A First Look at Electric Motor Noise For Future Propulsion Systems

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Introduction and Objectives

• Alternative propulsion systems being considered for commercial aircraft that replace or augment the core gas turbine engine with electric motors to drive the propulsor.

• The noise levels from these motors is unknown and will depend on many factors such as motor installation, structural vibrations and the electronics associated with driving the motor.

• There are existing motor noise prediction methods that can be applied to high power density motors with the understanding that extrapolation is necessary and needs to be validated.

• This work uses existing scaling laws, a simple vibration analysis and data to estimate noise levels from large electric motors.

• Comparisons are made with other noise sources from aircraft to determine the impact of electric propulsion on overall noise levels.
Electric Propulsion Concepts

- Boeing SUGAR-Volt
- NASA STARC-ABL
- NASA N3-X

Progression of Adoption of Electric Technologies

<table>
<thead>
<tr>
<th>Power Level for Electrical Propulsion System</th>
<th>Today</th>
<th>10 Yr</th>
<th>20 Yr</th>
<th>30 Yr</th>
<th>40 Yr</th>
</tr>
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<tbody>
<tr>
<td>kW class</td>
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<tr>
<td>All electric and hybrid electric GA</td>
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<td>1-2 MW class</td>
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<td>Turboelectric 100 PAX regional</td>
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<tr>
<td>Turboelectric distributed propulsion 150 PAX</td>
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<tr>
<td>2-5 MW class</td>
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<tr>
<td>Turboelectric 737-150 PAX</td>
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<td>Hybrid electric 737-150 PAX</td>
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<td>5-10 MW</td>
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<td>Hybrid electric 737-150 PAX</td>
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<tr>
<td>Turboelectric and hybrid electric distributed propulsion 300 PAX</td>
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<tr>
<td>&gt; 10 MW</td>
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</table>
Electric Propulsion Systems

Hybrid-Electric

Turbo-Electric

Ring Motor Driving Low Spool On CFM56 engine

Courtesy Dr. Codrin-Gruie Cantemir, Ohio State University
Motor Noise – Empirical Predictions

For a conventional totally enclosed fan-cooled (TEFC) motors with powers under 750 kW, the A-weighted sound power level is estimated as:

\[ PWL = 27 + 10\log(kW) + 15\log(rpm) + 10\log(\text{conformal surface area}) \]

Second term: rated value of electric power
Third term: shaft speed in rpm
Fourth term: surface area in square-meters for computing sound power.

- The correlation includes a table to predict the un-weighted octave band sound power levels.
- High uncertainty: newer motors can be 5 to 10 dB quieter, cooling fans can increase the noise by 5 to 8 dB.

References

Motor Noise (Tone) – Vibration Analysis

**Rotor Deflection**

\[
d = \frac{W l^3}{2\pi^3 E I} = \frac{C_P B^2 D D_R^3}{P^4 h^3}
\]

where
- \( W \) = load from magnetic force
- \( l \) = circumferential distance between nodes
- \( E \) = modulus of elasticity
- \( I \) = moment of inertia
- \( C_P \) = coefficient that depends on \( P \)
- \( B \) = peak magnetic flux density
- \( P \) = number of poles

**Casing Vibration**

\[
r(t) = a + d\sin\omega t
\]

where \( a \) = radius of motor case

**Sound Intensity**

\[
L_I = 10 \log \frac{I}{I_{ref}} = 10 \log \left( \frac{(d\omega)^2}{2} \right) + 10 \log \left( \frac{\rho_0 c_0}{10^{-12}} \right) + 10 \log \left[ Re \left( \frac{iH_o^{(2)}(kr)}{H_1^{(2)}(kr)} \right) \frac{(d\omega)^2}{2} \left( \frac{H_1^{(2)}(kr)}{H_1^{(2)}(ka)} \right)^2 \right]
\]
NASA Sponsored Research on High Power Motors

The Ohio State University
13.8 MW Motor for 737-size aircraft
~50-inch outer diameter
5000 RPM

The University of Illinois
1 MW Motor for regional jet-size aircraft
~13-inch diameter
18,000 RPM
Fan Noise Estimates

Model fan test conducted in NASA Glenn 9’ x 15’ Low-Speed Wind Tunnel:
- P&W “Advanced Ducted Propulsor” (ADP)
- 22” diameter fan
- 840 fps fan tip speed
- FPR = 1.28 at takeoff
- With and without acoustic treatment
- Acoustic results reported by Dittmar, Elliott & Bock in 1999.

