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Abstract

Sound pressure measurements were recorded for a prototype of a spacecraft cabin ventilation fan in a test in the NASA Glenn Acoustical Testing Laboratory. The axial fan is approximately 0.089 m (3.50 in.) in diameter and 0.223 m (9.00 in.) long and has nine rotor blades and eleven stator vanes. At design point of 12,000 rpm, the fan was predicted to produce a flow rate of 0.0709 m^3/s (150 cfm) and a total pressure rise of 925 Pa (3.72 in. of water) at 12,000 rpm. While the fan was designed to be part of a ducted atmospheric revitalization system, no attempt was made to throttle the flow or simulate the installed configuration during this test. The fan was operated at six speeds from 6,000 to 13,500 rpm. A 13-microphone traversing array was used to collect sound pressure measurements along two horizontal planes parallel to the flow direction, two vertical planes upstream of the fan inlet and two vertical planes downstream of the fan exhaust. Measurements indicate that sound at blade passing frequency harmonics contribute significantly to the overall audible noise produced by the fan at free delivery conditions.

Introduction

Quiet and efficient fans are needed if spacecraft for future long-duration human exploration missions are to be safe and productive. The Man-Systems Integration Standards report (Ref. 1) describes on-orbit noise sources and noise limits for the Space Shuttle Orbiter and continues to be used as a reference for new missions. Environmental control equipment and avionics equipment were identified as significant continuous sources of noise. Octave band spectra are presented for eight components (including three fans: a cabin fan, an avionics fan, and an intermodule unit (IMU) fan) on the Space Shuttle's flight deck and mid deck. The cabin fan was proven to be the dominant source of noise among the measured components, exceeding recommended limits for both tone and broadband noise. The recommended limit for all broadband noise sources is Noise Criteria (NC) 50 and the recommended limit for all tones is the NC 40 curve, which is 10 dB less than the broadband limit for the octave band containing the tone (Refs. 1 and 2).

A new spacecraft cabin ventilation fan is currently being studied in an effort to identify sources of broadband and tone noise, and determine ways to improve aerodynamic and acoustic performance of the fan. Design point pressure rise and flow rate conditions were identified, and a working prototype of the fan has been produced by NASA. Reported here are the details of the aerodynamic, mechanical, and electrical design of the fan prototype. The prototype was operated for the first time in NASA Glenn's Acoustical Testing Laboratory. No attempt was made to simulate the ducting or other ventilation system components during this test. Narrowband sound pressure level measurements for six fan speed settings indicate that tones at blade passing frequencies contribute significantly to the overall noise produced by

the fan operating at free delivery conditions. Further testing is required to determine design point aerodynamic and acoustic performance.

Description of Prototype Design and Fabrication

Aerodynamic and Acoustic design

Details of the aerodynamic design and results of an aerodynamic analysis have been reported in Reference 4. The overall design goals were to minimize weight, volume, power, and audible noise while maximizing aerodynamic efficiency of an axial fan nominally suited for a spacecraft ventilation system. The design point goals were established and are presented in Table 1, as well as the design and predicted values for the prototype. Efforts were made to minimize rotor rotational speed and select a blade/vane count that would minimize broadband and tone noise.

A computational fluid dynamics (CFD) code was used iteratively to refine the input to a compressor design code used to develop the blade path, rotor blade shape, and stator vane shape shown in Figure 1. The acoustic theory of Tyler and Sofrin[3] indicated that by choosing either 11 or 22 stator vanes the first three blade passing harmonics tones would be cut-off if the fan were installed in an infinitely long duct.

Mechanical Design and Fabrication

The NASA Glenn Research Center's Mechanical and Rotating Systems Branch was given the aerodynamic design of the fan described above and developed an electromechanical conceptual design. Details of the conceptual design study have been presented in Reference 5 and a cross section is shown in Figure 2.

The conceptual design was advanced to a working prototype suitable for acoustic and aerodynamic ground tests. A cross-sectional view of the final prototype design is shown in Figure 4. Finite element analyses (FEA) using MSC Patran/Nastran were performed to refine the mechanical design, to determine candidate materials, and to ultimately verify that the final mechanical design and material choice would meet safety requirements.

A stereolithography manufacturing technique was chosen because it fit the structural requirements, budget, and time constraints of the project. Two prototypes were fabricated by The Technology House, LTD. of Solon, Ohio. The material selected was the Huntsman RenShape SL5530 photopolymer. Selected material properties are shown in Table 2. The two fan prototypes differed only in the thickness of cross-section layers of liquid resin that are cured by a solid-state laser. Prototype A has layer thickness of 0.127 mm (0.005 in.) and Prototype B has 0.051 mm (0.002 in.) layers for a smoother surface finish and increased dimensional accuracy.

MSC Nastran was used to perform the rotor finite element stress analysis. Fan rotational speed was set to its design point value of 12,000 rpm and blade loads were neglected. Plots of the rotor stresses are shown in Figure 5. Maximum stress of 3.09×10^6 Pa (448 psi) was located at the rotor bore where the rotor mates to the rotor shaft. The margin of safety for the current design is 4.05.

Results of the rotor modal analysis are shown in the Campbell diagram of Figure 6. The modal analysis is used to identify the resonance frequencies of the rotor that could be excited during operation. The critical speeds of the fan rotor are indicated in Table 3. In order to prevent damage to the fan, prolonged operation at these critical speeds should be avoided.

The fan would be damaged if the rotor blade tips rubbed against the shroud during operation. Finite element analysis was used to predict maximum blade/hub displacements at design speed. The predicted rotor blade/hub displacement was 0.0254 mm (0.001 in.) at 12,000 rpm-significantly less that the 0.254 mm (0.010 in.) rotor tip gap.

