A First Look at Electric Motor Noise For Future Propulsion Systems

Dennis L. Huff
Brenda S. Henderson
Edmane Envia

Acoustics Technical Working Group Meeting
April 19-20, 2016

Introduction and Objectives

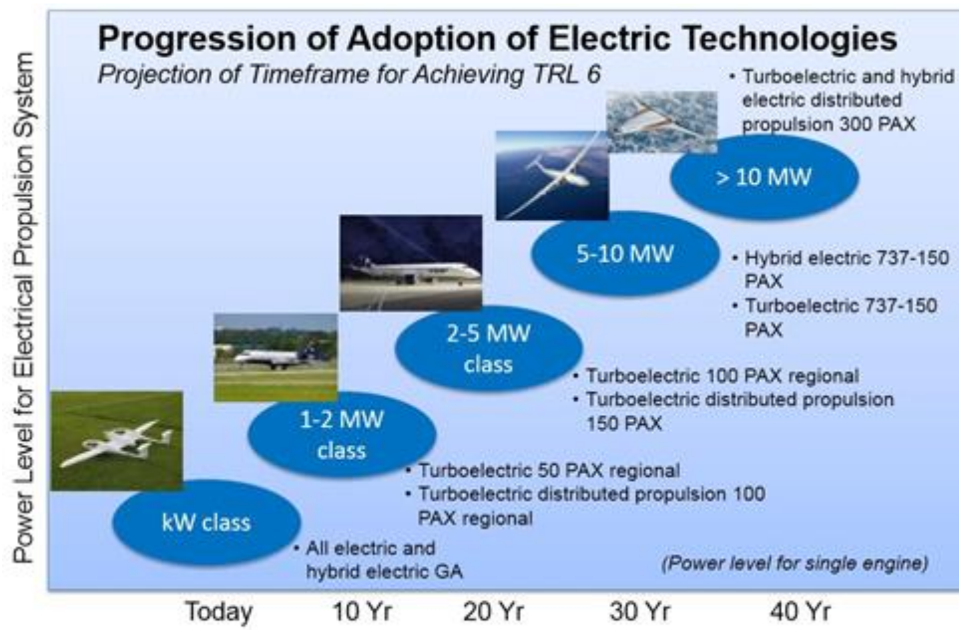
- **Alternative propulsion systems being considered for commercial aircraft that replace or augment the core gas turbine engine with electric motors to drive the propulsor.**
- **The noise levels from these motors is unknown and will depend on many factors such as motor installation, structural vibrations 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

