

OPEN ROTOR AEROACOUSTIC MODELING

ABSTRACT

Owing to their inherent fuel efficiency, there is renewed interest in developing open rotor propulsion systems that are both efficient and quiet. The major contributor to the overall noise of an open rotor system is the propulsor noise, which is produced as a result of the interaction of the airstream with the counter-rotating blades. As such, robust aeroacoustic prediction methods are an essential ingredient in any approach to designing low-noise open rotor systems. To that end, an effort has been underway at NASA to assess current open rotor noise prediction tools and develop new capabilities. Under this effort, high-fidelity aerodynamic simulations of a benchmark open rotor blade set were carried out and used to make noise predictions via existing NASA open rotor noise prediction codes. The results have been compared with the aerodynamic and acoustic data that were acquired for this benchmark open rotor blade set. The emphasis of this paper is on providing a summary of recent results from a NASA Glenn effort to validate an in-house open noise prediction code called LINPROP which is based on a high-blade-count asymptotic approximation to the Ffowcs-Williams Hawkins Equation. The results suggest that while predicting the absolute levels may be difficult, the noise trends are reasonably well predicted by this approach.

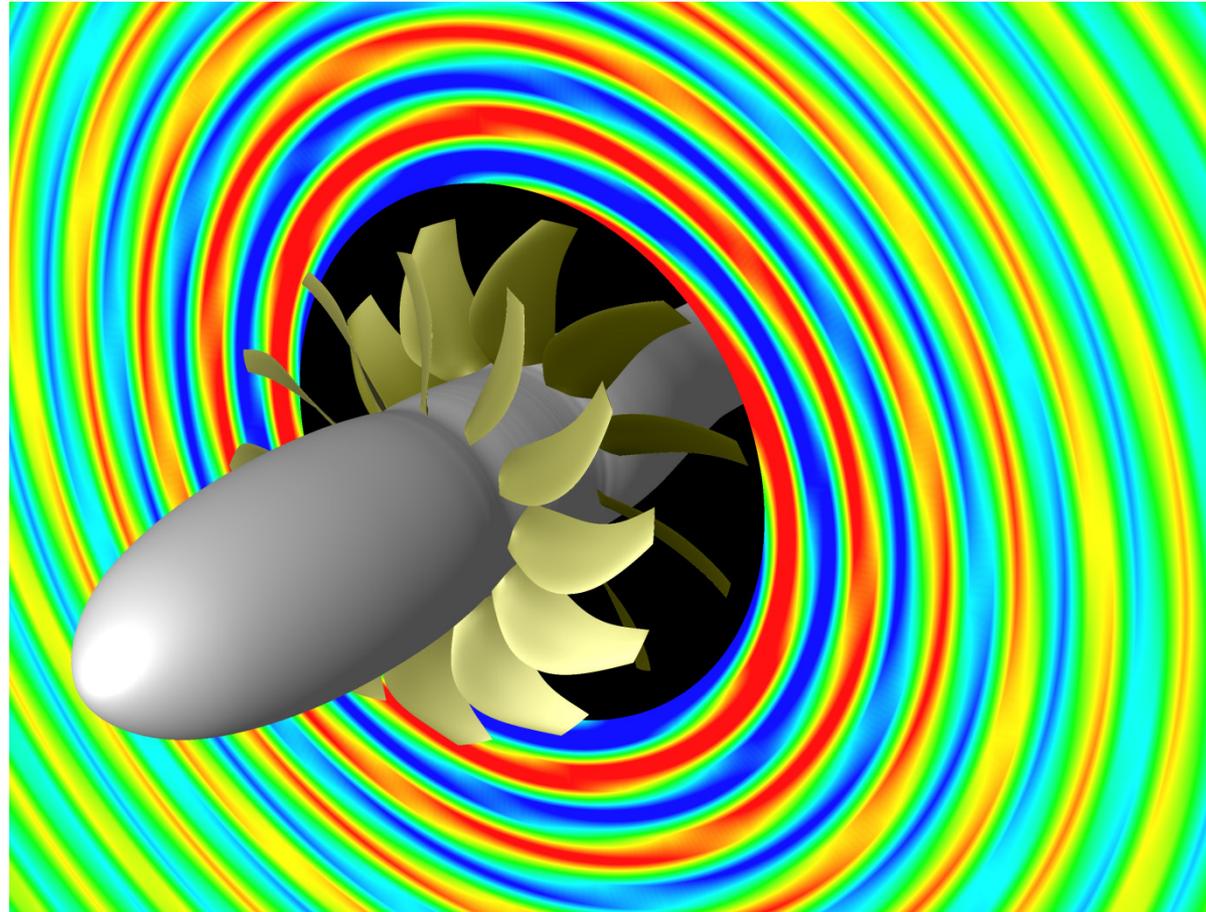


OPEN ROTOR AEROACOUSTIC MODELING

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CMFF'12
Budapest, Hungary
September 4-7, 2012

**This work has been sponsored by
the Subsonic Fixed Wing Project.**



Outline



- ❖ **Background**
- ❖ **Focus of This Work**
- ❖ **Technical Approach**
- ❖ **Representative Results**
- ❖ **Conclusions & Recommendations**

Why Open Rotors?



Open Rotor Model in
NASA Wind Tunnel (1985)



GE UDF Engine
on MD-80 Aircraft (1987)



PW/Allison 578-DX Engine
on MD-80 Aircraft (1989)

- ❖ Due to their high propulsive efficiency, open rotors have a significant fuel efficiency advantage over conventional turbofans.
- ❖ The feasibility of open rotor technology was demonstrated in the 1980's, but performance compromises were made to meet the noise regulations of the time.
- ❖ Changes to the design paradigm (e.g., blade count increase and tip speed reduction) and improved 3D aerodynamic design tools have made possible open rotor systems that can meet the current (more stringent) noise rules while maintaining their fuel burn advantage.

Current Open Rotor Research



U.S.



