Acoustics and Performance of a Scaled Spacecraft Cabin Ventilation Fan

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An axial fan was designed at NASA Glenn Research Center using tools developed for aircraft turbine engines. The fan unit design size, flow rate and pressure rise were chosen to be broadly in the range of the Orion cabin fan. A ground test prototype was built and tested, confirming design predictions. Pressure rise and flow rate measurements were conducted over a range of fan speeds while in-duct and radiated acoustic measurements were collected. Unsteady flow measurements were acquired between the rotor and stator. These methods are a hybrid of the techniques used for small fans and those used for aircraft engine component tests. A larger version of the fan was recently designed, based on the original fan, using aerodynamic scaling laws resulting in a design with approximately twice the flow rate and twice the pressure-rise compared to the original fan. The mechanical structure was optimized using generative design for low weight. The paper discusses this larger fan design including the scaling laws, the predicted performance and acoustics.

Nomenclature

c	=	speed of sound, m/s
dP	=	measured pressure rise, $p_2 - p_1$
f	=	frequency, Hz
He	=	Helmholtz number, $f\,R\,/\,c$
p_1	=	pressure upstream of the fan
p_2	=	pressure downstream of the fan
R	=	duct radius, m
T_1	=	upstream temperature
U	=	axial flow speed
V_{tip}	=	rotor tip speed
γ	=	ratio of specific heats for air, 1.4 for the present calculation
ρ	=	air density
φ	=	dimensionless flow rate, $\varphi = \frac{U}{V_{tip}}$
ψ	=	dimensionless pressure rise, $\frac{dP}{\frac{1}{2}\rho V_{tip}^2}$

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I. Introduction

FANS associated with the Environmental Control and Life Support (ECLS) system have been recognized as a historical contributor to the noise environment experienced in manned spacecraft.[1] In order to support crew health and performance, a collaboration across NASA centers was pursued to incorporate aeronautics research into spacecraft ventilation fan design. Specifically, a multi-center effort was pursed to utilize turbomachine design methods for high performance and low noise aircraft engine fans. The resulting fan was built and tested as described in a series of recent reports.[2-6] The measurements showed the fan met the intended acoustic and aerodynamic design point with excellent efficiency. A test report was also published recently.[7] In summary, a custom fan could be built to a specific design point and achieve good results.

The present report describes a larger fan model in development at NASA that will extrapolate from the original design to meet a higher aerodynamic performance requirement. The intent is to demonstrate that a suitable fan can be modified relatively easily using aerodynamic scaling laws and acoustic considerations. The following section will give a brief overview of the 2020 aerodynamic, acoustic and mechanical design. Next, a scaled-up version will be presented with motivation from the measured performance of the original. The report will finally describe aerodynamic and acoustic predictions and give a conclusion.

II. Quiet Space Fan 1 Design

The design point for the original quiet space fan was selected to match the original Orion cabin fan, 150 CFM airflow at a pressure rise of 3.64 inches H_2O. The motivation was discussed by Allen[2] while the resulting aerodynamic design was given by Tweedt.[8] The rotor diameter was selected to be 3.14 inches with a design shaft speed of 12,000 RPM. The acoustic concepts included in the design are explained by Koch[3], specifically the selection of a blade and vane count that resulted in reduced tone noise, using a method similar to that for aircraft engine fans.

The fan mechanical design developed in 2020 and described in the introduction was intended to be simple and cost effective to build. There are four main parts, plus fasteners. Three of the parts are intended to be printed using direct metal laser sintering. The rotor is intended to be machined. In order to provide for the widest possible dissemination of the design, the drawings and Computer Aided Design (CAD) files were released via the NASA Technical Reports Server as a supplement to a recent report.[9] They can be retrieved by any reader interested in manufacturing, studying or advancing the design. A schematic of the 2020 Spacefan is given in Figure 1. For convenience, this design will be referred to as QSF-1, denoting the Quiet Space Fan based on the original Orion Cabin Fan design point.

