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Quiet Spacecraft Cabin Ventilation Fan: Vibration Measurements Results

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ABSTRACT

Quiet, efficient fans with minimal vibrations are needed to maximize the mechanical life of atmospheric revitalization system fans used for human life support systems for long duration space exploration missions. Several metal spacecraft cabin ventilation fan prototypes have been designed, built, and tested at the NASA Glenn Research Center Acoustical Testing Laboratory. Tests performed in 2021 of the first prototype of the metal fan measured vibrations greater than desired at design point speed and backpressure conditions. To try to reduce those vibrations, a second prototype of the fan design was developed which included a new lighter rotor with a tighter balance tolerance, a new collet to attach the rotor to the motor shaft more securely and repeatably, and a new bracket to center and hold the motor in the fan centerbody more precisely. The second prototype of the fan was tested in 2023 and the vibrations were measured with the fan operating at design point speeds in isolation but not throttled to design point back pressure conditions since it was not installed with inlet and exhaust ducting. Peak vibration was reduced from 4 mm/s to 1 mm/s. This paper is part of a series of reports documenting the performance of the prototype fan.

1. INTRODUCTION

Astronauts need quiet, efficient, and durable fans for life support systems in spacecraft, particularly for long duration exploration missions. In 2021, NASA Glenn Research Center (GRC) and Johnson Spaceflight Center (JSC) designed, built, and tested a metal spacecraft cabin ventilation fan prototype suitable for aerodynamic, acoustic, and mechanical ground tests.[1] The 2021 tests revealed that while aerodynamic and acoustic measurements indicated that the fan was operating as intended, vibrations were greater than desired. Recommendations were made to try to reduce fan vibrations. This report will summarize the design changes, describe the experiment, discuss the results, and offer suggestions for future efforts.

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2. DETAILS OF THE FAN TESTED IN 2021

2.1 Fan Design

During 2020 and 2021, NASA GRC was assigned a two-part task for advancing high-performance ventilation fans for spacecraft. The first task was to take the aerodynamic design from 2010[2] and create a new mechanical design for manufacturing using modern metal additive manufacturing. We were exploring the possibility that printed metal fans might be considered for long-term operation in a spacecraft cabin ventilation application, such as the International Space Station or the Gateway Outpost, which is imagined to orbit the moon and support human missions to the lunar surface someday.[3, 4, 5] The second part of the task was to test the manufactured fan's aerodynamic and acoustic performance in a custom-built small fan test rig at NASA GRC.[1]

The rotor designed for the 2021 experiment was attached to the motor shaft with a keyless bushing, accessible behind a cover making up the rotor spinner. An exploded view of the assembly is shown in Figure 1. The Maxon 305015 brushless DC motor has a 5 mm (0.20 in) diameter through shaft extending 20 mm (0.79 in) from the front and an overall length of 98 mm (3.89 in). The shaft is supported internally by front and rear ball bearings internal to the motor.

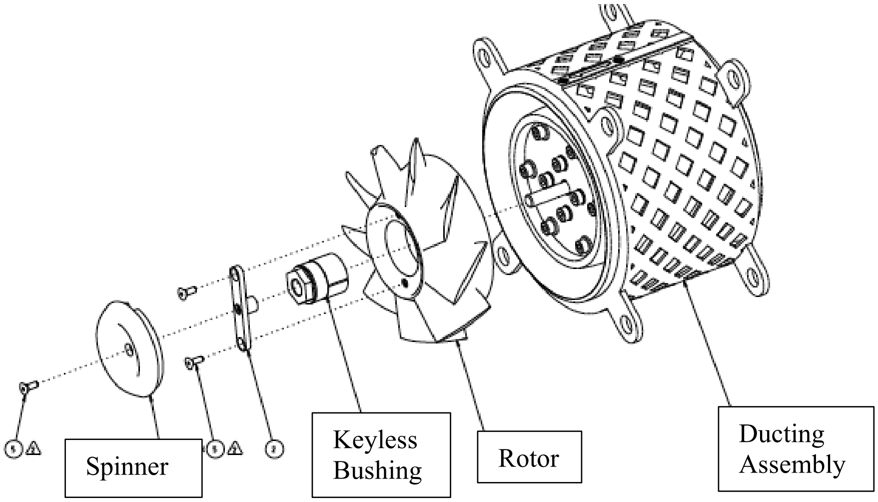


Figure 1: The 2021 Metal Spacecraft Cabin Ventilation Fan.

