An Assessment of Open Rotor Noise Prediction Tools

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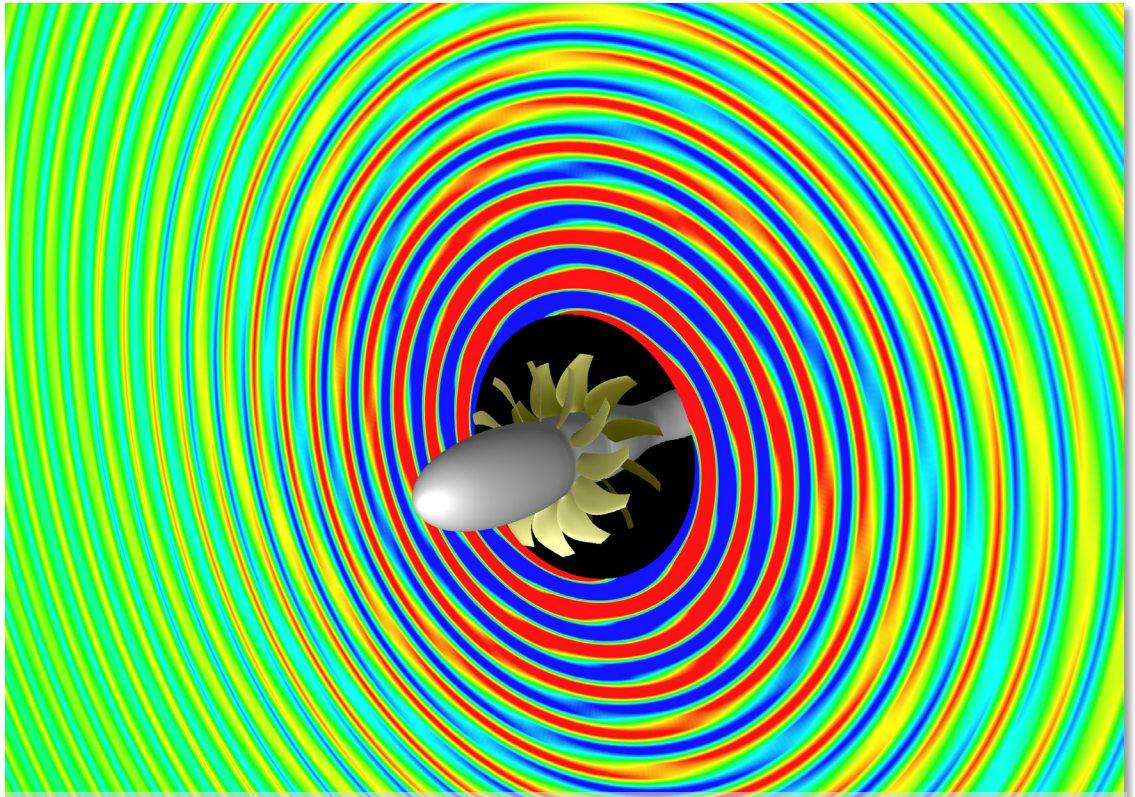
Acoustics Technical Working Group Meeting, NASA Langley

October 23-25, 2012

This work has been supported by the Fixed Wing Project.



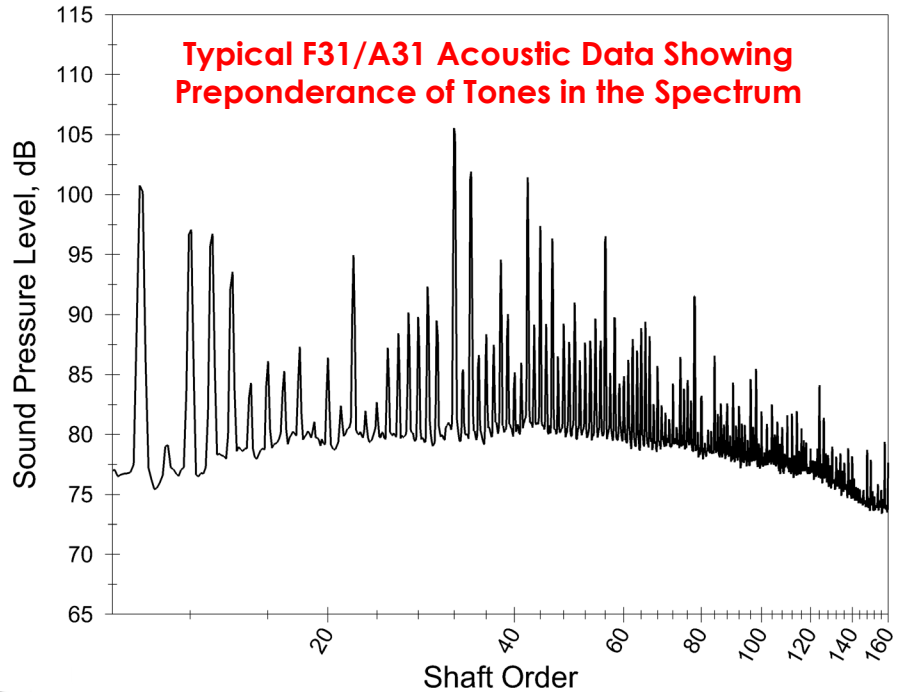
Open Rotor Interaction Tone Noise Radiation Pattern