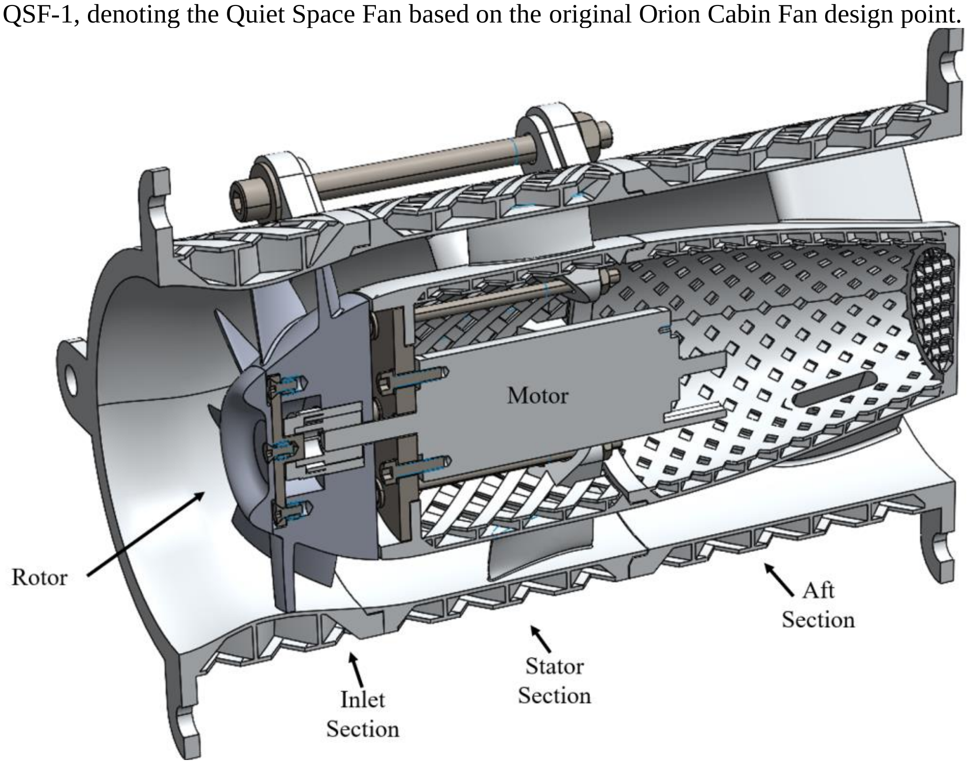

Figure 1. 2020 Spacefan CAD model

The QSF-1 was built in 2021 and tested at NASA GRC and JSC. The data from GRC was described by Stephens and Koch[5], where a small test rig was built with a motorized throttle to generate a fan map. The resulting pressure rise and flow rate data is shown in Figure 2. This shows the performance at design point is nearly met, although the measurements conducted at GRC do not include corrections for duct or inlet losses.