Europe



Rolls-Royce



SAFRAN
Snecma



AIRBUS
AN EADS COMPANY

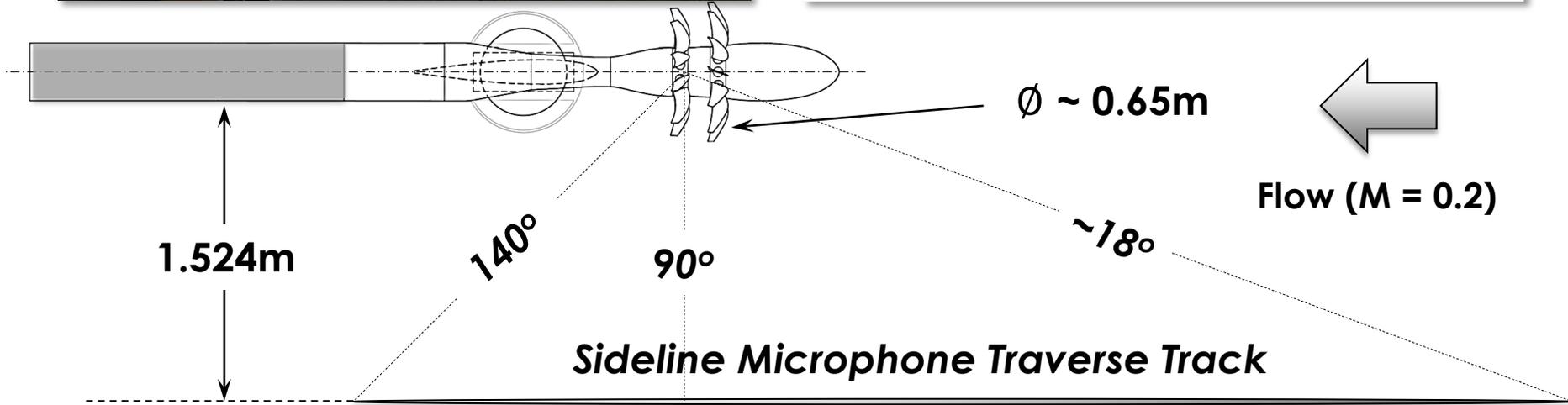
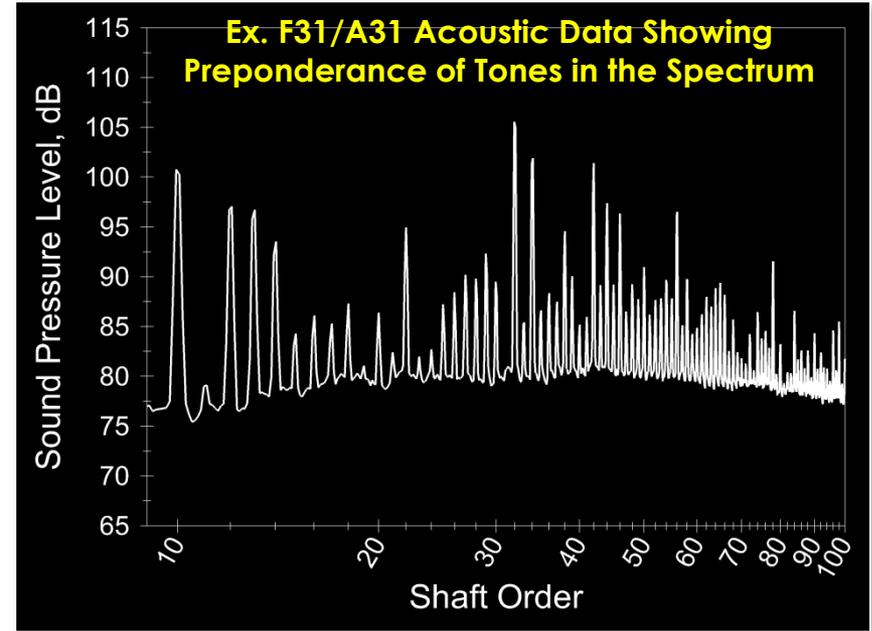
- ❖ There is renewed research in both U.S. and Europe, through government and industry partnerships, for developing open rotor propulsion systems that are competitive with modern turbofan engines.

NASA Research



- ❖ One of NASA's objectives has been to assess the current prediction capability for aero/acoustic performance of open rotors. The testbed for this activity is a baseline GE blade set called F31/A31 for which significant amount of aerodynamic and acoustic data was acquired in model scale tests.
- ❖ F31/A31 is a vintage 1990s design which has 12 blades on the front rotor and 10 blades on the aft rotor. It was tested in both low-speed regime (representative of approach and takeoff conditions) and high-speed regime (representative of climb and cruise conditions). Uninstalled as well as installed configurations were tested.
- ❖ The focus of this presentation is on a subset of the low-speed tests for which the tip speed was varied, but the blade setting angles and tunnel Mach number were held fixed.

F31/A31 Wind Tunnel Data



Plan View of F31/A31 Installation in NASA Wind Tunnel

Modeling Challenge



- ❖ The fundamental challenge of aeroacoustic prediction is the large difference between the aerodynamic and acoustic scales:

Aerodynamic $p / p_{amb.} \sim O(1)$

Acoustic $p / p_{amb.} \sim O(10^{-3} - 10^{-6})$

- ❖ This difference necessitates the development of specialized modeling techniques to adequately resolve the acoustic perturbations. This is most often done by separating the two scales through linearization of the equations of motion.
- ❖ The bulk of existing prediction capability does in fact rely on linearized methods. The most popular approach is an extension of acoustic analogy which includes solid surfaces in arbitrary motion, i.e., the Ffowcs-Williams Hawkins (FW-H) Equation.

Acoustic Prediction Methodology



Aerodynamic
Calculation Step

Unsteady Aerodynamic Simulations
(Needed to Define Acoustic Source Strength Distribution)



Acoustic
Calculation Step

Ffowcs-Williams Hawkins (FW-H) Eq.
(Used for Computing Acoustic Radiation from the Blades)

Accuracy of the acoustic predictions is strongly influenced by the underlying aerodynamic input.

Need efficient computational methods for computing the unsteady aerodynamics.