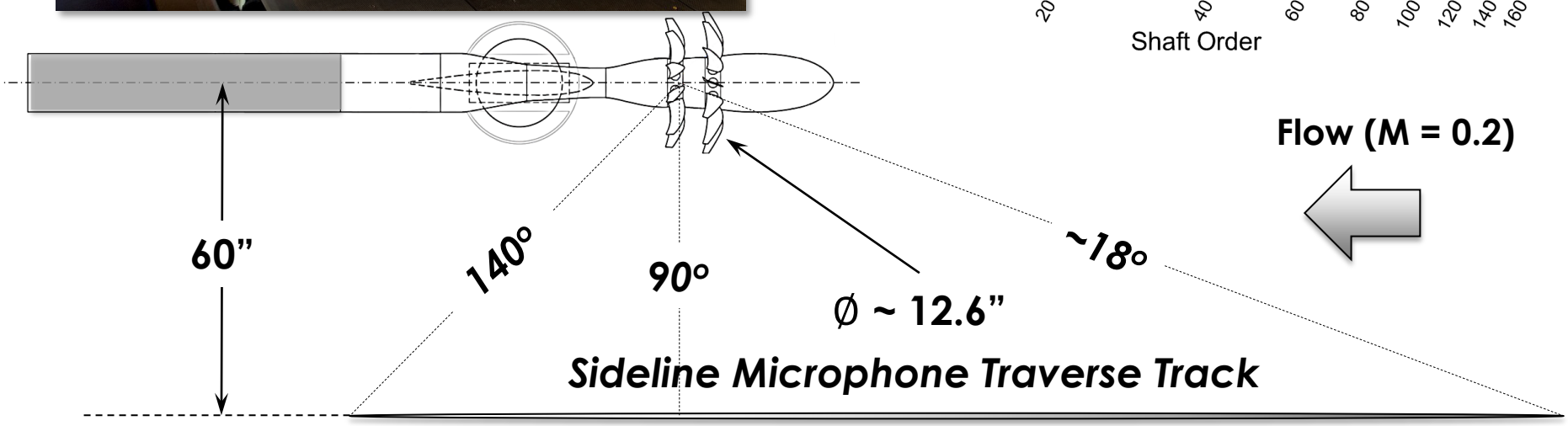
Objective of This Study

- Assess the current capability for predicting the aerodynamic and acoustic performance of open rotors.
- The testbed is a 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 with a 12-bladed front rotor and a 10-bladed aft rotor. This blade set 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 interim 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.

Ref.: Envia, E., "Open Rotor Aeroacoustic Modelling," *Proceedings of Conference on Modelling Fluid Flow*, edited by. J. Vad, Budapest, Hungary, 2012.

