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Aerodynamic and Acoustic Performance Testing of Metal Spacecraft Cabin Ventilation Fan

David Stephens, Jonathan Goodman, Rebecca Buehrle, L. Danielle Koch, and Dan Sutliff
Glenn Research Center, Cleveland, Ohio

August 2023

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Summary

A metal spacecraft cabin ventilation fan suitable for aerodynamic and acoustic ground tests was designed and two copies of the fan assembly were fabricated. Both fans were tested for aerodynamic performance and acoustic levels in the NASA Glenn Research Center Acoustical Testing Laboratory. A new test rig for small axial flow fans was designed to accommodate the instrumentation and back pressure adjustments. Measurements performed included static pressure measurements for evaluating performance, acoustic measurements using a 72-channel in-duct microphone array and an external microphone, and interstage hot wire measurements of the fan wake. This report documents the test setup. A series of follow-on reports will document the results. These fan units, the data, and the test facility described are valuable resources available for supporting NASA's aeronautics research and space exploration missions.

Introduction

Fans are critical components in spacecraft atmospheric revitalization and ventilation systems. Environmental noise continues to be a significant concern for manned spaceflight and fans are a major contributor (Ref. 1). Beginning in 2006, the NASA Glenn Research Center Acoustics Branch has been conducting research to examine the aerodynamic and acoustic performance of small fans (Refs. 2 to 4). A central research question was formed: Could the tools and techniques that had primarily been used to develop quiet and efficient fans for aircraft propulsion systems be put to broader use to support long-duration human exploration missions? By 2010, research attention became focused on cabin ventilation fans, historically some of the dominant sources of noise onboard spacecraft. A fan design nominally suited for a spacecraft cabin ventilation system was analyzed by Tweedt in 2010 using codes and techniques for turbomachinery computational fluid dynamics (CFD) at Glenn (Ref. 5). Tweedt later used the same flow rate, pressure rise, and overall size constraints to design and analyze the aerodynamic performance of a new axial fan, incorporating best practices in low noise aircraft engine design (Ref. 6). Tone noise predictions for this fan were generated by Koch in 2011 (Ref. 7). The aerodynamic design of the axial fan Tweedt developed in 2010 (Ref. 6) was used to create an additively manufactured thermoplastic prototype fan that was tested in 2012 (Ref. 8) in Glenn's Acoustical Testing Laboratory (Refs. 9 and 10). In that test, far-field noise measurements were recorded as the fan was tested in isolation, without inlet and exhaust ducts, and without the ability to throttle the fan through its operating range and to its design point.

The present report describes an 18-month task to design, build, and test a metal version of this fan, including mapping its aerodynamic and acoustic performance throughout its operating range. First, details about the metal fan design and manufacture are presented. Next, the report describes the test rig developed to control the back pressure on the fan using a throttle plug while measuring the flow rate and pressure rise. Instrumentation specific to this test included a 72-channel duct-mounted microphone array and a two-axis traverse for a hot wire probe. Finally, the results of the aerodynamic and acoustic tests are presented and discussed.

Metal Fan Design and Analysis

The aerodynamics of the rotor, stator, and duct were designed by Tweedt (Ref. 6) and were the same as those used in the plastic prototype tested in 2011 (Ref. 7). The mechanical design of the fan was intended for easy construction and limited machining. Fastener count was controlled and focused on using nuts and bolts rather than tapped holes where possible. The casing was formed in three parts, with an upstream inlet section, a stator section, and a strut section. The casing was specially designed for additive manufacturing and includes unique lightweighting features.

Fan Lightweighting

Efforts were made to reduce the weight of the casing to demonstrate the advantages of additive manufacturing. A stiffening rib structure was developed, with a flange on top that forms what resembles a T-beam, which greatly increases stiffness compared to conventional ribs while reducing weight. The T-beams conform to the periphery of the casing. Figure 1 shows a cutaway view of the design.

The conformal T-beams are oriented on splines that spiral along the axial direction in both directions of the casing with an incidence angle of 45°. The splines repeatedly intersect as they spiral in opposing directions, forming a waffle-like pattern. Figure 2 provides an external view of the design.

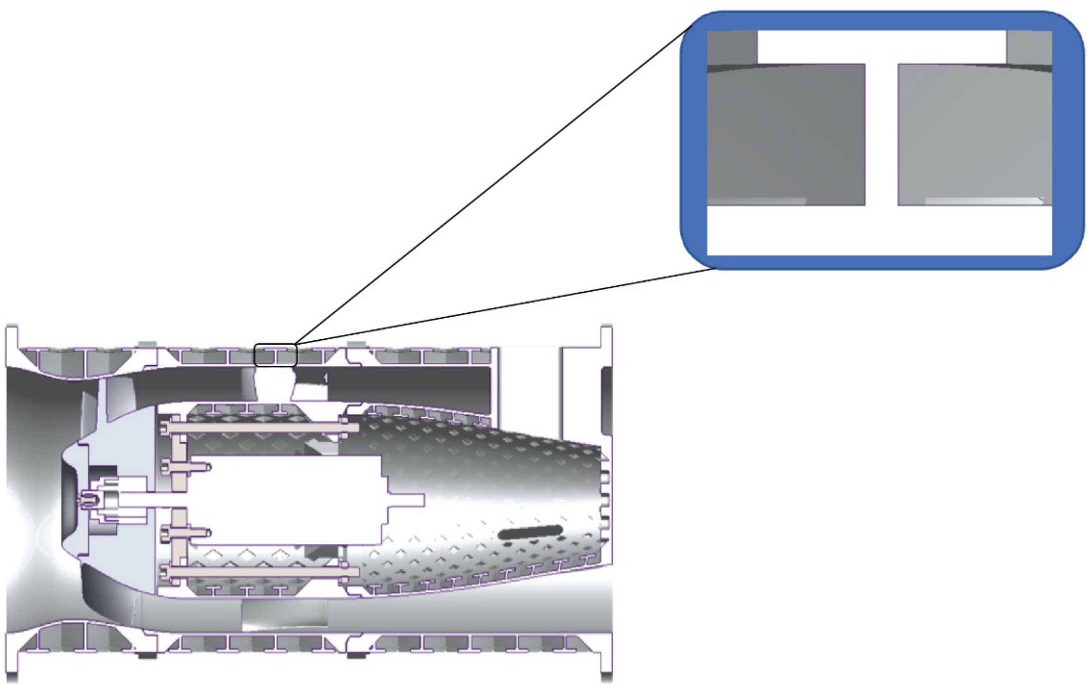

Figure 1.—Cutaway view of metal Spacefan illustrating T-beam stiffening.

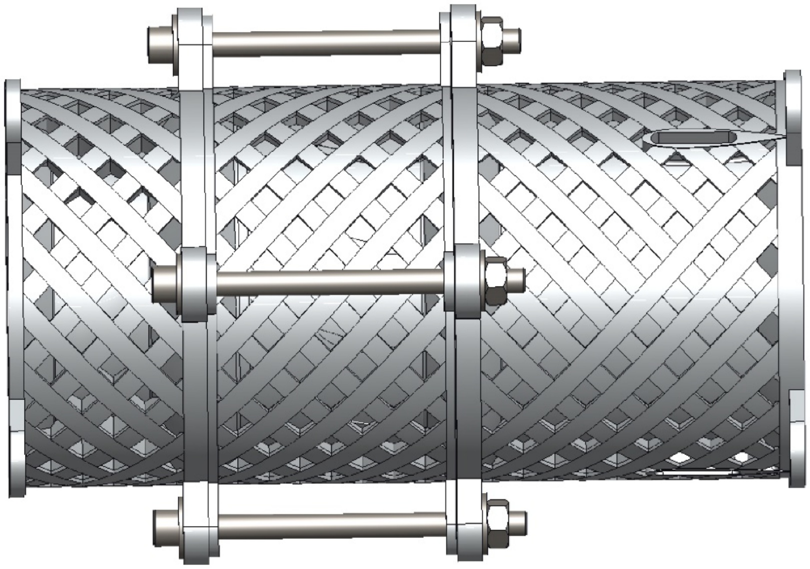

Figure 2.—External view of T-beam structure.

Removable Rotor

One of the significant improvements for the new design is the ability to dismantle the rotor from the motor. This increases the versatility and flexibility of the design, allowing for future modifications and upgrades. In the previous design, the rotor was permanently cemented on the motor, preventing disassembly.

To enable disassembly of the rotor, a keyless bushing was selected to serve as the interface between the rotor and the motor. The keyless bushing not only friction grips the motor's shaft but also grips on to the rotor, creating a mechanical linkage between the shaft and rotor. To access the tightening mechanism of the keyless bushing from the upstream side of the fan, the nose fairing was made as a separate part that can be detached from the rest of the rotor. Figure 3 and Figure 4 illustrate the design of the rotor assembly.

Modal Analysis

A modal analysis was conducted on the rotor using Creo Simulation software (PTC) (Ref. 11) to determine its modal frequencies to ensure that none would be excited under the operating conditions of the fan. The modal analysis was performed under a free-free, that is, unconstrained, boundary condition with the material properties of T6061 aluminum. Figure 5 combines a table of the modal frequencies of the rotor with images of associated shapes.

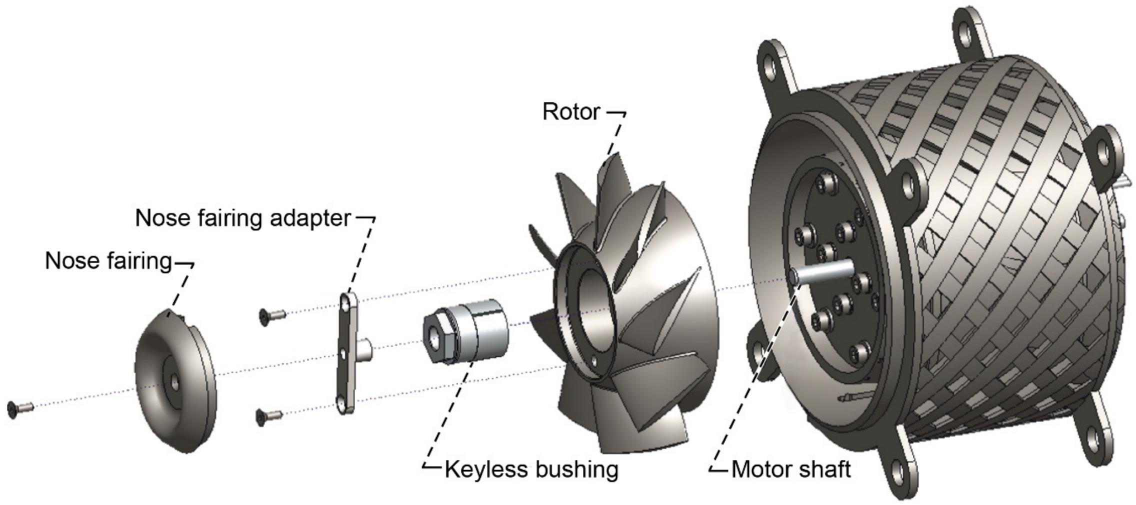

Figure 3.—Exploded view of rotor assembly.

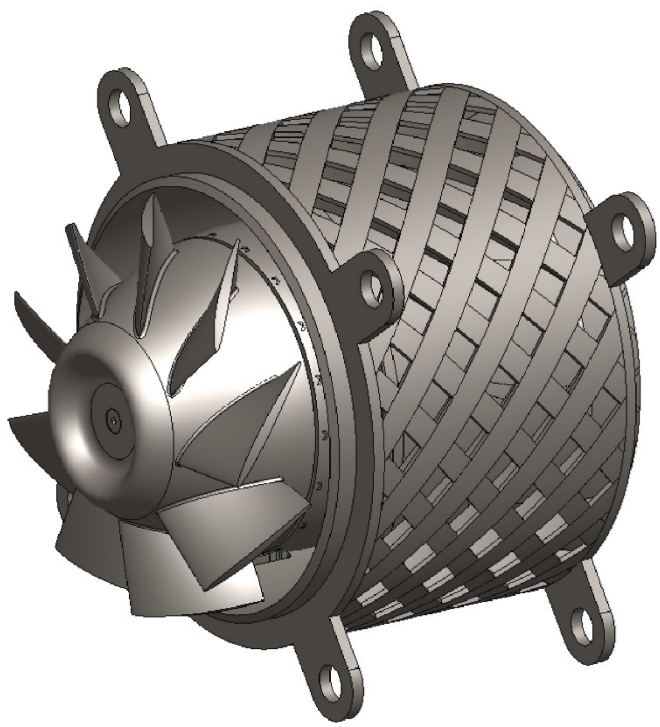

Figure 4.—Rotor assembly.

Mode no., Hz	Frequency	
1	0.0	Rigid-body modes
2	0.0	
3	0.0	
4	0.0	
5	0.0	
6	0.0	
7	7429.4	Blade first-bending modes (a)
8	7462.8	
9	7487.2	
10	7509.8	
11	7541.3	
12	7541.7	
13	7839.9	
14	7885.6	
15	8055.9	
16	14004.9	Blade second-bending modes (b)
17	14092.7	
18	14148.8	
19	14195.7	
20	14243.3	
21	14248.0	
22	14258.9	
23	14287.1	
24	14347.3	
25	17429.5	Dipole modes (c)
26	17451.1	
27	24753.1	Blade third-bending modes (d)
28	24761.2	
29	24795.3	
30	24810.8	
31	24822.5	
32	24852.7	
33	24862.2	
34	24921.3	
35	24928.3	

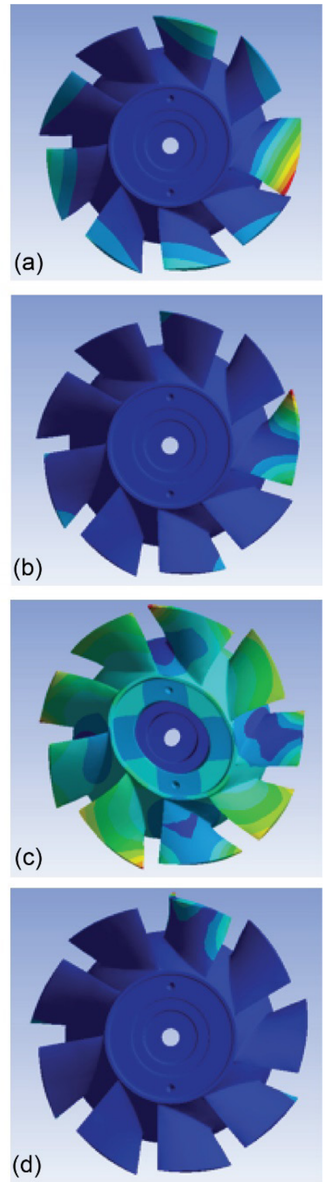

Figure 5.—Modal analysis summary of rotor.

Static Structural Analysis

A structural analysis was performed using CREO Simulate. The boundary conditions were a centrifugal force on the blades resulting from them spinning at 12,000 rpm, and 1 psi of pressure force was applied to the bottom surface of the blades to account for the lift force generated by the fan. The 12,000 rpm value is based on the maximum fan speed that the fan's speed controller is set to allow, and the lift pressure value is a highly conservative estimate based on expected fan performance. The stress levels are shown in Figure 6.

The highest stress on the blade occurs at the root of the blades at the junction fillet between the hub of the blisk and the blades. Figure 7 provides a zoomed-in view of the rotor stress levels. A maximum von Mises stress of 845 psi corresponds to a safety factor of about 19.