2.2 Rotor Balance

The balance grade of a rotor, G, is described by ISO-21940-11[6] as:

$$G = e \times \Omega, \qquad (1)$$

where the shaft angular velocity Ω is in radians/second and e is the eccentricity with units of millimeters. The eccentricity is also known as the specific unbalance, which is the unbalance U normalized by the rotor mass,

$$e = \frac{U}{m_{rotor}} = r\frac{m_{unbalance}}{m_{rotor}}, \qquad (2)$$

where r is a radius in mm corresponding to the unbalance mass $m_{unbalance}$. For our rotor at operating speed,

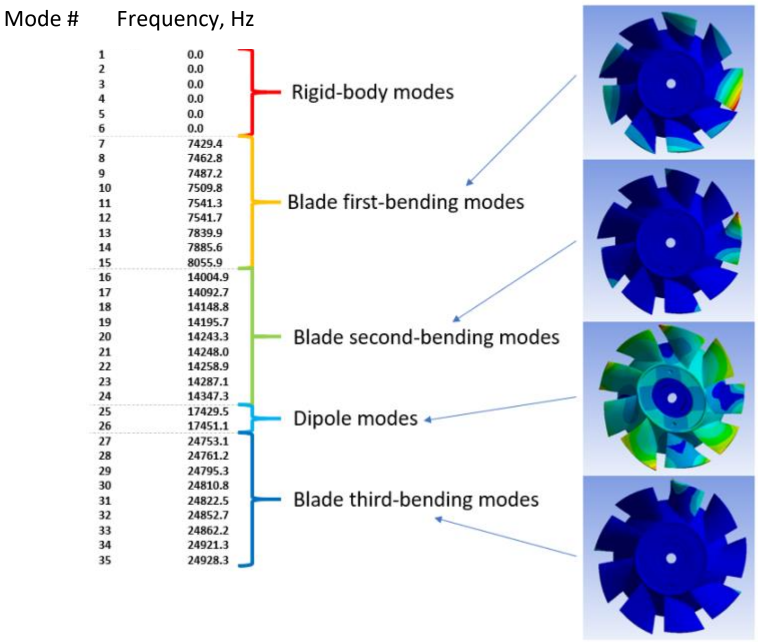
$$\Omega = \frac{12000}{60} \times 2\pi = 1257\, rad/s. \qquad (3)$$

The residual unbalance tolerance for the fan tested in 2021 was specified to be 0.762 g-mm (0.03 g-in or 0.001 oz-in). The mass of the rotor assembly was 191 g (0.420 lbm), which included the spinner, keyless bushing and bushing cover, rotor, and three fasteners. Therefore, the eccentricity, e, was calculated to be 0.0040 mm (0.00016 in) and the balance grade, G 5. This balance quality grade is consistent with a variety of rotating equipment such as fans and pumps, as described in the ISO-21940-11 standard.

The rotor assembly was balanced by the Balancing Company of Vandalia, Ohio and the residual balance of the two fan units were: Fan 1: 0.0002 oz-in (0.006 gm-in) @ 85° at the back of the rotor and 0.0007 oz-in (0.020 gm-in) @ 250° at the front of the spinner; and for Fan 2: 0.0003 oz-in (0.009 gm-in) @ 335° at the back of the rotor and 0.0014 oz-in (0.040 gm-in) @ 100° at the front of the spinner. The residual balance of this rotor was also checked on the GRC balance rig, further suggesting that the balance tolerance and the repeatability of the rotor assembly could be improved if vibration of the fan was to be reduced.