F31/A31 Wind Tunnel Acoustic Data





Plan View of F31/A31 Installation in the Wind Tunnel

F31/A31 Tone Noise Spectrum

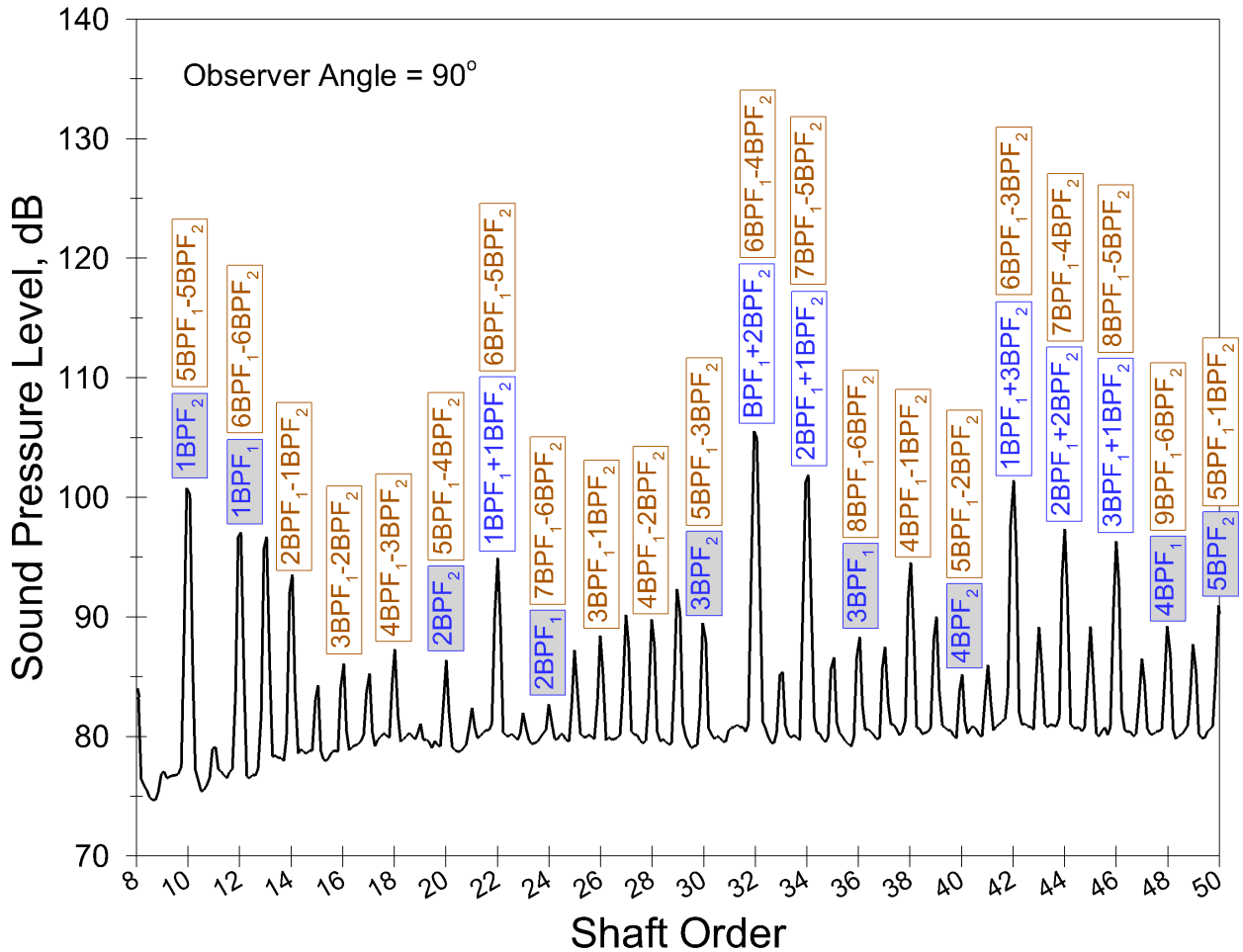
$BPF_1 = B_1\Omega_1$

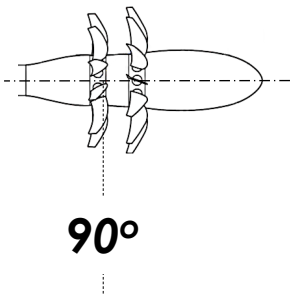
$BPF_2 = B_2\Omega_2$

Sum Tones

Diff. Tones

Rotor Tones





<u>Theoretically</u>, any tone with frequency $|mB_1\Omega_1+kB_2\Omega_2|$, where B_1 & B_2 are rotor blade counts, Ω_1 & Ω_2 are rotor rotational frequencies, and m & k are arbitrary integers, can be generated by the F31/A31 blade set.

Acoustic Prediction Methodology

Aerodynamic Calculation Step

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

Acoustic Calculation Step

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

Need efficient computational methods for computing the rotor blades' unsteady aerodynamic loading.