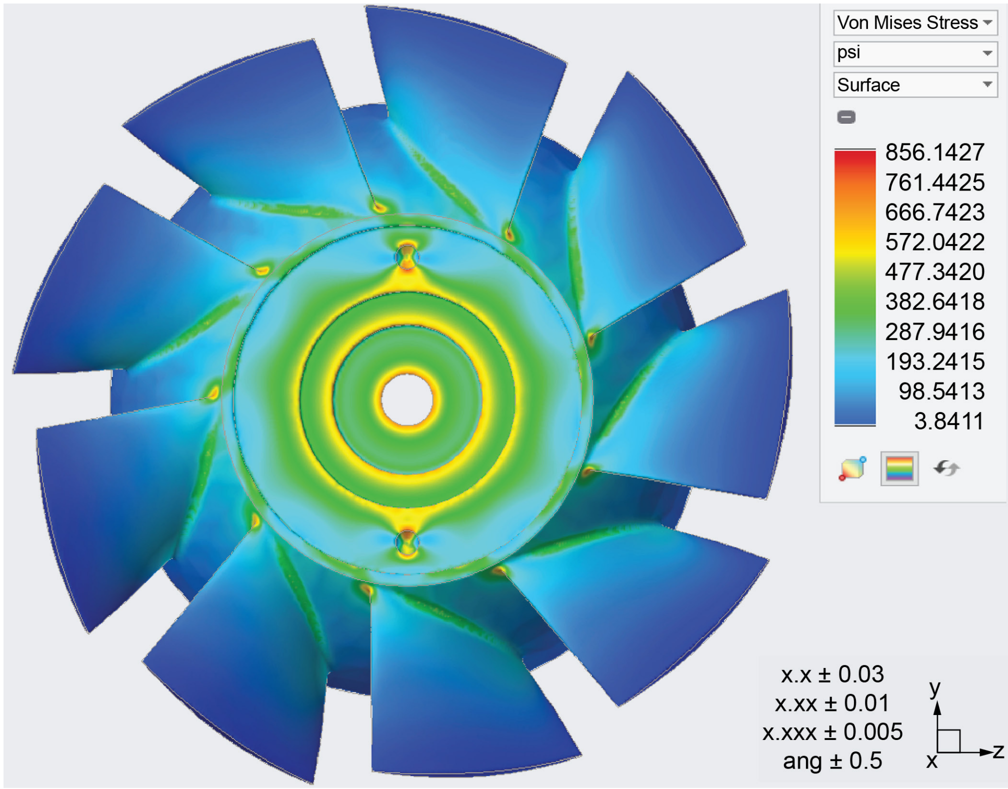

Figure 6.—Rotor stress levels.

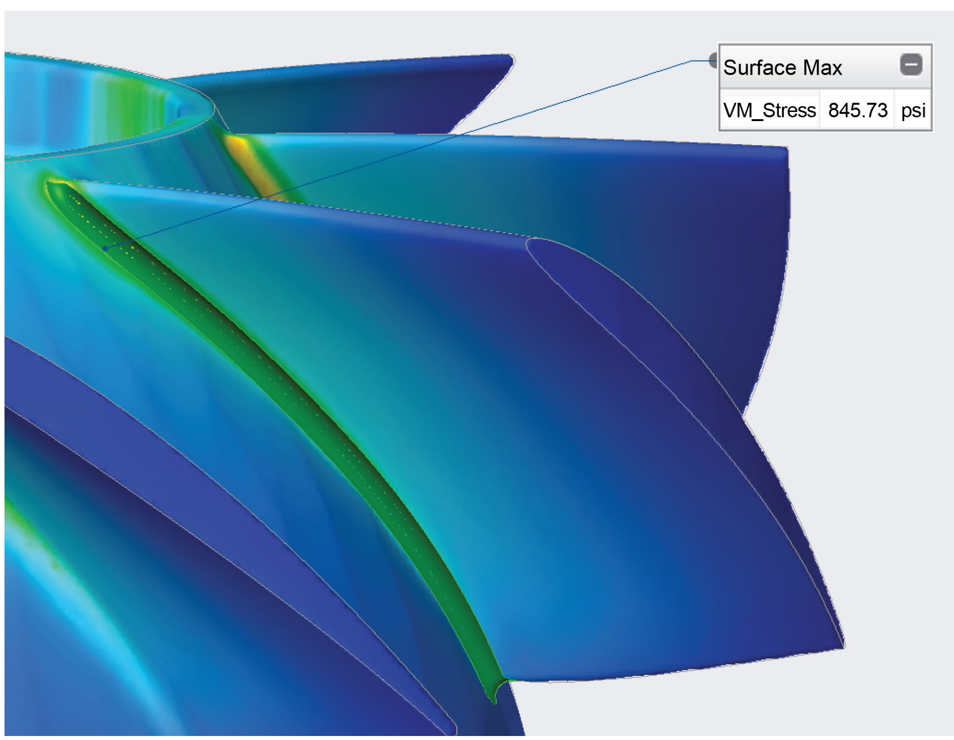

Figure 7.—Rotor blade stress levels.

Manufacturing

The design of the fan assembly included three additively manufactured casing sections. These were printed in AlSi12 alloy using direct metal laser sintering (DMLS). The rotor, nose cone, and motor mounts were machined from T6061 aluminum.

Observations

The fan assemblies were measured for rotor tip gap and concentricity using feeler gauges. The tip gaps measured on the two units were extremely similar, with a tip gap of 0.20 mm (0.008 in.) for unit 1 and 0.23 mm (0.009 in.) for unit 2. Concentricity was within the measurement capability of the feeler gauge method.

It was anticipated that metal printed using DMLS would have a very rough surface when compared with typical aerospace turbomachinery components. Surface roughness of the fan units was measured using a calibrated profilometer. After the flow passage upstream of the fan was hand polished, its roughness was measured at 1.3 µm (51 µin) Ra. The other interior flow surfaces were essentially unfinished due to very limited access for polishing and had a surface roughness of around 8 µm (300 µin) Ra.

The total assembly weight (rotor, stator, casing, motor, thermocouple, and two accelerometers) was 1,635 g (3.6 lb).

Balancing

Considerable time and energy were spent deciding on the requirements for balancing the fan rotor. Multiple team members had experience with balancing fan rotors of different sizes, but all those rotors were larger than the present unit. A vibration report from the Air Movement and Control Association, Inc., (AMCA) regarding centrifugal fans (Ref. 11) suggested that values less than 0.76 mm/s (0.03 in./s) would correspond to "very good" vibration levels. A calculation about the rotor unbalance gave some guidance about what to require from a balance vendor. The eccentricity or specific unbalance is the ratio of the unbalanced mass over the mass of the rotor, multiplied by the radius r of the unbalance

$$e = \frac{U}{m_{\text{rotor}}} = r\frac{m_{\text{unbalance}}}{m_{\text{rotor}}} \tag{1}$$

where U is the unbalance of the part. The balance grade is defined as

$$G = e \times \omega \tag{2}$$

where the shaft rate is ω in rad/s. Expressing G in units of mm/s, the balance grade is simply the vibration of the system, such as G1 means G = 1 mm/s. For this rotor at operating speed

$$\omega = \frac{12{,}000}{60} \times 2\pi = 1{,}257 \text{ rad/s} \tag{3}$$

To achieve a G1 vibration, e = 0.0008 mm is necessary. The rotor volume is 3.37 in^3 and so the mass is m_{rotor} = 149 g (5.26 oz or 0.33 lbm), assuming it is manufactured from aluminum. This means the unbalance U = 0.119 g-mm. With the conversion factor 720 g-mm to 1 oz-in., that gives a requirement of 0.00016 oz-in. (0.0045 g-in.), given that balancing in the United States is often done in English imperial units.

Test Rig Design

A test rig was also designed and assembled to allow small fans to be throttled through their operating envelopes so that aerodynamic and acoustic measurements could be acquired.

Standards

The test rig design largely followed International Organization for Standardization (ISO) Standard 5801, 3rd ed. (Ref. 13), for an aerodynamic testbed. The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Standard 68 was also a valuable reference (Ref. 14). Similarly, ISO 5136, 2nd ed. (Ref. 15), was used to guide the design and methods for noise testing of a ducted fan. The test rig size was constrained slightly by the dimensions of the test chamber, but this is expected to have a very minor effect.

Bellmouth

A bellmouth was designed for the 3.5-in. duct section, based on the ISO standard recommendations and prior experience. A two-curve profile was chosen for the lip and the size turned out to be a good fit for printing via stereolithography (SLA). A rendering of the bellmouth is shown in Figure 8.

The inlet static pressure was simulated using SOLIDWORKS® Flow Simulation software (Dassault Systèmes)(Ref. 12). A 150 ft^3/min airflow was pulled through the bellmouth and the static pressure on the wall was evaluated. The straight part of the duct was the logical place to put a wall static tap, but the availability of easy-to-use CFD confirmed that about an inch downstream of the end of the curvature was suitable for a wall tap. Figure 9 illustrates a cut plane showing simulation results of relative pressure.

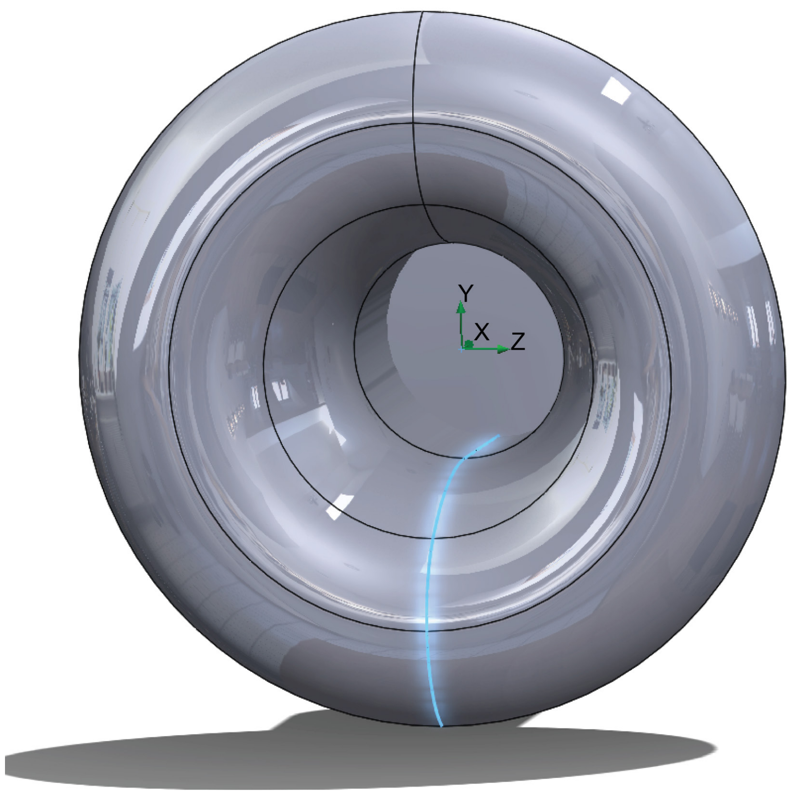

Figure 8.—Rendering of inlet bellmouth.

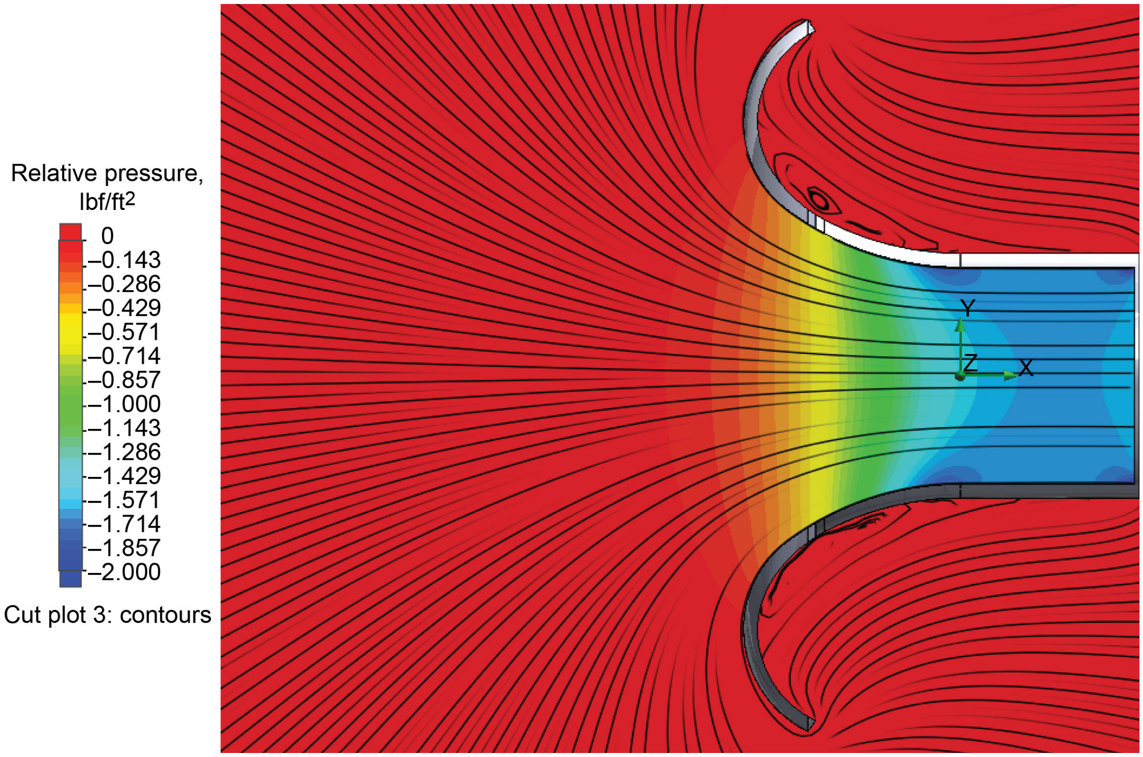

Figure 9.—Simulation of airflow through bellmouth, 150 ft^3/min. Streamlines in black on top of contours of static pressure.

The pressure was extracted along the blue line highlighted in Figure 8. The resulting pressure is shown in Figure 10. The velocity is low at the upstream extent of the bellmouth and the pressure is correspondingly high. This result shows the pressure tap should be placed between 0.60 to 0.75 ft from the bellmouth highlight.

Throttle

A critical part of testing the Spacefan was applying an appropriate amount of flow resistance to the duct to push the fan to the design point on the fan map (a representation of the pressure rise vs. flow rate for different fan rotation speeds). This system also had to be adjustable so that different setpoints could be achieved. The adjustment needed to be controlled remotely so that test points could be varied without entering the test chamber or interrupting the test. A Velmex BiSlide linear actuator and controller were already available and were determined to have more than sufficient range of motion and load capability. A string potentiometer was used to measure the position of the BiSlide. A few accessories were procured and a throttle cone was three-dimensional- (3D-)printed using SLA. The cone was inserted into the outlet of the anechoic termination to block airflow. The completed assembly is shown in Figure 11.

A simple control program was developed to control the throttle, which communicates to the motion controller by requesting motor steps in a serial command string. The linear motion is actuated by a lead screw with a pitch of 1 mm per rotation, driven by a stepper motor with 400 steps per revolution. Prior to any testing experience, this seemed like sufficiently small steps. The test rig operator would insert or withdraw the throttle to achieve the desired fan back pressure. The control program interface used is shown in Figure 12. In practice, this was sufficiently usable for a manually conducted test. If many test runs were to be conducted, either a feedback loop could be used or a look-up table generated.

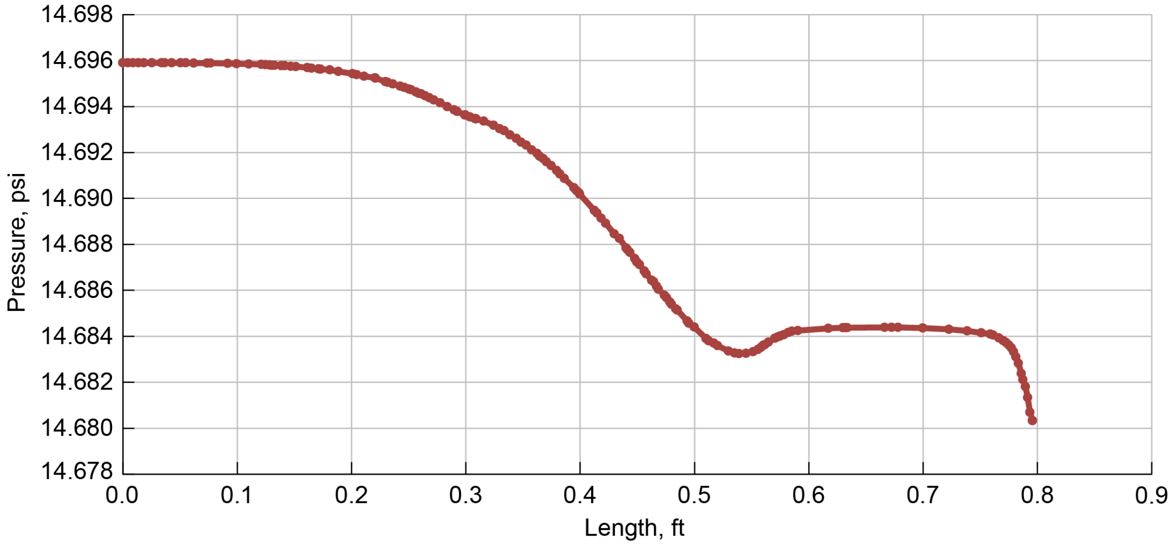

Figure 10.—Axial pressure along bellmouth.

