values. A low-noise blade-vane count was chosen to reduce tonal noise generated by rotor-stator interaction for the first three blade passing frequency harmonics. In-duct microphone array measurements indicated that the most evident tones occur at frequencies of 1,800 Hz (1 BPF) and 7,200 Hz (4 BPF). Using reverberant room standard testing methods, the A-weighted sound power level for the fan operating at design point conditions was measured to be 71 dBA. This report describes the current set of publicly available information for this fan. The fan was designed, optimized, and tested with tools and techniques that NASA has traditionally used for turbofan engine research. This demonstrates that technology developed for aerospace applications can be used more broadly, since quiet and efficient fans are needed for many ventilation systems in spacecraft, aircraft, watercraft, land vehicles, and buildings.

I. Introduction

Noise inside spacecraft cabins has been a serious problem since the beginning of the space age and poses risks to future long duration space exploration missions [1–4]. Spacecraft cabin noise interrupts sleep and interferes with speech communication. Exposure to loud sounds for a long time results in permanent hearing loss. The Environmental Control and Life Support (ECLS) system ventilation fans have been known to be dominant sources of noise onboard the Apollo Command Module, the Space Shuttle, and the International Space Station (ISS). Often, mufflers, silencers, and acoustic liners have been added to the ventilation system ductwork to try to reduce spacecraft cabin noise. These remedies have been costly and difficult. Sometimes noisy fans in use on-orbit have been replaced with quieter fans which added significant mass and volume to the spacecraft.

There is a need for quiet, efficient, and durable ventilation fans for a variety of long-duration human space exploration habitats currently in development. NASA's Gateway Habitation and Logistics Outpost (HALO) [5,6] and low-Earth Orbit free-flyer habitats are examples of spacecraft that could benefit from research in ventilation fan performance [7]. In December 2021, NASA announced it had signed Space Act Agreements totaling over $400 million with three United States companies (Blue Origin, Nanoracks LLC, and Northrop Grumman Systems Corporation) to develop commercial space stations to maintain uninterrupted U.S. presence in low-Earth orbit [8].

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Blue Origin has partnered with Sierra Space and others to develop the "Orbital Reef," a commercial space station envisioned to operate like a mixed-use research park in space, with transportation and accommodations for researchers and visitors, alike [9]. Nanoracks has partnered with Lockheed Martin to develop a suite of space stations named StarLabs that operate at different orbital positions for designated purposes, expanding the capabilities available to researchers who want to work in low Earth orbit [10]. The Space Act Agreement with Northrop Grumman will allow the team to develop the detailed plans and space station requirements for a modular space station, building from the company's experience supporting the International Space Station.

The NASA Glenn Research Center (GRC) has conducted fan noise research for improved aircraft engine propulsion systems since the 1940s and more recently began to study spacecraft cabin fan noise around 2005. NASA GRC has been recognized for expertise, facilities, test rigs, and instrumentation for investigating turbomachinery aerodynamic, mechanical, and acoustic performance. Since aircraft propulsion has been a core-competency of NASA GRC and research typically focused on very large fans for turbofan engines, it was not immediately apparent how this expertise could be used for these much smaller spacecraft ventilation fans.

In 2005, NASA GRC performed initial experiments on small fans for cooling electronics onboard spacecraft [11-13]. Installation effects were also quantified for small fans for electronics cooling, since noise often increases if the fan rotor operates near upstream or downstream obstructions, such as finger guards, vanes, struts, probes, and convoluted ducting [14,15].

In 2008, NASA held a workshop entitled "Quiet, Efficient Fans for Spaceflight," which helped to shift research attention at NASA GRC from small fans for electronics cooling toward axial fans for spacecraft cabin ventilation. At this small workshop, different perspectives on small fan performance in spacecraft were shared. Engineers from NASA Johnson Space Flight Center (JSC) and NASA Ames Research Center (ARC) described experiences with small fan performance and the challenges of designing, building, and operating quiet systems for the International Space Station. Engineers from NASA Marshall Space Flight Center (MSFC) gave an overview of the atmospheric revitalization systems and fans used for ventilation inside spacecraft cabins. Engineers from NASA GRC presented a history of aircraft engine noise research [2,16,17]. After this workshop, engineers at NASA GRC became more involved in research on axial fans for spacecraft cabin ventilation since these fans were identified as a dominant source of noise onboard spacecraft, and there was potential to capitalize on GRC's aircraft engine noise reduction expertise, computational tools, and experimental facilities.

By 2009, NASA identified design specifications for an axial fan that would be suitable for research purposes, Table 1. Nominally, the fan was representative of the kind of ventilation fans used for spacecraft, and the overall size envelope of the fan was a cylinder 4 inches in diameter and 9 inches long. The volumetric flow rate design goal was 150.3 cfm at 21.1ºC (70ºF) and 101 kPa (14.7 psia), and the design goal for the system total-pressure rise was 906 Pa (3.64 inches of water). Several important parameters were left unconstrained to give the fan designer some flexibility to explore design options. Using these constraints, the aerodynamic design of two fans were produced, one by Hamilton Sundstrand and a NASA Quiet Space Fan (QSF) designed by Tweedt [18,19].

In 2010, a plastic prototype of the NASA QSF designed by Tweedt was printed via stereolithography and then tested at the NASA GRC Acoustical Testing Laboratory (ATL). For these preliminary tests, the plastic fan was operated at design point speeds but not backpressured to design point conditions. Acoustic measurements from this experiment indicated blade passing frequency tones were prominent above the broadband noise, similar in character to noise spectra from aircraft engines [20, 21].

From 2021-23, a metal version of the NASA Quiet Space Fan shown in Figure 1 was designed, partially additively manufactured, and tested at design point conditions in the NASA GRC ATL. This version of the fan design was intended to serve as a baseline for future research and ground-based tests and was not designed to meet spaceflight qualifications. The geometry for the metal version of the NASA Quiet Space Fan has been made public, and is available for download as supplementary files provided with the NASA Technical Memorandum by Stephens, et al. [22]. By disseminating the geometry publicly, NASA can help raise the bar on small fan performance generally, since many fan system engineers can use the fan design for their own research and development purposes. This approach has been demonstrated to be useful by the aircraft engine engineering communities worldwide, such as the NASA Rotor 37 test case, as described by Van Zante [17,22]. The metal NASA Quiet Space Fan tests were highlighted in the 2023 American Institute of Aeronautics and Astronautics' Aerospace America Year in Review Issue in the recap of progress in aeroacoustics research [23]. Quiet and efficient fans for spacecraft cabin ventilation systems were also included in the 2014 and 2024 NASA Small Business Innovation Fund Solicitation (SBIR). This fan was also described as a baseline geometry in the NASA SBIR solicitation for 2024 [24, 25].