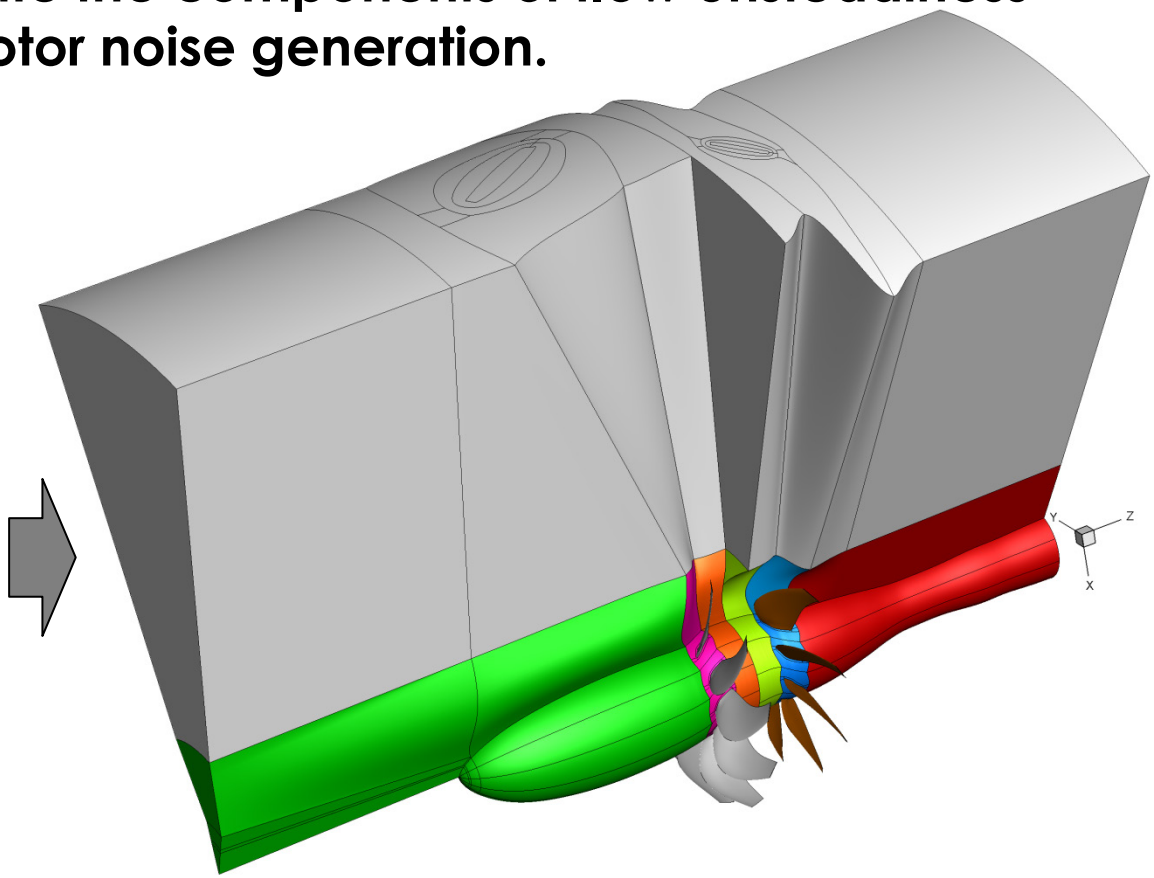
Unsteady Aerodynamic Simulations

- For the work described here, 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.