Unsteady Aerodynamic Simulations

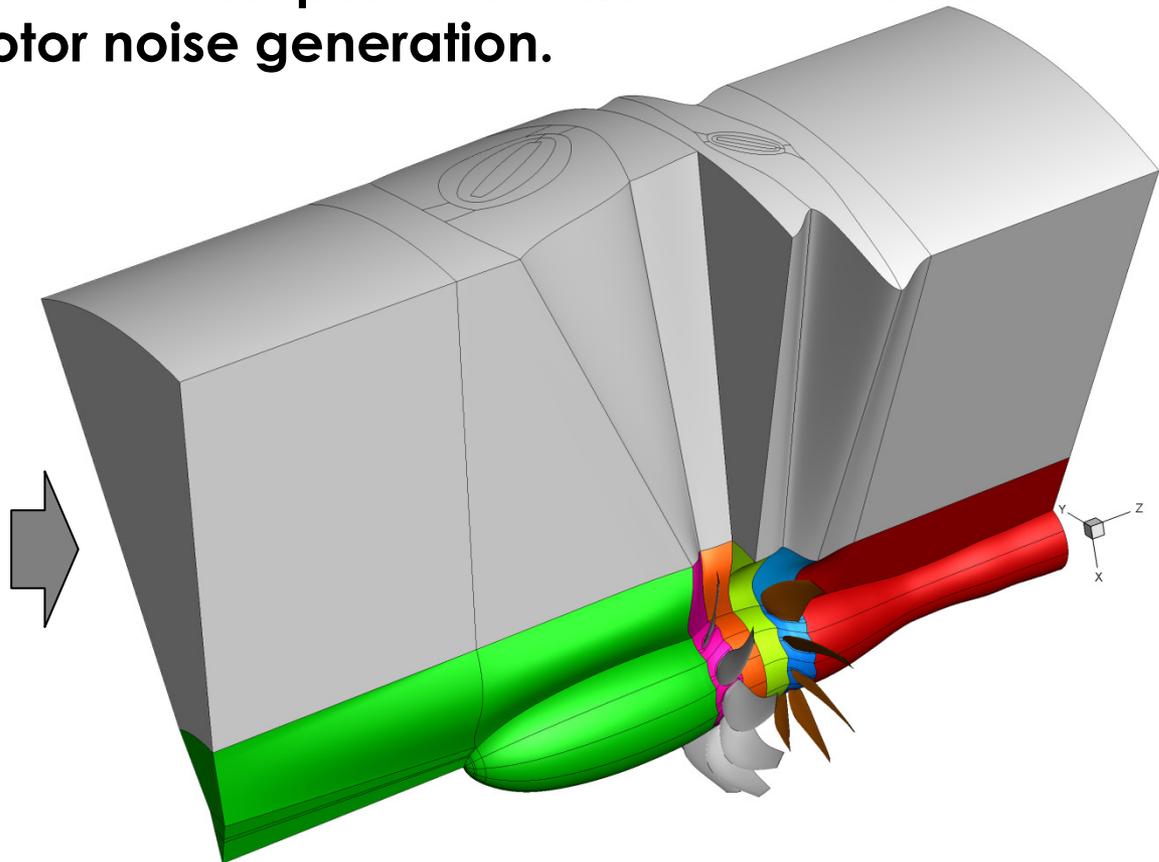


- ❖ In this work, Numeca's FINE™/Turbo CFD software package was used for aerodynamic calculations.
- ❖ The nonlinear harmonic (NLH) method was employed to selectively calculate the components of flow unsteadiness relevant to open rotor noise generation.

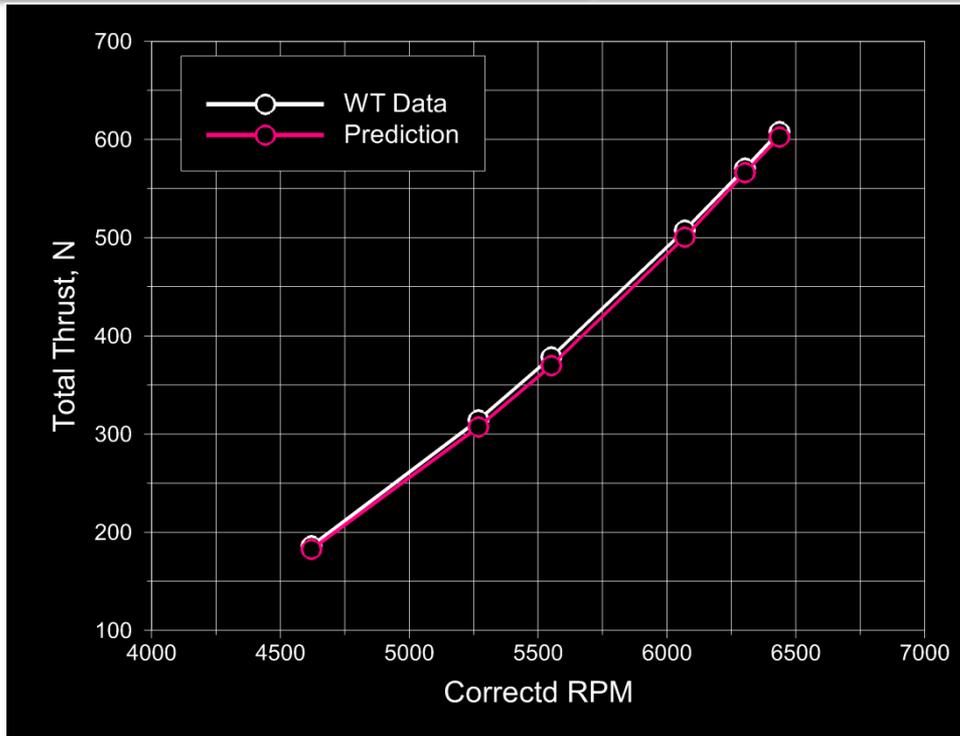
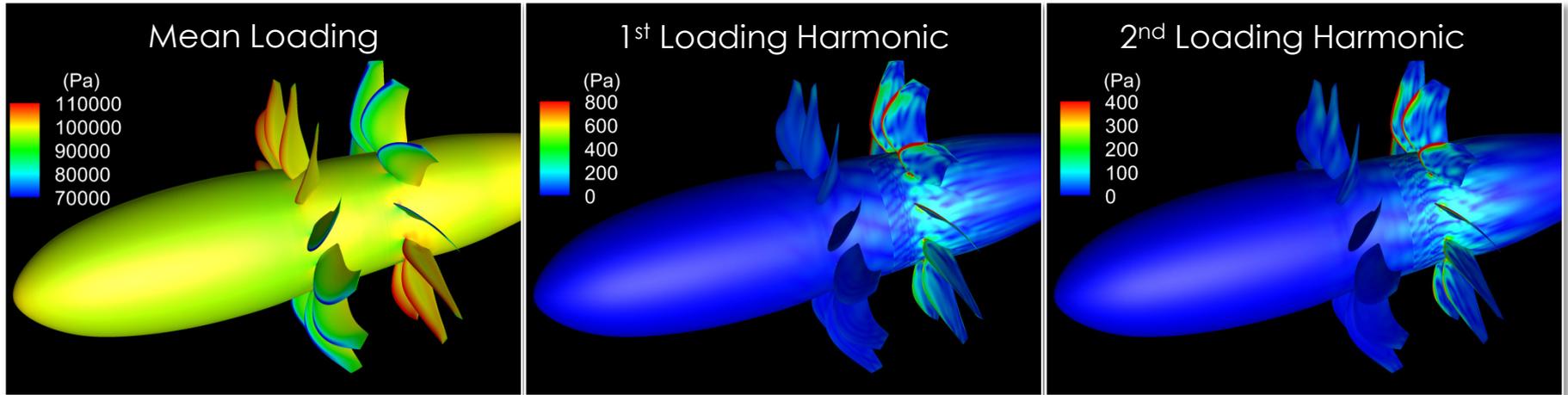
Computational Domain & Gird Blocks Used in the Aerodynamic Simulations

NLH Requires Only One Passage Per Blade Row

Total Mesh Size ~27.1M Pts.