Finally, in order to minimize the weight of the final prototype design to make it geometrically resemble a fan for a spaceflight ventilation system, material was removed from the duct wall in a grid-like pattern as shown in Figure 3. Minimum duct wall thickness of the final design was chosen to be 0.318 cm (0.125 in.) in order to maintain fan-housing stiffness and contain fragments of the rotor should it fail during operation.

Flange thicknesses were reduced, and excess material between flange boltholes was removed. Additionally, a flow straightener was installed in the fan inlet from metal honeycomb that was 2.54 cm (1.00 in.) thick with 0.476 cm (0.188 in.) square cells and a foil thickness of 0.076 mm (0.003 in.).

Electrical Design

The design team chose a brushless DC motor, Maxon EC-4 pole 305015, for several reasons. This motor was chosen since it met the torque and speed requirements of the fan, and its availability and cost fit within project constraints. The motor diameter was 30.0 mm (1.18 in.) and the motor length was 99.0 mm (3.90 in.)—small enough to fit well within the fan centerbody. The wiring exited the motor through the aft end face. This was important since the motor wiring was to be routed through one of three hollow support struts placed as far downstream of the fan rotor as practically possible in an effort to minimize rotor/strut interaction noise without exceeding the maximum desired overall axial length of the fan.

The fan motor speed controller consisted of a brushless servo amplifier and ancillary support circuitry. The servo amplifier drives the motor rotation by providing current pulses to the fan motor. The frequency of the current pulses establishes the fan motor speed. The servo amplifier has an external analog input for setting the speed. A digital potentiometer configured as a voltage divider is attached to the analog input. The fan motor with the fan attached was run at various potentiometer settings and the fan speed was measured with an optical tachometer. A look-up table was created with this data for setting the fan speed for testing. For safety purposes, an emergency stop relay circuit was used to enable and disable the servo amplifier to control fan rotation.

Description of Experiment

Facility

The NASA Glenn Acoustical Testing Laboratory (ATL) (Ref. 6), illustrated in Figure 7 is a fully anechoic chamber with interior dimensions of 7.0- by 5.2- by 5.2-m (23- by 17- by 17-ft). The walls, ceiling, and floor of the chamber are completely covered with fiberglass wedges that are 0.86 m (34 in.) deep. The wedges are designed to absorb 99 percent of all sound above 100 Hz. Dense rubber material in the walls and ceiling reflects and absorbs ambient sound coming from outside the chamber. A separate control room, located adjacent to the chamber, houses all of the electronic equipment as well as the test operators. Steel grating is mounted over the floor wedges to allow personnel to walk throughout the chamber but still allow sound to pass through to the wedges below. Half of these grates were removed for this test in order to mitigate sound reflections as much as possible.

Four stationary condenser microphones were located in each corner of the test chamber at 3.04 m (10.0 ft) from the fan, as shown in Figure 7. Figure 8 shows a photograph of the microphone array used to acquire the acoustic data presented in this report. The array consists of 13 condenser microphones spaced 7.6 cm (3.0 in.) apart. As shown in the figure, the microphones pointed downward and were arranged horizontally in a line so that they were all the same distance from the floor. An overhead three-axis traverse was used to remotely position the microphone array relative to the test article. Each axis of the traverse is powered separately by its own electric motor and provides positioning accuracy of ± 0.03 mm (± 0.001 in.). A series of concentric tubing to allow the array is manually adjusted to position the array at the desired location along the vertical z-axis. The maximum travel distances provided by the x, y, and z axes were 4.85 m (15.9 ft), 3.41 m (11.2 ft), and 4.27 m (14.0 ft), respectively.

Instrumentation

The signals from the thirteen Brüel & Kjær Falcon 4939 0.64 cm (0.25 in.) condenser microphones and the four stationary microphones were input to a Larson-Davis model PRM902 1.3 cm (0.50 in.) preamplifier, using a Brüel & Kjær UA0035 adapter. A Brüel & Kjaer Nexus 2690 conditioning amplifier powered all

microphones. A Precision Filters, Inc. high pass filter, set to 200 Hz, filtered the microphone signals. The amplified and filtered signal was then recorded by a DataMax DTX-9R data acquisition computer.

The temperature, atmospheric pressure, and humidity inside the chamber were monitored by a Vaisala PTU 303 transmitter. One chromel-alumel type K thermocouple was attached to the fan motor housing and monitored using an Altek 422 meter. An Endevco 2221 D accelerometer was mounted to one of the unused fan exhaust flange boltholes and measured the vibrations in the axial direction. Accelerometer measurements were displayed in the control room with an Endevco 6634B charge amplifier/digital display. Finally, a Keyence FU-35FA/FS-M1H fiber optic sensor monitored the speed of the rotor. The signal from the sensor was converted to revolutions per minute (rpm) using a Newport INF7 digital display. The data acquisition computer also recorded the speed signal.

Procedure

There were several objectives of this experiment. The first objective was to run the fan prototype to determine if it operated mechanically and electrically as expected. The second objective was to collect sound pressure measurements using the traversing microphone array for six fan speed settings.

Figure 9 is a diagram that shows the location of the microphone survey planes for this experiment. The spacecraft vent fan prototype was mounted in the center of the anechoic chamber 140.3 cm (55.25 in.) above the floor grating. An x-y-z coordinate system was used to describe the location of the microphone array relative to the fan. The origin of the coordinate system was located along the axis and in the inlet plane of the fan. The microphone located at the center of the array served as the reference. The distance between the center microphone and the origin in each of the three coordinate directions was used to describe the location of the array relative to the fan. The microphone measurement positions are described in Table 4.