2.3 Modal Analysis

An important part of the vibration of rotating machinery is anticipating a match between rotor vibration modes and the frequencies excited by the rotation of the machine. A modal analysis was conducted with Ansys Mechanical and the frequencies of various vibration modes were identified, as shown in Figure 2. Since the shaft frequency at design speed was anticipated to be 200 Hz (12,000 rpm), the first blade bending mode of 7430 Hz is well beyond any reasonable harmonic for excitation. The stator was similarly analyzed, and the lowest vibration mode was found to be around 2800 Hz. This is above eleven (the number of stator vanes) times the shaft frequency, so no self-excited vibration was expected during operation.



Mode #	Frequency, Hz
1	0.0
2	0.0
3	0.0
4	0.0
5	0.0
6	0.0
7	7429.4
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
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
26	17451.1
27	24753.1
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 2: Modal analysis results.

2.4. Vibrations Observed During Testing in 2021

A duct rig was constructed to backpressure the fan and the rig was instrumented to measure the aerodynamic and acoustic performance of the spacecraft cabin ventilation fan prototype.[1] Pressure transducers were located upstream and downstream of the rotor and microphones were placed inside and outside of the duct. The fan speed was controlled during the test and the test rig included a throttle plug driven by a precision traverse to adjust the back pressure in the duct. Equipment safety and health monitoring instrumentation included a current transducer attached to the 48 Volt feed line for the motor controller, a tachometer to measure motor shaft speed, a thermocouple mounted to the motor housing, and accelerometers mounted to the fan unit casing. The motor controller had no trouble managing the fan speed, and the current consumed by the system and the resulting fan speed were well-behaved. The motor housing was well-cooled by the airflow through the system and the conduction of the aluminum housing and the temperature remained within normal operating range. The accelerometers, however, did produce some interesting and safety-relevant measurements that bore further scrutiny. The spacecraft cabin ventilation fan prototype built and tested in 2021 is shown in Figure 3. The PCB model 320C33 accelerometers are visible, spaced 90 degrees apart.

The first fan unit tested was observed to have significant vibration. During testing, the acceleration was monitored in real time using LabVIEW software as a time-trace and as a scrolling root mean square (RMS) level. The fan was subsequently removed from the duct rig and operated at design point conditions without backpressure to collect additional vibration data. Efforts were then taken to diagnose the causes of the vibration, knowing that some of the common problems associated with machine vibrations include imbalances, bent shafts, soft mounting conditions, misalignment, looseness, resonance, rubs, oil whirl, or broken components of the motor as reported by Taylor. [7]

After testing, the accelerometer data was postprocessed for additional analysis. Velocity was calculated by integrating the acceleration measurement and digital high-pass filtering at one quarter shaft rate. The resulting measurements are shown in Figure 4 and Figure 5. The time trace is dominated by a single periodic signal at the shaft frequency, suggesting a once-per-revolution imbalance. The peak velocity measured was just under 4 mm/s, suggesting an effective vibration grade of G 4. This vibration was essentially insensitive to the back pressure on the fan, suggesting aerodynamic forcing was not causing the vibration.

The noise implications of the vibration were measured with a microphone outside the fan casing while the unit was installed in a ducted test rig. The intent was to listen to case-radiated sound and largely neglect the sound radiated from the inlet and exit of the ducts. The measured sound spectrum at design point is shown in Figure 6, indicating substantial noise at shaft rate.