Example Aerodynamic Predictions



Pressure Distribution at Nominal Takeoff Condition (~6400 RPM)

Measured & Predicted Propulsor Thrust as a Function of RPM

A total of six tip speed conditions were simulated. The front and aft rotor RPMs were equal for all cases.

Open Rotor Noise Model



$$p'_{\text{acoustic}}(\vec{x}, t) = \overbrace{\sum_{n=-\infty}^{\infty} \left(\underbrace{A_n^{(1)}}_{\text{Amplitude}} e^{-inB_1\Omega_1 t} + \underbrace{A_n^{(2)}}_{\text{Amplitude}} e^{-inB_2\Omega_2 t} \right)}^{\text{Thickness Noise}} +$$

Thickness noise is produced at the blade passing harmonics of each rotor.

$$\overbrace{\sum_{m=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \underbrace{A_{m,k}^{(1,2)}}_{\text{Amplitude}} e^{-i \overbrace{(mB_1\Omega_1 + kB_2\Omega_2)}^{\text{Tone Frequency}} t}}^{\text{Loading Noise}}$$

B_1 & B_2 and Ω_1 & Ω_2 are front and aft rotor blade counts and angular frequencies, respectively.

Loading noise is produced at the blade passing harmonics of each rotor as well as at the sum & difference combinations of the front and aft rotor frequencies. Loading noise tends to dominate thickness noise for open rotors because the blades are very thin and highly loaded.

Open Rotor Noise Model (Cont'd)



❖ Expressions for tone amplitudes (From FW-H Eq.)

Thickness Noise Amplitude:

$$A_n^{(i)} = \int_0^{2\pi/\Omega_i} \int_{S_{B_i}} \underbrace{\rho_0 v_n Q_T}_{\text{Thickness Source Strength (geometric input)}} \underbrace{G}_{\text{Propagation}} ds d\tau$$

Blade Normal Velocity
Green's Function

Loading Noise Amplitude:

$$A_{m,k}^{(i)} = \int_0^{2\pi/\Omega_i} \int_{S_{B_i}} \underbrace{F_j Q_L}_{\text{Loading Source Strength (aerodynamic input - CFD)}} \underbrace{n_j G}_{\text{Propagation}} ds d\tau$$

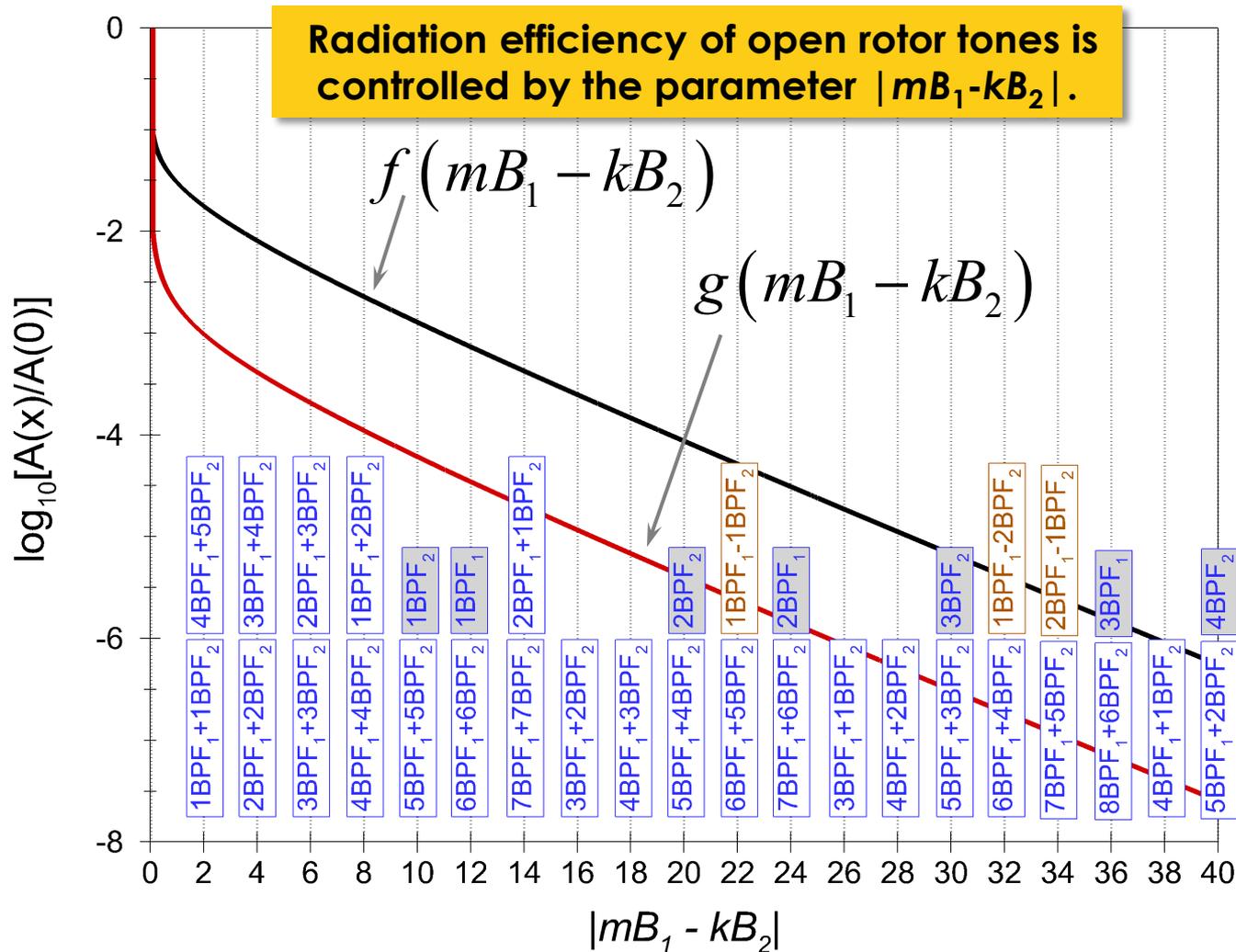
Blade Loading

Asymptotic approximations to these expressions yield efficient means of computing the tone amplitudes.