This report will summarize these recent experiments in more detail and includes a comprehensive reference list capturing the many years of spacecraft cabin ventilation fan research at NASA GRC.

II. Fan Design and Manufacture

A. Aerodynamic Design and Analyses

Tweedt used a two-step process for the aerodynamic design of the NASA Quiet Space Fan using tools and techniques used for aircraft engine fan design. First, a preliminary fan aerodyanamic design was created using a modified version of a NASA-developed Compressor Design Program called NCDP [26]. The fan preliminary design parameters given in Table 1. Computational Fluid Dynamics (CFD) was used to develop and assess and refine the design. Predictions of the flow through the fan designs were generated by Tweedt using an Axisymmetric Viscous Solver (AVCS) and TSWIFT, which is a modified version of the Multiblock Analysis Code for Turbomachinery called Swift developed by Chima [18,27,28]. Streamlined (clean) aerodynamics and a low fan rotational speed were expected to yield a quiet and efficient fan suitable for use as a baseline for future research and as a test bed for noise reduction concepts. While the preliminary aerodynamic design of the fan featured 13 stator vanes, the final aerodynamic design of the fan featured 11 stator vanes. This choice was based on the results of the preliminary acoustic design of the fan, described below.

More recently, a CFD analysis of the rotor was performed with FUN3D, which solves the Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations using implicit time marching and a dynamic overset grid. This effort demonstrated that FUN3D could yield accurate predictions for internal flow fields, even though FUN3D was originally intended for exterior flows. FUN3D was used to predict the fan stall point, which occurred at a mass flow rate of 43.8 cfm resulting in a reduction in adiabatic efficiency. Efforts like these demonstrate that the NASA Quiet Space Fan can be used for many research and development purposes, especially as the aerospace industry works toward electrification of aircraft engines [29].

B. Acoustic Design and Analysis

Efforts were made to minimize the tonal noise produced by rotor-stator interaction, beyond what best practices in aerodynamic design alone could achieve. The acoustic design method used to reduce fan tone noise for the NASA Quiet Space Fan was described by Koch [30]. A fast method to identify fan blade-vane counts to minimize tone noise for axial ducted fans was developed. In this method, duct acoustic theory and aircraft engine rotor-stator interaction theory were combined to predict the set of circumferential acoustic duct modes that were expected to be generated and to propagate through the fan duct. Mode sound power levels were not predicted in this preliminary design method. Rather, by predicting the number of cut-on circumferential modes for each vane count, a set of low-noise vane counts for a given rotor and duct design can be identified. This method assumes that a fan with fewer cut-on modes will be quieter. While the rule-of-thumb for aircraft engine fan designs suggests that to reduce tone noise from rotor-stator interaction the number of stator vanes should be equal to twice the number of rotor blades plus a few more, this method identifies additional potential low noise designs with fewer vanes.

Using the preliminary aerodynamic design of the NASA Quiet Space Fan with a rotor with 9 blades as a starting point, the low-noise vane counts for each of the first four Blade Passing Frequency (BPF) harmonics were predicted for a given duct size. The preliminary aerodynamic design of the NASA Quiet Space Fan featured 13 stator vanes and tones at the 1 BPF and 2 BPF harmonics were predicted to be cut off at the design speed of 12,000 rpm. The final aerodynamic design of the NASA Quiet Space Fan featured 11 stator vanes since the results of the acoustic analysis indicated that a fan design featuring 11 vanes would cut off the 1 BPF, 2 BPF, and 3 BPF tones at the design speed of 12,000 rpm. Acoustic measurements to validate these predictions are described below.

While rotor-stator interaction noise is one mechanism for generating tones with axial ducted fans, inlet distortion can increase tone noise, too. Other predictions for inlet distortion were also generated using a code based on theory from Sofrin and Mathews. These predictions have not yet been experimentally validated and are a topic for recommended future research [31].

C. Electrical and Mechanical Design and Manufacture

The electrical and mechanical design and manufacture of the metal fan are described in [22, 32]. Both the 2010 plastic prototype and the 2021 metal prototype used a Maxon 48V EC 4 pole brushless DC motor (part number 305015). For the 2021 experiment the fan speed was controlled using a Maxon ESCON Servokontroller (part number 409510) and the fan speed was varied using a dedicated laptop computer running the Maxon motor controller software.

The metal rotor was machined traditionally from aluminum T6061. The design allowed for the rotor to be removed from the motor shaft, as shown in Figure 2, which improved the modularity of the design, since the plastic rotor featured in the first prototype was epoxied onto the rotor shaft. Modal analyses were performed using both CREO

Simulate and Ansys Mechanical to predict the vibration mode frequencies and to confirm that we would not excite any natural frequencies of the structure at operating speeds.

The stationary parts of the 2021 metal version of the NASA Quiet Space fan were additively manufactured from AlSi12 using the Direct Metal Laser Sintering (DMLS) technique. The fan casing design was a demonstration of the advantages of additive manufacturing for strong yet lightweight structures. As shown in Figure 1, it featured a stiffening ribbing structure that resembled T-beams to greatly increase stiffness as compared to conventional ribs while reducing weight. The conformal T-beams are oriented along splines that spiral along the axial direction. The splines repeatedly intersect forming a waffle-like pattern. The metal fan assembly with the motor weighed 1.63 kg (3.6 lbm).. The surface finish of the 3D printed parts varied since some surfaces were hand-polished and some surfaces were not. Future research into surface finish methods for additively manufactured metal parts is recommended.

There were many challenges designing, manufacturing, and testing this fan during 2021 due to the limitations associated with working during the COVID-19 pandemic. As such, vibrations measured during tests of the fan were greater than desired, so the rotor was redesigned in 2022. The modified design, shown in Figure 3, intended to reduce vibrations, featured a new lighter rotor with a tighter residual unbalance tolerance, a new collet to attach the rotor to the motor shaft more securely and repeatably, and a new bracket to center and hold the motor in the fan centerbody more precisely. Tests in 2023 confirmed that vibrations were reduced, as shown in Figure 4. Additional recommendations were made to guide the development of improved prototypes [33].