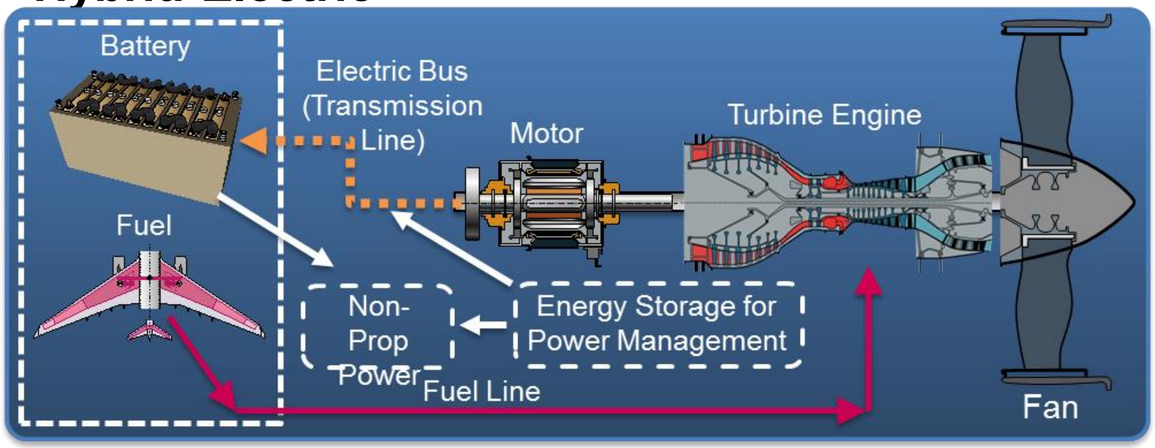
NASA STARC-ABL

NASA N3-X

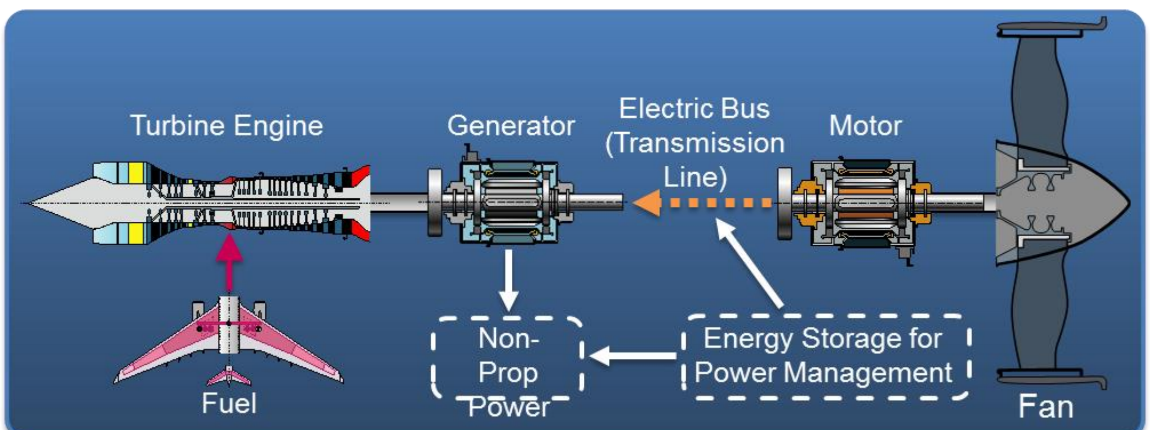


Electric Propulsion Systems

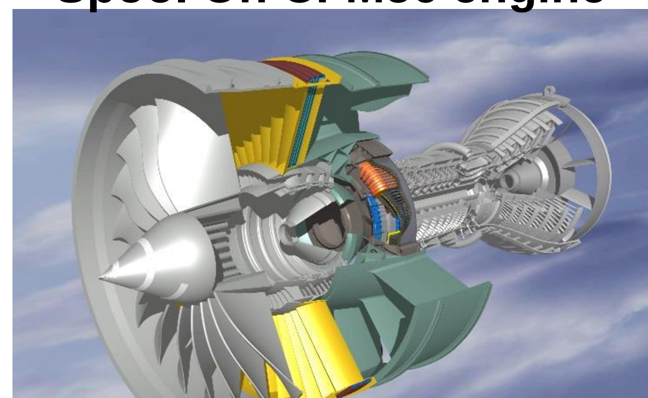
Hybrid-Electric



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:

$$PWL = 27 + 10\log(kW) + 15\log(rpm) + 10\log(conformal\ surface\ area)$$

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

Crocker, M.J., "Handbook of Noise and Vibration Control," John Wiley & Sons, Inc., Chapter 82, pp. 1001-1009, 2007.

***Noise and Vibration Control for Mechanical Equipment*, Manual TM5-805-4/AFM 88-37/NAVFAC DM-3.10, manual prepared by Bolt, Beranek, and Newman for Joint Department of the Army, Air Force, and Navy, Washington, DC, 1980, Chapter 7.**

Motor Noise (Tone) – Vibration Analysis

Rotor Deflection

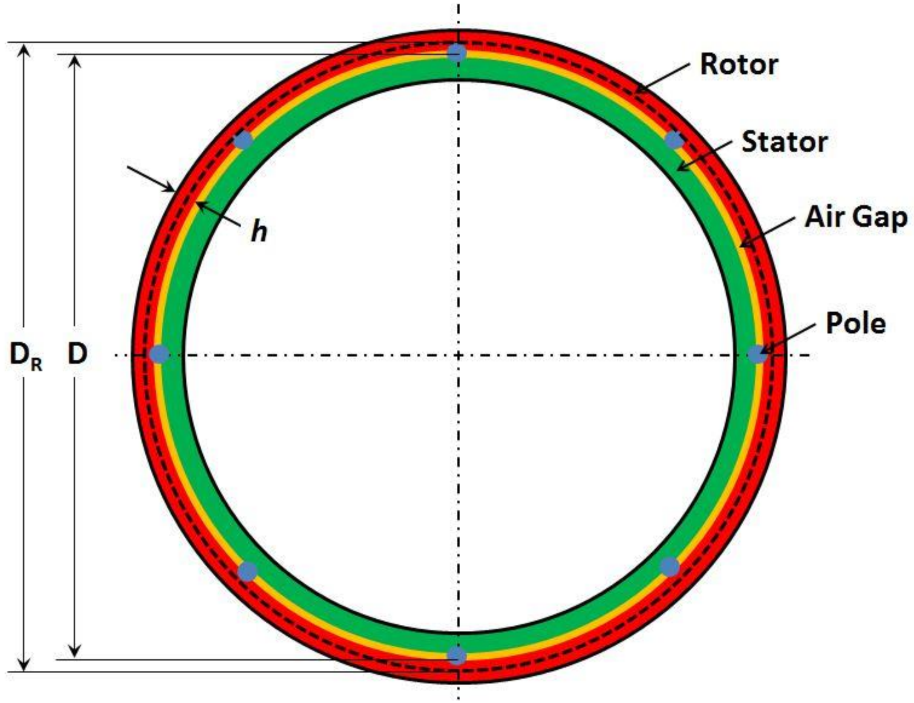
$$d = \frac{Wl^3}{2\pi^3 EI} = \frac{C_P B^2 D D_R^3}{P^4 h^3}$$

where W = load from magnetic force
l = circumferential distance between nodes
E = modulus of elasticity
I = moment of inertia
Cp = 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