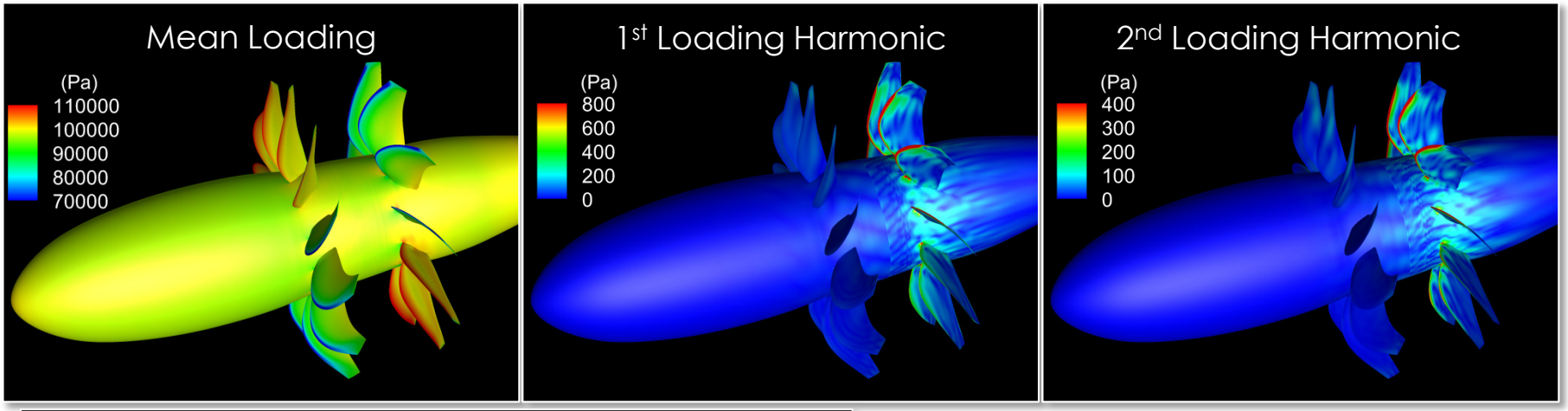
Computational Domain & Grid Blocks Used in the Aerodynamic Simulations

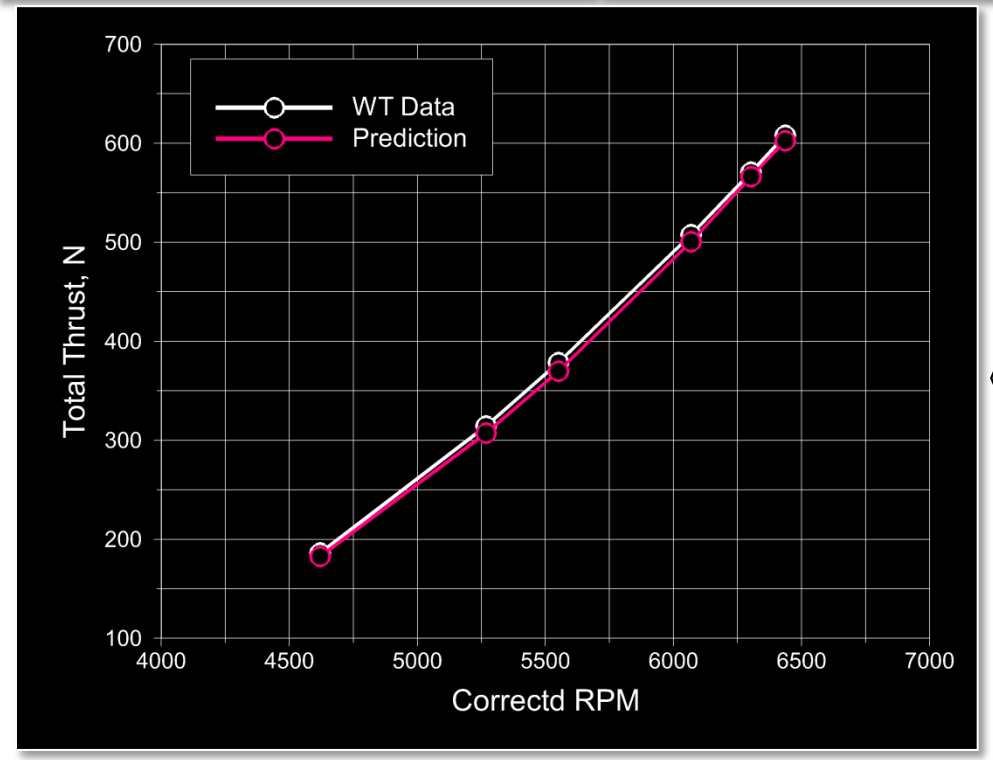
NLH Requires Only One Passage Per Blade Row

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 (LINPROP)

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

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

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

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 thin and highly loaded.