III. Aerodynamic and Acoustic Experiments

D. Test Facility and Fan Test Rig

Tests of the spacecraft cabin ventilation fans reported here were performed in the NASA GRC Acoustical Testing Laboratory with a fan test rig, as shown in Figure 5. The NASA GRC ATL is a reconfigurable anechoic/hemi-anechoic chamber and has been used by researchers to measure noise from systems and components. The NASA ATL was constructed in 2000 and used to quantify the noise emissions of the Fluids and Combustion rack for the International Space Station [34,35].

The NASA ATL was configured to be a fully anechoic chamber for the tests summarized in this report. The ATL test chamber measures 7.0 m (23 ft) wide, 8.2 m (27 ft) long, and 6.1 m (20 ft high). The sides of the chamber are covered in 0.86 m (34 in) fiberglass wedges protected by a fabric layer and a 53 % open area metal perforate that absorb sound down to 100 Hz. The wedges that are used to cover the floor are modular and are installed on 2 ft by 2 ft sections. Metal grating is installed over the floor wedges so that people and equipment can access the test chamber when it is in the anechoic configuration. A separate control room is adjacent to the chamber, which helps to protect people while performing the experiments in the anechoic chamber. The ATL also features a ceiling-mounted remote-controlled traverse system, which has been used to hold microphone arrays for noise surveys.

A fan test rig, intended for research purposes, was designed based on guidance from two fan testing standards: ASHRAE 68 [36] and ISO 5136 [37]. Main components are shown in Figure 6. A calibrated bellmouth guides and measures the flow entering the fan test rig. The 72-channel in-duct microphone array was added to the rig and could be installed either upstream or downstream of the fan. An anechoic termination prevented sound reflections at the end of the fan test rig from interfering with the measurements. Flow was regulated with a throttle on a linear actuator, so that fan performance could be tested through its operating range. Instrumentation included but is not limited to accelerometers, thermocouples, pressure taps, current probes, in-duct and far field microphones, and a traversing hot wire probe. The hot wire probes were used to measure the velocities downstream of the rotor to characterize rotor wakes. Data from these experiments is used to validate aerodynamic and acoustic predictions that engineers can use to improve design and analysis tools for fans. More details are given in Reference 22.

E. Aerodynamic Measurements

The fan aerodynamic data was desired to quantify fan performance, validate computational fluid dynamics codes, understand more about additively manufactured fans, and work towards more efficient and quieter designs needed for life support systems for ambitious long duration space exploration missions and other ventilation systems. Fan pressure rise was measured as a function of flow rate for a variety of fan speeds, thereby mapping the fan performance through its operating range. Results were compared to predictions at design speed. Comparisons between predicted and measured fan performance confirmed that tools and techniques typically used for aircraft engine fan aerodynamic design can be used to produce efficient ventilation fans. The static pressure rise of the NASA Quiet Space Fan was measured to be 3.478 psia at 12,000 rpm and 150 cfm, tested conditions. The variation of pressure rise with flow rate and fan speed is given in Figure 7 and the variation of fan efficiency with flow rate and fan speed is given in Figure 8 [38–40].

More recently, the metal NASA Quiet Space Fan was also tested by Air Movement and Control Association, Inc. (AMCA International). Measurements of airflow and pressure rise were made at three speeds (8000, 10,000, and 12,000 rpm) in accordance with AMCA Standard 210-16 [41]. The total pressure rise of the NASA Quiet Space Fan was measured to be 3.487 psia at 12,000 rpm, though measurements were not taken at speeds and flowrates at corrected to standard sea level conditions. Closer attention to these corrections is recommended. Figure 9 is a comparison design goals and the predicted system total-pressure rise and flow rate at design point to AMCA International aerodynamic test results, corrected to air at Standard Sea Level conditions. Figure 10 is a comparison of the static pressure rise at tested conditions from the NASA GRC rig and the AMCA standardized tests.

Detailed measurements of the fan wakes were also recorded. The metal Quiet Space Fan included a small port between the rotor and the stator through which an x-wire probe was inserted to simultaneously measure velocity and flow angle, as shown in Figure 11. Velocities for the fan at design point conditions were measured in two axial locations between the rotor and the stator, as shown in Figures 12 and 13. Detailed data like these can be used to validate computational fluid dynamics codes useful for turbomachinery and fan design and analysis so engineers can work towards producing quieter fans [42].

F. Acoustic Measurements

Noise produced by the Quiet Space Fan was measured with the in-duct microphone array for the NASA fan and a Commercial-Off-the-Shelf (COTS) fan of similar size and capacity, Figures 14-15. In-duct microphone array measurements indicated that the most evident tones occur for frequencies of 1,800 Hz (1 BPF) and 7,200 Hz (4 BPF). Rotor-stator interaction is just one mechanism that can produce tones at blade passing frequency harmonics. The 1 BPF tone that was evident from the in-duct microphone array measurements could be produced by inflow distortion from a source upstream of the fan test rig, and additional attention to this is recommended.

External microphones arranged upstream of the bellmouth of the fan duct rig were also used to measure the noise from the NASA and COTS fan, Figures 16-17. The NASA spacecraft cabin ventilation fan prototype featured a low-noise blade-vane count intended to cut off the tones for first three blade passing frequency harmonics produced by the interaction of the rotor wakes with the stator vanes at design speed. By comparing sound power levels, the NASA fan was approximately 10 dB quieter than a similar-sized commercial off-the-shelf fan tested in the same rig [43].

More recently, the metal spacecraft cabin ventilation fan prototype was also tested by Air Movement and Control Association, Inc (AMCA International). Measurements of noise was made at three speeds (8000, 10,000, and 12,000 rpm) in accordance with AMCA Standard 300-14 [44]. The variation of A-weighted sound power levels with flow rate and speed is shown in Figure 18. The A-weighted sound power level for the fan operating at design point conditions was measured to be 71 dBA.

IV. Recommendations

Quiet and efficient fans are needed for ventilation systems onboard spacecraft, aircraft, ships, and in buildings. Continued research is recommended to more thoroughly validate existing aerodynamic and acoustic prediction tools and develop new noise-reduction technologies for fans. Research should include an investigation of fan performance for distorted inflow, since fan noise typically increases when flow entering the fan is distorted by obstructions such as finger guards, filters, probes, structs, vanes, and convoluted ductwork. An exploration and development of post-processing techniques for improving the surface finish of additively manufactured parts is also recommended. Improved acoustic duct liners and mufflers are also needed.