The test procedure was as follows: a) set fan test speed, b) record fan speed, ambient pressure, temperature, humidity, fan casing vibration level, and motor housing temperature, and c) move the microphone array to desired measurement positions and record sound pressures for 10 sec at each measurement position using a 200 kHz sampling rate. The tested fan speed settings and corresponding blade passing frequencies are listed in Table 5.

Discussion of Results

The fan performed mechanically and electrically as expected. The motor was not actively cooled; rather, the three hollow support struts downstream of the fan vanes vented the enclosed area around the fan. Motor housing temperatures did not exceed 337 K (147 °F), well below the recommended limit for continuous operation of 350 K (170°F). No mechanical difficulties were experienced during the 40 hr of operation. Vibration levels in the axial direction did not exceed 1.5 mm/s (0.06 in./sec).

Measurements from the microphone at the center of the rake are presented in Figures 10 and 11. Figure 10 compares the narrowband spectra from a single microphone located downstream and above the fan, stopped at one point in the Survey Number 4 (x = 39.00 in., y = 0.00 in., z = 40.75 in.). This point was chosen since blade passing frequency harmonics were maximized at this location for the design point speed of 12,000 rpm. Figure 11 compares contour plots of frequency as a function of axial location for all tested fan speeds.

Both Figure 10 and 11 indicate that the highest sound pressure levels measured were those at blade passing frequency harmonics, and are thus associated with the aerodynamic design of the fan. The reader is reminded that the fan was designed to operate in a ducted system, and that inlet and exhaust ducting was not included in this initial test of the fan. So while the fan was operated at design speed, it was not operating at design pressure rise and flow rate conditions during this experiment. It is hypothesized that by mimicking the ventilation system by installing ducting upstream and downstream of the fan, tone noise at the first three harmonics of the blade passing frequency can be significantly reduced by taking advantage of the cut-off phenomenon. Additionally, tones expect to propagate are hypothesized to

decrease as the wakes from the rotor blades narrow when the fan operates at design conditions. Additional aerodynamic and acoustic tests are required to test these hypotheses.

The plots in Figure 11 exhibit the acoustic radiation patterns similar to those of aircraft engine fans with sound pressure level minima occurring halfway between the inlet and the exhaust, a trend that is independent of the fan speed. There appear to be faint "ripples" in the sound pressure level contours if one closely examines Figure 11, most visible in Figure 11b and Figure 11c for frequencies above 10 kHz, but present at all speeds and all frequencies. The nature of these ripples is not known but is currently thought to be associated with the electromechanical performance of the microphone traverse system, though further tests are needed to confirm this.

The tones measured from 20 to 35 kHz are attributed to the motor. Limits on the amplitude of ultrasonic tones are given in Reference 1. The measurements indicate that for the conditions tested the fan does not exceed the recommended limits for ultrasonic noise (105 to 115 dB for the measured frequency range). And while humans would not be affected by the ultrasonic tones produced by the fan motor, the ultrasonic tones are well within the audible range for many animals and could influence any onboard animal experiments (Refs. 7 and 8). The motor is also considered to be a source of audible broadband noise. Audible broadband noise from the motor was observed (but not measured) when the motor was operated alone prior to assembly of the fan.

Conclusions and Recommendations

A prototype of a ventilation fan notionally suited for a spacecraft cabin ventilation system has been fabricated. An initial test of the mechanical, electrical, and acoustic performance of the fan has been conducted in the NASA Glenn Acoustical Testing Laboratory. Results indicated that the fan prototype performed mechanically and electrically as expected. The fan was tested without ducting upstream or downstream, as would be present in typical spacecraft ventilation systems. The fan was operated at six speed settings ranging from 6,000 to 13,500 rpm. Acoustic measurements were recorded using a thirteen-microphone traversing array. A limited examination of the acoustic data from a single microphone indicated that tones at blade passing frequency and its harmonics were dominant and is associated with the aerodynamic design of the fan. The motor was observed to be a source of broadband noise, and considered to be the source of ultrasonic tones.

Several recommendations are suggested at this time:

a) Efforts should be made to either identify a motor speed encoder suitable for the operational speed range of the motor that will fit on the aft end of the motor shaft or to relocate the optical sensor to the aft end of the fan. For this test, a hole was drilled into the inlet duct to hold the optical speed sensor. The rotor hub was painted black, and white tape was attached to the rotor hub. While this arrangement did produce a reliable speed measurement, the modifications to the duct could be a source of noise and the tape affixed to the rotor could be a source of imbalance resulting in structure-borne noise.

b) Efforts could be made to identify different motor control designs to try to minimize the audible noise produced by the motor.

c) Efforts could be made to identify different ways to attach the rotor hub to the motor shaft. In this prototype, the rotor was glued to the motor shaft. This type of attachment makes it difficult to disassemble if different stator concepts are to be investigated.

d) A speed feedback loop in the motor controller may be useful in maintaining the fan at constant speed settings, something that may be desirable in future aerodynamic and acoustic tests that involve backpressuring the fan.

e) Additional analyses and structural tests are needed to determine if the operational speed range of the fan can be safely extended.

f) The aerodynamic performance of the fan should be experimentally measured for a range of fan speeds and flow rates.

g) Acoustic measurements with the fan backpressured to design point conditions are needed.

h) Once more is known about the fan's aerodynamic and acoustic performance at design point conditions, investigations to further improve the fan could be conducted.