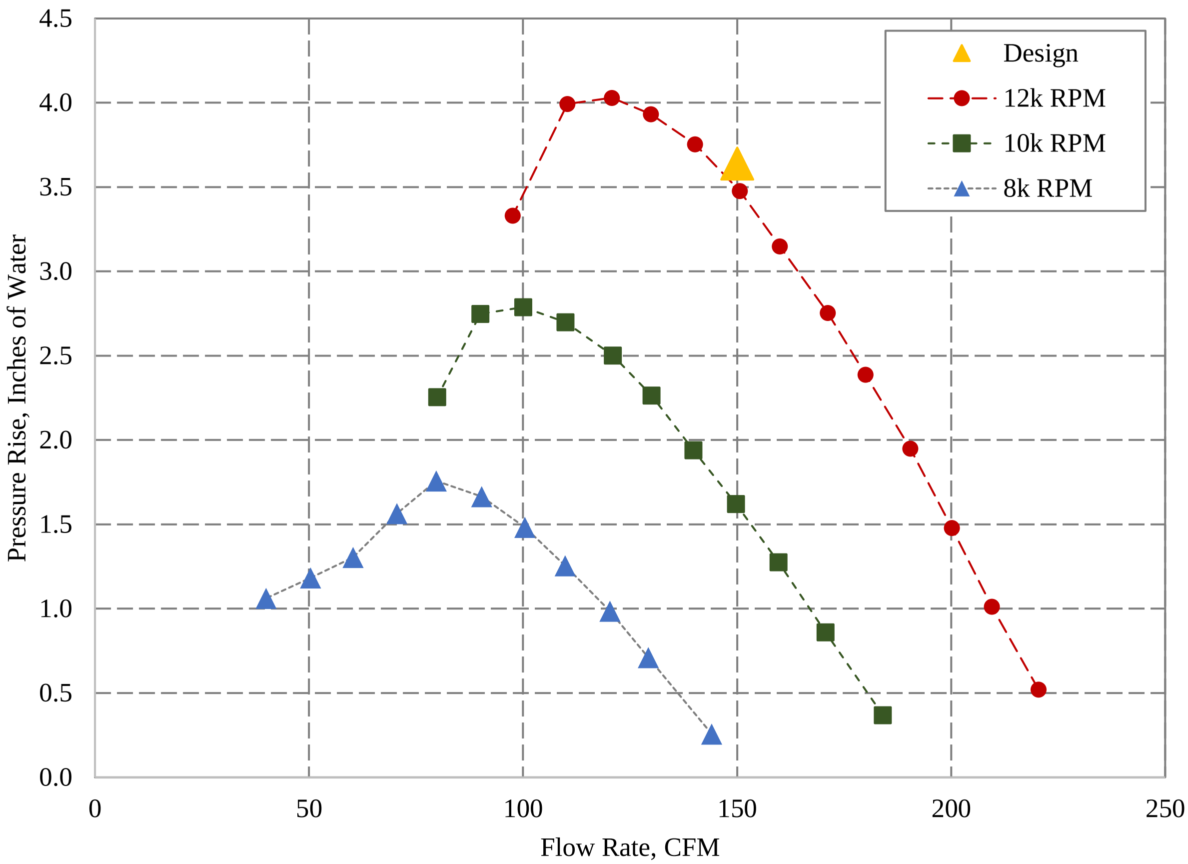

Figure 2. Fan map measured from QSF-1 S/N 2 in 2021 at GRC.

The fan performance map can be normalized by rotor tip speed (V_{tip}) to give a dimensionless pressure, $\psi = \frac{dP}{\frac{1}{2}\rho V_{tip}^2}$ and tip speed $\varphi = \frac{U}{V_{tip}}$, where dP is the measured pressure rise, U is the axial flow speed and ρ is the air density. This collapses the fan map as shown in Figure 3. This set of points were fit with a piecewise polynomial.

For $\varphi < 0.169$, $\psi = -173.7\ \varphi^3 + 87.811\ \varphi^2 - 11.213\ \varphi + 0.8096$.

For $\varphi \geq 0.169$, $\psi = 88.109\ \varphi^3 - 83.159\ \varphi^2 + 21.454\ \varphi - 1.0328$.

The value of $\varphi = 0.169$ is the normalized flow rate where the fan stalls and the pressure produced drops suddenly as the throttle is closed. There was little hysteresis observed and the fan pressure rise recovers approximately at this flow rate also. The details of the fan flow and the dynamics of the stall could be investigated further but it is probably of limited practical interest as users probably want to avoid fan stall. This gave a well-behaved curve that matched the shape of the data quite well. This scaling is expected to hold as long as the Reynolds number and Mach number range of the flow is consistent with the data used for the fit. The utility of having a non-dimensional expression is that the results can be re-dimensionalized to predict the performance for different values of V_{tip}, which is dependent on the shaft speed and the fan diameter.