V. Conclusion

Motivated to improve the safety and productivity of ambitious long duration human space exploration missions and transfer that knowledge broadly, NASA has made geometry for a metal prototype of a spacecraft cabin ventilation system fan publicly available via the NASA Technical Reports Server. The NASA Quiet Space Fan was designed, fabricated, and then tested at the NASA GRC Acoustical Testing Laboratory using a duct rig inspired by several fan testing standards. Standardized tests were also performed by AMCA. The fan was throttled through its operating range, and results indicated that the measured aerodynamic and acoustic performance was in good agreement with predictions. The NASA Quiet Space Fan is 8.89 cm (3.50 in) in diameter, 22.9 cm (9.00 in) long, and the metal fan weighs 1.63 kg (3.6 lbm). The fan was designed to generate a system total pressure rise of 906 Pa (3.64 inches of water) at 0.0709 m3/s (150.3 cfm) of airflow at 12,000 rpm (at 21.1ºC (70ºF) and 14.7 psia). Using turbofan engine design practices, a low-noise blade-vane count was chosen to try to reduce rotor-stator interaction tone noise generated by this fan by cutting off tones at the first three blade passing frequency harmonics. In-duct microphone array measurements indicated that the most evident tones occur for frequencies of 1,800 Hz (1 BPF) and 7,200 Hz (4 BPF). This report summarized these recent experiments in more detail and included a comprehensive reference list capturing the many years of spacecraft cabin ventilation fan research at NASA GRC. Efforts to compare predictions and measurements are ongoing. This is one way that technology developed for aerospace applications can be used more broadly, since quiet and efficient fans are needed for many ventilation systems.

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Figures and Tables

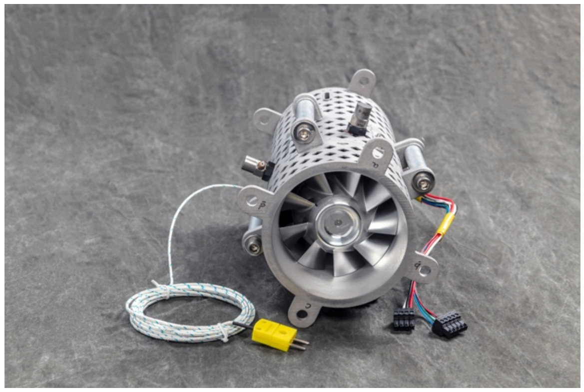

Figure 1: The NASA metal Quiet Space Fan prototype designed and tested 2021-2023.

	Goals	Preliminary Aerodynamic Design Value
Flow rate	0.0709 m^3/s (150.3 cfm)	0.0709 m^3/s (150.3 cfm)
Total pressure rise	906 Pa (3.64 inches of water)	925 Pa (3.716 inches of water)
Pressure	101 kPa (14.7 psia)	101 kPa (14.7 psia)
Temperature	21.1° C (70° F)	21.1° C (70° F)
Maximum diameter	0.102 m (4.0 in)	8.89 cm (3.50 in) flowpath diameter
Rotor hub diameter	Unconstrained	6.60 cm (2.60 in)
Maximum axial length	0.223 m (9.0 in)	22.9 cm (9.00 in)
Rotor tip clearance gap	0.23 mm (0.009 in)	0.23 mm (0.009 in)
Rotor speed	Unconstrained	12,000 rpm to 13,600 rpm
Number of blades	Unconstrained	9
Number of vanes	Unconstrained	13
Rotor exit Mach number	Unconstrained	0.10 to 0.11 with approximately 35° swirl
Blade row spacing	Unconstrained	3.45 cm (1.37 in) approximately 2 rotor axial chord lengths

	Final Design Values of the NASA Quiet Space Fan
Flow rate	0.0709 m^3/s (150.3 cfm)
Total pressure rise	925 Pa (3.716 inches of water)
Pressure	101 kPa (14.7 psia)
Temperature	21.1° C (70° F)
Maximum diameter	8.89 cm (3.50 in) flowpath diameter
Rotor hub diameter	6.60 cm (2.60 in)
Maximum axial length	22.9 cm (9.00 in)
Rotor tip clearance gap	0.23 mm (0.009 in)
Rotor speed	12,000 rpm
Rotor blade tip speed	(50.2 m/s) 165 ft/s at rotor inlet (52.7 m/s) 173 ft/s at rotor exit
Number of blades	9
Number of vanes	11
Rotor exit Mach number	0.10 with approximately 35° swirl
Blade row spacing	3.556 cm (1.40 in), midspan blade row axial spacing, 1.94 meridonal-chord lengths of the rotor blade

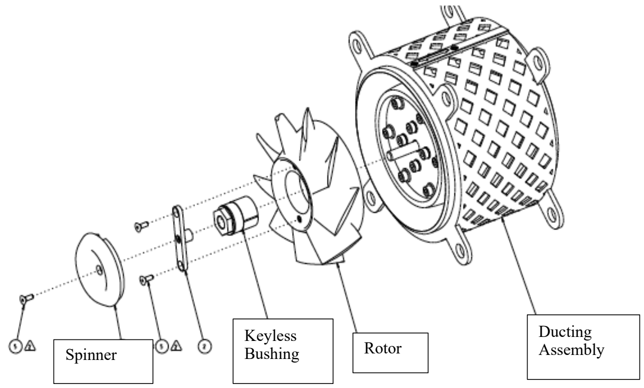

Figure 2: NASA's metal Quiet Space Fan rotor assembly in for the 2021 prototype

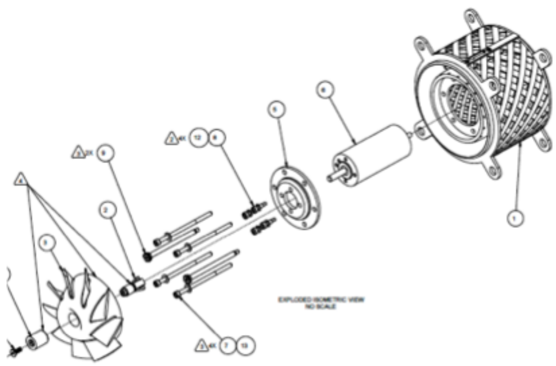
Figure 3: NASA's metal Quiet Space Fan rotor assembly for the 2023 prototype