Features of Open Rotor Noise



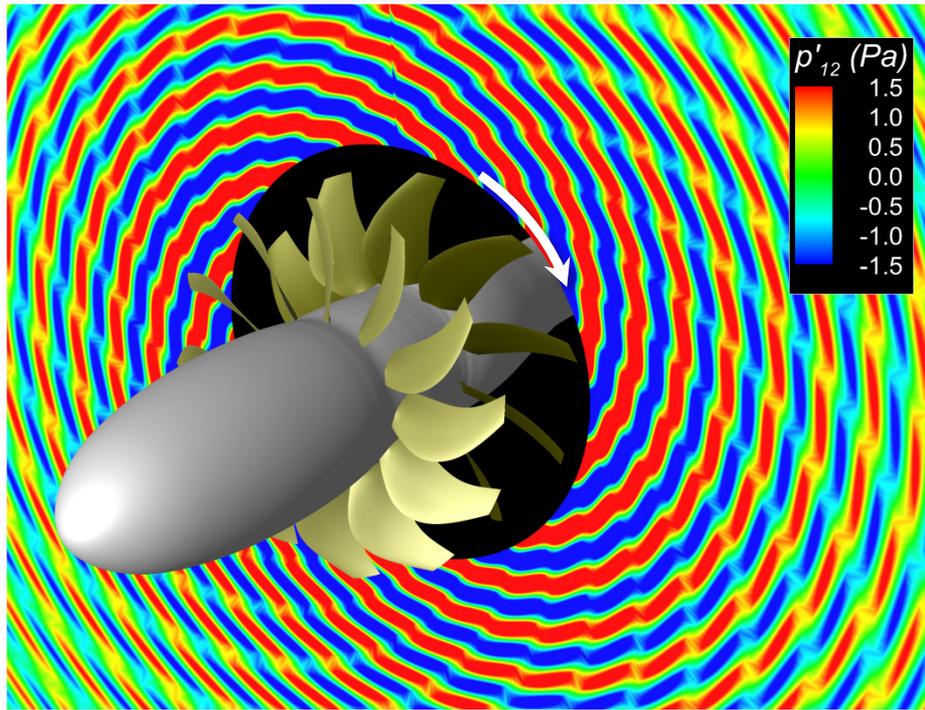
$$A_{m,k}^{(i)} \propto f(mB_1 - kB_2), g(mB_1 - kB_2)$$



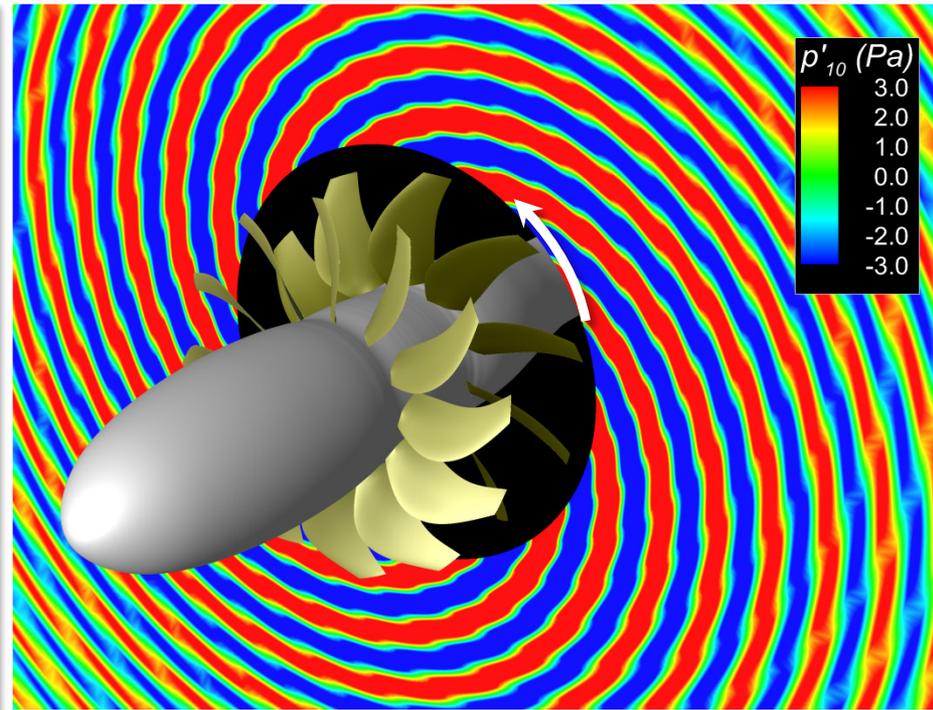
Predicted Radiation Patterns of Rotor Tones

- ❖ BPF_1 ($=12\Omega$) & BPF_2 ($=10\Omega$) tones (i.e., 12th & 10th shaft orders), are produced by the front and aft rotors, respectively. Their associated wavefronts rotate in opposite directions. (Note that $\Omega_1 = \Omega_2 = \Omega$)