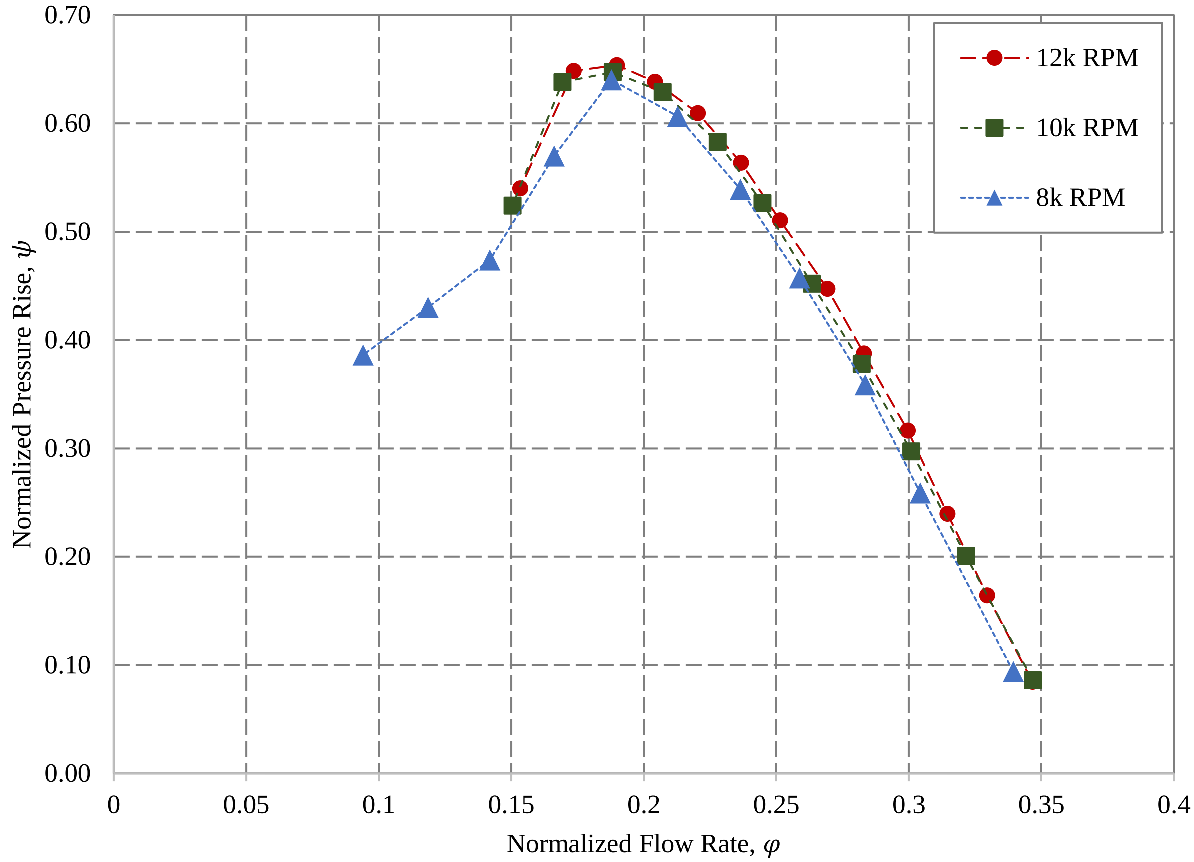

Figure 3. Dimensionless fan map

III. Scaled Fan Design

The piecewise-polynomial calculation discussed in Section II was implemented in a spreadsheet. Specifying a rotor diameter and shaft speed gives a predicted fan map. Figure 5 of the report by Allen[2] shows design points for various ventilation fans used in NASA spacecraft. A line passing through the origin and the QSF-1 design point (150 CFM, 3.64 inches H_2O) would pass quite close to the Gateway Cabin Fan design point (250 CFM, 7 inches H_2O), so it seems reasonable that the QSF-1 could be scaled up to meet the higher performance point. A rotor tip diameter of 3.59 inches and shaft speed of 14,300 RPM meets the design point and the resulting prediction is given in Figure 4. This is an increase of 14% in diameter and 19% in shaft rate. The rotor tip diameter of 3.59 inches corresponds to an internal duct diameter of 4 inches, up from 3.5 inches for the original design. It seemed reasonable to select a pipe diameter of a size that is already manufactured. This larger fan will be denoted as QSF-2.

The expected power required to spin this fan can be estimated by calculating the isentropic temperature rise,

$$\Delta T = T_1\left(\frac{p_2}{p_1}^{\left(\frac{\lambda-1}{\lambda}\right)} - 1\right)$$

Given:

p_2 is the pressure in the duct downstream of the fan,
p_1 is the pressure upstream of the fan (approximated as 101.325 kPa),
T_1 is the upstream temperature (approximated as 25°C), and
γ is the ratio of specific heats for air, 1.4 for the present calculation.

This gives a temperature rise of 1.35°C for 7 inches of water. Isentropic work is calculated by multiplying the temperature rise and the mass flow and the specific heat capacity, $W = c_p\,\dot{m}\,\Delta T$. This gives 211 Watts isentropic.