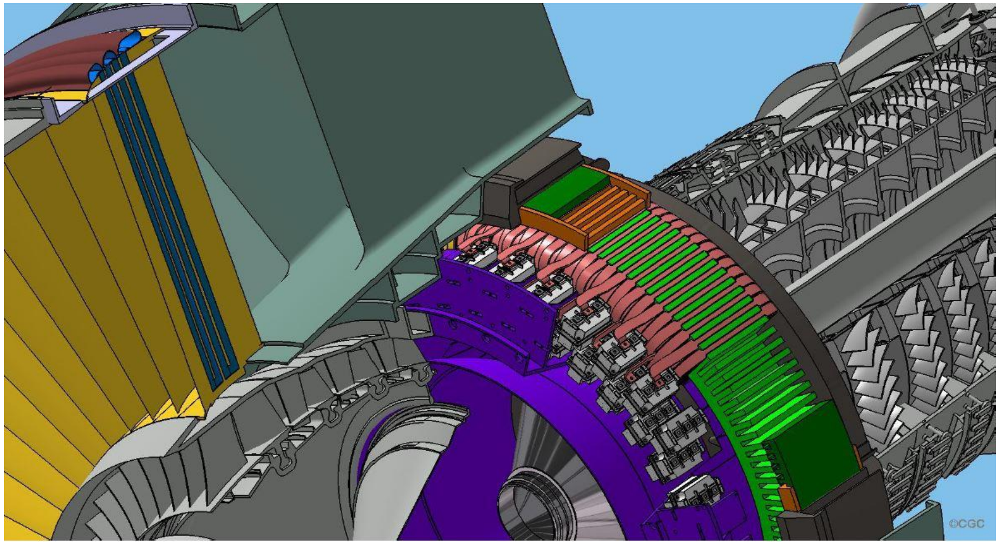


Motor with Outer Rotor

Sound Intensity

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

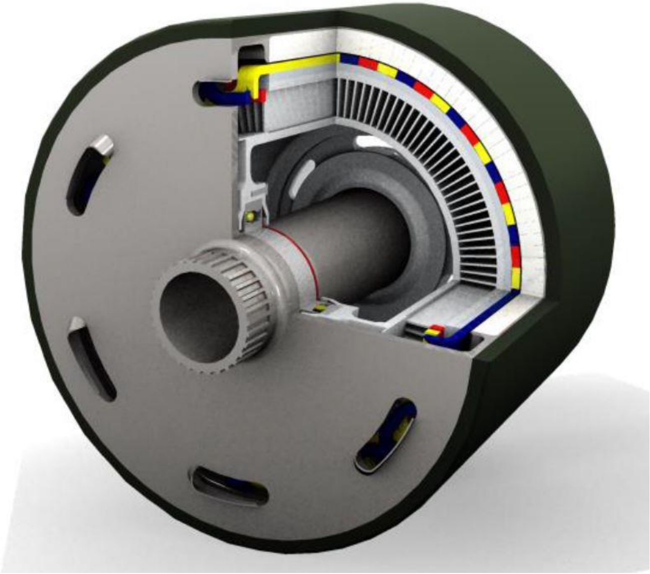
NASA Sponsored Research on High Power Motors