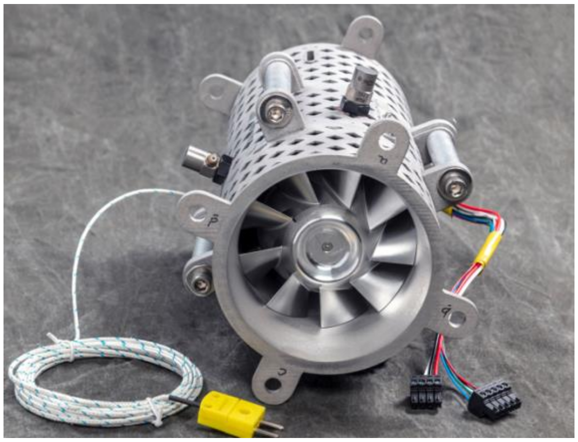


Figure 3: This is the metal spacecraft cabin ventilation fan with the rotor tested in 2021. The two accelerometers attached to the case are visible, as are the bolts attaching the inlet to the stator.

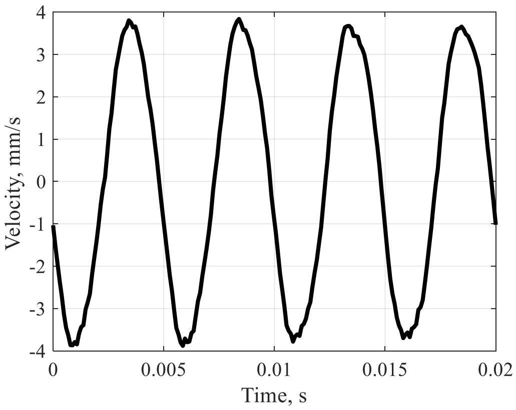


Figure 4: Vibration of the spacecraft cabin ventilation fan in 2021 at design point, velocity time trace.

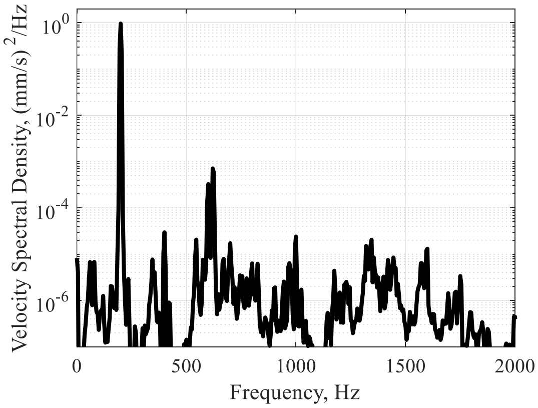


Figure 5: Vibration of the spacecraft cabin ventilation fan in 2021 at design point, frequency content of velocity signal.

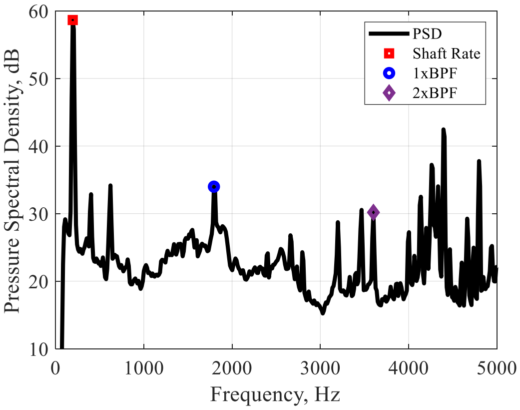


Figure 6: Measured case-radiated noise.

For comparison, a commercial off-the-shelf (COTS) fan with a similar diameter to the spacecraft cabin ventilation fan was used for checking out the test rig and validating the sensor measurements. Operating at 15,000 rpm (250 Hz), the COTS fan produced similar flow rate and pressure rise to the NASA design. The vibration velocity is shown in Figure *7*, with a corresponding vibration grade of around G 1. Figure 8 shows that the signal is complicated with lots of harmonics in addition to the shaft rate coherent signal. The COTS fan is significantly shorter than the spacecraft cabin ventilation fan (L/D ~2 vs ~4), with a different bearing system and uses an integrated motor with speed control.