Open Rotor Noise Model (Cont'd)

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

Thickness Noise Amplitude:

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

Blade Normal Velocity

Rotor Blade Surface

Loading Noise Amplitude:

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

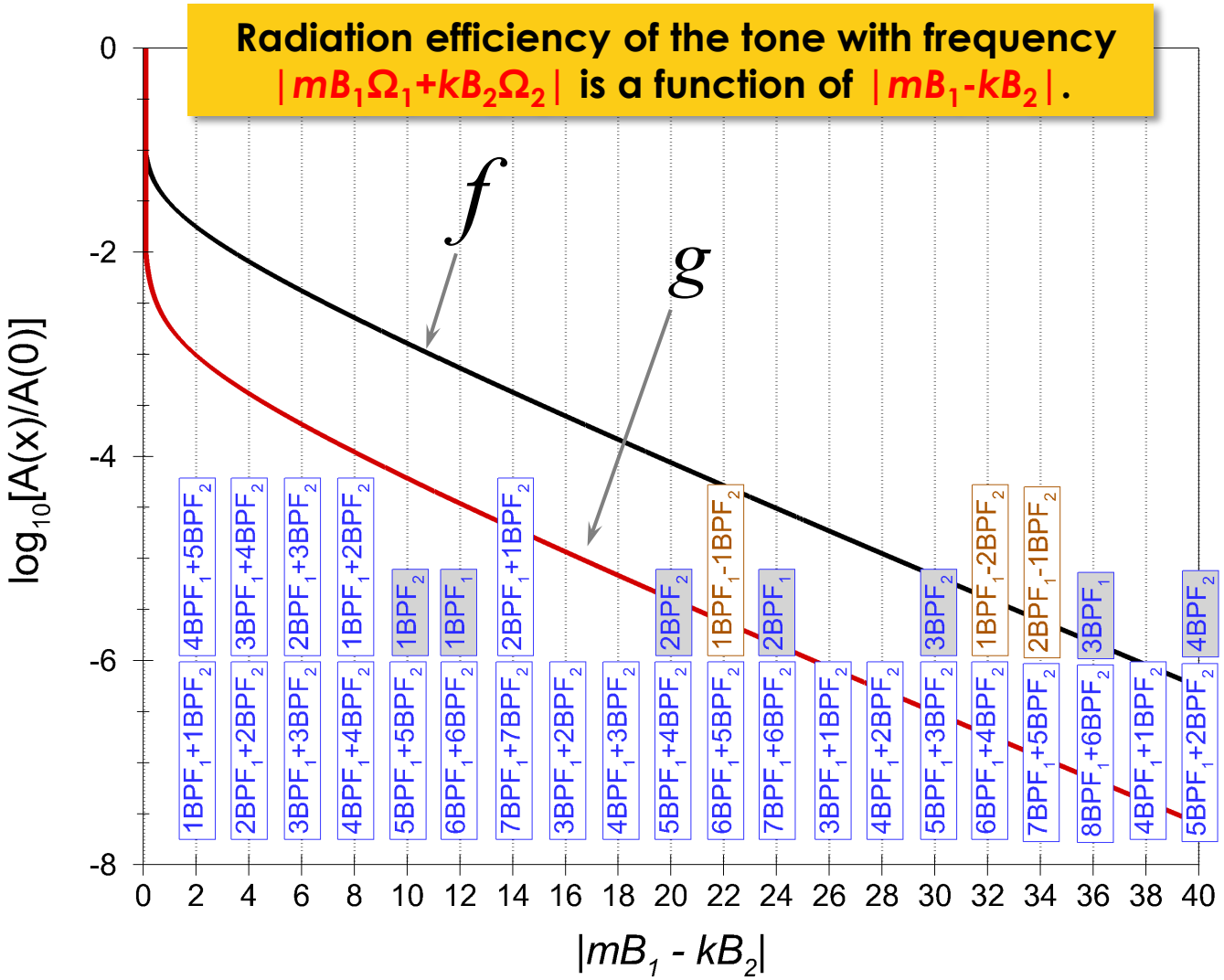
Blade Loading

Green's Function

In the LINPROP code, asymptotic approximations to the radiation efficiency integrals yield closed-form and efficient expressions for computing the tone amplitudes.