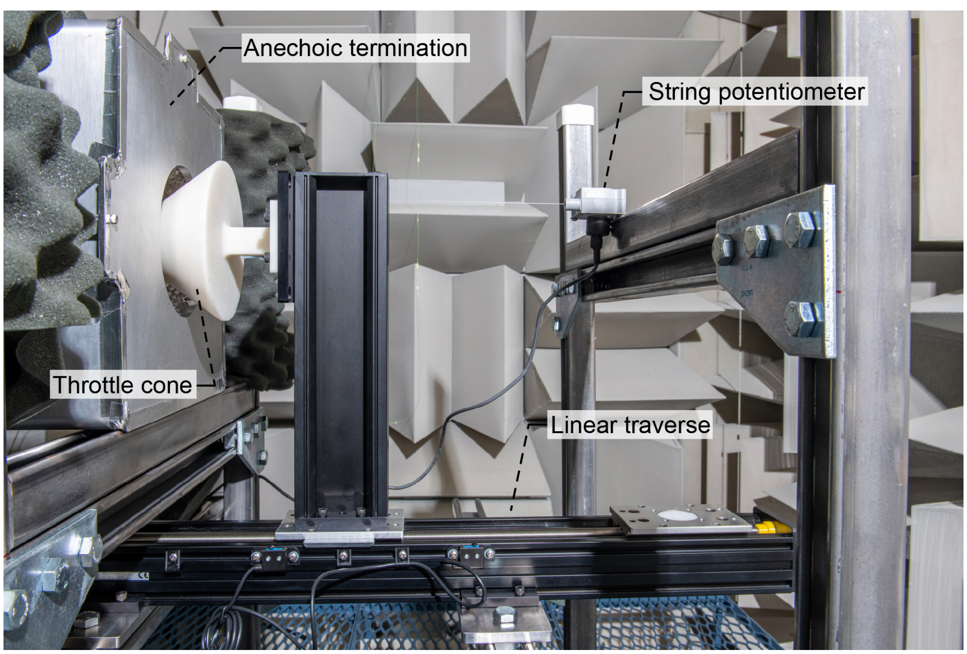

Figure 11.—Ducted test rig exit showing throttle assembly with annotations.

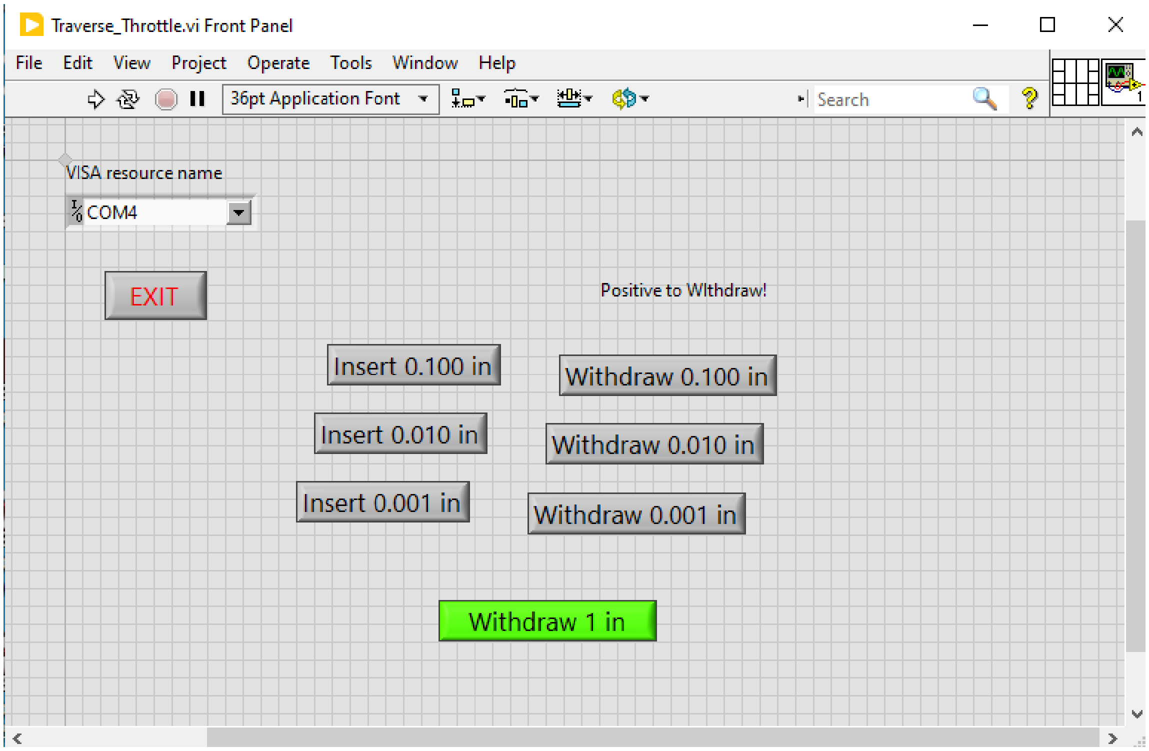

Figure 12.—LabVIEW program control panel for throttle control.

Microphone Array

An array of wall-mounted microphones was utilized to thoroughly document the duct-borne noise created by the fan. A convergence of several opportunities made it possible to do this on a small scale and at a low cost:

- Relatively low expected noise levels enabled the use of inexpensive microphones.
- Existing electronics for a 72-element array were available.
- A duct with holes could be made using 3D-printed plastic.
- The Spacefan scale and available sensor count are a good fit for describing the sound field in the duct.

Microphones

A 72-channel mode array had been developed for static (without flow) ultrasonic noise testing (Ref. 16). The microphones used for that system have been discontinued, so a different electret condenser sensor was selected based on sensitivity, frequency range, and dimensions. The model CME–1538–100LB from CUI Devices had an advertised frequency range from 100 Hz to 20 kHz. The 4-mm (0.157-in.) diameter was small enough to be compatible with the intended array dimensions.

Array Dimension Design

A previous test at Glenn with in-duct microphone mode measurements (Ref. 18) used a T-array, with an axial line array intersecting a circular ring of sensors. To design the present array, the circular array of 23 elements was specified with a spacing of 12 mm (0.475 in.). The remaining 49 sensors would be used for an axial array, with one overlap with the circular array. The 50 elements in the axial array at the same spacing produces an axial length of 591 mm (23.275 in.). The resulting performance is that the array can determine a maximum azimuthal mode of order 11 with a frequency of 14,215 Hz, not including convective flow effects. The lower frequency resolution is set by the axial length and is 281 Hz. The array design details are outlined in Table 1. Figure 13 shows the array design based on these specifications.

Assembly of Array

The array tube was manufactured using SLA. It was decided to print the part with its axis at an angle to the build layers to avoid deformation. The finished part seemed to be of good accuracy and printing the microphone holes in the part set the dimensions. The holes were slightly oversized and the microphones fit through them without friction. This was to avoid adding any prestress to the microphones that might affect the frequency response. The microphone array tube is pictured in Figure 14.

A plug was also built that slid inside the array to help set the depth of the microphones. The microphones were held in place with low-temperature hot glue. Figure 15 shows a closeup of the microphone array.

TABLE 1.—MICROPHONE ARRAY DESIGN PARAMETERS

Parameter	Value
Inputs	
Duct inner diameter, in.	3.5
Microphone spacing, in.	0.475
Microphone diameter, mm	4
Length of axial array, in.	24
Calculated acoustic properties	
Upper frequency of azimuthal array, Hz	14,215
Upper azimuthal mode	11
Lower frequency of axis, Hz	281.25
Calculated geometric properties	
Inner circumference, in.	11.00
Microphone diameter, in.	0.157
Number of microphones in circumference	23
Spacing between microphones, in.	0.321
Number of microphones in axial array	50
Total number of microphones	72

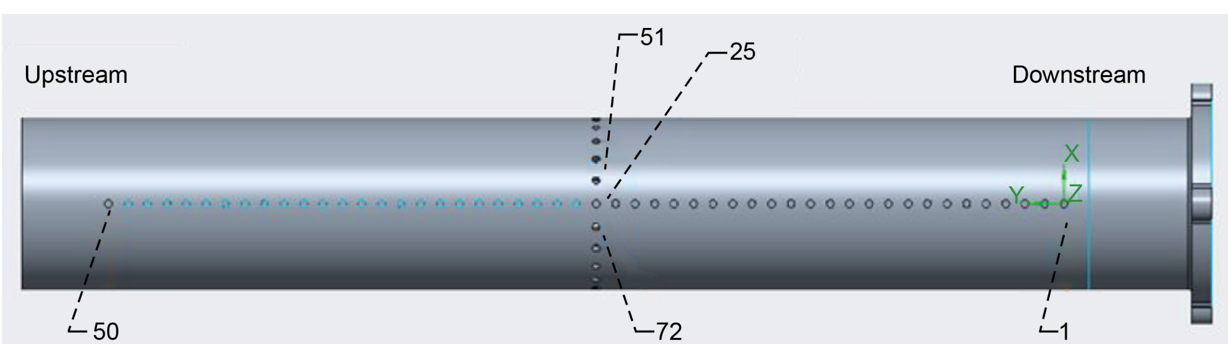

Figure 13.—Rendering of microphone array.

The microphone cables, each a twisted pair, were connected to the 50-pin cables using a set of three breakout boards (Figure 16). This allowed for easy troubleshooting while still limiting the number of connections required.

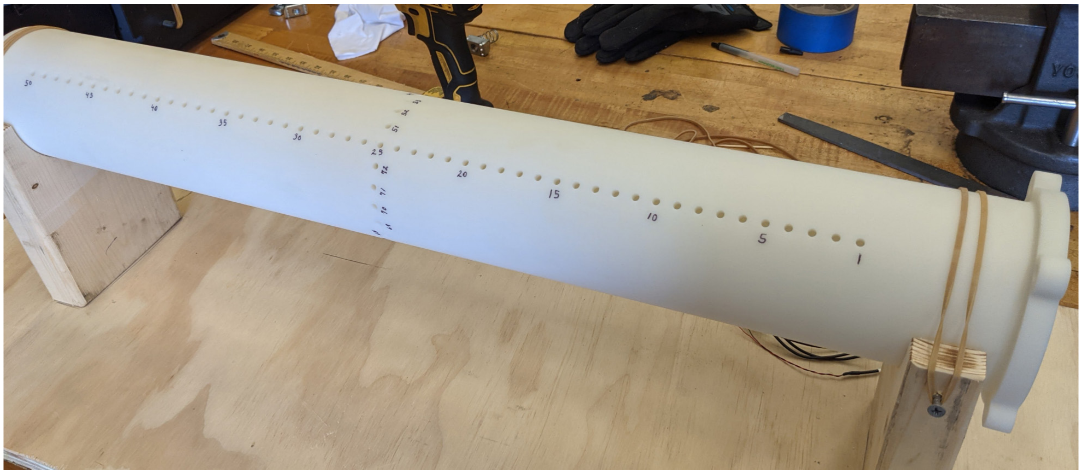

Figure 14.—Microphone array tube before installation of sensors.

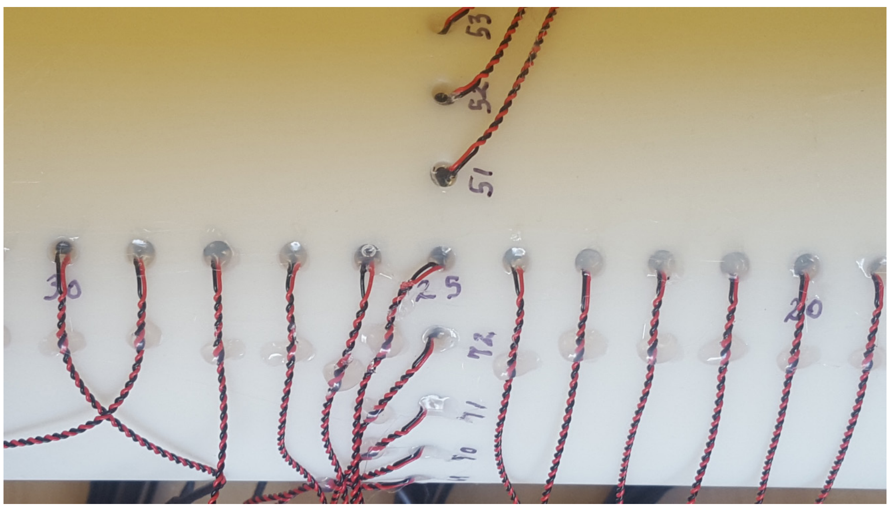

Figure 15.—Microphone array showing installation, numbering, and adhesive.

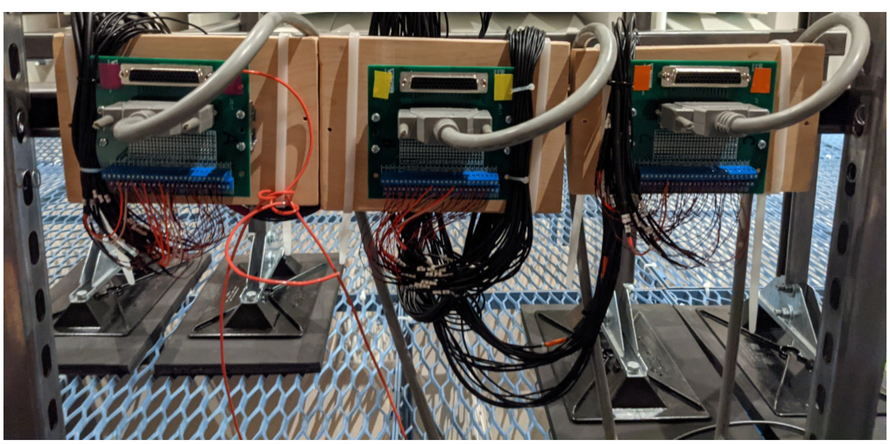

Figure 16.—Microphone array breakout connectors.

Array Electronics

The electret microphones were powered by a set of amplifier boards designed by OptiNAV, which were previously used at the Acoustical Testing Laboratory (Ref. 16). Each board supports eight channels of signal output via a 25-pin connector that breaks out to eight BNC connectors. The boards were wired in groups of three, giving 24 channels that are connected to a 50-pin input cable. Figure 17 shows the internal wiring of the larger of two microphone array electronics boxes; Figure 18 shows the exterior of these boxes once assembled.

The 25-pin connectors each carry eight channels through BNC cables to a data acquisition system or to an oscilloscope for troubleshooting. The 50-pin connectors each connect to 24 microphones for a total of 72 channels. The 50-pin cables are a convenient and low-cost way to bundle many channels together. In this way, the data system and electronics can be located in the control room using a set of three 50-ft cables that run into the test chamber.

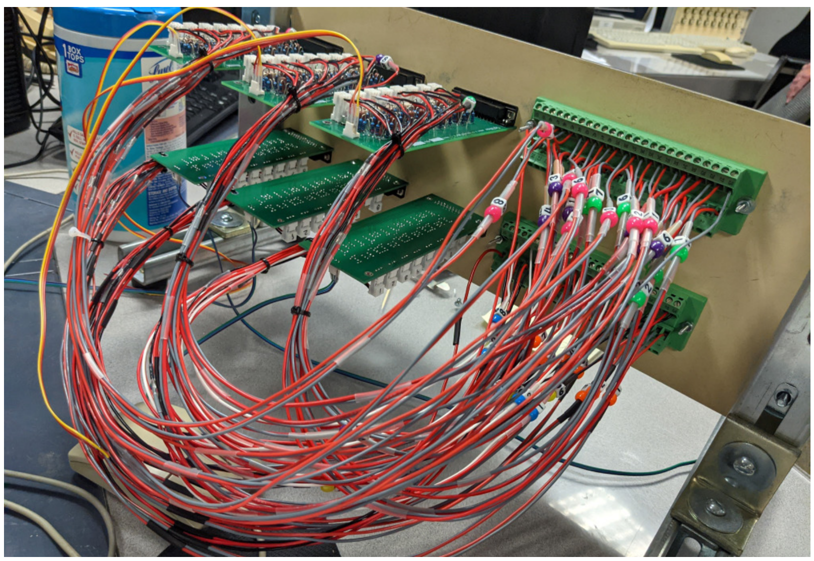

Figure 17.—Internal wiring of array microphone electronics.