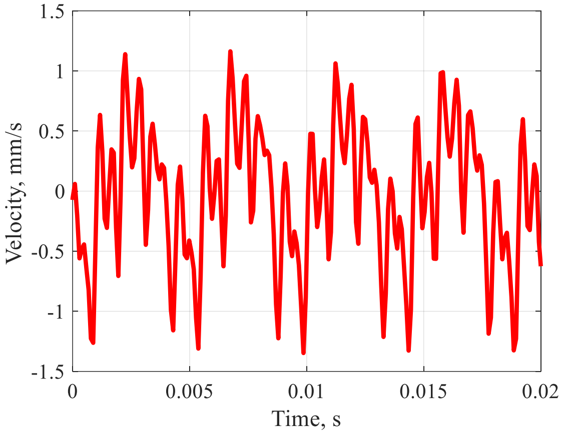


Figure 7: Vibration of COTS fan near design point for the spacecraft cabin ventilation fan, velocity time trace.

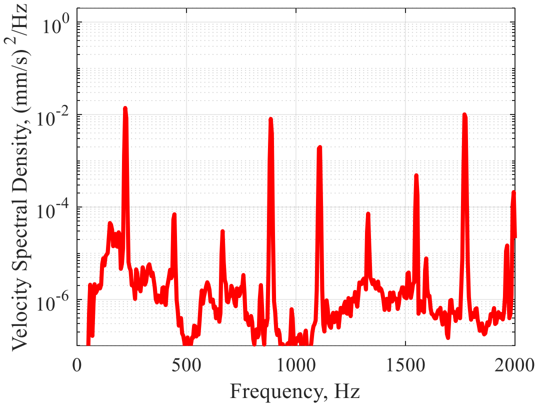


Figure 8: Vibration of the COTS fan near design point for the spacecraft cabin ventilation fan, frequency content of velocity signal.

3. DETAILS OF THE FAN TESTED IN 2023

3.1. Fan Design

The rotor was redesigned in 2022 to reduce vibration and tested in January 2023, and was manufactured by Xometry, Inc. out of 7075 aluminum. To accomplish this, the keyless bushing was replaced by a 4-finger collet modeled after designs typically used for model aircraft propeller attachments. The fingers fit into matching slots in the rotor. The front of the collet is threaded to accept a custom collet nut that pulls the rotor into the fingers, engaging the fingers onto the motor shaft. A machine screw with threads in the opposite direction to the collet nut reduced the risk of the collet nut loosening during operation. The new collet design was intended to improve repeatability of the assembly of the rotor onto the motor shaft and reduce the number of parts in the design. Also, it aligned parts with the greatest possible variability along the centerline to minimize the impact of their variability. The rotor was substantially lightened by removing mass from the rear face. The updated rotor assembly is shown in Figure 9.

An additional design goal was to reduce the overhang of the rotor on the motor, and this was accomplished with the use of a new motor mount plate, including an offset center mount where the motor was fastened. This means the motor is positioned more forward in the final assembly as compared to the 2021 design, which would hopefully help reduce the impact of any remaining imbalance on the vibration. Cross-sections of the original and updated rotor assembly are shown in Figures 10 and 11, respectively.

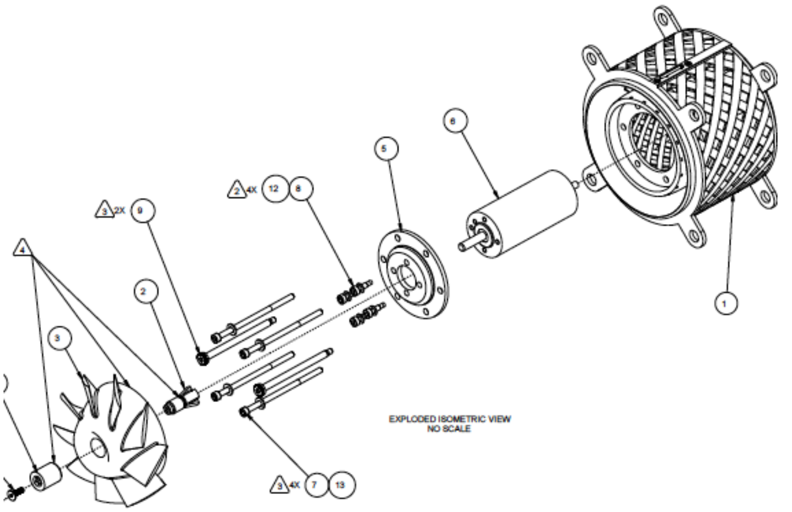


Figure 9: The metal spacecraft cabin ventilation fan tested in 2023 with redesigned rotor assembly.