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TABLE 1.—SPACECRAFT CABIN FAN DESIGN POINT GOALS AND DESIGN/PREDICTED VALUES

	Goals	Predicted/Model 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 in. of water)	925 Pa (3.716 in. 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.)	0.089 m (3.5 in.) flowpath diameter
Maximum axial length	0.223 m (9.0 in.)	0.223 m (9.0 in.)
Rotor tip clearance gap	0.23 mm (0.009 in.)	0.23 mm (0.009 in.)
Rotor speed	Unconstrained	12,000 rpm
Number of blades	Unconstrained	9
Number of vanes	Unconstrained	11

TABLE 2.—SELECTED PROPERTIES OF SL5530 MATERIAL

Mechanical Properties	
Tensile Strength (ASTM D 638)	4.69×10^7 – 6.14×10^7 Pa (6,800 to 8,900 psi)
Elongation at Break	1.3 – 2.9%
Flexural Modulus (ASTM D 790)	3.50×10^9 – 3.63×10^9 Pa (507 to 527 ksi)
Flexural Strength (ASTM D 790)	9.58×10^7 – 1.08×10^8 Pa (13,900 to 15,700 psi)
Thermal Properties	
Heat Deflection Temp (at 66 psi)	443 to 523 K (338 to 482 °F)
Heat Deflection Temp (at 264 psi)	383 to 393 K (230 to 248 °F)
Description	
Color Appearance	Clear Amber
Hardness	90 D
Application	High Heat

TABLE 3.—PREDICTED CRITICAL SPEEDS OF THE ROTOR

4E	11E	22E
11,350 rpm (Mode 1)	4,050 rpm (Mode 1)	2,025 rpm (Mode 1)
	5,650 rpm (Mode 2)	2,800 rpm (Mode 2)
	11,200 rpm (Mode 3)	3,600 rpm (Mode 3)
		11,450 rpm (Mode 4)
		12,050 rpm (Mode 5)

TABLE 4.—DESCRIPTION OF MICROPHONE SURVEYS

Survey Number	Survey Plane Orientation	Number of steps	X locations, in.		Y locations, in.		Z locations, in.	
			Start	Step size	Start	Step size	Start	Step size
0	Point	1	–84.00	0.00	0.00	0.00	56.45	0.00
1	Horizontal	57	–84.00	3.00	0.00	0.00	56.45	0.00
2	Horizontal	29	–84.00	6.00	–33.00	0.00	56.45	0.00
3	Horizontal	29	–84.00	6.00	33.00	0.00	40.75	0.00
4	Horizontal	57	–84.00	3.00	0.00	0.00	40.75	0.00
5	Horizontal	29	84.00	–6.00	–33.00	0.00	40.75	0.00
6	Horizontal	29	84.00	–6.00	33.00	0.00	56.45	0.00
7	Vertical, inlet	28	–72.00	0.00	0.00	0.00	56.45	–3.00
8	Vertical, inlet	14	–72.00	0.00	–33.00	0.00	56.45	–6.00
9	Vertical, inlet	14	–72.00	0.00	33.00	0.00	56.45	–6.00
10	Vertical, exit	14	72.00	0.00	0.00	0.00	56.45	–3.00
11	Vertical, exit	7	72.00	0.00	–33.00	0.00	56.45	–6.00
12	Vertical, exit	7	72.00	0.00	33.00	0.00	56.45	–6.00
13	Vertical, inlet	28	–36.00	0.00	0.00	0.00	56.45	–3.00
14	Vertical, inlet	14	–36.00	0.00	–33.00	0.00	56.45	–6.00
15	Vertical, inlet	14	–36.00	0.00	33.00	0.00	56.45	–6.00
16	Vertical, exit	14	36.00	0.00	0.00	0.00	56.45	–3.00
17	Vertical, exit	7	36.00	0.00	–33.00	0.00	56.45	–6.00
18	Vertical, exit	7	36.00	0.00	33.00	0.00	56.45	–6.00

TABLE 5.—TEST CONDITIONS

Speed (rpm)	6000	7000	8500	11000	12000	13500
Speed (Hz)	100	117	142	183	200	225
Blade passing frequency (Hz)	900	1,050	1,275	1,650	1,800	2,025
Wavelength of BPF tone (m)	0.38	0.32	0.27	0.21	0.19	0.17
Max audible BPF harmonic	22	19	15	12	11	9

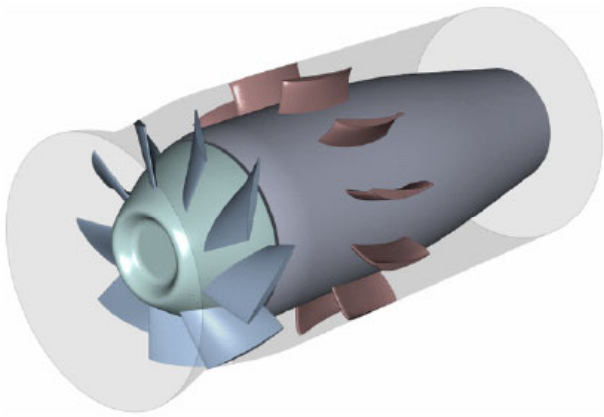

Figure 1.—Aerodynamic Design of Spacecraft Cabin Ventilation Fan Prototype

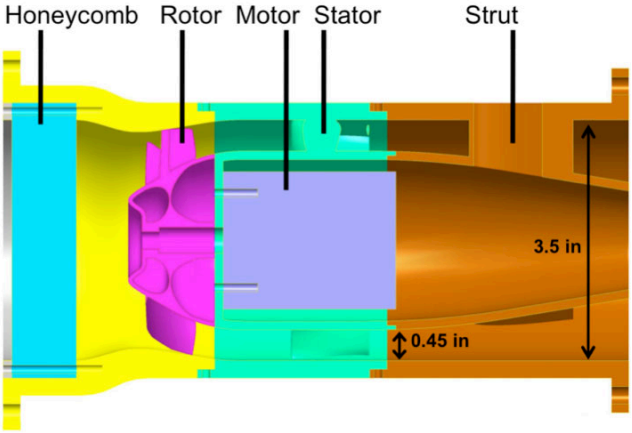

Figure 2.—Conceptual Electromechanical Design of Spacecraft Cabin Ventilation Fan Prototype