Figure 18.—Assembled amplifier boxes for microphone mode array.

External Microphones

Four external microphones were used to acquire time histories to evaluate noise radiated from the test article. Three microphones were arranged to measure noise radiated from the inlet; one microphone was set up to measure case radiated noise. The three inlet radiated noise microphones were mounted on poles at a radius of 3 ft from the inlet duct lip. The microphones' faces were oriented toward the inlet and placed at angles relative to the duct centerline of –45°, 0°, and 45° in the horizontal plane of the duct centerline. The microphone measuring the case radiated noise was placed directly above the fan plane, 6 in. from the duct. The positions of the microphones are as illustrated in Figure 19 and Figure 20; the photograph in Figure 21 also shows their positions around the test rig.

The microphones used were PCB Piezotronics model 378C01 ICP microphone systems, which consist of a quarter-inch free-field, prepolarized 377C01 microphone and a 426B03 preamplifier with a programmed Transducer Electronic Data Sheet (TEDS). Time histories from the microphones were acquired using an HBM GEN3i data acquisition system with an acquisition sample rate of 100,000 samples/s and bandwidth filtering at 100 Hz to 40 kHz with a 10 s acquisition time. The sensitivity was read from the TEDSs and applied to record the acoustic pressure time histories in pascals. Table 2 to Table 5 provide a full record of the GEN3i data acquisition system parameters.

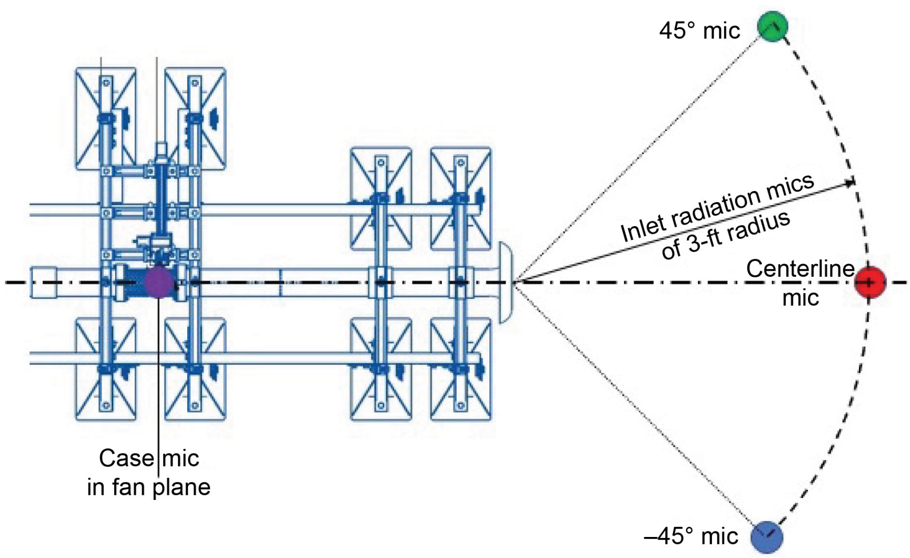

Figure 19.—Top view of test rig showing microphones (mics) for inlet radiated noise.

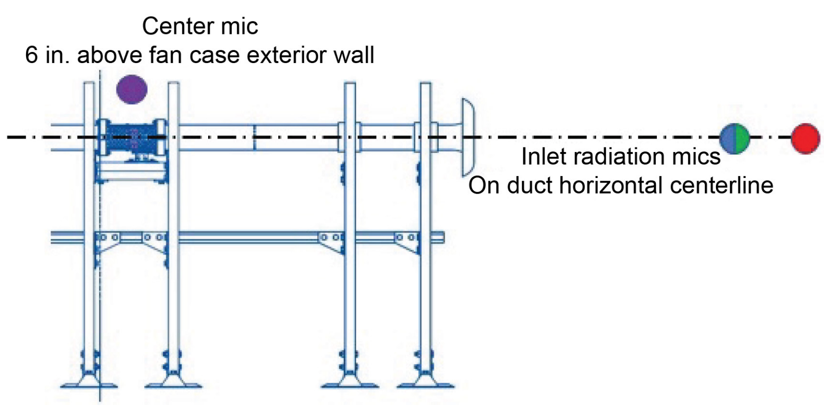

Figure 20.—Side view of test rig showing microphones (mics) for inlet radiated noise.

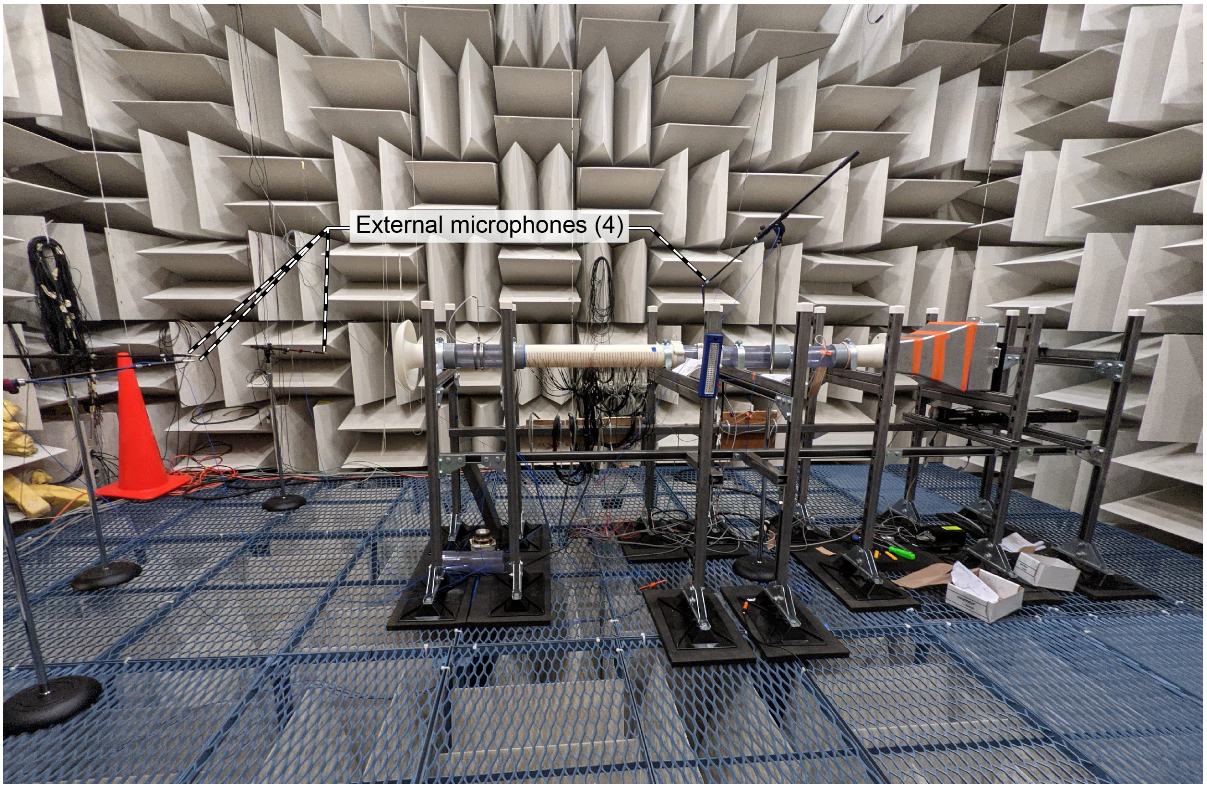

Figure 21.—Photograph of external microphones around test rig.

TABLE 2.—GENERAL GEN3i INFORMATION, PART 1

Memory and timebase—continuous					
Name	Timebase source	Continuous timebase	Continuous mode	Continuous length	External clock divider
Group1	Internal	100,000	Specified time	10	1

TABLE 3.—GENERAL GEN3i INFORMATION, PART 2

General—recorder			
Name	Physical name	Enabled	Recorder type
Recorder A	Recorder A	On	GEN series 250 kS/s
Recorder B	Recorder B	On	GEN series 250 kS/s
Recorder C	Recorder C	On	GEN series 250 kS/s

TABLE 4.—CHANNEL INFORMATION DUCT MICROPHONES

Name	Physical name	Amplifier mode	Phys unit/tech unit	Technical units	Signal coupling	Input coupling	Span	Filter type	Filter frequency high, kHz
Input basic voltage (Recorder A)									
Duct01	Ch A01	Basic	1V/V	V	AC	SE positive	40	BandPass	40
--------	--------	------	-----	--	---	------------	----	-----------	----
Duct32	Ch A32	Basic	1V/V	V	AC	SE positive	40	BandPass	40
Input basic voltage (Recorder B)									
Duct33	Ch B01	Basic	1V/V	V	AC	SE positive	40	BandPass	40
--------	--------	------	-----	--	---	------------	----	-----------	----
Duct64	Ch B32	Basic	1V/V	V	AC	SE positive	40	BandPass	40
Input basic voltage (Recorder C)									
Duct65	Ch C01	Basic	1V/V	V	AC	SE positive	40	BandPass	40
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Duct72	Ch C08	Basic	1V/V	V	AC	SE positive	40	BandPass	40

TABLE 5.—CHANNEL INFORMATION FOR EXTERNAL MICROPHONES

Name	Physical name	Amplifier mode	Excitation current (on)	Tech units multiplier PU/TU, mV/Pa	Span	Technical units multiplier	Tech units	Filter type	Filter frequency high, kHz
Input-accelerometer (Recorder C)									
FF-45R	Ch C09	Accel	0.004	2.567	7.792	389.5	Pa	BandPass	40
FF-cent	Ch C10	Accel	0.004	2.296	8.712	435.6	Pa	BandPass	40
FF-45L	Ch C11	Accel	0.004	1.758	11.38	568.9	Pa	BandPass	40
FF-case	Ch C12	Accel	0.004	1.932	10.35	517.6	Pa	BandPass	40

Hot Wire Equipment Setup

Rotor–stator interaction noise is an important sound source in axial turbomachines. For a single-stage fan such as the Spacefan, the mechanism is the rotor wake impinging on the stator. Measurements of the rotor wake are a useful diagnostic for investigating this noise source. Because the rotor is spinning, measurements in the stationary frame must have a sufficiently high frequency response to acquire many data points as the rotor blade moves past. For this nine-blade rotor spinning at 200 Hz, a frequency response of 10 kHz is desirable. Prior hot wire work on the wake of small fans was done at Glenn (Ref. 3).

For measurements on the present fan assembly, a TSI Incorporated model 1249 miniature cross-wire probe was used with an A.A. Lab-Systems hot wire anemometer. A slot in the stator section of the Spacefan assembly allowed the wire to be inserted and a rotary table allowed rotating the hot wire probe to the expected angle of the flow. The hot wire traverse assembly is shown in Figure 22.

A slot for the hot wire probe was included in the 3D print for the stator section. The probe could be inserted at two locations, corresponding to planes of predicted wake data 2a and 2b as described in the design report by Tweedt (Ref. 6). A set of three plugs was also built to cover the probe slot when not in use or to allow the probe to be inserted and the remaining portion of the slot covered. For the upstream probe location, the probe was inserted facing downstream and then rotated into position, as shown in Figure 23. The inserted probe with slot cover is shown in Figure 24. Once inserted, the probe could be traversed across the width of the annular flow passage to make measurements of the rotor wakes between hub and tip.

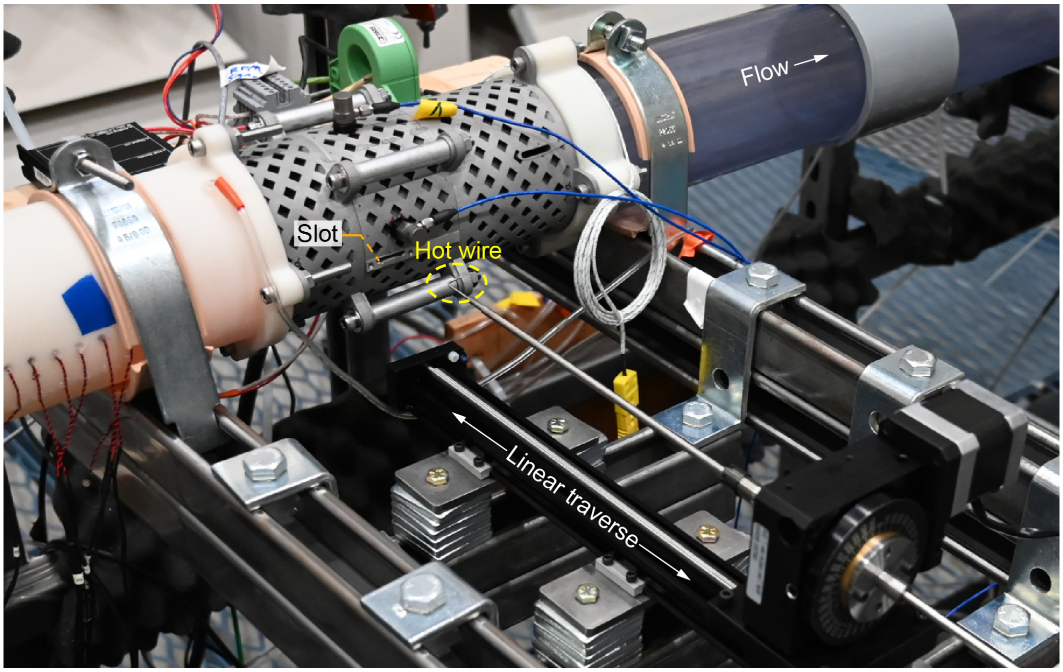

Figure 22.—Hot wire traverse assembly.

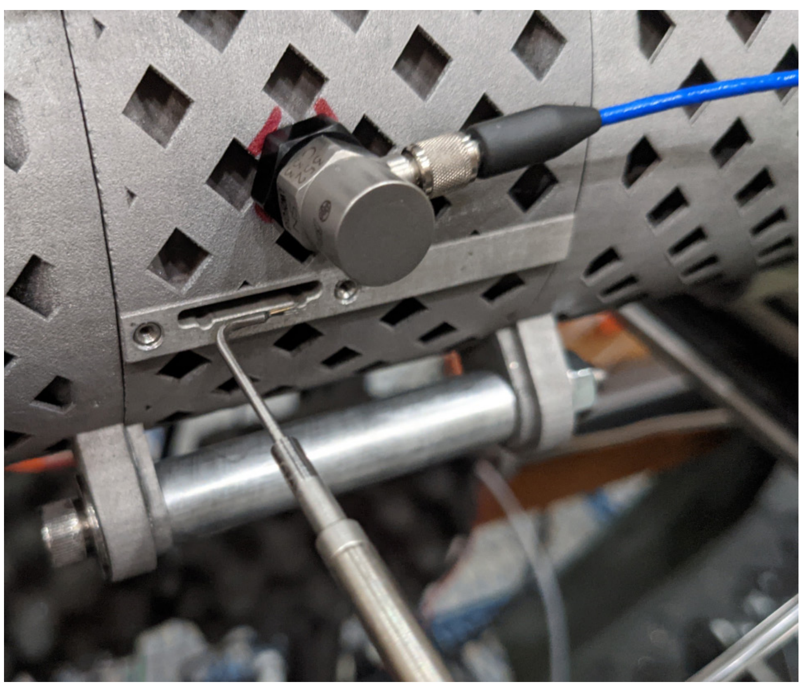

Figure 23.—Hot wire probe being inserted in upstream location while facing downstream.

