A Study of Preliminary Design Methods for Low Noise Fans

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Outline

• Visual abstract
• Motivation
• Objective
• Preliminary aerodynamic design
• Acoustic design method
• Comparison with other NASA fans
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• Questions
We were motivated to make a quiet and efficient spaceflight cabin vent fan.

We asked: Given a preliminary aero design of a fan, how might we choose the number of stator vanes to minimize tone noise from rotor-stator interaction?

To do so, we developed this fast preliminary acoustic design method for fans using aircraft engine techniques.

Evaluate your options.
Try to choose a low-noise vane-count.

Ideally low-noise vane-counts will have no 'cut-on' circumferential modes at design point conditions.

It is possible to include acoustic design constraints early into the design process of ducted axial fans.
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Motivation

• Quiet spacecraft cabin ventilation fans are needed for ambitious long duration space exploration missions.

• NASA’s Gateway Outpost concept is one example.

https://www.nasa.gov/gateway/overview

Image credit: NASA
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Objective

• To develop a fast preliminary design method to identify low-noise stator vane counts that might minimize tone noise for axial ducted fans used in spacecraft life support systems.

• Can tools and techniques developed to reduce aircraft engine noise pollution be used to help make human space exploration safer and more productive?

• In turn, can tools and techniques developed for space exploration be used to improve small fan performance for aircraft and other cooling and ventilation systems used here on Earth?
Preliminary aerodynamic design

- A preliminary aerodynamic design of the spacecraft cabin ventilation fan was generated for NASA by Daniel Tweedt.

- The intent was to use state-of-the-art aerodynamics so that this fan would serve as a useful baseline for continued aerodynamic and acoustic research.

- The question became: Will a stator with 13 vanes minimize tone noise for this fan?

<table>
<thead>
<tr>
<th>Goals</th>
<th>Preliminary Aerodynamic Design Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate</td>
<td>0.709 m³/s (150.3 cfm)</td>
</tr>
<tr>
<td>Total pressure rise</td>
<td>925 Pa (3.716 inches of water)</td>
</tr>
<tr>
<td>Pressure</td>
<td>101 kPa (14.7 psia)</td>
</tr>
<tr>
<td>Temperature</td>
<td>21.1°C (70°F)</td>
</tr>
<tr>
<td>Maximum diameter</td>
<td>8.89 cm (3.50 in) flowpath diameter</td>
</tr>
<tr>
<td>Rotor hub diameter</td>
<td>6.60 cm (2.60 in)</td>
</tr>
<tr>
<td>Maximum axial length</td>
<td>0.223 m (9.0 in)</td>
</tr>
<tr>
<td>Rotor tip clearance gap</td>
<td>0.23 mm (0.009 in)</td>
</tr>
<tr>
<td>Rotor speed</td>
<td>12,000 rpm to 13,600 rpm</td>
</tr>
<tr>
<td>Number of blades</td>
<td>9</td>
</tr>
<tr>
<td>Number of vanes</td>
<td>13</td>
</tr>
<tr>
<td>Rotor exit Mach number</td>
<td>0.10 to 0.11 with approximately 35° swirl</td>
</tr>
<tr>
<td>Blade row spacing</td>
<td>3.45 cm (1.37 in) approximately 2 rotor axial chord lengths</td>
</tr>
</tbody>
</table>
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Acoustic design method

Step 1: Calculate the ‘cut-on’ modes for each blade passing frequency. ‘Cut-on’ modes are the circumferential duct modes that can propagate through the fan duct.

- I used code shared by Ed Envia and Dan Sutliff which was based on duct acoustic theory by Morse and Ingard. Others have used the “cutget” tool in Actran, commercial noise prediction software.
- Relevant input to this calculation included rotor hub radius, duct radius, circumferential and radial mode number. Output was the eigenvalues for each duct mode.
- The cut-off frequency and the cut-off ratio can then be determined.
- With this information, the set of cut-on modes can be identified for each blade passing harmonic frequency.

<table>
<thead>
<tr>
<th>Preliminary Acoustic Design Method for the Spacecraft Cabin Vent Fan</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 BPF Cut-on circumferential modes</td>
</tr>
<tr>
<td>2 BPF Cut-on circumferential modes</td>
</tr>
<tr>
<td>3 BPF Cut-on circumferential modes</td>
</tr>
</tbody>
</table>
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Acoustic design method

Step 2: Calculate which circumferential duct modes are generated by rotor-stator interaction.