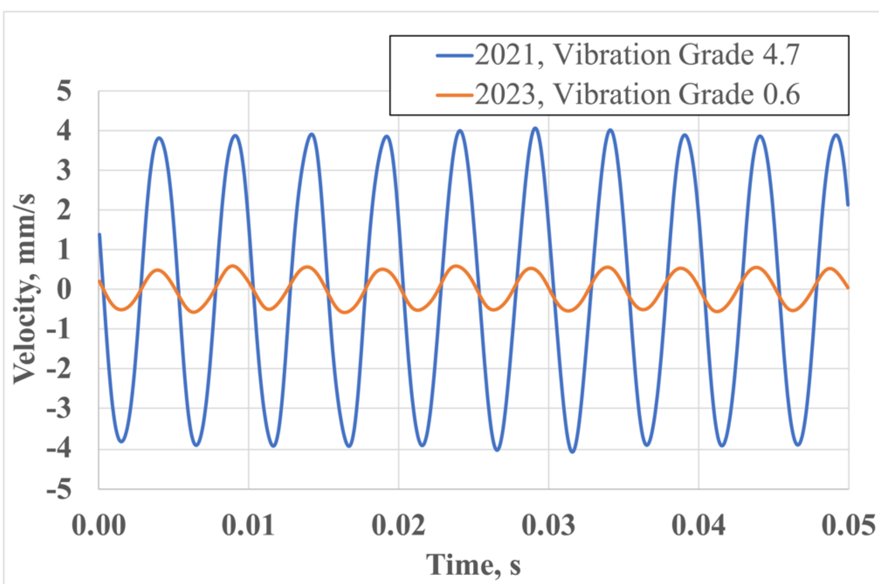

Figure 4: Comparisons of vibrations from 2021 and 2023 prototypes, from Reference 33.

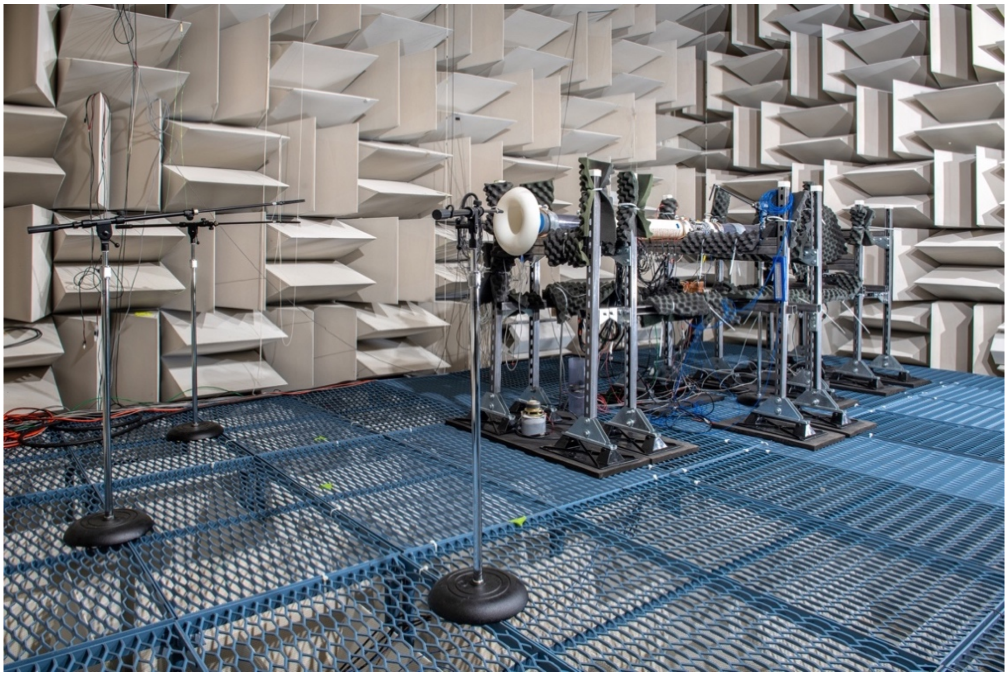

Figure 5: Photograph of the fan test rig and external microphones installed in the NASA GRC Acoustical Testing Laboratory, NASA-2021-C-02345.

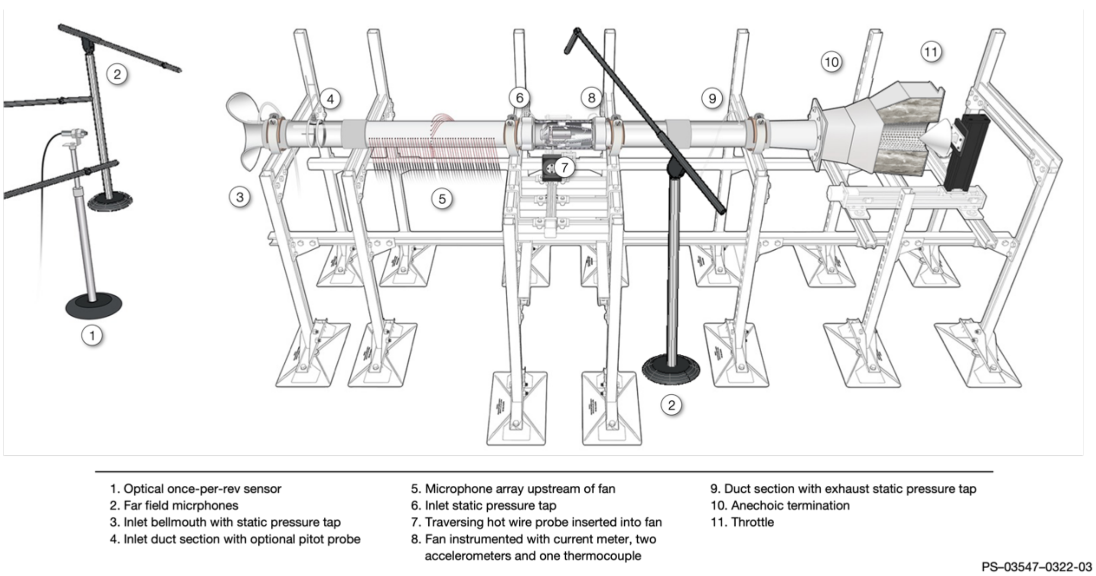

Figure 6: Illustration of fan test rig and selected instrumentation available used to test the NASA metal spacecraft ventilation fan prototype.