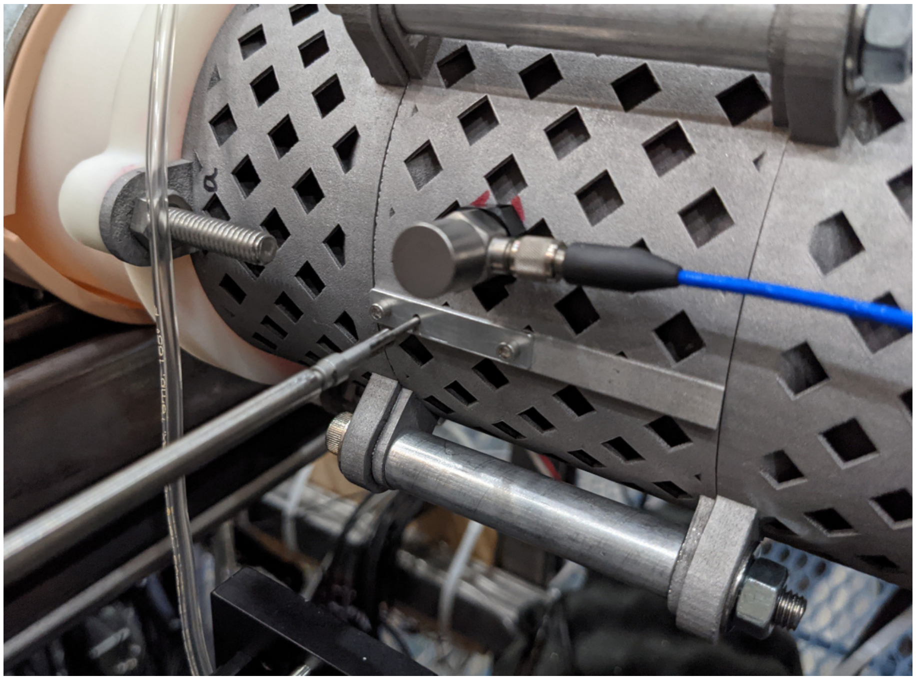

Figure 24.—Hot wire probe and slot cover installed in upstream location.

Pressure Instrumentation

To quantify the aerodynamic performance of the Spacefan, steady pressure measurements would be needed. Three Setra Model 239 differential pressure transducers (Figure 25) were used for these measurements. One measured the difference between room ambient pressure and a static tap in the throat of the inlet bellmouth. Another was used for a pitot-static probe inside the duct, upstream of the fan. The third measured the pressure rise with static taps on each side of the fan. The first two units measured pressure differentials over the 0 to 1 inH_2O range; the third measured them over the 0 to 15 inH_2O range.

Inlet Static Measurement

As described previously, the inlet was designed as an intersection of two elliptical shapes, evaluated using CFD, and printed using SLA. An inlet tap was placed in the straight section, where the expected pressure gradient was small. The inlet mounted on the test rig is shown in Figure 26. The largest pressure differential measured by the static tap was 0.74 inH_2O, corresponding to a wide-open throttle and a 12,000 rpm fan speed. This was calculated to be approximately 220 ft^3/min of air.

Pitot-Static Tube

A short duct section was used with a pitot-static probe installed. This was intended to verify the inlet static measurement while also being removable. It was anticipated that a large probe upstream of the fan would cause a flow distortion that would increase noise generated by the fan, which was obviously undesirable in a fan noise test. The pitot-static probe assembly is pictured in Figure 27.

Figure 25.—Setra Model 239 pressure transducers used for testing.

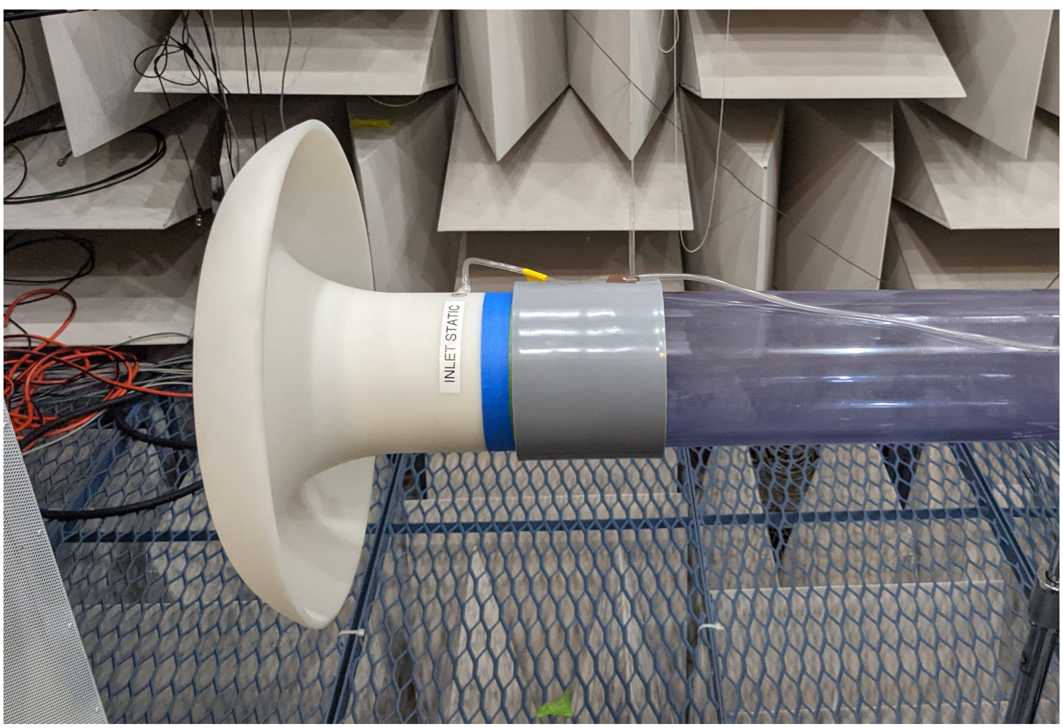

Figure 26.—Bellmouth inlet.

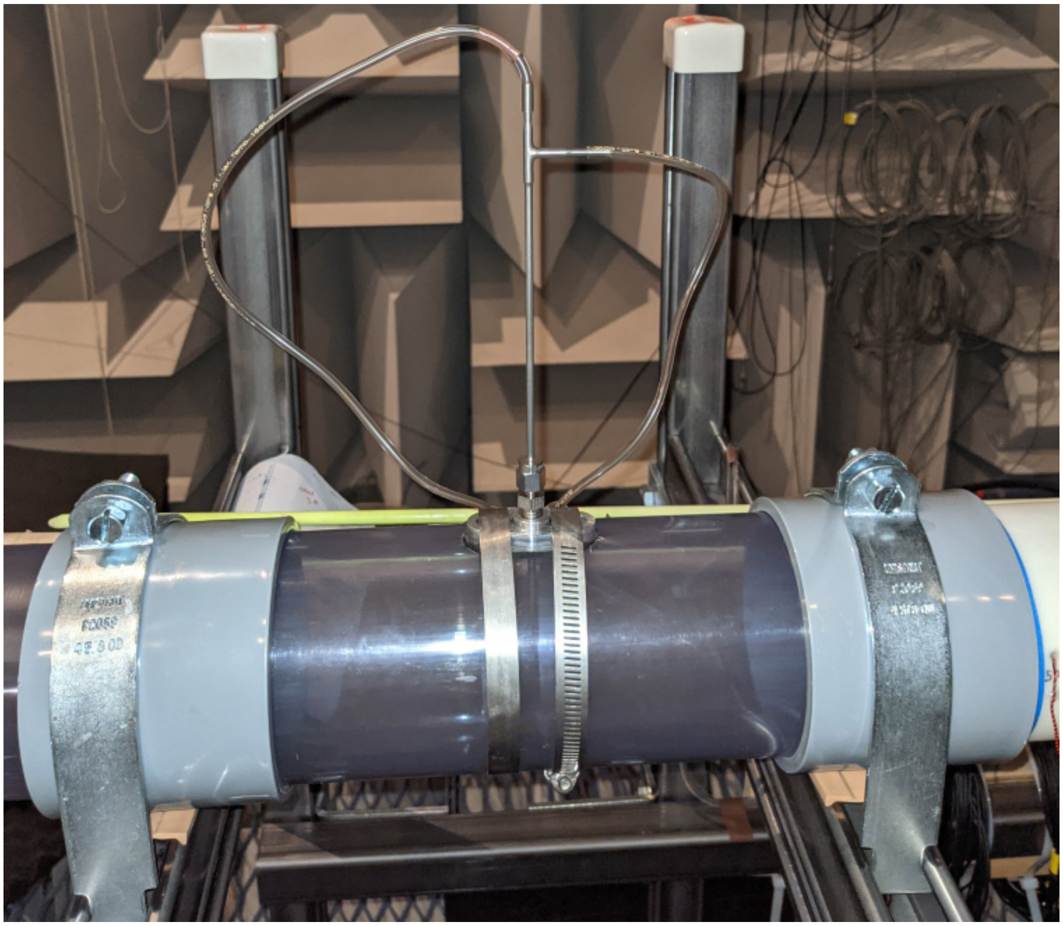

Figure 27.—Pitot-static probe section of duct.

Static Pressure Rise

The inlet static and pitot-static tube measurements were both designed to measure airflow through the duct. The other key aspect of the aerodynamic performance of the fan was the pressure rise. This was readily measured with static taps on each side of the fan, but the downstream location initially selected was found to be too close to the fan outlet. The static tap was moved far downstream, then a consistent set of data was acquired. The final locations are tabulated in Table 6 and shown in Figure 28. The largest pressure differential measured by the fan pressure rise static taps was 4.0 inH_2O at 12,000 rpm and 120 ft^3/min.

Other Instrumentation

The motor's temperature was monitored with a Type K thermocouple that was bonded to the motor casing before the fan was assembled. A pair of PCB Piezotronics model 320C33 accelerometers were mounted to the exterior of the fan casing and used to monitor motion of the fan during operation. These three sensors are shown in Figure 29. Current to the motor controller to drive the fan was measured with a Phoenix Contact universal current transducer (part number MCR–SL–CUC–100–U–2308108) with the positive 48-V wire passing through it.

Rig data was recorded with a National Instruments Ethernet CompactDAQ chassis (NI cDAQ–9188) and a computer running a customized virtual instrument developed by the authors using the LabVIEW® (National Instruments) 2020 graphical programming environment (Figure 30).

TABLE 6.—LOCATION OF PRESSURE TAPS ON TEST RIG

Location	Axial distance from sensor to face of Spacefan	
	in.	cm
Face of Spacefan	0	0.0
Upstream static	1.625	4.1
Downstream static	–36.250	–92.1
Back of bellmouth lip	47.500	120.7
Bellmouth static	44.375	112.7
Exit of anechoic termination	–88.250	–224.2

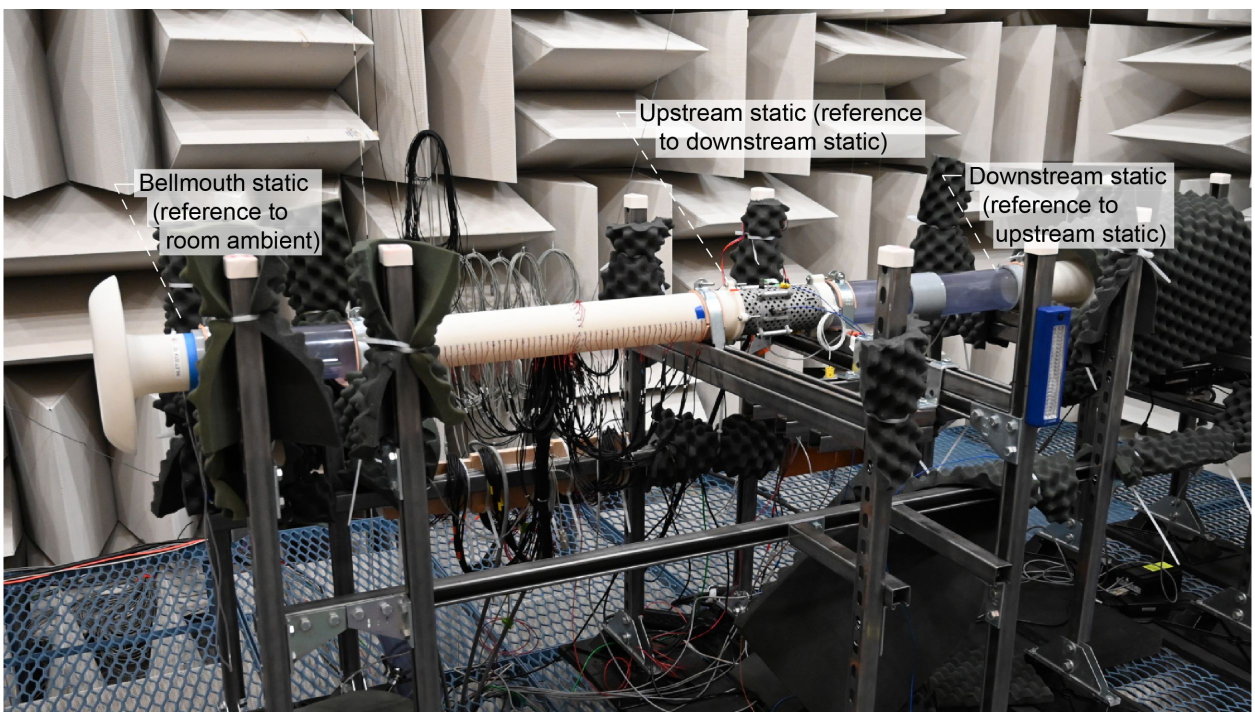

Figure 28.—Static tap locations on test rig duct.

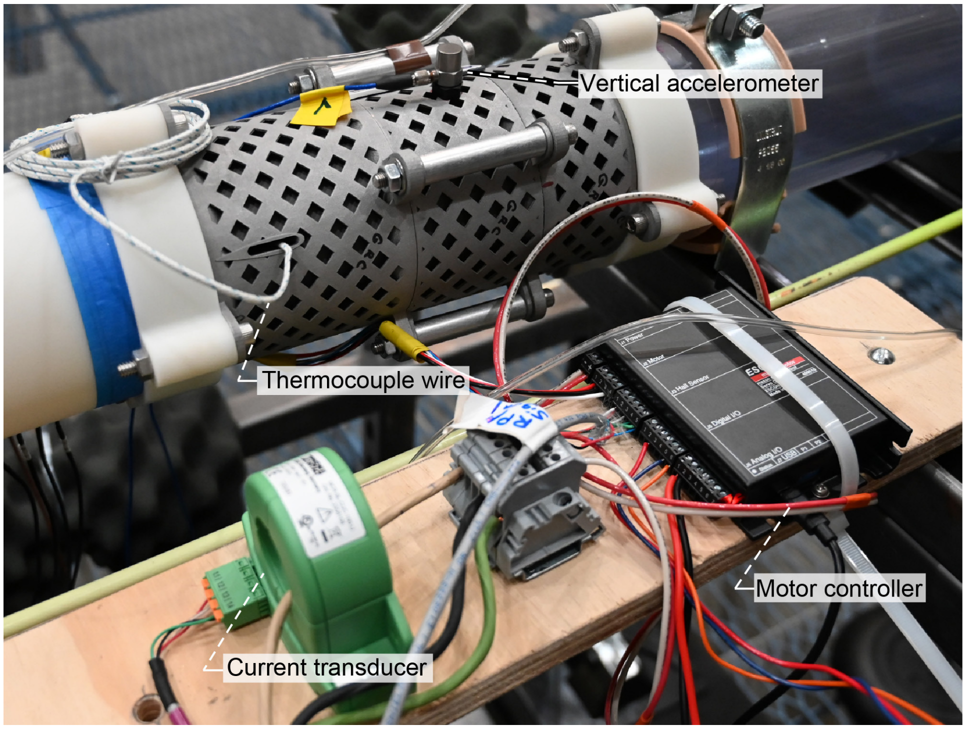

Figure 29.—Wiring for fan controller and sensors.