- I used the equation from Tyler and Sofrin's article in the Journal of Aircraft, "Axial Flow Compressor Noise Studies," to compute values of m for different values of V:
  \[ m = nB + kV \]

- I created a plot of m versus V (keeping B constant), for each blade harmonic, \( n = 1, 2, 3 \). The shaded area represents the cut-on modes found from Step 1.

  \( m = \) the circumferential mode order  
  \( n = \) the blade harmonic index  
  \( B = \) the number of rotor blades  
  \( k = \) the stator harmonic index  
  \( V = \) the number of stator vanes

Example of a plot to find which circum. modes are cut-on for different number of stator vanes. The 1 BPF tone is cut-on for \( m = -1, 0, 1 \).
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Acoustic design method

• The plot on the left includes results for only \( k = -1 \) and \( k = -11 \).
• The plot on the right includes results for all values of \( k = -1 \) through \( k = -11 \).
• We know from Step 1 that for 1 BPF:
  \[
  -1 \leq m_{\text{cuton}} \leq 1 \\
  m_{\text{cutoff}} \leq -2 \\
  m_{\text{cutoff}} \geq 2
  \]
• The y axis bounds in the plot on the right were set to \( m = \pm 2 \), corresponding to the \( m_{\text{cutoff}} \) values.

The cut-on mode range is shaded gray.
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Acoustic design method

Step 3: Count the number of cut-on modes for each value of V, the number of stator vanes. Vane counts with no cut-on modes may minimize fan tone noise.

- The plot on the left shows the number of cut-on circumferential modes for each value of V, generated by examining the plot on the right.

- This is the result for the 1 BPF tone for the spacecraft cabin vent fan. Similar plots were generated for 2, 3 and 4 BPF.

- There are vane counts with no cut-on modes.

The 1 BPF tone of the spacecraft cabin vent fan is predicted to be cut-off for a stator with 6, 7, and 11+ vanes.

The cut-on mode range is shaded gray.
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Acoustic design method

• Another way of representing this same information is to construct “\( \mathcal{V} \)” graphs for each vane-count, which represents the cutoff frequency for each mode.

• These are plots of frequency vs. circumferential mode number.

• Modes inside the “\( \mathcal{V} \)” are cut-on.

• Modes outside the “\( \mathcal{V} \)” are cut off.

Preliminary acoustic design with of the spacecraft cabin vent fan with 9 rotor blades and 13 stator vanes. BPF 3 and 4 are cut-on.

Preliminary acoustic design with of the spacecraft cabin vent fan with 9 rotor blades and 11 stator vanes. BPF 4 is cut-on.
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Comparison to other NASA fans

Modes inside the “V” are cut-on

Modes outside the “V” are cut off.

<table>
<thead>
<tr>
<th>Spacecraft Cabin Vent Fan</th>
<th>Advanced Noise Control Fan</th>
<th>Advanced Ducted Propulsor</th>
<th>Source Diagnostic Test Fan</th>
</tr>
</thead>
<tbody>
<tr>
<td>9 Rotor blades</td>
<td>16 Rotor blades</td>
<td>18 Rotor blades</td>
<td>22 Rotor blades</td>
</tr>
<tr>
<td>11 Stator vanes</td>
<td>13 Stator vanes</td>
<td>45 exit guide vanes</td>
<td>54 exit guide vanes</td>
</tr>
<tr>
<td>12,000 rpm (design point)</td>
<td>1800 rpm (design point)</td>
<td>5425 rpm (at approach)</td>
<td>7808 rpm (at approach)</td>
</tr>
<tr>
<td>Rotor hub radius = 1.30 in</td>
<td>Rotor hub radius = 7.38 in</td>
<td>Rotor hub radius = 5.35 in</td>
<td>Rotor hub radius = 3.30 in</td>
</tr>
<tr>
<td>Duct radius = 1.75 in</td>
<td>Duct radius = 24.00 in</td>
<td>Duct radius = 11.00 in</td>
<td>Duct radius = 10.99 in</td>
</tr>
</tbody>
</table>

Photo credits: NASA
A Study of Preliminary Design Methods for Low Noise Fans
Comparison to other NASA fans

A quiet fan design “Rule of Thumb” exists.