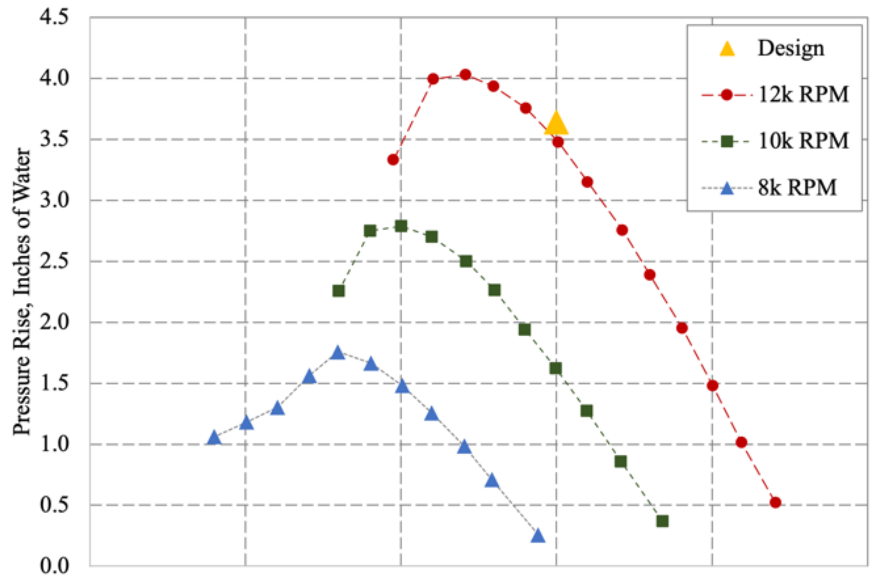

Figure 7: Variation of fan pressure rise with flow rate and speed for the NASA metal spacecraft cabin ventilation fan prototype tested in 2021, Reference 22.

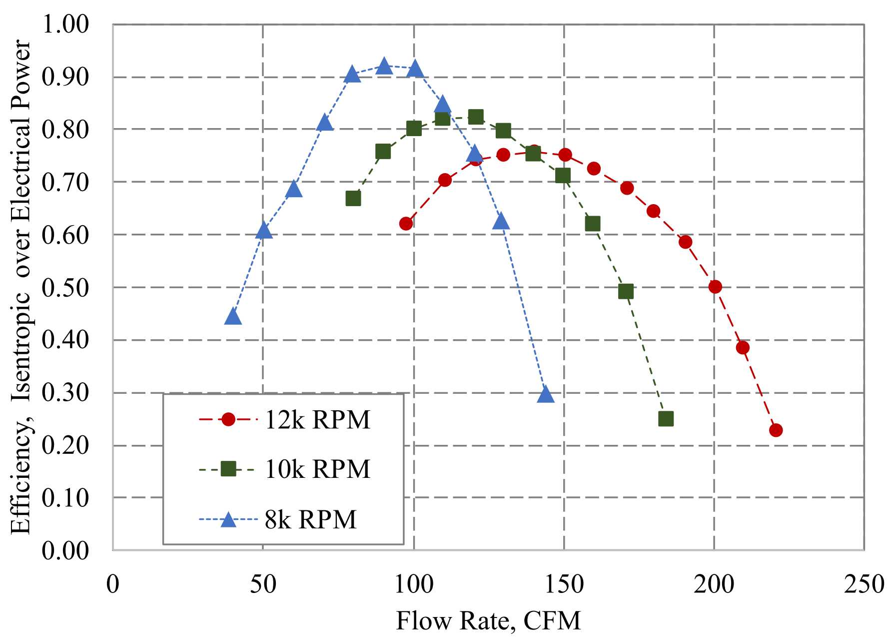

Figure 8: Variation of fan efficiency with flow rate and fan speed from the test in 2021, Reference 22.

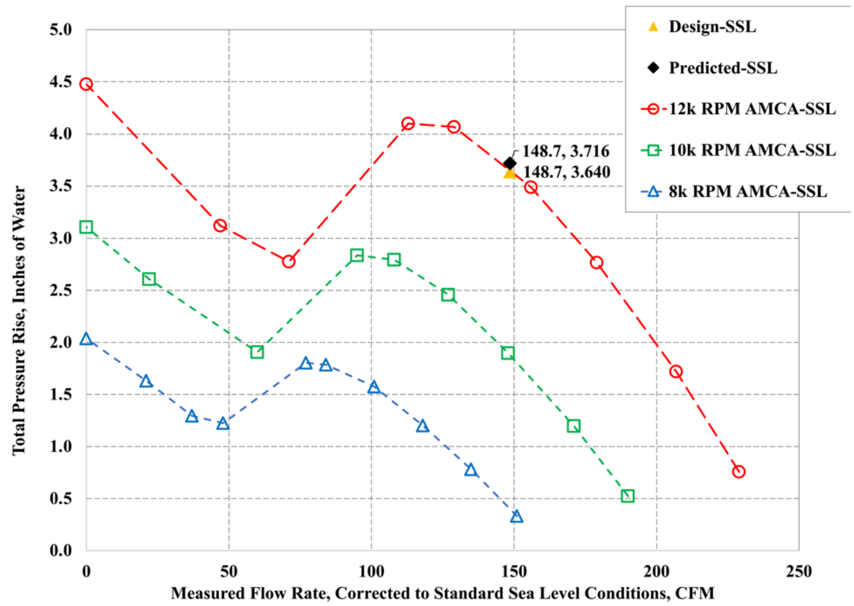

Figure 9: Performance of the NASA Quiet Space Fan measured by AMCA compared to the design and predicted fan system performance for air at Standard Sea Level (SSL) conditions.