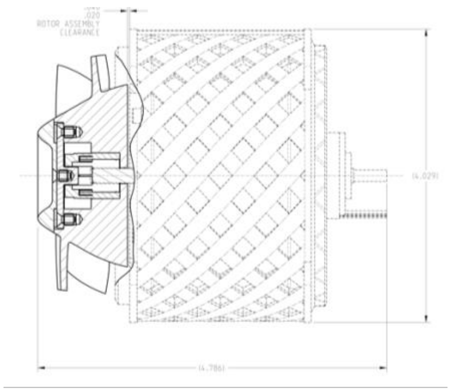


Figure 10: The rotor assembly for the 2021 test.

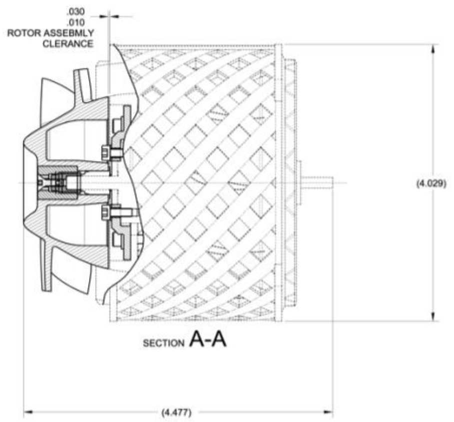


Figure 11: The rotor assembly for the 2023 test.

3.2 Rotor Balance

Once again, Equations 1-3 were used to calculate the balance grade of a rotor, *G*, as described by ISO 21940-11.[6] The rotor tested in 2023 was also operated at 12,000 rpm which corresponds to an angular velocity, Ω, of 1257 rad/s.

The residual unbalance tolerance for the fan tested in 2023 was specified to be 0.090 g-mm (0.004 g-in). The mass of the rotor assembly, which included the blisk, four finger collet, collet, nut, and fastener was estimated to be 121 g (0.267 lbm). Therefore, the eccentricity, *e*, is calculated to be 0.0007 mm and the balance grade, G 0.9. This balance quality grade is consistent with a variety of rotating equipment such as compressors and machine-tool drives, as described in the ISO 21940-11 standard.[6]

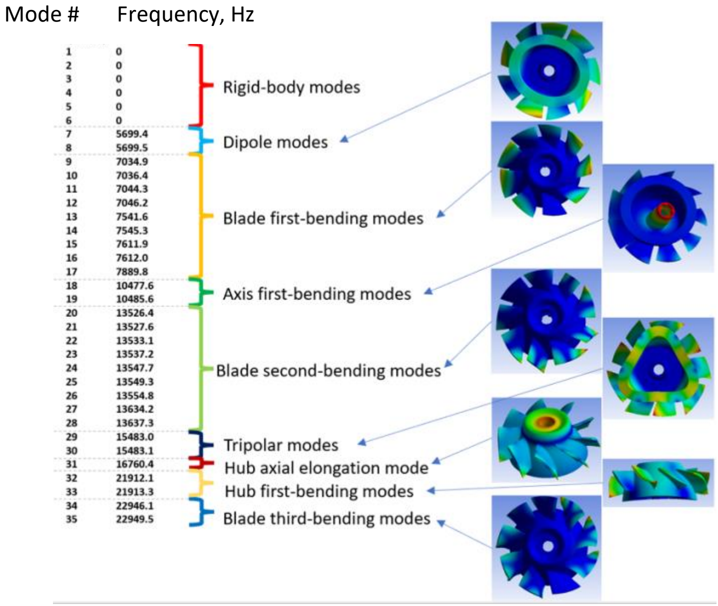
As delivered from Xometry, Inc., the new rotor was measured to have an unbalance of 1.583 g-mm (0.062 g-in). The rotor assembly was balanced at NASA GRC and the residual balance of the fan tested in 2023 was 0.116 g-mm (0.0045 g-in), a reduction by a factor of 14. Using the residual unbalance for the value of U, the eccentricity of the redesigned rotor tested in 2023 was calculated to be 0.00095 mm and the predicted balance quality grade calculated to be G 1.2