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

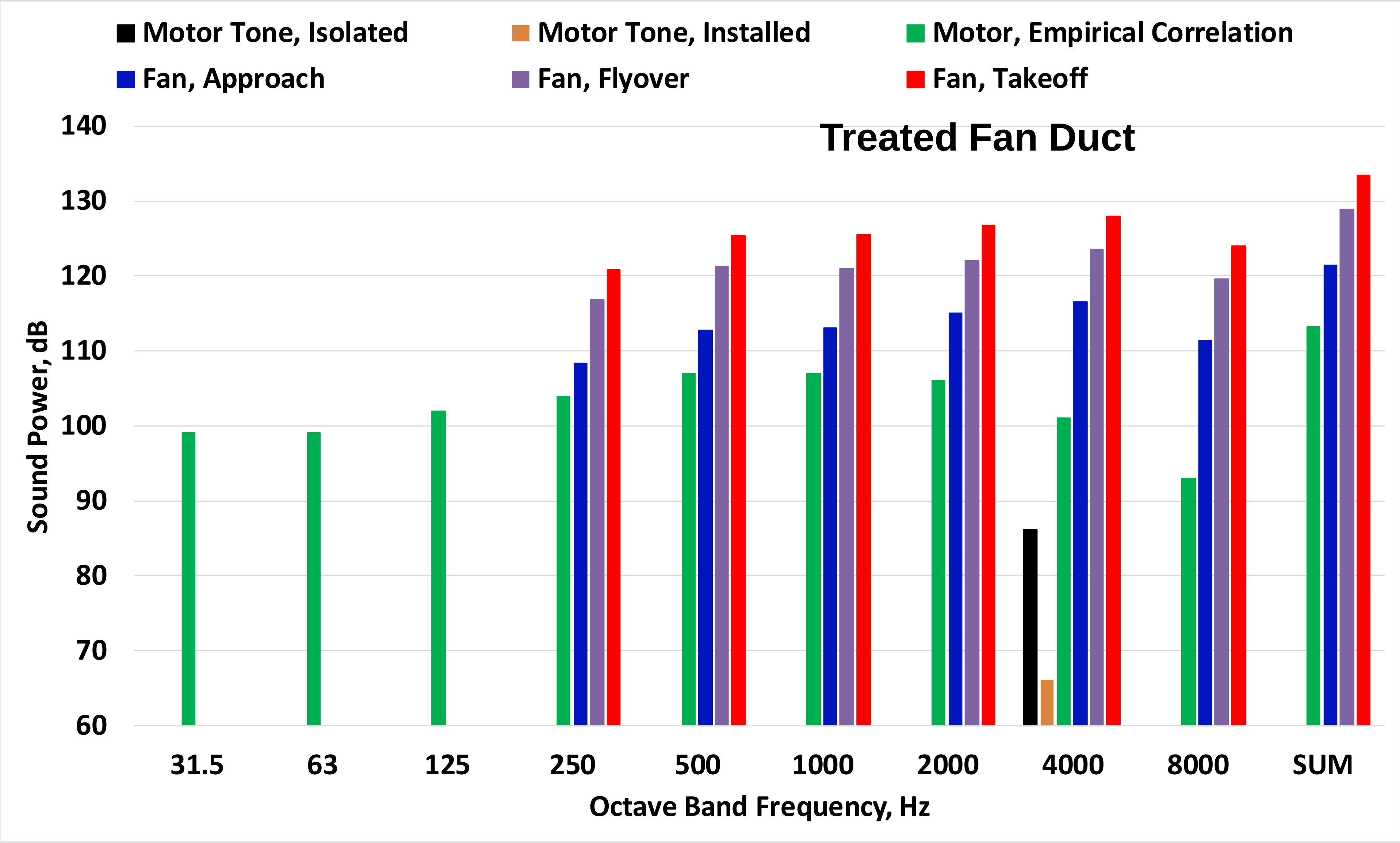
Fan Noise Estimates

Model fan test conducted in NASA Glenn 9' x 15' Low-Speed Wind Tunnel:

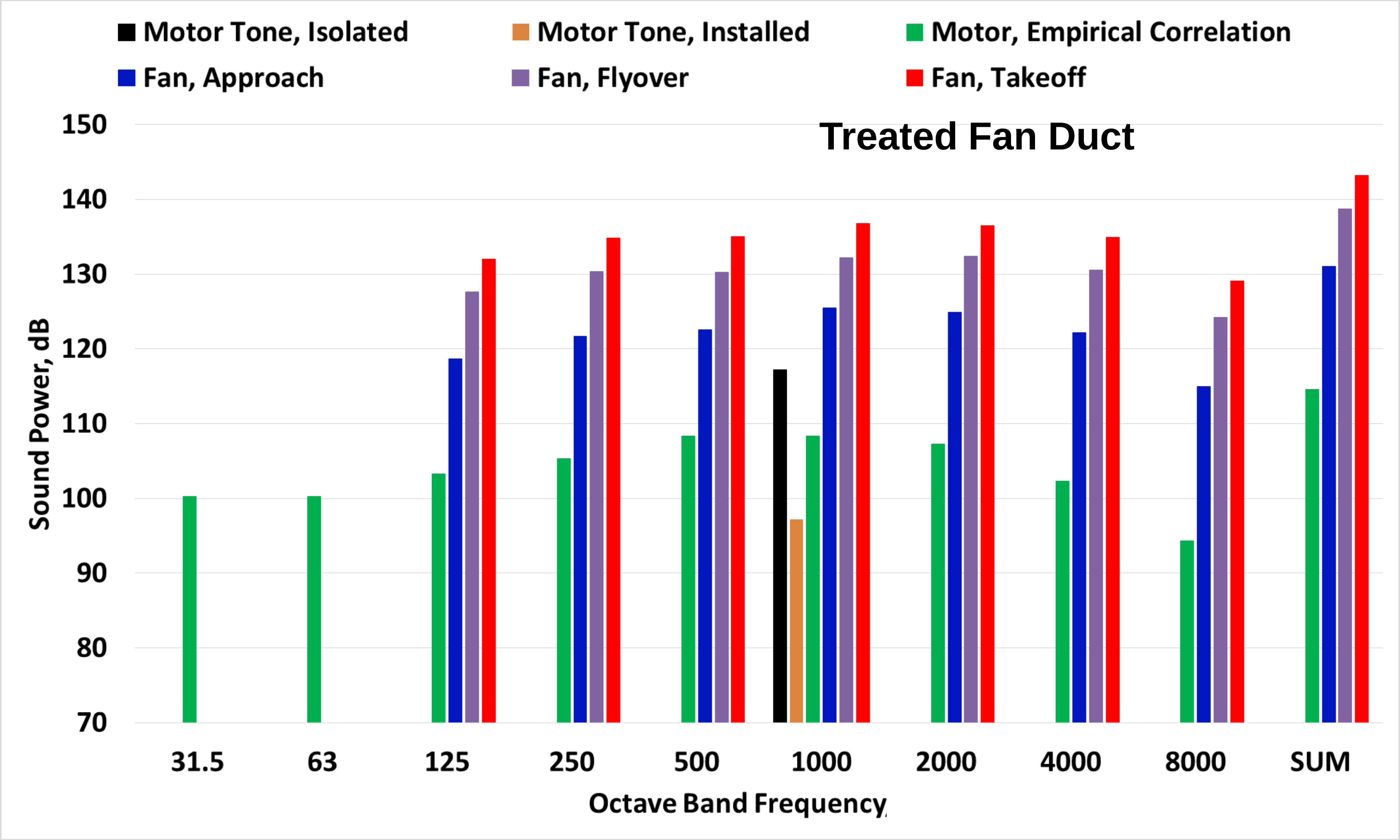
- **P&W "Advanced Ducted Propulsor" (ADP)**
- **22" diameter fan**
- **840 fps fan tip speed**
- **FPR = 1.28 at takeoff**
- **With and without acoustic treatment**
- **Acoustic results reported by Dittmar, Elliott & Bock in 1999.**

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



Predicted Sound Power for 13.8 MW Motor



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

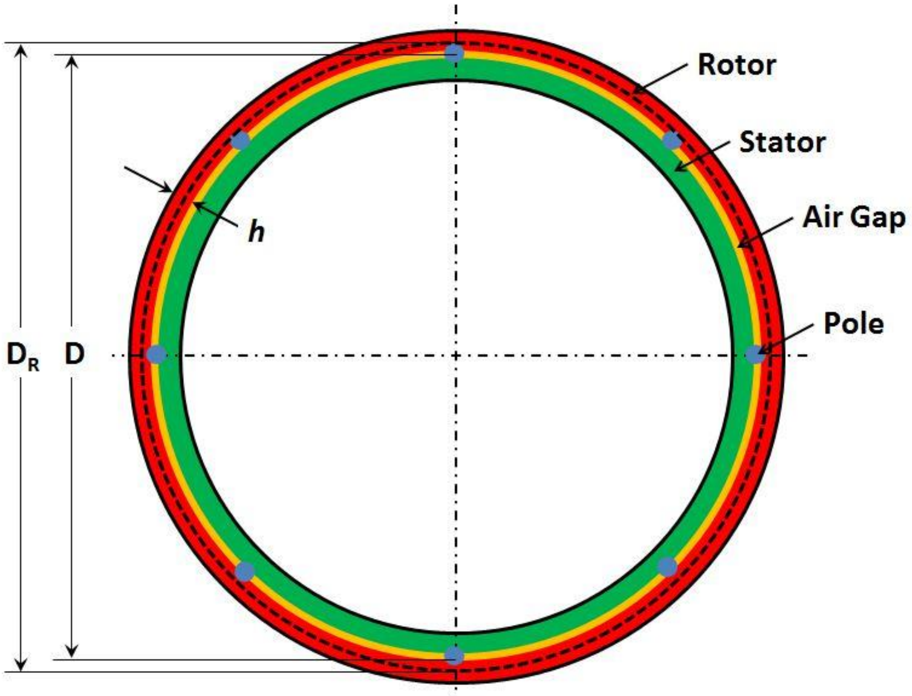
	737-Size	Regional Jet
	13.8 MW, OSU Motor	1 MW, U. of Illinois Motor
Peak Flux Density, B (weber/in^2)	5.00 E-04	5.00 E-04
Gap Diam., D (in)	47.32	11.72
Mean Rotor Diam., D_R (in)	49.70	12.53
Outer Rotor Diam., D_O (in)	50.47	13.125
Radial Depth of Rotor, *h* (in)	0.768	0.591
Deflection, d (in)	7.21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