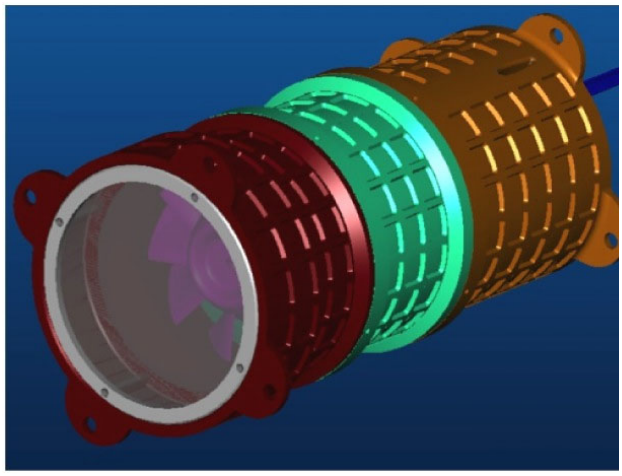

Figure 3.—Final Design of Spacecraft Cabin Ventilation Fan Prototype showing surface pocketing for weight reduction

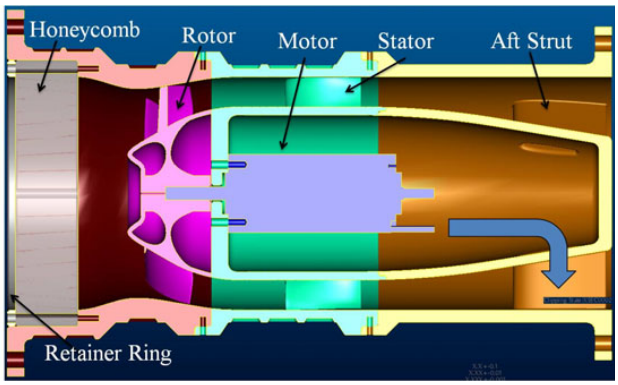

Figure 4.—Final Design of Spacecraft Cabin Ventilation Fan Prototype

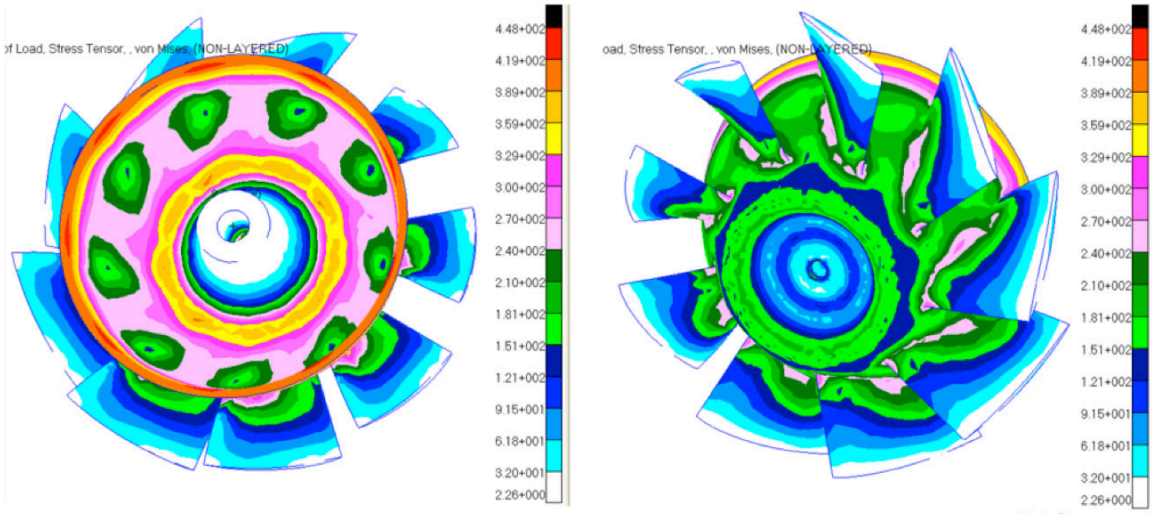

Figure 5.—Rotor stress analysis results for final design of spacecraft cabin ventilation fan prototype