3.3 Modal Analysis

A modal analysis was conducted in simulation software and the frequencies of various vibration modes were identified for the rotor tested in 2023, as shown in Figure 12. The analysis was a free-free (no constraints) modal analysis of the blisk and was performed with Ansys Mechanical 2022r1. The shaft frequency at design point conditions was 200 Hz (12,000 rpm) and the first blade bending mode of 7435 Hz was well beyond any reasonable harmonic for excitation. The analysis also indicated that the first dipole modes of the rotor would occur at 5700 Hz, again well above the shaft frequency. This is also well above the first three harmonics of the blade passing frequency for the rotor that has 9 blades: 1 BPF = 1800 Hz, 2 BPF = 3600 Hz, 3 BPF = 5400 Hz.

3.4 Vibrations Observed During Testing in 2023

The rotor was reassembled on the fan unit and vibrations were measured during operation up to 13,000 rpm. The results were immediately noticeable and significant. The new vibration level is shown in Figures 13 and 14 at design point condition, 12,000 rpm (200 Hz). Vibration peak velocity was reduced to 0.6 mm/s, exceeding the predicted balance quality grade of G 1, a result of the design changes and final balance of the rotor. The new rotor assembly met our balance goals with a reduction in vibration of 6-fold. Unfortunately, repeat acoustic measurements were not obtained due to the facility being unavailable.



Mode #	Frequency, Hz
1	0
2	0
3	0
4	0
5	0
6	0
7	5699.4
8	5699.5
9	7034.9
10	7036.4
11	7044.3
12	7046.2
13	7541.6
14	7545.3
15	7611.9
16	7612.0
17	7889.8
18	10477.6
19	10485.6
20	13526.4
21	13527.6
22	13533.1
23	13537.2
24	13547.7
25	13549.3
26	13554.8
27	13634.2
28	13637.3
29	15483.0
30	15483.1
31	16760.4
32	21912.1
33	21913.3
34	22946.1
35	22949.5

Figure 12: Modal analysis for the rotor tested in 2023.

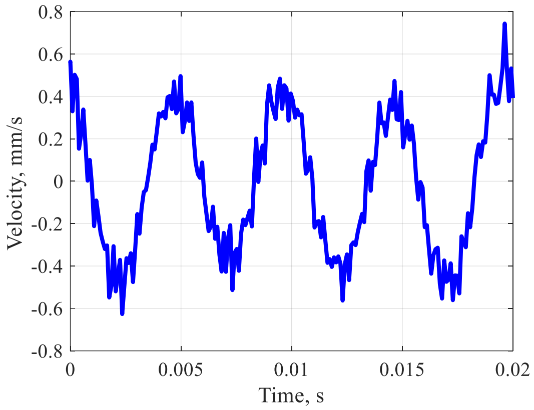


Figure 13: Vibration of the spacecraft cabin ventilation fan tested in 2023 with the redesigned rotor, velocity time trace.