The efficiency of the QSF-1 was found to scale with $1/\sqrt{V_{tip}}$ giving 65% efficiency including motor and controller losses, for a total estimate of 326 Watts electrical power required.

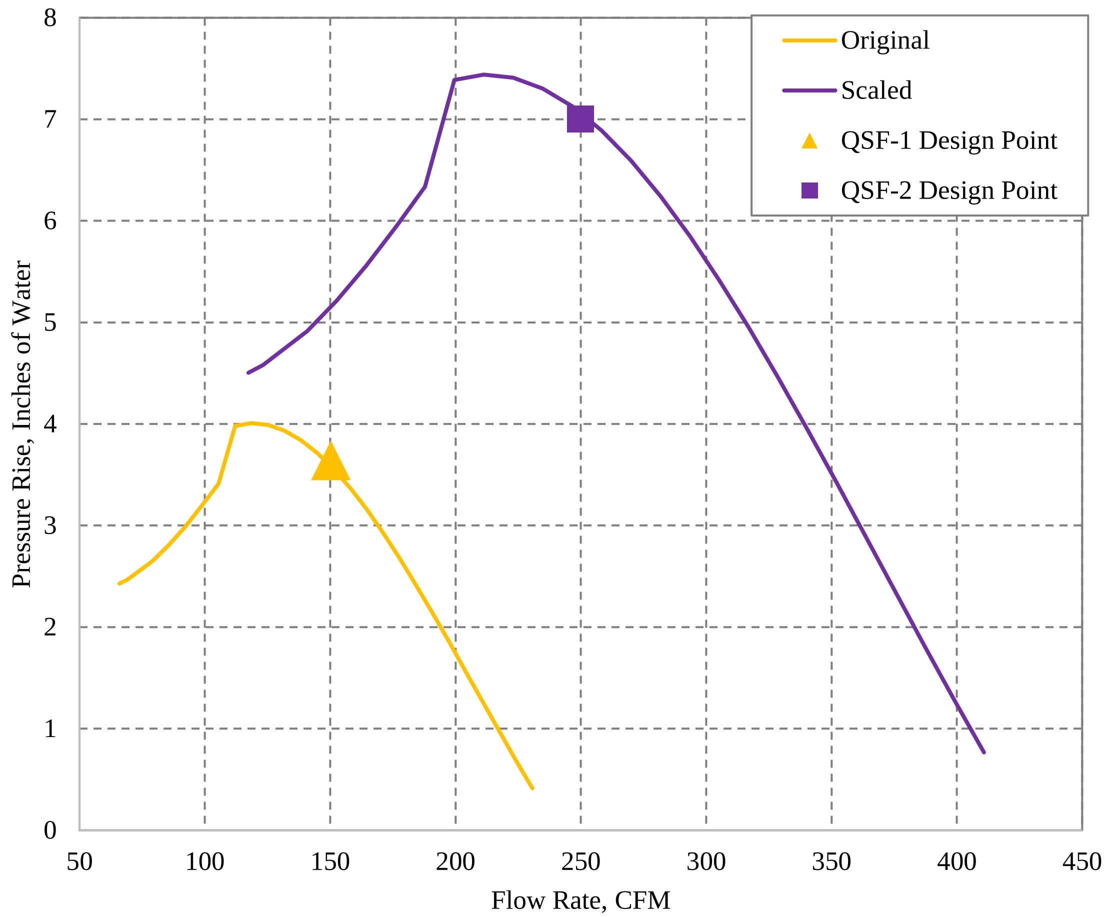

Figure 4. Predicted performance of scaled fan

A mechanical design of the larger fan was developed that increased the inlet diameter from 3.5 to 4 inches resulting in a scale factor of approximately 1.143. A larger brushless DC motor was selected, the Portescap 35ECS80 10B 14 48V rated at 330W. Unlike the QSF-1 which made improvements to the original plastic version designed in 2010, this new version was designed from a clean-slate leveraging lessons learned from the prior two designs. The design only shares a scaled version of the original flow surfaces, though the aft region was truncated to round the length of the fan. A large language model (Open AI's GPT-4) was used to create a MATLAB script that imported the CREO Parametric contour points that defined the fan's flow surface profile, scales it by an amount determined by the user, and outputs a scaled points file that can be imported into CREO Parametric to define the new scaled profile. The blisk length was shortened to minimize the size of the rotating mass; however, a motor mount section was added behind the blisk to maintain the same flow section profile as the original design. Both prior designs rely on additive manufacturing for all non-moving components while this new design minimizes the use of additive manufacturing to a single part to reduce cost and improve surface finish. In the QSF-2 design, the aft stators were eliminated and the wires to power the motor were passed through hollow stator vanes. The stator section was manufactured with a hybrid technique. The