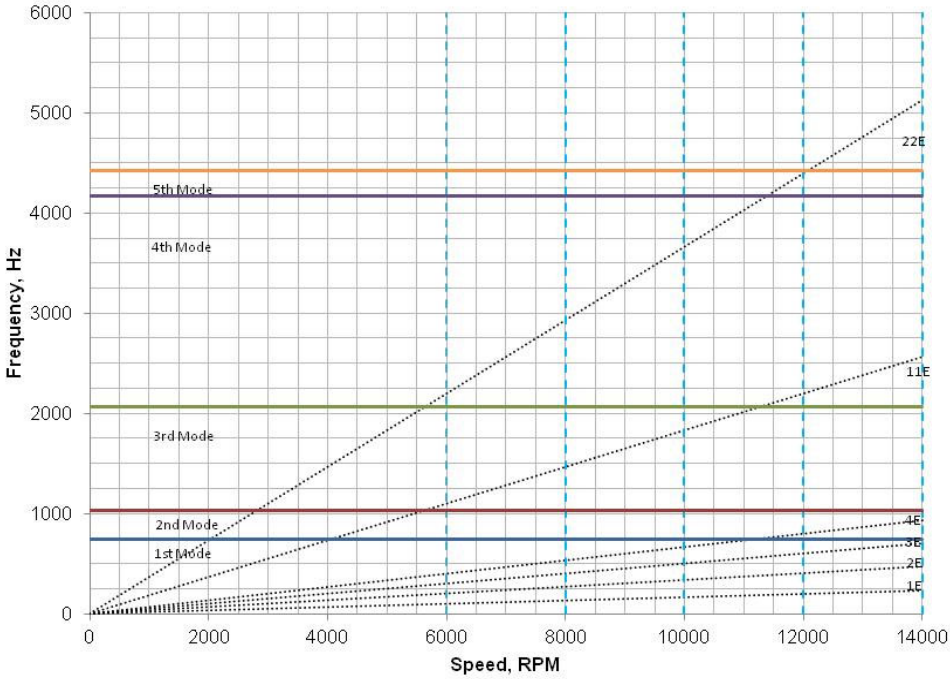

Figure 6.—Campbell diagram for final design of spacecraft cabin ventilation fan prototype

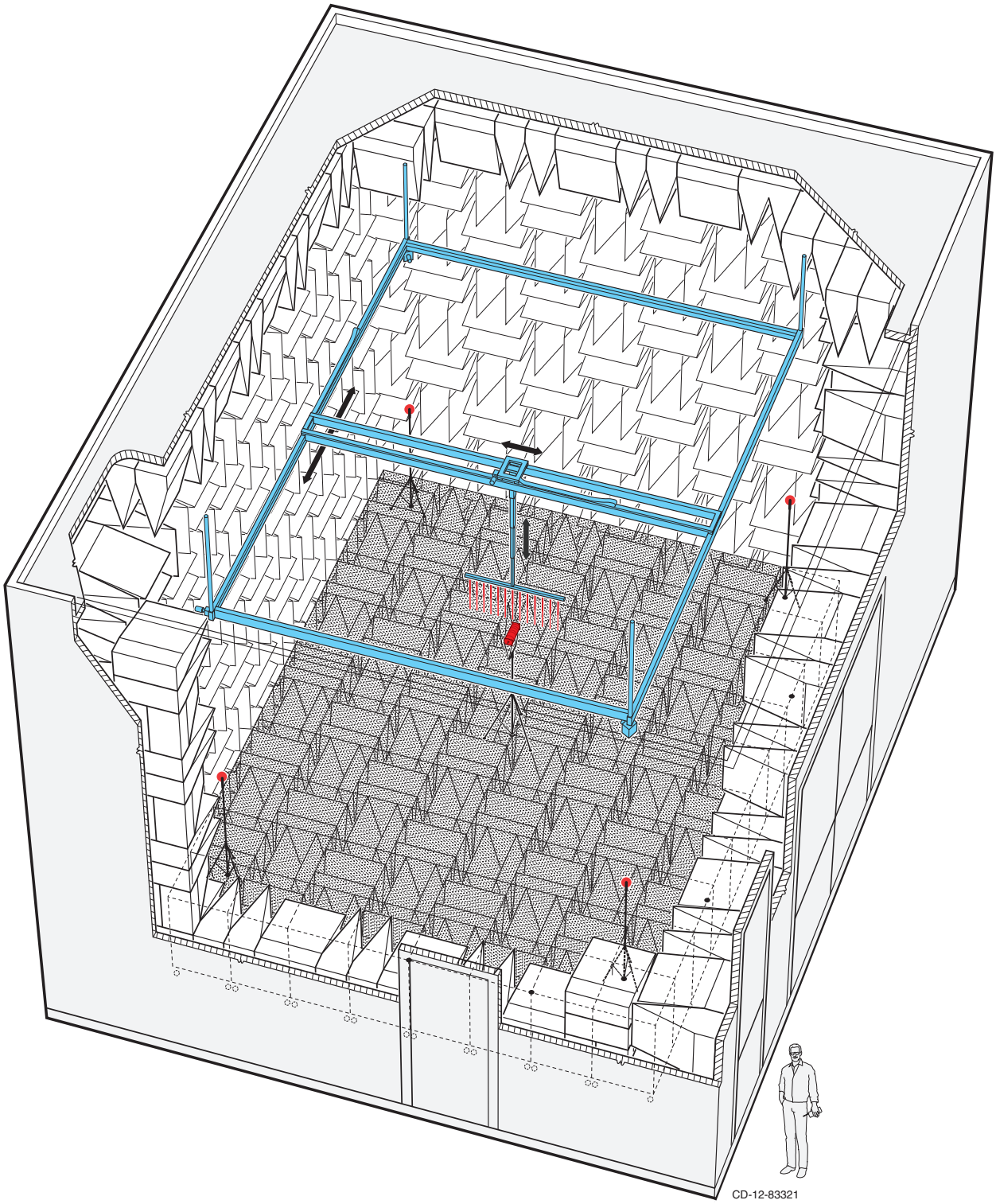

Figure 7.—The spacecraft cabin ventilation fan prototype in the NASA Glenn Acoustical Testing Laboratory

Figure 8.—Photograph of spacecraft cabin ventilation fan prototype and traversing microphone array in the NASA Glenn Acoustical Testing Laboratory