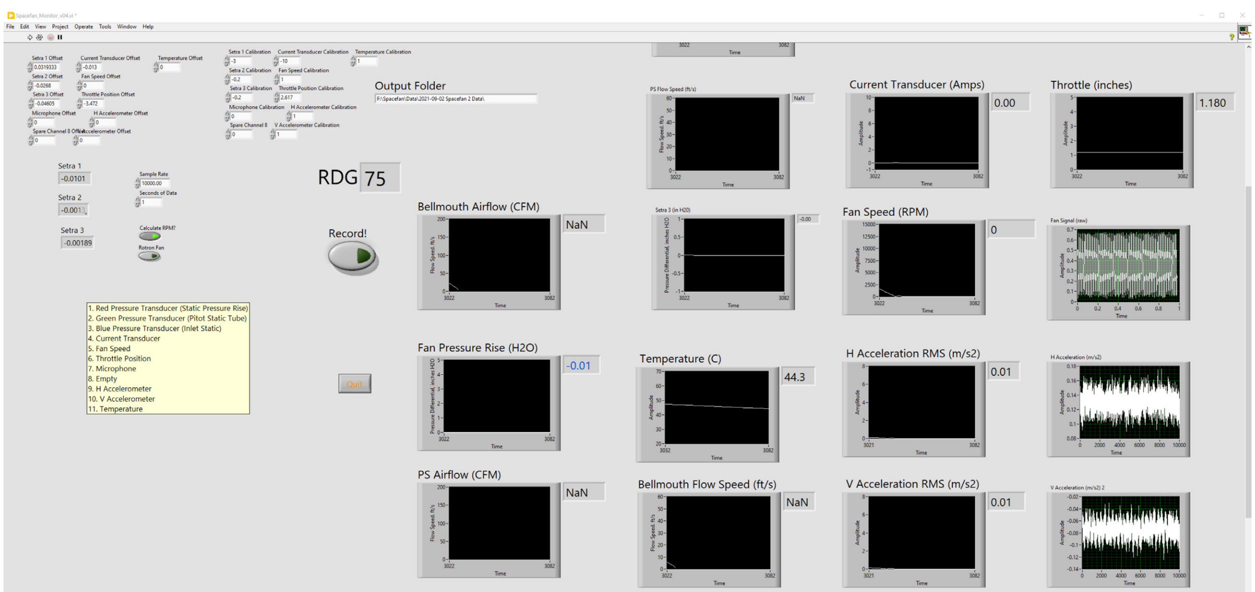

Figure 30.—LabVIEW program for aerodynamic data acquisition.

Testing

The principal objective of the test was to collect data that could validate the design tools and methods used to develop the fan. At a minimum, airflow volume and pressure rise needed to be measured, along with the blade passing frequency tones and associated duct modes.

Test Matrix

Table 7 lists run days, readings per day, and configurations. Individual readings can be found in Table 8 in the Appendix.

Test Procedure

The test procedure for making a fan map is to set the throttle wide open, then set the fan to the desired speed. The airflow reaches a steady state in a matter of seconds. This condition is nearly unloaded. A small amount of pressure rise is measurable and causes airflow, but the fan is very far from the design point. The throttle can then be closed to achieve either the desired flow rate or pressure rise corresponding to the test plan. The test procedure is to set the flow rate at a value close to a multiple of 10 ft^3/min and then measure the pressure rise. The throttle position sometimes required iteration, but when an adequate position is reached, a steady-state data point is recorded.

Array Configurations

Given that only one microphone array is available, upstream and downstream noise are documented separately with sequential runs, noted as Run 6 and Run 7 in Table 7. The length of the duct upstream of the fan was kept constant because this would affect the inflow turbulence into the fan and thus the noise generation. The array is shown in the upstream position in Figure 31 and in the downstream position in Figure 32.

TABLE 7.—TEST RUN SUMMARY

Test date	Run number	Fan[a]	Purpose of test	Number of readings
8/20/2021	1	COTS	Test rig checkout	33
8/26/2021	2	Johnson	Fan checkout	27
8/30/2021	3	Johnson	Fan mapping and upstream acoustics	20
8/31/2021	4	Glenn	Fan checkout	12
8/31/2021	5	Johnson	Vibration testing	12
9/2/2021	6	Glenn	Fan mapping and upstream acoustics	37
9/23/2021	7	Glenn	Downstream acoustics	38
10/5/2021	8	Glenn	Hot wire data position 2b	28
10/6/2021	9	Glenn	Hot wire data position 2a	33
10/14/2021	10	Glenn	Dynamic stall test 1	9
10/21/2021	11	Glenn	Dynamic stall test 2	28

[a]COTS is commercial off the shelf, Johnson refers to NASA Johnson Space Center, and Glenn is NASA Glenn Research Center.

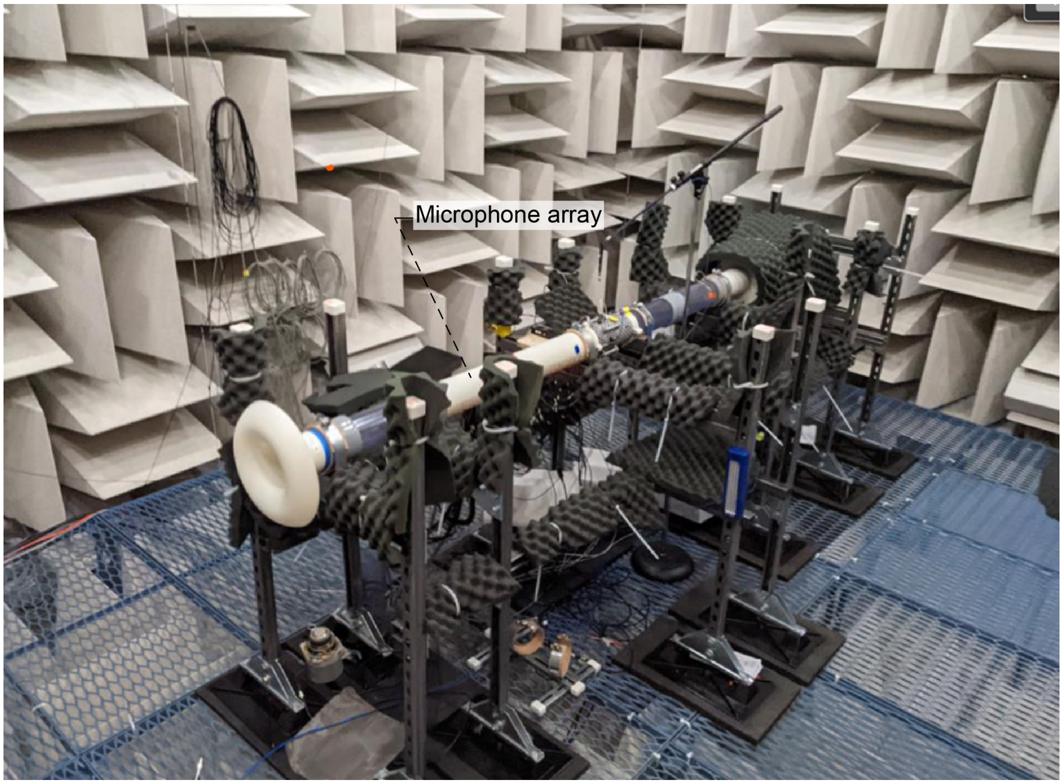

Figure 31.—Array location for upstream noise measurement.

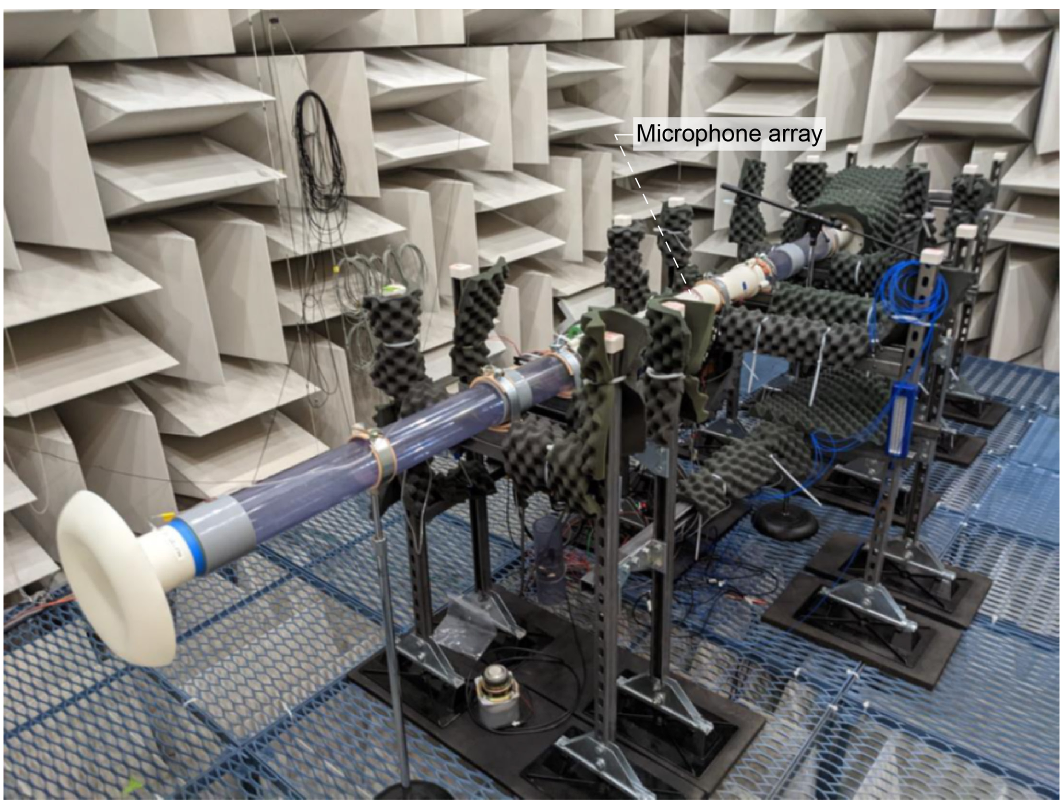

Figure 32.—Array location for downstream noise measurement.

Concluding Remarks

NASA Glenn Research Center's Spacefan design, developed in 2010, was adapted for manufacturing in metal using modern three-dimensional (3D) printing methods. Two fan assemblies were built and tested for aerodynamic and acoustic performance. In total, approximately 150 GB of data was acquired during the test, including both steady-state data such as pressures and temperatures and unsteady data from microphones and hot wires. Postprocessing of the mode array measurement and hot wire data sets is ongoing. Steady data and far-field microphone data were processed via the usual methods and will be presented in future reports.

The aerodynamic performance was measured at 96 percent of the simulated pressure rise and the design flow rate of 150 ft^3/min. It is not clear if this performance discrepancy is related to measurement uncertainty, design assumptions, secondary losses, or other approximations. For the purposes of a ventilation fan, the workflow from design to build was shown through testing to effectively produce a customized fan. Acoustically, the first three rotor–stator interaction tones appear to be cut off and minimally propagate to the far field, except for the first blade passing tone, which is likely generating sound by other mechanisms. The fan is also quieter than a commercial-off-the-shelf fan developing similar aerodynamic performance, although the overall length of the Spacefan is much greater. The preliminary conclusion is affirmative: advanced turbomachinery design methods can be used to produce a satisfactory custom ventilation fan.

Appendix—Run Logs

The commercial-off-the-shelf (COTS) Fan Run 1 was performed August 20, 2021, with the upstream microphone array and four far-field microphones. See Table 8 for results.

TABLE 8.—COTS FAN, RUN 1

Test point	Airflow, ft^3/min	Fan, rpm	Aerodynamic reading	Acoustic reading	Pressure rise (in H_2O)	Time	Comments
1	0	0	1	1	0	10:05 a.m.	
	170		2	2	0.19	10:09 a.m.	
2	160	11,000 (set 20 V)	3	3	0.73	10:10 a.m.	
3	140	↓	4	4	1.62	10:13 a.m.	
4	120		5	5	2.15	10:14 a.m.	
5	100		6	6	2.49	10:15 a.m.	
6	80		7	7	2.04	10:16 a.m.	
7	60		8	8	1.74	10:19 a.m.	
8	40		9	9	1.68	10:21 a.m.	
	38		10	10	1.66	10:22 a.m.	Hit limit switch
9	20						
10	196	13,000 (set 24 V)	11	11	0.27	10:29 a.m.	
	180	↓	12	12	1.14	10:30 a.m.	
11	160		13	13	2.11	10:32 a.m.	
12	140		14	14	2.75	10:33 a.m.	
13	120		15	15	3.2	10:34 a.m.	
14	100		16	16	2.77	10:39 a.m.	
15	80		17	17	2.68	10:40 a.m.	
16	60		18	18	2.36	10:42 a.m.	
	43		19	19	2.21	10:45 a.m.	Hit limit switch
17	40						
18	20						
19	220	15,000 (set 28 V)	20	20	0.34	10:48 a.m.	
	200	↓	21	21	1.56	10:50 a.m.	
20	180		22	22	2.57	10:52 a.m.	
21	160		23	23	3.35	10:53 a.m.	
22	140		24	24	3.88	10:56 a.m.	
23	120		25	25	4.16	10:57 a.m.	
24	100		26	26	3.4	10:58 a.m.	Fan stalled
25	80		27	27	3.29	10:59 a.m.	
26	60		28	28	2.99	11:01 a.m.	
27	40						
28	20						
29	150	15,000 (set 28 V)	29	29	3.64 (3.62 actual reading)	11:07 a.m.	For comparison with Spacefan design point
30	150	↓	30	30	3.65	11:18 a.m.	Remove pitot-static tube
31	150		31	31	3.67	11:39 a.m.	Add turbulence screen; turned on fan and ran test immediately
	150		32	32	3.65	11:42 a.m.	Add turbulence screen; left fan on, waited 1 min, ran test
	150		33	33	3.66	11:44 a.m.	add turbulence screen; left fan on, closed door, waited 1 min, ran test
32	150		34	34	3.65	12:07 p.m.	Add turbulence screen v2; turned fan on; waited 1 min; ran test
33	0	0					

The NASA Johnson Space Center Fan Speed Controller Checkout was performed August 26, 2021, by Stephens and Koch. Power supply set to 48 V. See Table 9 for results.

TABLE 9.—JOHNSON FAN SPEED CONTROLLER CHECKOUT

Reading no.	Fan controller upper set value, rpm	Fan speed set point, V	Fan speed, rpm	Vibe H, m/s^2	Vibe V, m/s^2	Temperature, °C	Motor nominal current limit, A	Controller fixed current limit, A	Comments
14	3,000	0	0	0.01	0.02	25.3	1	2	Does not control well at 0
15	3,000	3.33	1,000	0.12	0.15	25.2	1	2	
16	3,000	6.66	2,000	0.23	0.24	25.3	1	2	
17	3,000	10	3,000	0.31	0.32	25.6	1	2	
18	10,000	4	4,013	0.39	0.39	27	1	2	Continuous high-pitch sound heard
19	10,000	5	5,019	0.74	0.44	28.6	1	2	
20	10,000	6	6,022	1.55	0.52	30	1	2	
21	10,000	7	7,030	1.35	0.61	31.2	1	2	
	10,000	8	7,359	1.96	0.94	31.5	1	2	Expected speed was 8,000 rpm, power supply current = 0.47
								2	Computer running motor controller software in the chamber, error IT2
	10,000	7	7,025	1.31	0.59	31.2	2	4	Reset expected current
22	10,000	8	8,029	1.77	1.38	32.9	2	4	Checking out units on accelerometer sensitivity settings, low compared to COTS fan
	10,000	0	0					4	
23	10,000	9	9,035	1.32	3.25	32.8	2	4	
24	10,000	10	9,999	3.7	2.18	35.2	2	4	
25	12,000	9.166	10,972	4.11	3.49	34.9	2	4	Reset fan controller upper set value rpm, shutdown power supply cause rack started making a high-frequency noise, seemingly not the fan
26	12,000	10	10,972	3.5	3.5	41.8	3	4	Current limit warning, so increased nominal current limit, max current limit = 4
									Ramping down, not sure why we could not reach 12,000 rpm
27	12,000	10	11,998	4.12	6.88	36.5	3	4	Controller rated to 5 A continuous
			Minimum	0.01	0.02				
			Maximum	4.12	6.88				

The Johnson Fan Mic Array Test 1 was performed August 30, 2021, by Stephens, Sutliff, and Koch. The test's purpose was to acquire inlet microphone array data from the Johnson fan as delivered by Trifecta. See Table 10 for results.