stator section was additively manufactured with the hollow vanes then the flow surfaces of the stator were Computer Numerical Control (CNC) machined to improve the surface finish and reduce roughness. Generative design for modal optimization is still in its infancy; however, it was used indirectly to determine that the thinner and less mass contained in the outer casing, the higher the modal frequencies; hence, influencing the design of the casing to be thinner than the previous designs. Lessons from NASA's Quiet Electric Engine (QUEEN) project[10] were employed to design a new rotor assembly that facilitates repeatability so that the blisk maintains its balance to reduce vibrations. The larger fan CAD is shown in Figure 5. The intent is to release the geometry as CAD and drawing files as an attachment to this report when published on the NASA Technical Reports Server after the ICES 2024 meeting.

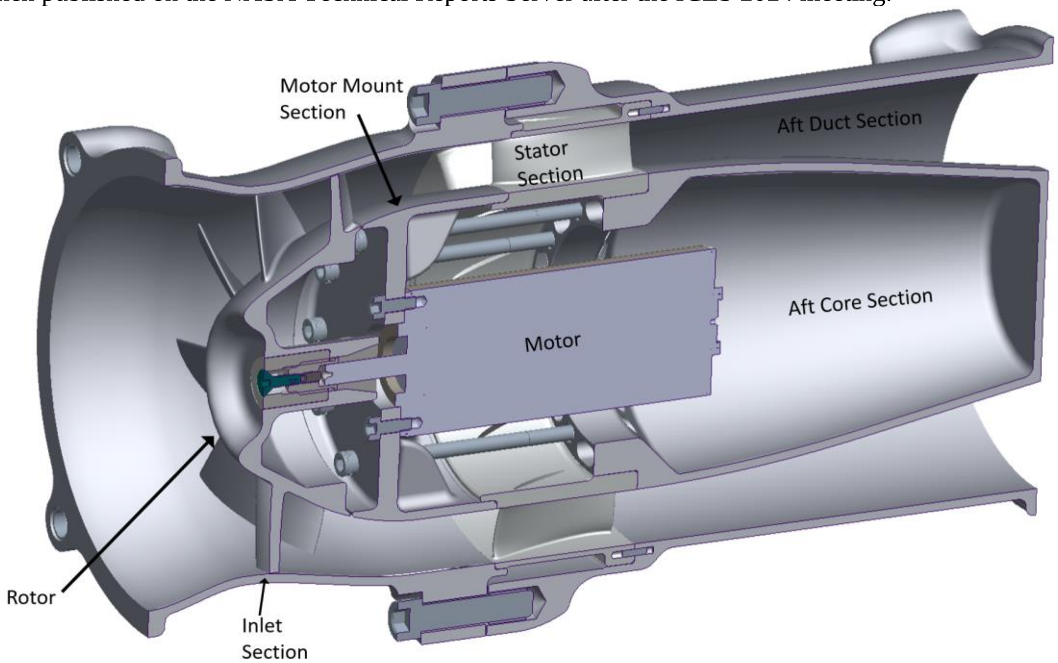

Figure 5. Scaled 2024 Spacefan prototype design

IV. Acoustic Considerations

The aerodynamic design of the fan is a major contributor to the noise. Sources such as trailing edge noise, tip leakage flows and rotor-stator interaction all contribute. The blade and vane counts for the original fan were chosen so the first three blade rate tones would be acoustically cut off.[3] This means that the sound generated would decay inside the duct and not propagate. This happens when the sound is generated at an azimuthal mode order (periodicity) that is higher than the highest duct mode that is cut on at the frequency of the sound source. Compared to the quiet space fan, aircraft engine fans typically have very large diameters and high blade counts. Consequently, only the first blade passing tone is typically cut off.