Acoustic data scaled to 31.5” for regional jet and 88” for 737-size aircraft. Representative of UHB engine for comparisons of fan noise with motor noise.
Predicted Sound Power for 1 MW Motor

Motor Tone, Isolated
Motor Tone, Installed
Motor, Empirical Correlation
Fan, Approach
Fan, Flyover
Fan, Takeoff

Treated Fan Duct

<table>
<thead>
<tr>
<th>Octave Band Frequency, Hz</th>
<th>31.5</th>
<th>63</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>8000</th>
<th>SUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound Power, dB</td>
<td></td>
<td></td>
<td></td>
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</table>
Predicted Sound Power for 13.8 MW Motor

Motor Tone, Isolated  
Fan, Approach  
Motor Tone, Installed  
Fan, Flyover  
Motor, Empirical Correlation  
Fan, Takeoff  

Treated Fan Duct

Sound Power, dB

Octave Band Frequency

31.5  63  125  250  500  1000  2000  4000  8000  SUM
Conclusions (1 of 2)

- Empirical correlations extrapolated to larger motors predict the sound power levels to be lower than the fan noise for a commercial subsonic aircraft:
  - 8 to 20 dB for 1 MW motor powering a regional jet-size aircraft.
  - 17 to 29 dB for 13.8 MW motor powering a 737-size aircraft.
  - Uncertainty is high.

- Motor tone predictions using a vibration analysis and input from design parameters for high power density motors show that the noise can be significantly higher or lower than the empirical correlations and exceeds the stated uncertainty.
  - 21 dB lower for the 1 MW motor (uncertainty is 5 to 10 dB).
  - 9 dB higher for the 13.8 MW motor (uncertainty is 5 to 8 dB).
  - The tone predictions are sensitive to the rotor deflection and casing stiffness.
Conclusions (2 of 2)

- On an octave band basis using the empirical correlations, only the noise levels for the 1 MW motor in the 250, 500, 1000 and 2000 Hz bands were close enough to the fan noise at approach conditions to impact the total engine noise.

- But the more sophisticated vibration analysis shows that it is likely that the 1 MW motor noise levels will be lower by as much as 21 dB and therefore would not contribute to the overall engine noise.

- Even with the lower sound power levels predicted for the motor, it is possible that a portion of a flyover during approach will include motor noise depending on the motor installation.

- Motors mounted within the engine core will likely have enough insertion loss due to the installation (~20 dB) that the motor noise will be insignificant.
Recommendations

• Further work is needed to verify that the empirical correlations and motor tone predictions are valid for larger motors.
• Experimental work is needed once prototype motors are available to confirm casing vibration levels and noise.

Acknowledgments

This work was supported by the Hybrid Gas-Electric Propulsion sub-project of NASA’s Advanced Air Transportation Technologies (AATT) project in the Advanced Air Vehicles Program. Thanks to Dr. Codrin-Gruie Cantemir, of the Ohio State University for providing valuable information about high power density motors.
Backup
## Motor Design Parameters and Noise Predictions

<table>
<thead>
<tr>
<th></th>
<th>737-Size</th>
<th>Regional Jet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13.8 MW, OSU Motor</td>
<td>1 MW, U. of Illinois Motor</td>
</tr>
<tr>
<td>Peak Flux Density, B (weber/in^2)</td>
<td>5.00 E-04</td>
<td>5.00 E-04</td>
</tr>
<tr>
<td>Gap Diam., D (in)</td>
<td>47.32</td>
<td>11.72</td>
</tr>
<tr>
<td>Mean Rotor Diam., D_R (in)</td>
<td>49.70</td>
<td>12.53</td>
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<tr>
<td>Outer Rotor Diam., D_O (in)</td>
<td>50.47</td>
<td>13.125</td>
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<tr>
<td>Radial Depth of Rotor, h (in)</td>
<td>0.768</td>
<td>0.591</td>
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<tr>
<td>Deflection, d (in)</td>
<td>7.21 E-04</td>
<td>1.24 E-05</td>
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<tr>
<td>Motor Length, L (in)</td>
<td>7.48</td>
<td>8.40</td>
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<tr>
<td>Number of Pole Pairs</td>
<td>12</td>
<td>10</td>
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<tr>
<td>RPM</td>
<td>5000</td>
<td>18000</td>
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<tr>
<td>Frequency, Hz</td>
<td>1000</td>
<td>3000</td>
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<tr>
<td>Sound Power Prediction (dB)</td>
<td>117.2</td>
<td>86.1</td>
</tr>
</tbody>
</table>
Motor Noise (Tone) – Vibration Analysis