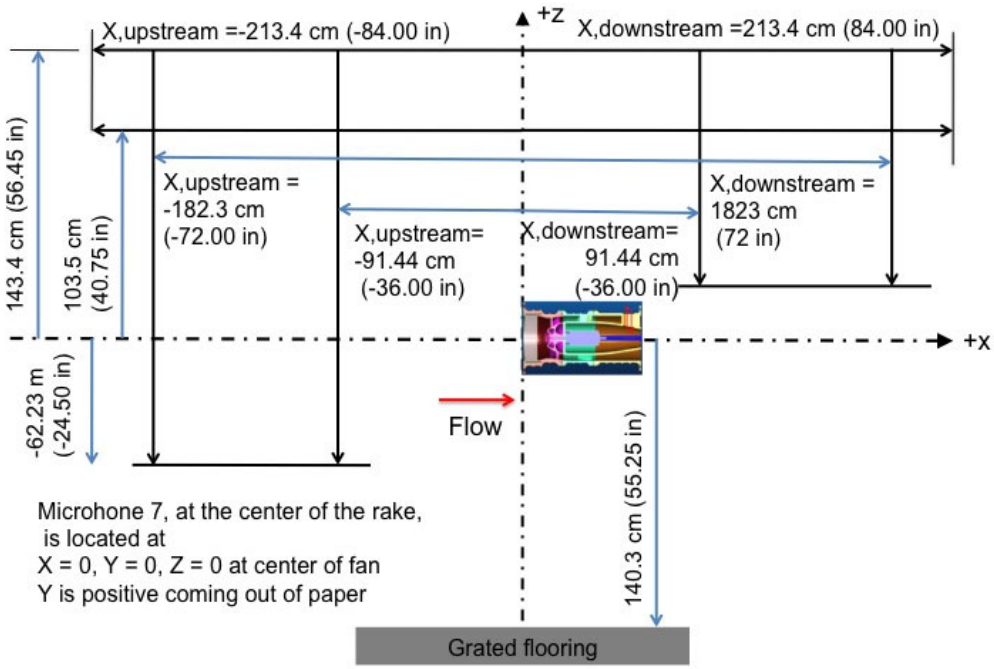

Figure 9.—Microphone survey planes are shown in solid black lines.

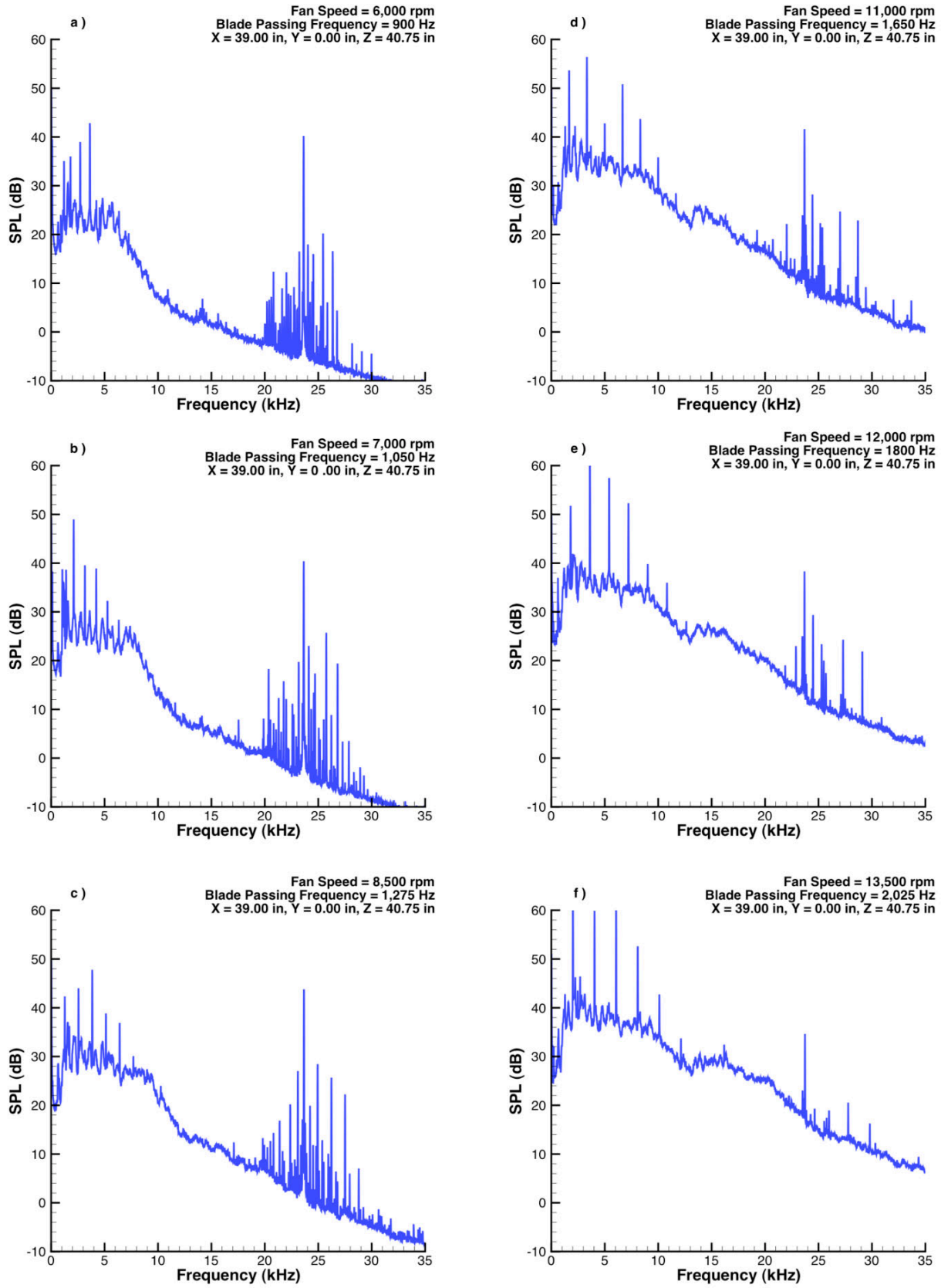

Figure 10.—Narrowband sound pressure levels are plotted as a function of narrowband center frequencies for all tested fan speeds. Measurements are from a single microphone located at the center of the traversing array. Test day conditions, instrument corrected values are plotted.