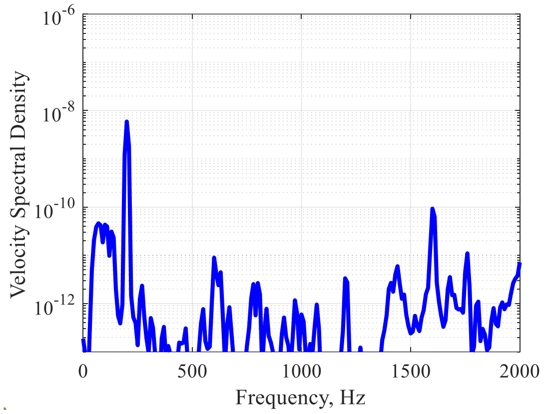


Figure 14: Vibration of the spacecraft cabin ventilation fan tested in 2023 with redesigned rotor, frequency content of velocity signal.

4. RECOMMENDATIONS

To further improve the performance of this fan, design changes to the duct pieces mating surfaces are recommended. The duct pieces were additively manufactured using Direct Metal Laser Sintering (DMLS) during the early days of the pandemic when in-person work was severely curtailed, and which significantly influenced the design and manufacturing choices. While the fit of the printed parts was very good, the fit would be improved if the mating surfaces were designed to be machined after printing. Pilot surfaces would help to locate the rotor in the center of the duct more precisely. While the new motor mount centered the motor and the rotor with respect to the stator, we had some difficulty aligning the inlet duct and the rotor to ensure sufficient rotor blade tip clearance around the circumference of the part. To overcome this challenge, a 0.31 mm (0.012 in) shim was used to move the inlet forward and some “finesse” was used to hold the inlet in place while the four nuts were tightened onto the casing bolts (one bolt is seen in the middle of the fan at the 3:00 position in Figure 3) so the rotor blade tip gap was sufficient for this vibration test.

5. CONCLUSION

Tests performed in 2021 of a metal spacecraft cabin ventilation fan prototype revealed vibrations greater than desired at design point speed and backpressure conditions. To try to reduce those vibrations, a second prototype of the fan design was developed which included several design changes. The new design featured a new lighter rotor with a tighter balance tolerance, a new collet to attach the rotor to the motor shaft more securely and repeatably, and a new bracket to center and hold the motor in the fan centerbody more precisely. The second prototype of the fan was tested in 2023 and the vibrations were measured with the fan operating at design point speeds in isolation but not throttled to design point back pressure conditions since it was not installed with inlet and exhaust ducting. Peak vibration was reduced from 4 mm/s to 1 mm/s. Results of this experiment also indicated that the fit of the inlet relative to the rotor could be improved if the printed duct pieces were designed with pilot surfaces machined after printing with Direct Metal Laser Sintering.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1. Stephens, D., Goodman, J., Buehrle, R., Mirhashemi, A., Koch, L. D., Shook, T. D., Sutliff, D., Allen, C., Matty, C., "Highlights of Aeroacoustic Tests of a Metal Spacecraft Cabin Vent Fan Prototype," NASA-TM- 20220012622, 2022.
2. Tweedt, D. L., "Aerodynamic Design and Computational Analysis of a Spaceflight Vehicle Cabin Ventilation Fan," NASA CR-2010-216329, 2010.
3. Fuller, S., Lehnhardt, E., Zaid, C., Halloran, K. "Gateway program status and overview." *Journal of Space Safety Engineering*, Vol. 9, No. 4, pp. 625-628. 2022.
4. Smitherman, D., Schnell, A. "Gateway lunar habitat modules as the basis for a modular mars transit habitat." Vol. 2020 IEEE Aerospace Conference, pp. 1-12. 2020.
5. Smitherman, D. V., Canerday, S., Perry, J., Howard, D. "Concepts for Phased Development of a Lunar Surface Base," AIAA- 2020-4051, 2020.
6. International Organization for Standardization, "Mechanical vibration - Rotor balancing - Part 11: Procedures and tolerances for rotors with rigid behaviour," International Organization for Standardization ISO-19240-11, 2016.
7. Taylor, J. I., *The Vibration Analysis Handbook: A Practical Guide for Solving Rotating Machinery Problems* (Vibration Consultants, Inc., Tampa, FL, 1994).