The analysis in this paper identifies a few additional low-noise blade-vane count candidates for some fans.

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<td>16 Rotor blades</td>
<td>18 Rotor blades</td>
<td>22 Rotor blades</td>
</tr>
<tr>
<td>11 Stator vanes</td>
<td>13, 14, 15, 26, 28, 30 vanes</td>
<td>45 exit guide vanes</td>
<td>54 exit guide vanes</td>
</tr>
</tbody>
</table>

**Rule of thumb for fans that minimize rotor stator tone noise?**

Number of stator vanes should be roughly equal to twice number of rotor blades plus a few extra.

\[ V = 2 * B + (a \ few \ extra) \]

- \( V = 2*B + 3 = 21 \) (but also 11)
  would cutoff 1, 2 and 3 BPF

- \( V = 2*B + 2 = 34 \)
  would cutoff 1 and 3 BPF

- \( V = 2*B + 6 = 51 \)
  would cutoff 1 and 2 BPF

- \( V = 2*B + 0 = 44 \)
  would cutoff 1 BPF

1 BPF cutoff \( V = 6, 7, 11^+ \)

2 BPF cutoff \( V = 7, 11, 12, 13, 14, 15, 21^+ \)

3 BPF cutoff \( V = 11, 21, 22, 23, 31^+ \)

Photo credits: NASA
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Recommendations

• Sofrin and Mathews suggested that rough estimates of the relative modal sound power for the circumferential modes of the first BPF would be useful in quiet fan design.

• While this may be the case for the fan that they studied, comparisons from this theory with measurements of NASA's ANCF were not in agreement.

**Conclusion**

- A fast preliminary acoustic design method was developed that can be used to try to minimize tone noise generated by ducted axial fans.

- The aerodynamic design of a fan as a starting point, so that the number of rotor blades, rotor speed, duct axial Mach number, and ratio of the rotor hub radius to the duct radius is fixed while the number of stator vanes is varied in this analysis.

- Duct duct acoustic theory is combined with rotor-stator interaction theory to predict the set of cut-on circumferential modes that are expected to be generated and propagate through the fan duct.

### Input to the Preliminary Acoustic Design Method for the Spacecraft Cabin Vent Fan

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of rotor blades</td>
<td>9</td>
</tr>
<tr>
<td>Rotor hub radius</td>
<td>1.3 in</td>
</tr>
<tr>
<td>Duct radius</td>
<td>1.75 in</td>
</tr>
<tr>
<td>Rotor speed</td>
<td>12,000 rpm</td>
</tr>
<tr>
<td>Duct Axial Mach No.</td>
<td>0.11</td>
</tr>
<tr>
<td>Number of stator vanes</td>
<td>1 to Vmax</td>
</tr>
</tbody>
</table>
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Conclusion

- By calculating and counting the number of cut-on circumferential modes for each vane-count, a set of low-noise vane-counts for a given rotor and duct design can be identified for each blade passing frequency.

- This method was used to determine the set of low-noise vane-counts for the spacecraft cabin vent fan and three other NASA fans.

- This technique can be used to include acoustic design criteria early in the design of an axial fan and provide valuable information to guide the final design of low noise fans.

| Output from the Preliminary Acoustic Design Method for the Spacecraft Cabin Vent Fan |
|--------------------------------------------------|----------------------------------|
| 1 BPF Cut-on circum. modes                       | $-1 \leq m_{cuton} \leq 1$       |
| 2 BPF Cut-on circum. modes                       | $-2 \leq m_{cuton} \leq 2$       |
| 3 BPF Cut-on circum. modes                       | $-3 \leq m_{cuton} \leq 3$       |
| Vane counts that cut off the 1 BPF tone           | 6, 7, or 11+ vanes               |
| Vane counts that cut off the 2 BPF tone           | 7, 11, 12, 13, 14, 15, or 21+ vanes |
| Vane counts that cut off the 3 BPF tone           | 11, 21, 22, 23, or 31+ vanes     |
| Vane counts that cut off the first 3 BPF tones    | 11, 21, 22, 23, or 31+ vanes     |
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Thank you!

Questions?