TABLE 10.—JOHNSON FAN MIC ARRAY TEST 1

Reading no.	Throttle setting	Air flow, ft^3/min	Pressure rise	Fan controller upper set value, rpm	Fan speed set point, V	Fan speed, rpm	Vibe H, m/s^2	Vibe V, m/s^2	Temperature, °C	Motor nominal current limit, A	Controller fixed current limit, A	Comments
1		0.00		0	0	0						QSF_ATL_Spacefan1_###
2		144.00		8,000	6.666	8,034	1.81	1.40	31.3	3	4	
3	0.610	125.00		8,000	6.666	8,034	1.77	1.42	37.7	3	4	
4	0.350	104.90		8,000	6.666	8,034	1.81	1.42	39.3	3	4	
5	0.220	84.73		8,000	6.666	8,034	1.81	1.39	39.3	3	4	
6	0.170	65.17		8,000	6.666	8,032	1.8	1.36	39.2	3	4	
7	0.115	45.09	1.17	8,000	6.666	8,034	1.79	1.31	39.3	3	4	
8	2.103	180.35	0.33	10,000	8.333	10,035	2.88	2.68	42.5	3	4	
9	0.667	161.86	1.19	10,000	8.333	10,037	2.91	2.70	45.4	3	4	
10	0.419	141.35	1.92	10,000	8.333	10,037	2.93	2.73	47.4	3	4	
11	0.288	121.42	2.50	10,000	8.333	10,037	2.91	2.76	47.1	3	4	
12	0.164	79.71	2.27	10,000	8.333	10,037	2.85	2.70	45.5	3	4	
13	3.160	219.24	0.41	12,000	10	11,998	4.75	5.87	47.4	3	4	
14	0.771	199.00	1.46	12,000	10	11,984	5.06	6.97	50.6	3	4	
15	0.519	181.00	2.25	12,000	10	11,955	4.9	6.00	52.5	3	4	
16	0.382	160.34	2.87	12,000	10	11,878	4.77	6.32	53.5	3	4	Speed control could be tweaked
17	0.321	149.49	3.19	12,000	10	11,722	4.78	6.45	53.2	3	4	Speed a little off
18	0.282	141.88	3.50	12,000	10	11,772	4.78	6.37	52.6	3	4	
19	0.207	119.30	3.99	12,000	10	11,931	4.84	6.08	51.2	3	4	Speed
											4	Stall heard while closing throttle, so opened throttle, did not take point
20	0.321	nan	3.26	12,000	10	11,929	5.27	5.81	45.7	3	4	Bellmouth off, inlet static tap disconnected by accident, set throttle position
					Minimum		1.77	1.31				
					Maximum		5.27	6.97				

The NASA Glenn Research Center Fan Speed Controller Checkout was performed August 31, 2021, by Stephens and Koch. The test procedure was performed with the power supply set to 48 V. With the throttle wide open and fixed, and the power to the motor on, the fan controller was enabled with the switch in the test cell. After setting the fan speed voltage, pressed run to go to speed. After the data was recorded, the sequence moved to the next fan speed voltage. Table 11 lists the results.

TABLE 11.—GLENN FAN SPEED CONTROLLER CHECKOUT

Reading no.	Fan controller upper set value, rpm	Fan speed setpoint, V	Fan speed, rpm	Vibe H, m/s^2	Vibe V, m/s^2	Temperature, °C	Motor nominal current limit, A	Controller fixed current limit, A	Flow rate, ft^3/min	Comments
										Throttle set to 2 in.
1	12,000	0.0833	1,000	0.08	0.09	30.8	3	4		
2	12,000	1.666	1,997	0.13	0.14	29.4	3	4		
3	12,000	2.5	3,000	0.15	0.22	29.3	3	4	50.8	
4	12,000	3.333	4,010	0.24	0.31	29.5	3	4	69.39	
5	12,000	4.166	5,013	0.53	0.36	30.3	3	4	88.15	
6	12,000	5	6,010	0.87	0.64	30.9	3	4	106.73	
7	12,000	5.833	7,013	1.26	0.81	31.8	3	4	125.26	
8	12,000	6.666	8,016	1.49	1.98	33.7	3	4	144.1	
9	12,000	7.5	9,013	1.28	1.42	35.1	3	4	163.71	
10	12,000	8.333	10,016	1.71	2.24	36.9	3	4	182.42	
11	12,000	9.166	11,024	1.91	5.16	38.8	3	4	201.57	
12	12,000	10	11,998	3.18	4.51	41	3	4	219.04	
			Minimum	0.08	0.09					
			Maximum	3.18	5.16					

The Johnson Fan Speed Controller Checkout was performed August 31, 2021, by Stephens and Koch. In this test, the fan was not attached to ducts; it was fastened to the unistrut only with the inlet screen. The test procedure was performed with the power supply set to 48 V. With the power to the motor on, the fan controller was enabled with the switch in the test cell. After setting the fan speed voltage, pressed run to go to speed. After the data was recorded, the sequence moved to the next fan speed voltage. Table 12 lists the results.

TABLE 12.—JOHNSON FAN SPEED CONTROLLER CHECKOUT

Reading no.	Fan controller upper set value, rpm	Fan speed setpoint, V	Fan speed, rpm	Vibe H, m/s^2	Vibe V, m/s^2	Temperature, °C	Motor nominal current limit, A	Controller fixed current limit, A
1	12,000	0.8333	997	0.2	0.16	25.2	3	4
2	12,000	1.666	2,005	0.32	0.32	35.3	3	4
3	12,000	2.5	3,007	0.49	0.43	26.6	3	4
4	12,000	3.333	4,009	0.61	0.6	26.1	3	4
5	12,000	4.166	5,016	0.71	0.83	27	3	4
6	12,000	5	6,017	0.86	0.9	27.8	3	4
7	12,000	5.833	7,025	0.97	1.15	29.1	3	4
8	12,000	6.6666	8,027	1.25	1.42	30.5	3	4
9	12,000	7.5	9,029	1.44	1.87	31.6	3	4
10	12,000	8.333	10,036	3.01	2.32	33.5	3	4
11	12,000	9.166	11,043	3.28	2.76	35.6	3	4
12	12,000	10	11,984	3.72	3.47	37.8	3	4
			Minimum	0.2	0.16			
			Maximum	3.72	3.47			

The Glenn Fan Mic Array Test 1 was performed September 2, 2021, by Stephens, Sutliff, and Koch. The test's purpose was to acquire inlet microphone array data from the Glenn fan as delivered by Trifecta. Table 13 lists the results.

TABLE 13.—GLENN FAN MIC ARRAY TEST 1 (DAY 1)

Reading no.	Throttle setting, in.	Airflow, ft^3/min	Pressure rise	Fan controller upper set value, rpm	Fan speed setpoint, V	Fan speed, rpm	Vibe H, m/s^2	Vibe V, m/s^2	Temperature, °C	Motor nominal current limit, A	Controller fixed current limit, A	Comments
1		0.00	0.00	0	0	0	0	0.00				QSF_ATL_Spacefan2_###
2	1.800	144.31	0.25	8,000	6.666	8,010	1.7	2.17	27.6	3	4	
3	0.718	129.23	0.71	8,000	6.666	8,010	1.75	2.29	31.7	3	4	
4	0.536	120.58	0.98	8,000	6.666	8,010	1.89	2.48	33.9	3	4	
5	0.415	110.39	1.25	8,000	6.666	8,010	1.76	2.41	35	3	4	
6	0.329	100.48	1.48	8,000	6.666	8,010	1.75	2.33	35.7	3	4	
7	0.270	90.46	1.66	8,000	6.666	8,010	1.74	2.46	36.5	3	4	
8	0.219	80.08	1.75	8,000	6.666	8,010	1.7	2.26	36.9	3	4	
9	0.201	70.55	1.56	8,000	6.666	8,010	1.69	2.13	37.6	3	4	Change in sound heard that sounds like flow-induced noise
10	0.187	60.05	1.30	8,000	6.666	8,010	1.64	2.01	37.9	3	4	
11	0.156	50.17	1.18	8,000	6.666	8,010	1.63	1.99	36.8	3	4	
12	0.113	39.75	1.05	8,000	6.666	8,012	1.63	1.99	38.8	3	4	
13	1.999	183.14	0.37	10,000	8.333	10,016	1.6	2.27	42.5	3	4	Heard speed change
14	0.910	170.87	0.85	10,000	8.333	10,016	1.58	2.30	44.5	3	4	
15	0.649	159.81	1.29	10,000	8.333	10,016	1.57	2.32	46.2	3	4	
16	0.519	150.19	1.63	10,000	8.333	10,016	1.57	2.34	47.3	3	4	
17	0.424	140.35	1.95	10,000	8.333	10,016	1.55	2.35	47.8	3	4	
18	0.354	129.51	2.26	10,000	8.333	10,016	1.57	2.35	47.7	3	4	
19	0.303	120.90	2.50	10,000	8.333	10,016	1.57	2.38	47.1	3	4	
20	0.253	110.03	2.71	10,000	8.333	10,017	1.56	2.34	46.1	3	4	
21	0.223	100.75	2.79	10,000	8.333	10,017	1.56	2.33	45.6	3	4	
22	0.194	89.9	2.75	10,000	8.333	10,017	1.56	2.33	45	3	4	Heard change in aerodynamic sound during stall
23	0.188	79.96	2.26	10,000	8.333	10,012	1.58	2.34	44.5	3	4	
24	2.076	220.61	0.52	12,000	10	12,000	1.78	4.61	48.7	3	4	
25	1.064	209.94	1.01	12,000	10	11,999	1.76	4.75	51	3	4	
26	0.786	200.36	1.47	12,000	10	11,999	1.79	4.87	52.8	3	4	
27	0.619	190.47	1.95	12,000	10	11,999	1.83	4.84	54.9	3	4	
28	0.51	180	2.39	12,000	10	11,999	1.82	4.83	56.6	3	4	
29	0.44	171.72	2.76	12,000	10	11,999	1.86	4.85	57.9	3	4	
30	0.379	160.6	3.15	12,000	10	11,999	1.85	4.88	57.3	3	4	
31	0.323	149.96	3.49	12,000	10	11,999	1.86	4.88	55.9	3	4	Chamber vent fan on the whole time
32	0.284	140.08	3.75	12,000	10	11,999	1.86	4.89	54.4	3	4	
33	0.261	131.14	3.94	12,000	10	11,999	1.85	4.89	52.8	3	4	
34	0.222	120.62	4.03	12,000	10	11,999	1.87	4.88	51.7	3	4	
35	0.199	110.38	4	12,000	10	11,999	1.86	4.9	50.7	3	4	
36	0.188	97.27	3.34	12,000	10	11,999	1.93	4.92	49.8	3	4	Change in sound heard thought to be stall
37	2.277	nan	0	0	0	0	0.01	0.01	45.7	3	4	Turned chamber vent fan off
						Minimum	0.01	0.01				
						Maximum	1.93	4.92				

The Glenn Fan Aft Mic Array Test 1 was continued on September 23, 2021, by Stephens, Sutliff, and Koch. The test's purpose was to acquire aft microphone array data from the Glenn fan as delivered by Trifecta. Table 14 lists the results.

TABLE 14.—GLENN FAN AFT MIC ARRAY TEST 1 (DAY2)

Reading no.	Throttle setting, in.	Airflow, ft^3/min	Pressure rise	Fan controller upper set value, rpm	Fan speed setpoint, V	Fan speed, rpm	Vibe H, m/s^2	Vibe V, m/s^2	Temperature, °C	Motor nominal current limit, A	Controller fixed current limit, A	Comments
38		0	0	0	0	0	0	0		3	4	QSF_ATL_Spacefan2_###
39	2.182	142.81	0.28	8,000	6.666	8,010	1.34	2.88	26.6	3	4	
40	0.791	130.08	0.67	8,000	6.666	8,016	1.35	3.01	32.3	3	4	
41	0.566	120.26	0.94	8,000	6.666	8,016	1.38	3.07	34.4	3	4	
42	0.428	109.48	1.23	8,000	6.666	8,016	1.39	3.15	35.8	3	4	
43	0.344	100.43	1.43	8,000	6.666	8,016	1.39	3.19	36.7	3	4	
44	0.277	89.96	1.64	8,000	6.666	8,016	1.41	3.13	37.1	3	4	
45	0.226	79.7	1.74	8,000	6.666	8,016	1.39	3.06	37.1	3	4	
46	0.192	70.05	1.72	8,000	6.666	8,016	1.35	2.99	37.1	3	4	
47	0.184	60.19	1.34	8,000	6.666	8,016	1.31	2.74	37.3	3	4	Hearing stall
48	0.158	50.07	1.18	8,000	6.666	8,016	1.27	2.65	37.6	3	4	
49	0.107	40.23	1.09	8,000	6.666	8,016	1.27	2.61	37.8	3	4	
50	2.594	180.19	0.42	10,000	8.333	10,016	1.68	1.64	39.3	3	4	
51	1.014	170.44	0.82	10,000	8.333	10,016	1.68	1.62	43.4	3	4	
52	0.704	160.17	1.22	10,000	8.333	10,022	1.7	1.62	45.6	3	4	
53	0.547	150.11	1.57	10,000	8.333	10,022	1.71	1.6	47.4	3	4	
54	0.443	139.91	1.9	10,000	8.333	10,022	1.7	1.62	48.2	3	4	
55	0.37	130.1	2.2	10,000	8.333	10,023	1.74	1.62	48	3	4	
56	0.307	120.02	2.47	10,000	8.333	10,022	1.73	1.63	47	3	4	
57	0.263	110.98	2.67	10,000	8.333	10,023	1.73	1.63	45.8	3	4	
58	0.222	99.86	2.77	10,000	8.333	10,023	1.73	1.63	44.7	3	4	
59	0.195	90.04	2.75	10,000	8.333	10,022	1.7	1.62	43.7	3	4	
60	0.189	79.82	2.27	10,000	8.333	10,022	1.71	1.64	43.2	3	4	
61	1.251	209.63	0.96	12,000	10	11,999	2.44	2.21	49.4	3	4	Speed right, flow wrong
62	3.643	216.54	0.57	12,000	10	11,998	2.38	2.16	52.3	3	4	Speed right, flow at max. throttle
63	1.291	209.96	0.94	12,000	10	11,998	2.43	2.18	53.6	3	4	Repeat of point 61
64	0.861	199.87	1.43	12,000	10	11,999	2.43	2.16	54.9	3	4	
65	0.655	189.56	1.9	12,000	10	11,999	2.46	2.18	56	3	4	
66	0.546	179.89	2.29	12,000	10	11,999	2.51	2.14	57.4	3	4	
67	0.446	169.62	2.71	12,000	10	11,999	2.57	2.16	59.8	3	4	
68	0.383	160.52	3.1	12,000	10	11,999	2.64	2.13	58.9	3	4	
69	0.332	149.88	3.4	12,000	10	11,999	2.57	2.16	56.6	3	4	
70	0.289	140.25	3.69	12,000	10	11,999	2.59	2.16	54.6	3	4	
71	0.253	129.8	3.9	12,000	10	11,999	2.55	2.19	52.7	3	4	
72	0.224	119.95	4.01	12,000	10	11,999	2.56	2.31	51.2	3	4	
73	0.198	110.97	4	12,000	10	11,998	2.5	2.27	49.9	3	4	
74	0.183	93.58	3.25	12,000	10	11,999	2.58	2.37	49	3	4	Stall
75	1.179	nan	–0.01	0	0	0	0.01	0.01	45.9	3	4	
						Minimum	0.01	0.01				
						Maximum	2.64	3.19				

The vibration levels measured for the two fan units are summarized in Table 15.

TABLE 15.—CONFIRMATION OF PREVIOUS VIBRATION MEASUREMENTS

Johnson Fan Checkout 1			Glenn Fan Checkout 1		
	H, m/s^2	V, m/s^2		H, m/s^2	V, m/s^2
Minimum	0.01	0.02	Minimum	0.08	0.09
Maximum	4.12	6.88	Maximum	3.18	5.16
Johnson Fan Mic Array Test 1			Glenn Fan Mic Array Test 1		
Minimum	1.77	1.31	Minimum	0.01	0.01
Maximum	5.27	6.97	Maximum	1.93	4.92
Johnson Fan Checkout 2			Glenn Fan Aft Mic Array Test 1		
Minimum	0.2	0.16	Minimum	0.01	0.01
Maximum	3.72	3.47	Maximum	2.64	3.19
Minimum	0.01	0.02	Minimum	0.01	0.01
Maximum	5.27	6.97	Maximum	3.18	5.16

The Glenn Fan Hot Wire test was performed on October 5, 2021, by Stephens, Sutliff, and Mirhashemi. Table 16 lists the results.