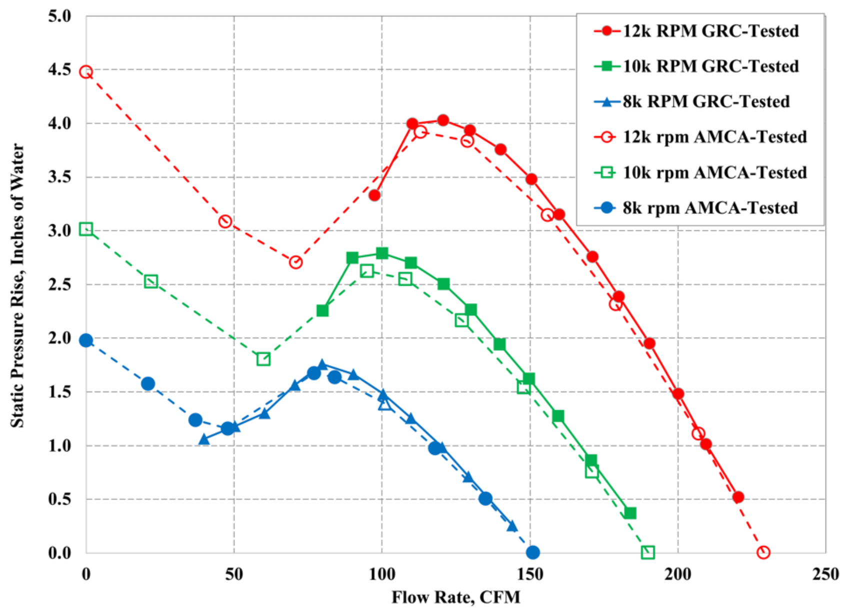

Figure 10: A comparison of fan performance as measured by NASA GRC and AMCA.

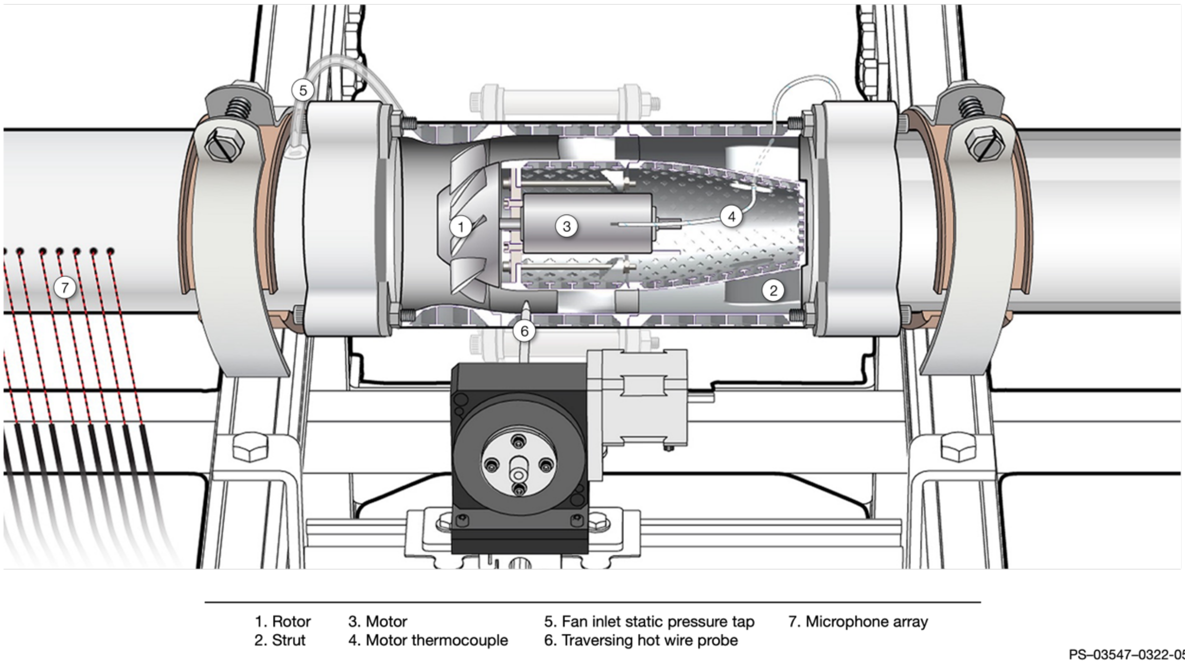

Figure 11: Actuated hot wire probe to measure flow velocity and angle between the rotor and the stator to characterize rotor wakes, Reference 42.

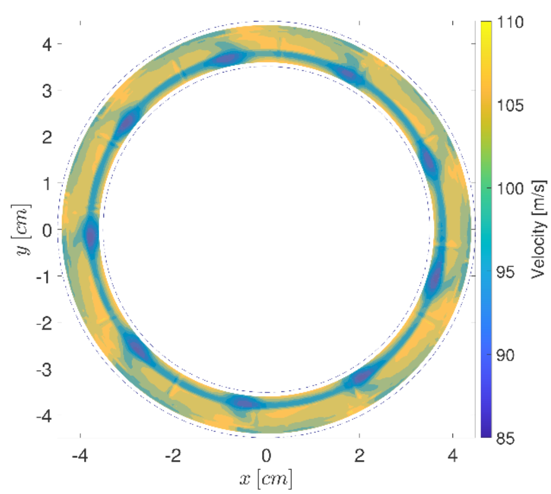

Figure 12: Velociy for the fan at design point conditions close to the trailing edge, Reference 42.

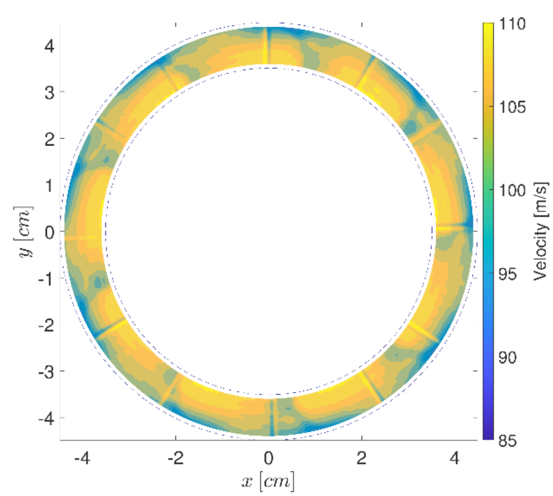

Figure 13: Velocity for the fan at design point conditions close to stator leading edge, Reference 42.

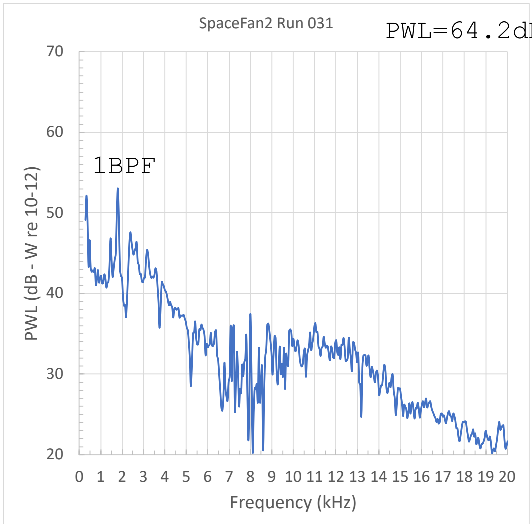

Figure 14: Internal array power spectra for the NASA Quiet Space Fan. Array placed upstream of the fan, Reference 43.