Motor Noise (Tone) – Vibration Analysis

Rotor Deflection

$$d = \frac{Wl^3}{2\pi^3 EI} = \frac{C_P B^2 D D_R^3}{P^4 h^3}$$

where W = load from magnetic force
l = circumferential distance between nodes
E = modules of elasticity
I = moment of inertia
Cp = coefficient that depends on P
B = peak magnetic flux density
P = number of poles



Motor with Outer Rotor

Casing Vibration

$$r(t) = a + d sin\omega t$$

where a = radius of motor case

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:

$$\varphi(r,t) = AH_o^{(2)}(kr)e^{i\omega t}$$

Corresponding radial velocity:

$$u(r,t) = \frac{\partial \varphi}{\partial r} = AkH_0^{(2)'}(kr)e^{i\omega t} = -AkH_1^{(2)}(kr)e^{i\omega t}$$

k = ω/c_o is the wavenumber
$H_o^{(2)}$ 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*:

$$u(r,t) = \frac{u_o H_1^{(2)}(kr)}{H_1^{(2)}(ka)} e^{i\omega t} = U e^{i\omega t}$$

$$p(r,t) = -\frac{\partial \varphi}{\partial t} = \frac{i\rho_o c_o u_o H_o^{(2)}(kr)}{H_1^{(2)}(ka)} e^{i\omega t} = P e^{i\omega t}$$

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 20μPa.

Motor Tone Noise

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

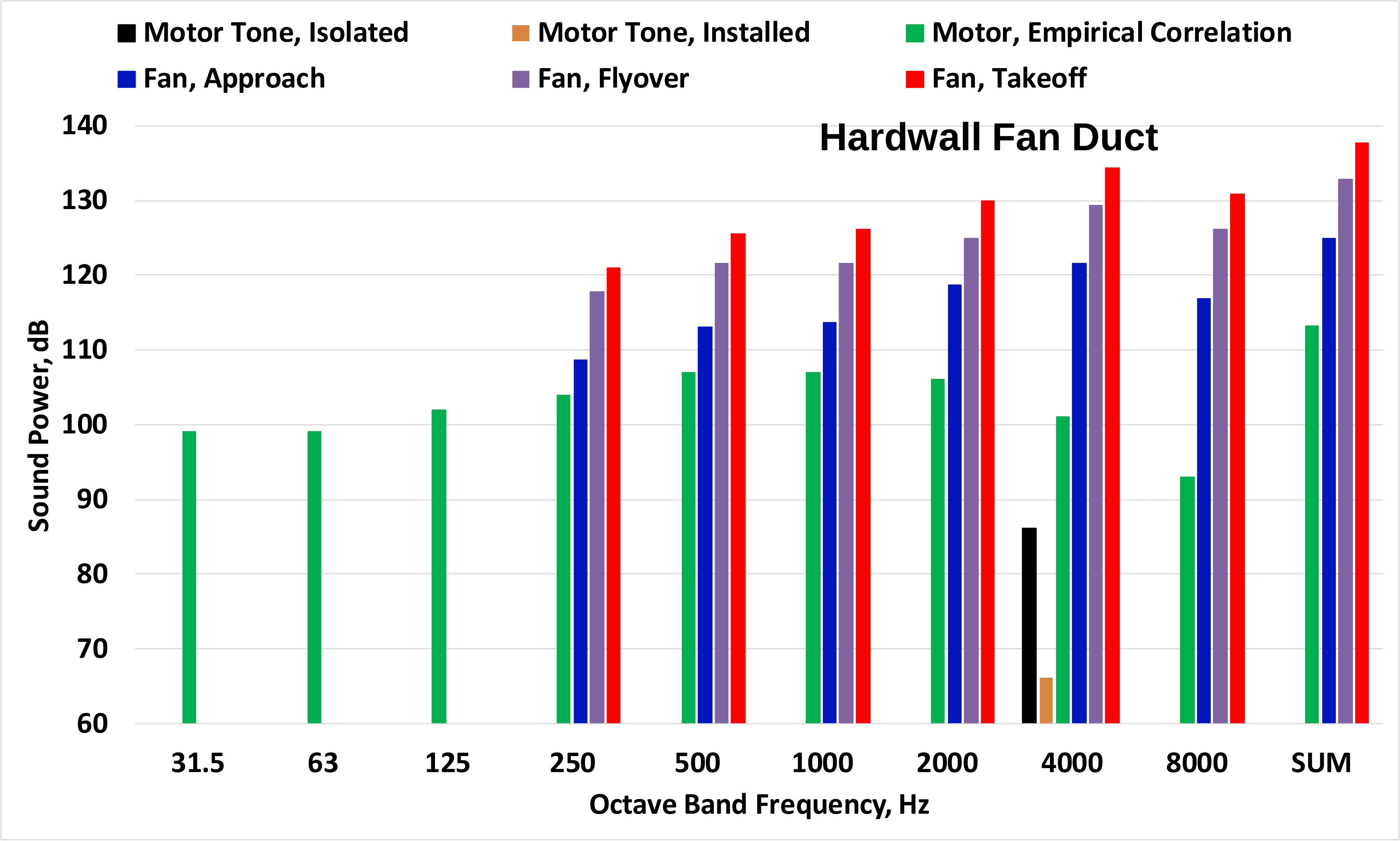
$$SPL = 10\log\left[\frac{(d\omega)^2}{2}\right] + 20\log\left(\frac{\rho_o c_o}{20x10^{-6}}\right) + 10\log\left[\left| i\frac{H_o^{(2)}(kr)}{H_1^{(2)}(ka)} \right|\right]^2$$