Front Rotor: BPF_1 Wavefront @ $z = 0$



Aft Rotor: BPF_2 Wavefront @ $z = 0$

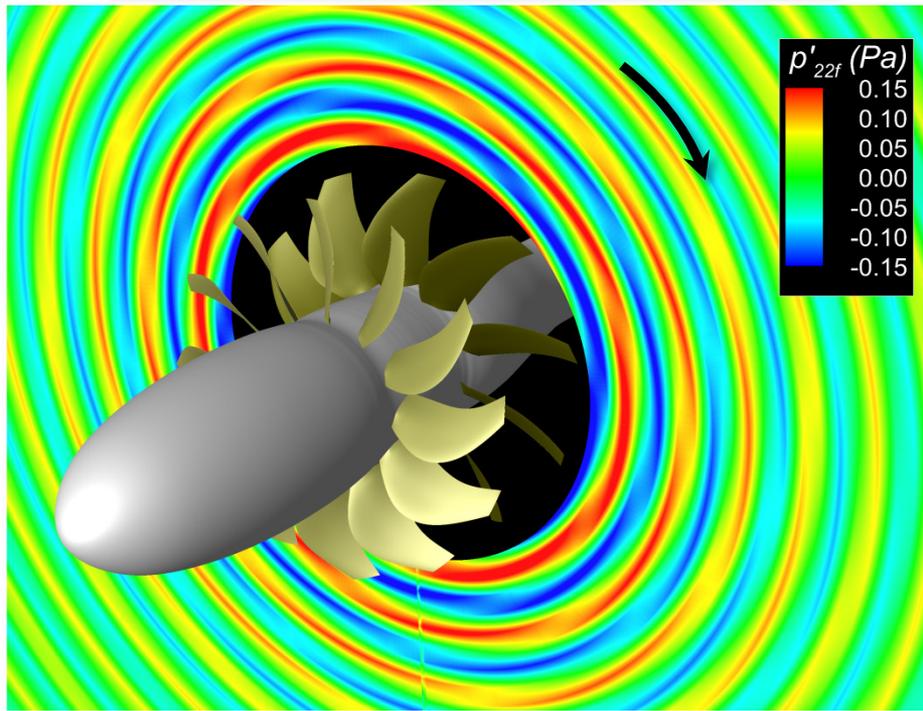


The aft rotor tone levels are typically larger than the front rotor tones since the blade loading perturbations are larger on the aft rotor.

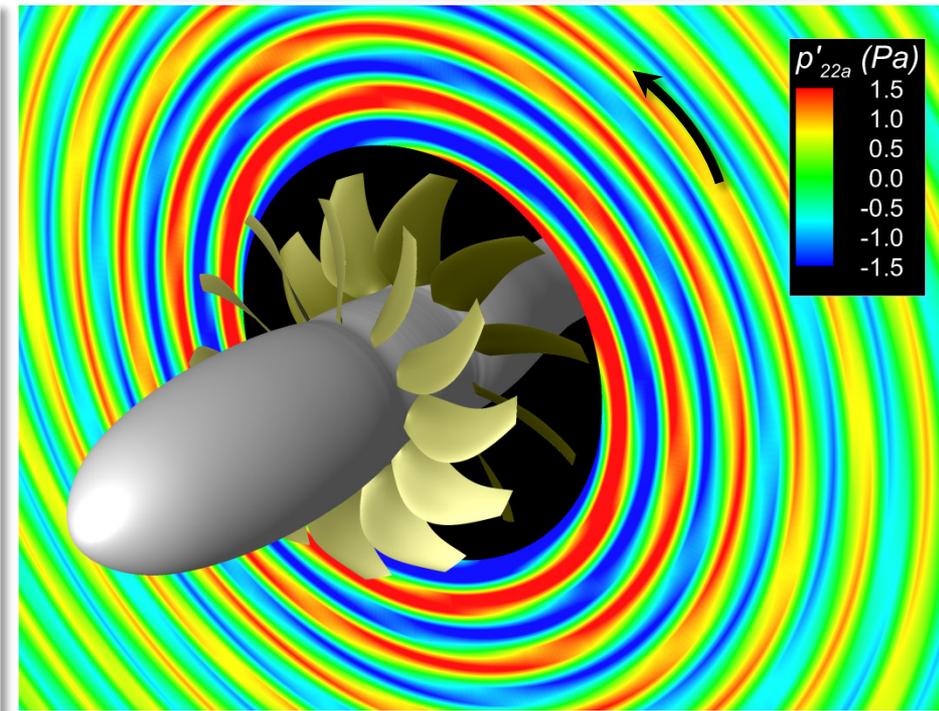
Predicted Radiation Patterns of Inter. Tones

- ❖ Interaction tone $BPF_1 + BPF_2 = 22\Omega$ (i.e., 22^{nd} shaft order) is produced by both the front and aft rotors. However, the respective levels are quite different and their wavefronts rotate in opposite directions.

Front Rotor 22Ω Wavefront @ $z = 0$

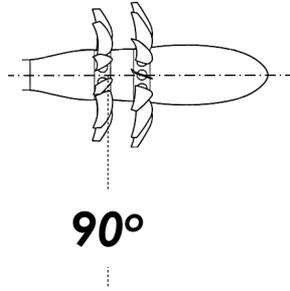
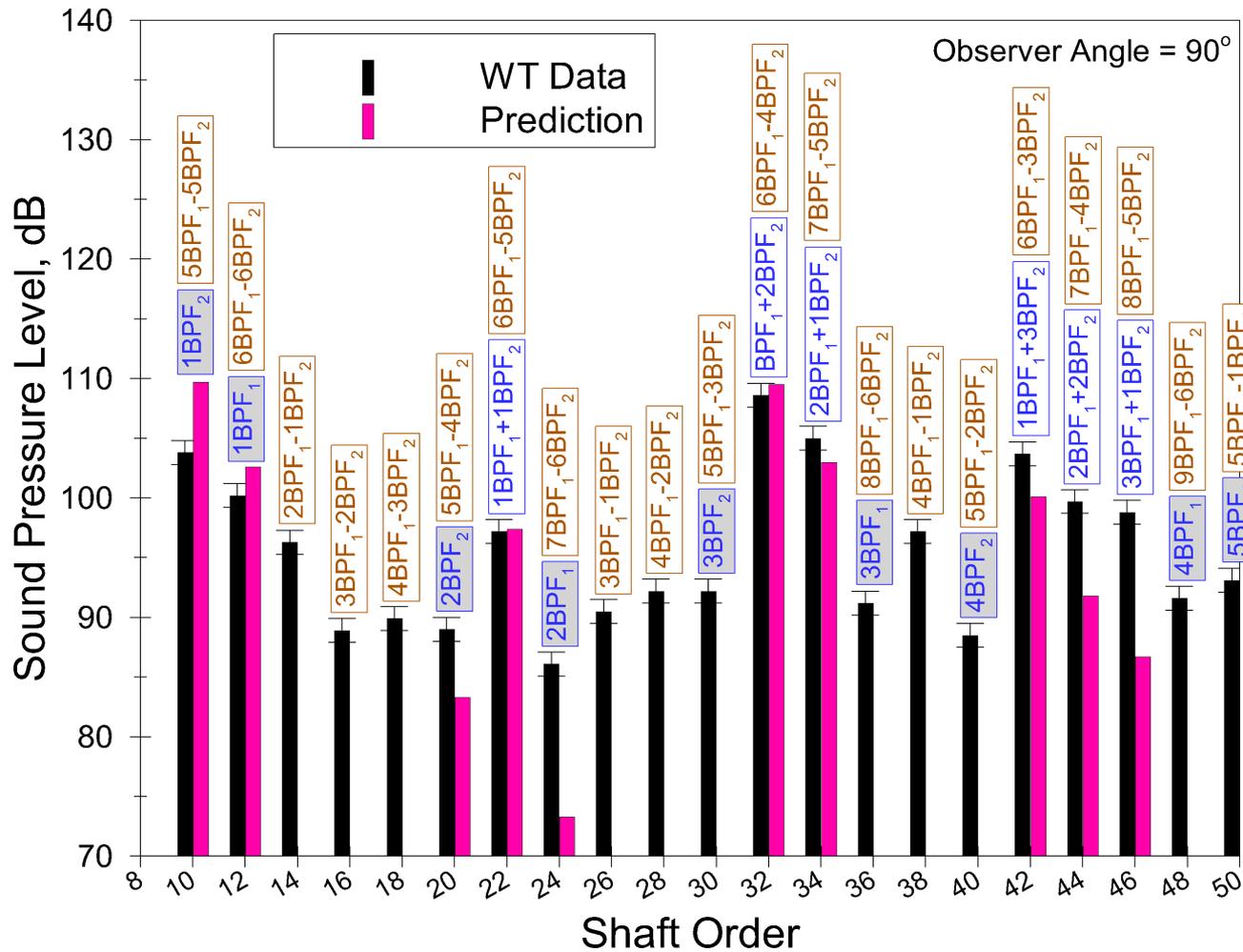