A quick spreadsheet tool for checking the modes generated by the rotor-stator interaction and comparing against the duct acoustics was developed. The acoustic tool Actran has a utility called cutget and this was used to generate the cut on frequencies for a circular duct. These frequencies were non-dimensionalized as Helmholtz number, $He = f\,R/c$, where f is frequency, R is the duct radius and c is the speed of sound. In this way the results can be applied to a duct of any diameter. Flow in the duct will change these results slightly. The results are shown in Figure 6. Using a linear fit to these results, the cut on modes can be calculated for a duct of a given size.

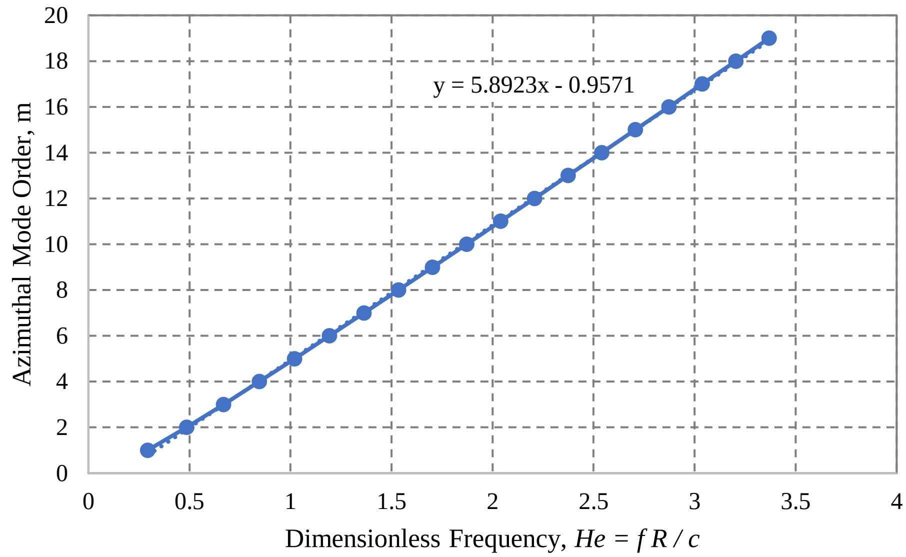

Figure 6. Mode cut on vs Helmholtz number for a circular duct with 12 m/s airflow.

A simplified version of the spreadsheet based acoustic tool is shown in Table 1. The inputs are shaft speed, duct diameter plus blade and vane count. The outputs in italics are the propagating duct modes generated by the fan, calculated as the Tyler-Sofrin modes[11] for blade/vane interaction order. For the values input here, the 4th blade passing frequency (BPF) is cut on with a mode order of m = 3, since a mode order up to 6 will propagate in the duct at 8580 Hz. This is essentially the same as the original quiet space fan, but the acoustic design will start to break down as the fan speed and duct size are further increased. Compared to the original design, n = 3 is closer to cut on and would propagate with slightly increased fan speed or duct diameter.

Table 1. Spreadsheet Acoustic Tool

RPM	14300
Shaft Rate (Hz)	238
Blades	9
Vanes	11
R (m)	0.051
c (m/s)	340

BPF Order	$n = 1$	$n = 2$	$n = 3$	$n = 4$	$n = 5$	$n = 6$
BPF Frequency, Hz	2145	4290	6435	8580	10725	12870
Helmholtz Number	0.32	0.64	0.96	1.28	1.60	1.92
Cut On Modes, m	*none*	*none*	*none*	3	1	-1, 10

V. Conclusion

A methodology for scaling an axial fan from one design point to another is demonstrated, accounting for aerodynamic and acoustic performance. The method is applied to a spacecraft ventilation fan, where previously measured performance and acoustic data was used to predict performance of a larger version. By increasing tip diameter and shaft speed the pressure rise is doubled and the flow rate increased by 2/3. With this method, the existing aerodynamic, acoustic and mechanical design can be quickly adapted to a new design point. The mechanical design of the fan has been completed and drawings and CAD will be released alongside this report with the hope that it will be a benefit to the manned spaceflight community.

Acknowledgments

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