Sound intensity can be calculated from:

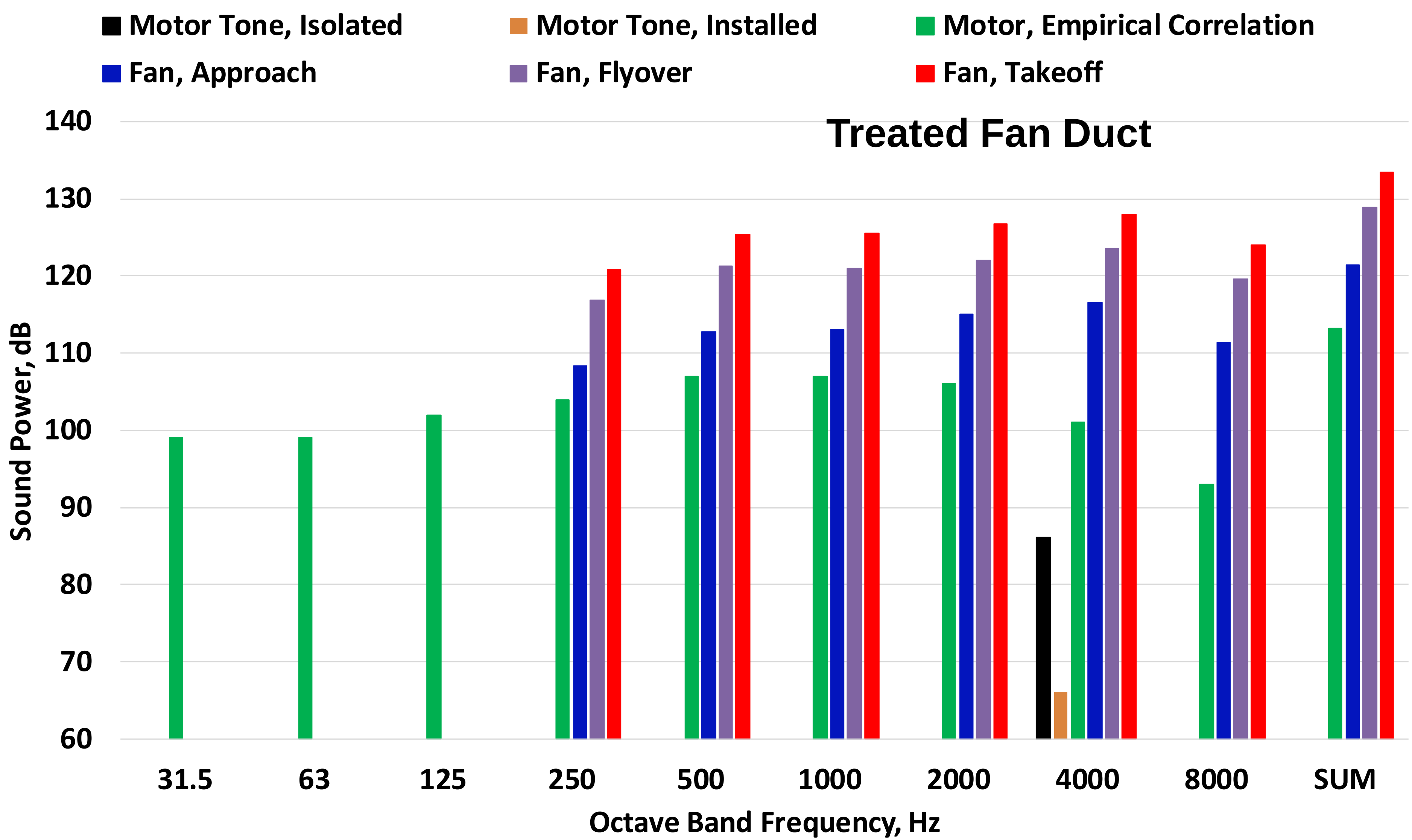
$$L_I = 10\log\frac{I}{I_{ref}} = 10\log\left[\frac{(d\omega)^2}{2}\right] + 10\log\left(\frac{\rho_o c_o}{10^{-12}}\right) + 10\log\left[Re\left\{\frac{iH_o^{(2)}(kr)}{H_1^{(2)}(kr)}\right\}\frac{(d\omega)^2}{2}\left|\frac{H_1^{(2)}(kr)}{H_1^{(2)}(ka)}\right|^2\right]$$

Sound power is computed from the intensity integrated over the surface area of the cylinder.