Radiation Efficiency of Open Rotor Tones

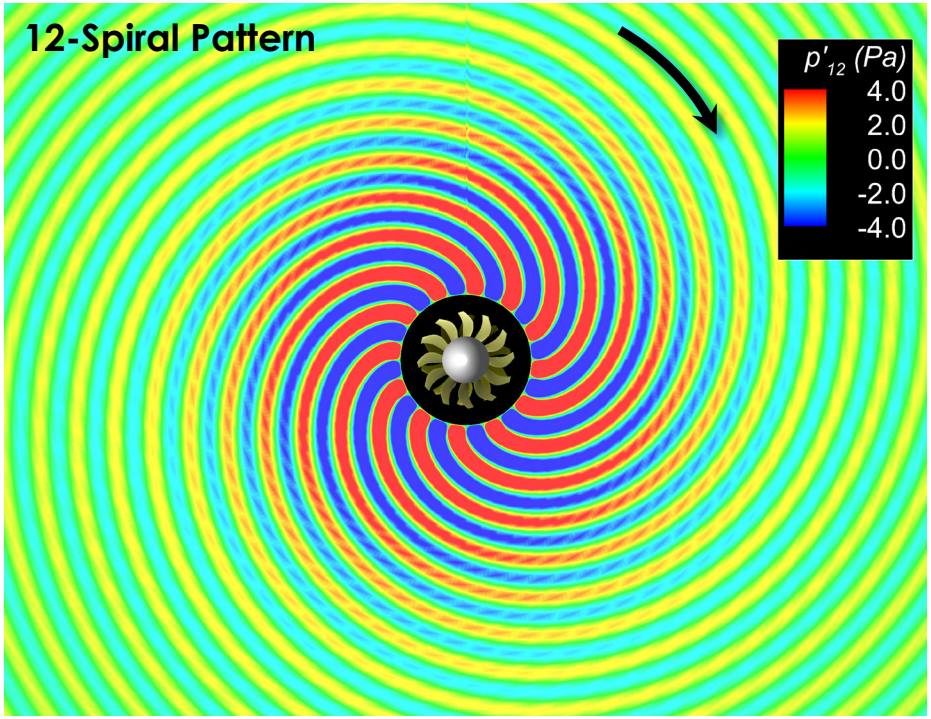
$$\text{Radiation Efficiency} \approx a * f + b * g$$



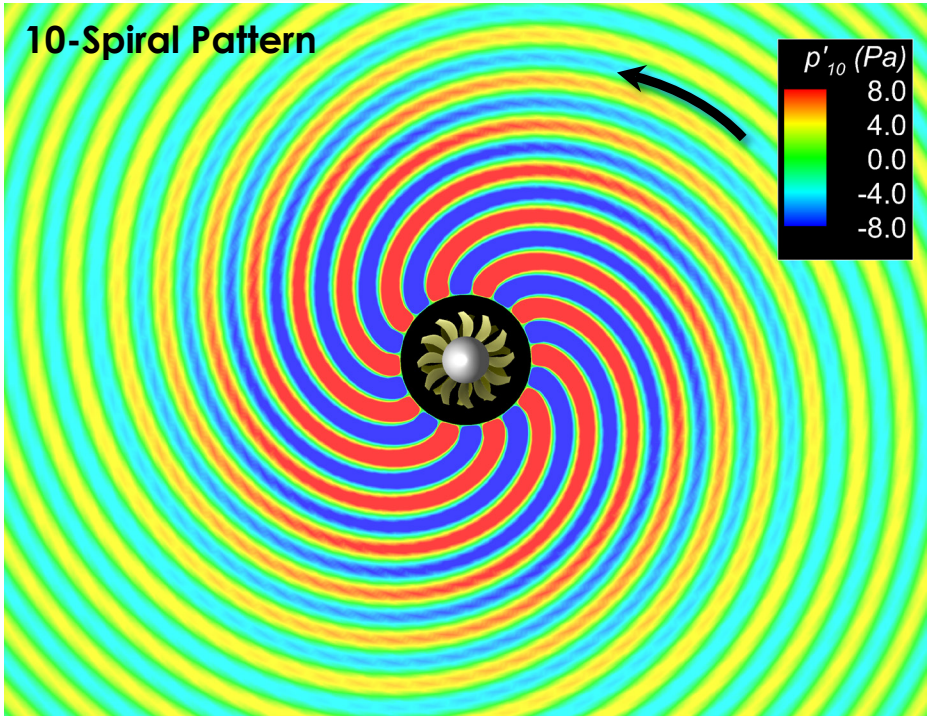
Predicted Radiation Patterns of Rotor Tones

- BPF_1 (=12Ω) & BPF_2 (= 10Ω) 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