Aft Rotor 22Ω Wavefront @ $z = 0$



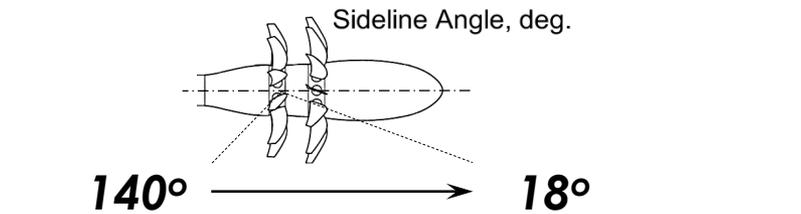
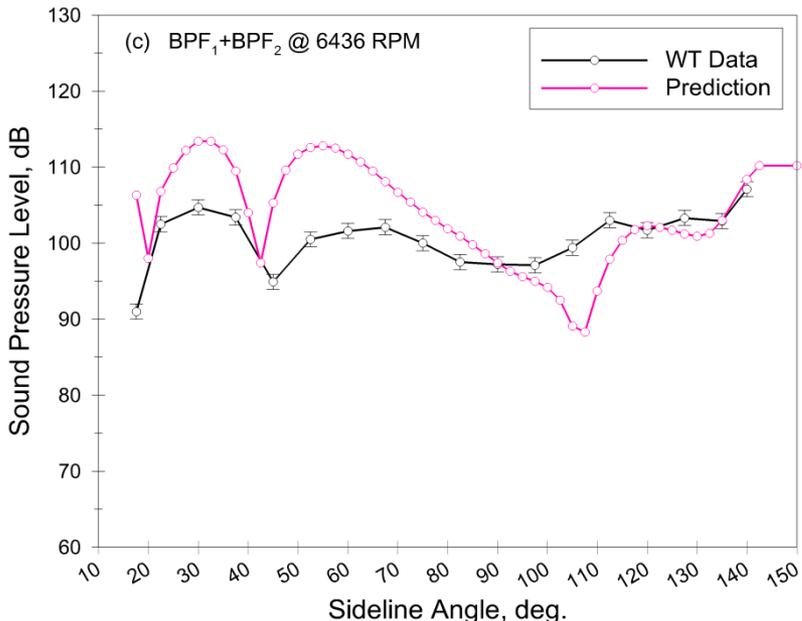
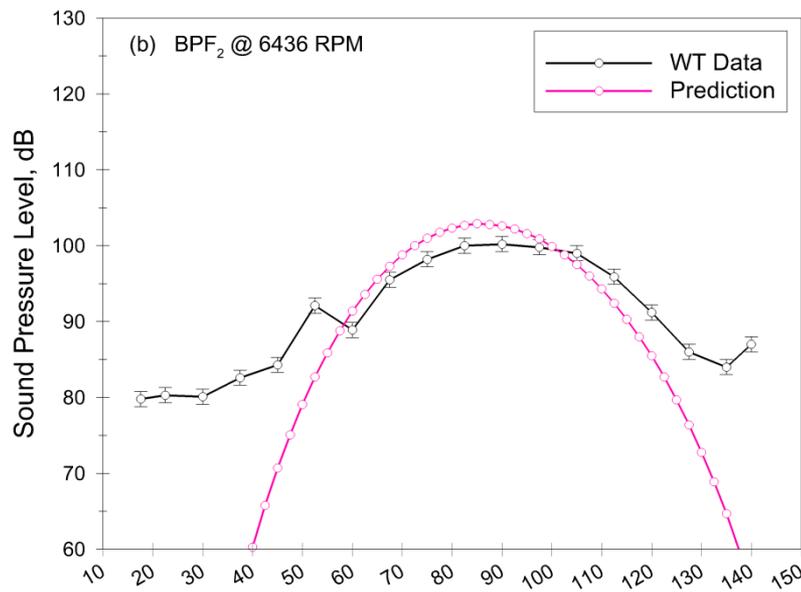
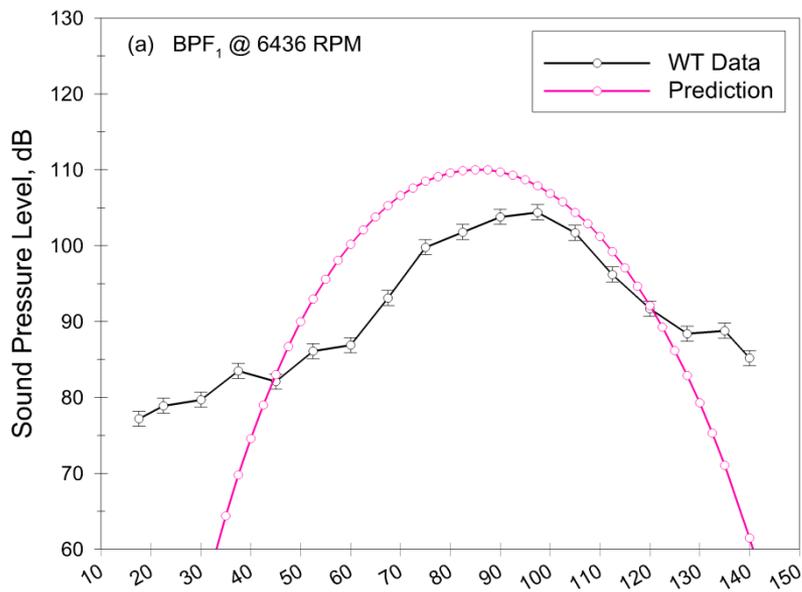
The aft rotor level for this tone is 10 times larger than its front rotor counterpart and hence controls the overall 22Ω tone characteristics.