TABLE 16.—GLENN FAN HOT WIRE TEST (DAY 1)

Reading no.	Throttle setting, in.	Airflow, ft^3/min	Pressure rise	Fan speed, rpm	Vibe H, m/s^2	Vibe V, m/s^2	Temperature, °C	Comments
1	0.326	150	3.5	12,000	3.75	3.63	52.7	HW 1, start of traverse
2	Repeat							HW 1, end of traverse
3	0.517	180	2.37	12,000	3.8	3.55	41.7	HW 2, start of traverse
4	Repeat							HW 2, end of traverse
5	0.223	120	4.02	12,000	3.77	3.55	51.4	HW 3, start of traverse
6	Repeat							HW 3, end of traverse
7	0.188	95	3.32	12,000	3.82	3.54	48.8	HW 4, start of traverse
8	Repeat							HW 4, end of traverse
9	0.662	160	1.26	10,023	1.43	4.28	52.2	HW 5, start of traverse
10	Repeat							HW 5, end of traverse
11	0.358	130	1.23	10,022	1.42	4.34	51.5	HW 6, start of traverse
12	Repeat							HW 6, end of traverse
13	0.226	100	2.8	10,022	1.44	4.26	48	HW 7, start of traverse
14	Repeat							HW 7, end of traverse
15	0.189	80	2.22	10,022	1.51	4.24	44	HW 8, start of traverse
16	Repeat							HW 8, end of traverse
17	1.2	140	0.37	8,016	1.38	3.16	45.5	HW 9, start of traverse
18	Repeat							HW 9, end of traverse
19	0.42	110	1.25	8,016	1.29	3.42	45.7	HW 10, start of traverse
20	Repeat							HW 10, end of traverse
21	0.223	80	1.76	8,016	1.17	3.41	43.4	HW 11, start of traverse
22	Repeat							HW 11, end of traverse
23	0.187	60	1.34	8,016	1.12	3.09	40.9	HW 12, start of traverse
24	Repeat							HW 12, end of traverse
25	0.113	40	1.06	8,016	1.09	2.96	39.9	HW 13, start of traverse
26								Moved to next condition too fast, end repeat missed
27	0.028	20	0.9	8,017	1.05	3.02	39.5	HW 14, start of traverse
28	Repeat							HW 14, end of traverse

The Glenn Fan Hot Wire test was continued October 6, 2021, by Stephens, Sutliff, Mirhashemi, and Koch. Table 17 lists the results.

TABLE 17.—GLENN FAN HOT WIRE TEST (DAY 2)

Reading no.	Throttle setting, in.	Airflow, ft^3/min	Pressure rise	Fan speed, rpm	Vibe H, m/s^2	Vibe V, m/s^2	Temperature, °C	Comments	
29	0	0	0						
30	0.323	150.19	3.49	11,998	3.09	3.38	42.6	HW 15, start of traverse	Something looks weird with the hot wire signal, decelerated, then accelerated and the problem went away
31	0.323	149.93	3.51	11,999	3.07	3.46	46.3	HW 15, end of traverse	
32	0.515	180.06	2.37	11,998	3.05	3.41	54.2	HW 16, start of traverse	
33	0.515	180	2.39	11,998	3.76	3.32	60.6	HW 16, end of traverse	Notice a sharp increase in H vibes
34	0.221	120.9	4.05	11,998	3.12	3.37	55.7	HW 17, start of traverse	Notice a sharp change in H vibes, could be associated with probe motion
35	0.222	119.16	4.05	11,999	3.66	3.33	51.5	HW 17, end of traverse	
36	0.221	120.96	4.05	11,999	3.58	3.31	50.9	HW 18, start of traverse	Repeat of HW 17 measurements
37	0.221	119.72	4.05	11,999	3.51	3.39	49.9	HW 18, end of traverse	
38	0.188	95.7	3.31	11,999	3.38	3.36	49.2	HW 19, start of traverse	Something looks weird with the hot wire signal
39	0.188	95.55	3.32	11,999	3.34	3.47	47.9	HW 19, end of traverse	Spiky signal on wire 1
40	0.667	160.17	1.25	10,023	1.72	3.77	50.5	HW 20, start of traverse	
41	0.667	159.71	1.26	10,022	1.74	3.78	51.8	HW 20, end of traverse	
42	0.357	130.02	2.25	10,023	1.68	3.74	50.5	HW 21, start of traverse	
43	0.357	130.07	2.25	10,023	1.7	3.77	49.8	HW 21, end of traverse	
44	0.222	99.74	2.8	10,023	1.66	3.74	47.4	HW 22, start of traverse	
45	0.222	99.88	2.77	10,022	1.66	3.73	46.5	HW 22, end of traverse	
46	0.189	80.14	2.27	10,023	1.61	3.76	45	HW 23, start of traverse	
47	0.189	79.8	2.27	10,023	1.65	3.7	43.9	HW 23, end of traverse	
48	1.186	139.96	0.39	8,016	1.1	3.24	44.7	HW 24, start of traverse	
49	1.186	139.29	0.38	8,017	1.42	3.22	45.2	HW 24, end of traverse	
50	0.422	109.8	1.25	8,016	1.41	3.45	45.9	HW 25, start of traverse	LabVIEW doesn’t want to write to serial port error, traverse error, unplugged/replugged USB, corrected
51	0.422	110.14	1.25	8,016	1.43	3.42	45.8	HW 25, end of traverse	
52	0.221	80.05	1.76	8,017	1.1	3.38	43.6	HW 26, start of traverse	Noticed a problem with coding of the timing of LabVIEW—seconds to wait and seconds of data acquisition flipped
53	0.221	80	1.76	8,016	1.34	3.39	40.6	HW 26, end of traverse	
54	0.185	60.8	1.29	8,017	1.38	3.1	39.8	HW 27, start of traverse	Settings corrected. Seconds to wait=2, seconds of data acquisition=7. String pot for hot wire traverse maybe next time
55	0.185	60.26	1.32	8,017	1.09	3.09	39.5	HW 27, end of traverse	
56	0.113	40.02	1.06	8,016	1.07	2.95	39.3	HW 28, start of traverse	
57	0.113	40.29	1.06	8,016	1.38	2.98	39.3	HW 28, end of traverse	
58	0.024	20.1	0.9	8,015	1.13	3.09	39	HW 29, start of traverse	
59	0.024	20.1	0.9	8,017	1.41	3.11	38.9	HW 29, end of traverse	
60	0.326	150.16	3.46	11,999	3.15	3.49	43.5	HW 30, start of traverse	Retaking design point with new timing settings
61	0.328	149.79	3.46	11,999	3.35	3.44	47.2	HW 30, end of traverse	

The Glenn Fan Stall Detection Test was performed on October 14, 2021, by Stephens, Koch, and Culley. Purpose 1 of the test was to measure fan motor current during stall by moving the throttle at 12,000 rpm. Purpose 2 was to measure fan performance on lines of constant throttle at design pressure rise and maximum pressure rise and vary motor speed with one ramp setting: 100 rpm/s. RDG=steady state data point; HSD=high speed data point. Table 18 lists the results.

TABLE 18.—GLENN FAN STALL DETECTION TEST (DAY 1)

Reading no.	Throttle setting, in	Airflow, ft^3/min	Pressure rise	Fan speed setpoint, V	Fan speed, rpm	Vibe H, m/s^2	Vibe V, m/s^2	Temperature, °C	Comments
RDG 1	2.731	0		0					
RDG 2	0.336	150	3.41	12,000	11,998	2.81	3.07	45.1	
HSD1		150	3.4	12,000	11,998				Tried to close throttle to stall, didn't quite hear it
HSD2		105	3.9	12,000	11,998				Tried to close throttle more to stall
RDG 3	0.33	150	3.41	12,000	11,998	2.81	3.05	50.3	
RDG4	0.33	149.6	3.45	12,000	11,998	2.92	3.07	31.5	
HSD3	0.33	90		12,000	11,998	3.03	2.84	43.8	Increased throttle travel to 3,000 steps, 5,000,000 samples
RDG5	0.327	149.7	3.44	12,000	11,998	2.85	3.03	45	
HSD4	0.328			12,000	11,998	3.01	2.84	47	250,000,000 by 8 samples at 500 kHz
RDG6	3.27	150	3.43	12,000	11,998	3.03	2.83	47.8	
HSD5	0.336	150	3.41	12,000	11,998	2.81	2.97	48.9	12,000 to 8,000 rpm, constant throttle
RDG6									
HSD6	0.328	150	3.41	12,000	11,998	2.81	2.93	48.4	12,000 to 8,000 rpm, constant throttle, 500 kHz
RDG7									
HSD7	0.221	118.79	3.98	12,000	11,999	2.83	2.98	48.3	
RDG8	0.223	112.26	3.98	12,000	11,999	2.82	2.99	48.3	
HSD8				12,000	11,999			46.5	12,000 to 8,000 rpm, constant throttle at max. pressure rise, 500 kHz
RDG9	0.223	78.85	1.74	8,000	8,016	1.58	3.57	44.8	

The Glenn Fan Stall Detection Test was continued on October 21, 2021, by Stephens and Koch. Purpose 1 of the test was to measure fan motor current during stall by moving throttle at different speeds: 12,000; 11,500; 11,000; and 10,000 rpm. Purpose 2 was to set the throttle at design pressure rise, flow, and speed, then decrease speed at different ramp rates. Table 19 lists the results.

TABLE 19.—GLENN FAN STALL DETECTION TEST (DAY 2)

Reading no.	Throttle setting, in.	Airflow, ft^3/min	Pressure rise	Fan speed setpoint, V	Fan speed, rpm	Vibe H, m/s^2	Vibe V, m/s^2	Temperature, °C	Comments
RDG 1		0							No speed, no flow, restarted after noticing we needed to connect additional current meter
RDG 2	0.321	149.18	3.51	12,000	11,998	2.97	3.02	33.3	Design point retake, noticed additional current probe not reading the same as last test, so stopped rig and repositioned probe and wire
HSD 1	Same								Rate = 102,400 samples 5,000,000 but steady at design
HSD 2	Same								Rate = 500,000 samples 25,000,000 but steady at design
RDG 3	0.321	149.75	3.49	12,000	11,999	2.9	3.04	48.6	Design point
HSD 3									Purpose 1, 12,000 rpm, rate 102,400 5,000,000
HSD 4									Purpose 1, 12,000 rpm, rate = 500,000 samples 25,000,000
RDG 4	0.32	149.07	3.49	12,000	11,999	2.88	3.02	49.3	
RDG 5	0.321	143.16	3.19	11,500	11,527	2.97	3.54	49.3	Speed setpoint differs by ~25 rpm lower than actual at speeds lower than 12,000
HSD 5	Same								Purpose 1, 11,500 rpm, rate 102,400 5,000,000
HDS 6	Same								Purpose 1, 11,500 rpm, rate = 500,000 samples 25,000,000
RDG 6	0.321	143.84	3.21	11,500	11,527	2.98	3.54	48.9	
RDG 7	0.321	137.42	2.92	11,000	11,026	2.98	4.95	48.6	
HSD 7	Same								Purpose 1, 11,000 rpm, rate 102,400 5,000,000
HSD 8	Same								Purpose 1, 11,000 rpm, rate = 500,000 samples 25,000,000
RDG 8	0.321	137	2.9	11,000	11,026	2.95	4.96	47.9	
RDG 9	0.321	130.25	2.66	10,500	10,526	2.72	5.66	47.9	
HSD 9	Same								Purpose 1, 10,500 rpm, rate 102,400 5,000,000
HSD 10	Same								Purpose 1, 10,500 rpm, rate = 500,000 samples 25,000,000
RDG 10	0.321	130.74	2.65	10,500	10,526	2.72	5.6	47.9	
RDG 11	0.321	124.46	2.41	10,000	10,023	1.7	4.98	46.2	
HSD 11	Same								Purpose 1, 10,000 rpm, rate 102,400 5,000,000
HSD 12	Same								Purpose 1, 10,000 rpm, rate = 500,000 samples 25,000,000
RDG 12	0.321	124.42	2.41	10,000	10,022	1.69	4.98	46.8	
Practice	0.321	149.18	3.48	12,000	11,999	2.85	2.99	38.8	Design point, speed ramp = 200 rpm/s, up and down to check controller
Practice									Design point, speed ramp = 400 rpm/s, up and down to check controller
Practice									Design point, speed ramp = 800 rpm/s, up and down to check controller
RDG 13	0.32	149.78	3.47	12,000	11,999	2.94	2.99	30.4	Design point, speed ramp = 100 rpm/s
HSD 13	Same								Purpose 2: Design point, speed ramp = 100 rpm/s, up and down to take data, rate 102,400 5,000,000
HSD 14	Same								Purpose 2: Design point, speed ramp = 100 rpm/s, up and down to take data, rate = 500,000 samples 25,000,000
RDG 14	0.32	150.02	3.48	12,000	11,999	2.86	2.99	38.4	Design point, speed ramp = 200 rpm/s
HSD 15	Same								Purpose 2: Design point, speed ramp = 200 rpm/s, up and down to take data, rate 102,400 2,500,000
HSD 16	Same								Purpose 2: Design point, speed ramp = 200 rpm/s, up and down to take data, rate = 500,000 samples 12,500,000
RDG 15	0.321	149.77	3.46	12,000	11,999	2.85	2.99	42.3	Design point, speed ramp = 400 rpm/s

TABLE 19.—GLENN FAN STALL DETECTION TEST (DAY 2)

Reading no.	Throttle setting, in.	Airflow, ft^3/min	Pressure rise	Fan speed setpoint, V	Fan speed, rpm	Vibe H, m/s^2	Vibe V, m/s^2	Temperature, °C	Comments
HSD 17	Same								Purpose 2: Design point, speed ramp = 400 rpm/s, up and down to take data, rate 102,400 samples 125,000
HSD 18	Same								Purpose 2: Design point, speed ramp = 400 rpm/s, up and down to take data, rate = 500,000 samples 6,250,000
RDG 16	0.32	149.24	3.48	12,000	11,999	2.85	2.95	44.2	Design point, speed ramp = 800 rpm/s
HSD 19	Same								Purpose 2: Design point, speed ramp = 800 rpm/s, up and down to take data, rate 102,400 samples 625,000
HSD 20	Same								Purpose 2: Design point, speed ramp = 800 rpm/s, up and down to take data, rate = 500,000 samples 3,125,000
RDG 17	0.218	119	4.01	12,000	11,999	2.85		45.5	Throttled to max pressure rise at 12,000 rpm
HSD 21	Same								Purpose 2: Design point, speed ramp = 800 rpm/s, up and down to take data, rate 102,400 samples 625,000
HSD 22	Same								Purpose 2: Design point, speed ramp = 800 rpm/s, up and down to take data, rate = 500,000 samples 3,125,000
RDG 18	0.218	120		12,000	11,998	2.85	3.01	43.6	Max pressure rise point, speed ramp = 400 rpm/s
HSD 23	Same								Purpose 2: Design point, speed ramp = 400 rpm/s, up and down to take data, rate 102,400 samples 125,000
HSD 24	Same								Purpose 2: Design point, speed ramp = 400 rpm/s, up and down to take data, rate = 500,000 samples 6,250,000
RDG 19	0.218	199.66	4.05	12,000	11,998	2.85	2.94	42	Max. pressure rise point, speed ramp = 200 rpm/s
HSD 25	Same								Purpose 2: Design point, speed ramp = 200 rpm/s, up and down to take data, rate 102,400 2,500,000
HSD 26	Same								Purpose 2: Design point, speed ramp = 200 rpm/s, up and down to take data, rate = 500,000 samples 12,500,000
RDG 20	0.218	120.08	4.03	12,000	11,998	2.84	2.89	41.1	Max. pressure rise point, speed ramp = 100 rpm/s
HSD 27	Same								Purpose 2: Design point, speed ramp = 100 rpm/s, up and down to take data, rate 102,400 5,000,000
HSD 28	Same								Purpose 2: Design point, speed ramp = 100 rpm/s, up and down to take data, rate = 500,000 samples 25,000,000

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