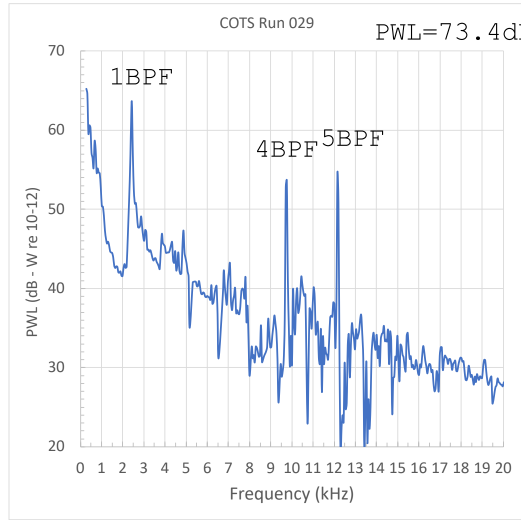

Figure 15: Internal array power spectra for the commercial-off-the-shelf (COTS) fan, Reference 43.

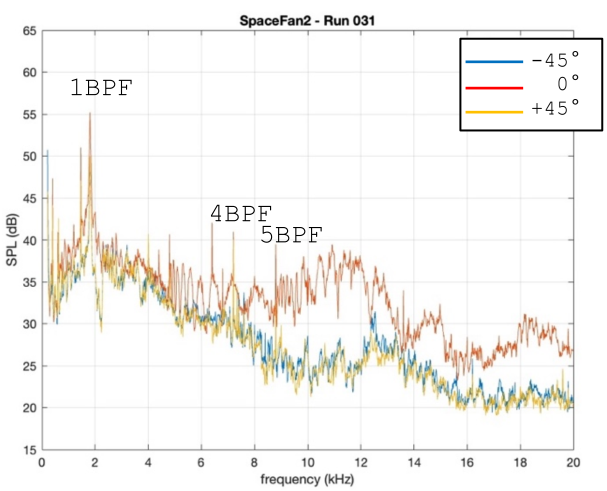

Figure 16: Spectra from the external microphones for the metal NASA Quiet Space Fan, Reference 43.

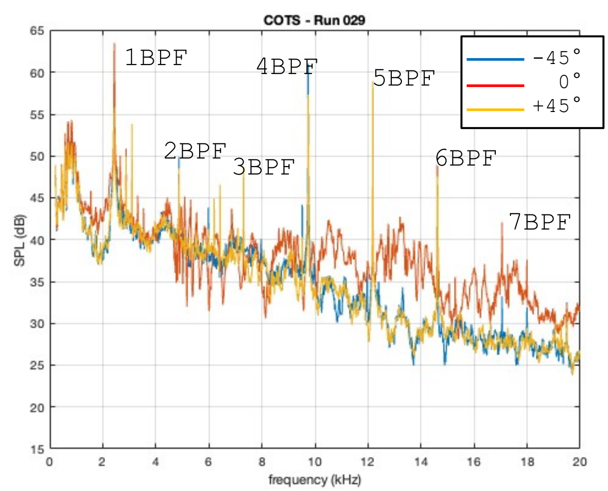

Figure 17: Spectra from the external microphones for the COTS fan, Reference 43.

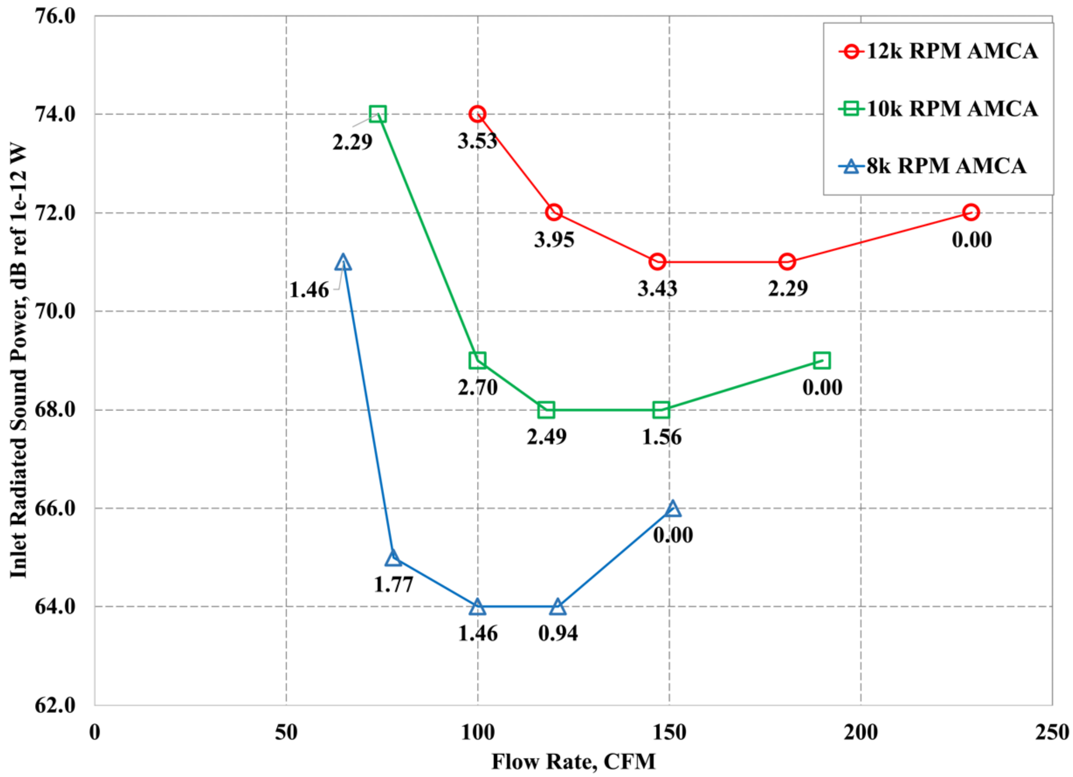

Figure 18: The variation of A-weighted sound power levels with flow rate corrected to standard air condtions and speed from tests at AMCA of the NASA Quiet Space Fan. Data labels refer to static pressure rise of the fan in inches of water.