Data-Theory Comparisons (Tone Levels)



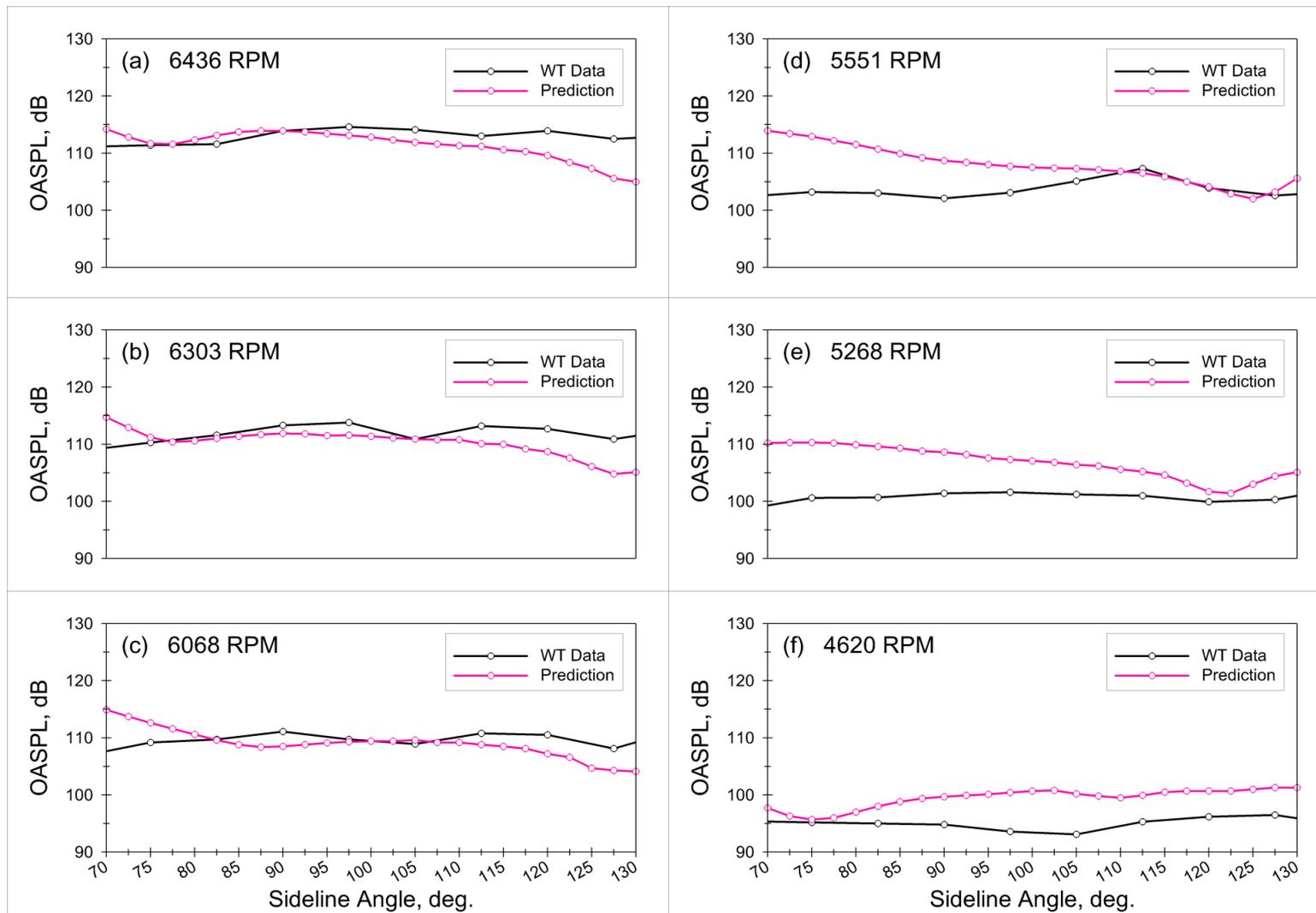
Interaction tone levels are reasonably well-predicted, but the harmonic fall off of rotor tones is not. Cause is likely related to imperfections in blade manufacture and installation which destroy the perfect phase relationships assumed in the theory.

Data-Theory Comparisons (Tone Directivity)



Basic trends are predicted, but not the absolute levels. The predicted fall off of rotor tone directivities is consistent with single rotation data. It is not clear why would the measured tone directivities level off or roll up at far upstream and far downstream angles.

Data-Theory Comparisons w. Tip Speed



Data-theory comparisons for the overall sound pressure level (OASPL) are reasonable for high tip speed conditions, but deteriorate at lower tip speeds.

Conclusions



- ❖ **An assessment of open rotor noise prediction capability is being conducted at NASA using detailed wind tunnel aerodynamic and acoustic data for a benchmark open rotor blade set.**
- ❖ **Data-theory comparisons in the low speed regime indicate that, while basic noise trends can be reasonably well captured, the absolute acoustic levels cannot be reliably and consistently predicted.**
- ❖ **The cause is likely related to the assumption made both in the aerodynamic and acoustic models that the blades in each rotor disc are identical and that they experience identical time histories that are spatially and temporally shifted from those of the reference blade.**
- ❖ **In reality, there are manufacturing and installation differences between blades which destroy the perfect phase relationships assumed in the theory and lead to the distribution of acoustic energy in all shaft orders not just the ones predicted by the theory.**

Recommendations



- ❖ Therefore, to improve the absolute level prediction capability, it would be necessary to modify the aerodynamic and acoustic theoretical models to account for these blade-to-blade differences in a manner consistent with reality.
- ❖ As such, it would be useful to experimentally measure these differences and quantify the impact of the blade variations on the aerodynamic and acoustic responses of the blades.
- ❖ If that proves too difficult a task, it may be possible to conduct theoretical parametric studies in which prescribed blade-to-blade variations (both in geometry and aerodynamic response) are introduced and the sensitivity of the resulting acoustic field to these variations is established.
- ❖ These results could then serve as guides for modifying the theoretical models to correctly account for the real blade effects.



Questions?