Rotor Deflection

\[
d = \frac{W l^3}{2\pi^3 EI} = \frac{C_P B^2 D D_R^3}{P^4 h^3}
\]

where \( W \) = load from magnetic force
\( l \) = circumferential distance between nodes
\( E \) = modules of elasticity
\( I \) = moment of inertia
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\( B \) = peak magnetic flux density
\( P \) = number of poles

Casing Vibration

\[
r(t) = a + d \sin \omega t
\]

where \( a \) = radius of motor case

Motor with Outer Rotor
Model Motor as a Cylinder Ignoring End Caps

Azimuthally symmetric oscillating cylinder with radial surface velocity:

\[ u_a(t) = u_o \cos \omega t = Re\{u_o e^{i\omega t}\} \]

Velocity potential in the acoustic field:

\[ \varphi(r, t) = A H_0^{(2)}(kr)e^{i\omega t} \]

Corresponding radial velocity:

\[ u(r, t) = \frac{\partial \varphi}{\partial r} = Ak H_0^{(2)'}(kr)e^{i\omega t} = -Ak H_1^{(2)}(kr)e^{i\omega t} \]

\[ k = \frac{\omega}{c_o} \] is the wavenumber

\[ H_0^{(2)} \] and \[ H_1^{(2)} \] are Hankel functions of the second kind

\[ c_o \] is the speed of sound
Assume 100% Acoustic Radiation Efficiency (worse case scenario)

Setting the acoustic velocity equal to that of a cylinder with \( r = a \):

\[
\begin{align*}
    u(r, t) &= \frac{u_o H_1^{(2)}(kr)}{H_1^{(2)}(ka)} e^{i\omega t} = U e^{i\omega t} \\
    p(r, t) &= -\partial \phi \over \partial t = \frac{i \rho_o c_o u_o H_0^{(2)}(kr)}{H_1^{(2)}(ka)} e^{i\omega t} = P e^{i\omega t}
\end{align*}
\]

The sound pressure level is given by:

\[
SPL = 10 \log \frac{P_{rms}^2}{P_{ref}^2}
\]

where \( P_{rms}^2 = \frac{1}{2} |P|^2 \)

|\( P | \) is the magnitude of the complex pressure amplitude

\( P_{ref}^2 \) is 20\( \mu \)Pa.
Motor Tone Noise

Using $|P| = \rho_0 c_0 u_0 \left|i \frac{H_o^{(2)}(kr)}{H_1^{(2)}(ka)}\right|$ and $u_o = d\omega$ gives:

$$SPL = 10 \log \left[\frac{(d\omega)^2}{2}\right] + 20 \log \left(\frac{\rho_0 c_0}{20 \times 10^{-6}}\right) + 10 \log \left[\left|i \frac{H_o^{(2)}(kr)}{H_1^{(2)}(ka)}\right|^2\right]$$

Sound intensity can be calculated from:

$$L_I = 10 \log \frac{I}{I_{ref}} = 10 \log \left[\frac{(d\omega)^2}{2}\right] + 10 \log \left(\frac{\rho_0 c_0}{10^{-12}}\right) + 10 \log \left[\text{Re} \left\{\frac{iH_o^{(2)}(kr)}{H_1^{(2)}(kr)}\right\} \frac{(d\omega)^2}{2} \left|\frac{H_1^{(2)}(kr)}{H_1^{(2)}(ka)}\right|^2\right]$$

Sound power is computed from the intensity integrated over the surface area of the cylinder.
Predicted Sound Power for 1 MW Motor

- Motor Tone, Isolated
- Motor Tone, Installed
- Motor, Empirical Correlation
- Fan, Approach
- Fan, Flyover
- Fan, Takeoff

Hardwall Fan Duct

Octave Band Frequency, Hz

Sound Power, dB

- 31.5
- 63
- 125
- 250
- 500
- 1000
- 2000
- 4000
- 8000
- SUM
Predicted Sound Power for 1 MW Motor

Motor Tone, Isolated
Motor Tone, Installed
Motor, Empirical Correlation
Fan, Approach
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Fan, Takeoff

Treated Fan Duct

Sound Power, dB vs. Octave Band Frequency, Hz

Motor Tone, Isolated
Motor Tone, Installed
Motor, Empirical Correlation
Fan, Approach
Fan, Flyover
Fan, Takeoff
Predicted Sound Power for 13.8 MW Motor

Hardwall Fan Duct

Motor Tone, Isolated
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Sound Power, dB

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