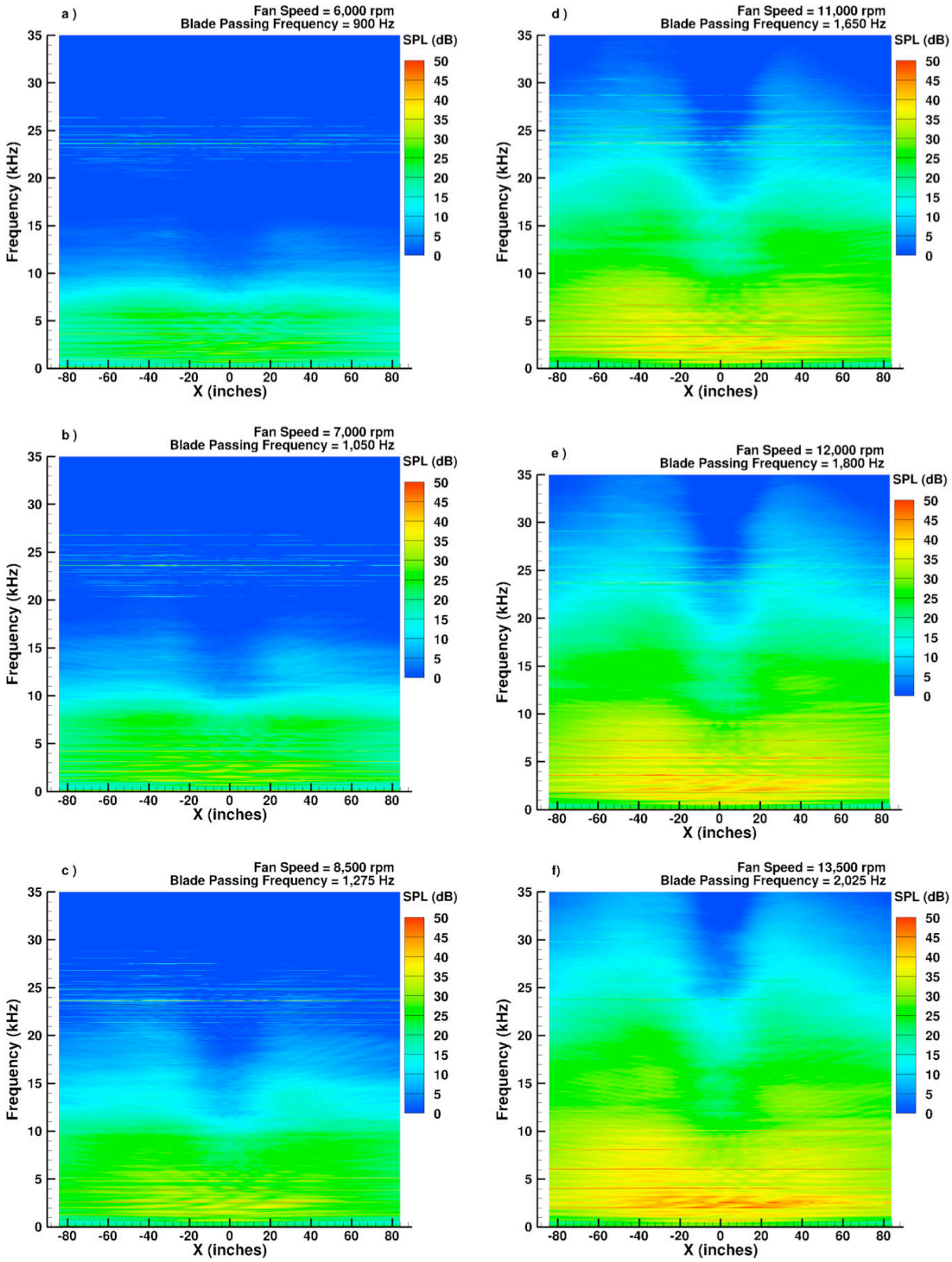

Figure 11.—Narrowband sound pressure level contours are plotted as for all tested fan speeds. Measurements are from a single microphone moved axially from upstream of the fan downstream. The y and z position of the microphone was constant for this survey (y=0.00 in, z= 40.75 in). Test day conditions, instrument corrected values are plotted.

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14. ABSTRACT
Sound pressure measurements were recorded for a prototype of a spacecraft cabin ventilation fan in a test in the NASA Glenn Acoustical Testing Laboratory. The axial fan is approximately 0.089 m (3.50 in.) in diameter and 0.223 m (9.00 in.) long and has nine rotor blades and eleven stator vanes. At design point of 12,000 rpm, the fan was predicted to produce a flow rate of 0.0709 m^3/s (150 cfm) and a total pressure rise of 925 Pa (3.72 in. of water) at 12,000 rpm. While the fan was designed to be part of a ducted atmospheric revitalization system, no attempt was made to throttle the flow or simulate the installed configuration during this test. The fan was operated at six speeds from 6,000 to 13,500 rpm. A 13-microphone traversing array was used to collect sound pressure measurements along two horizontal planes parallel to the flow direction, two vertical planes upstream of the fan inlet and two vertical planes downstream of the fan exhaust. Measurements indicate that sound at blade passing frequency harmonics contribute significantly to the overall audible noise produced by the fan at free delivery conditions.

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