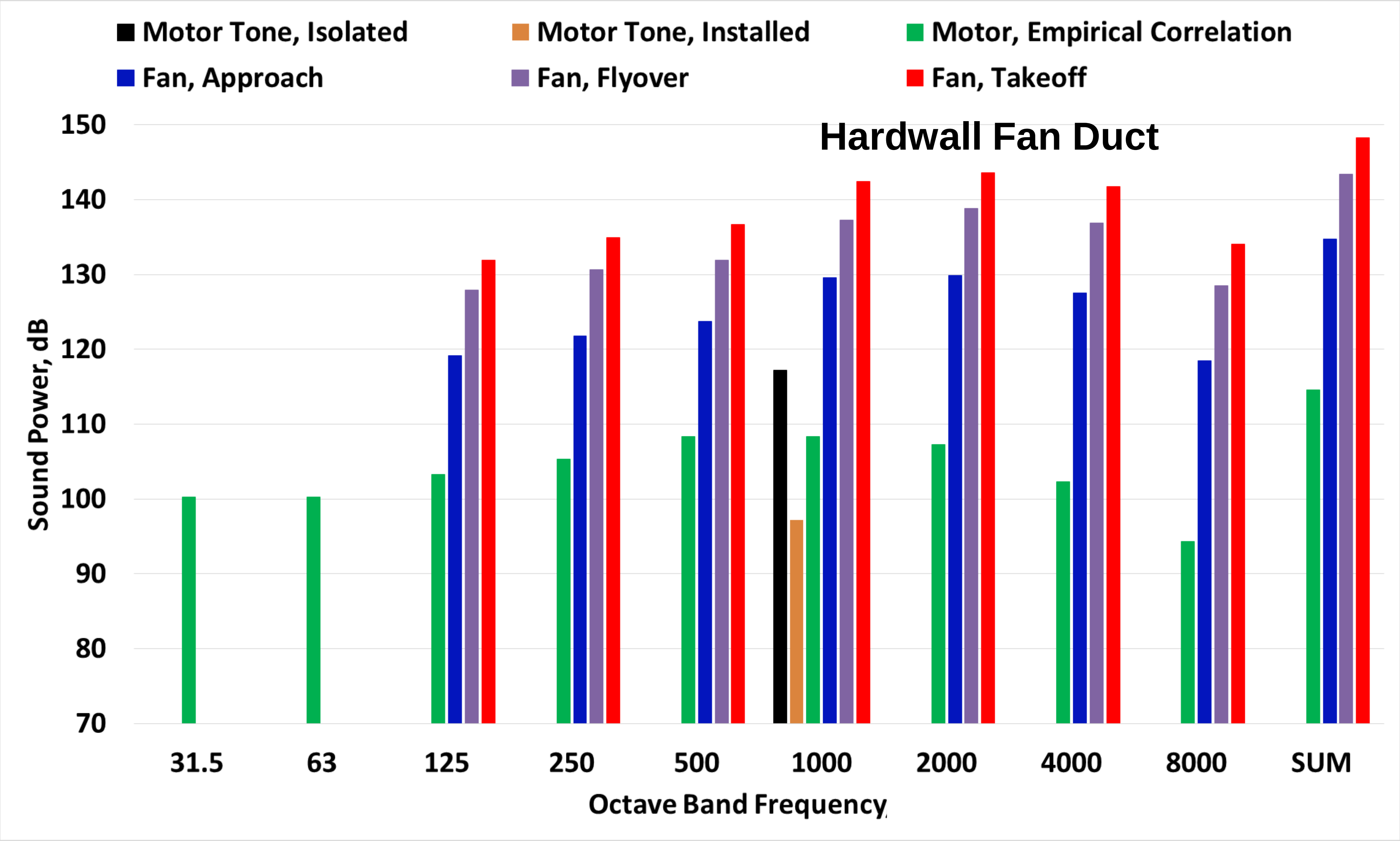
Predicted Sound Power for 1 MW Motor



Predicted Sound Power for 1 MW Motor



Predicted Sound Power for 13.8 MW Motor



Predicted Sound Power for 13.8 MW Motor