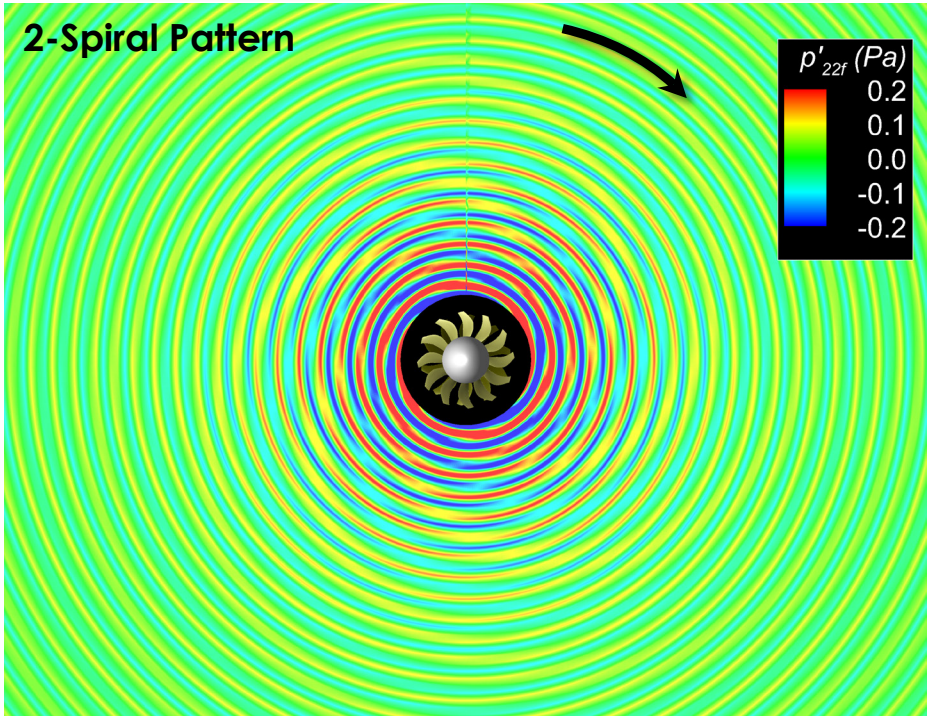


The aft rotor tone levels are typically larger than the front rotor tones since the blade loading perturbations are larger on the aft rotor.

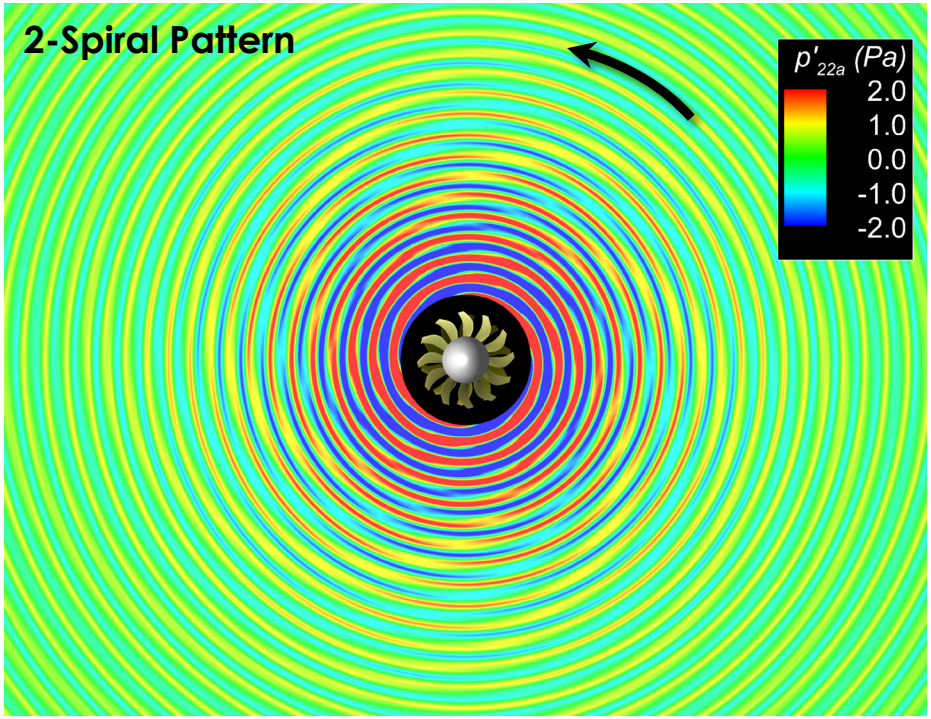
Predicted Radiation Patterns of Inter. Tones

- Interaction tone $BPF_1+BPF_2 = 22\Omega$ (i.e., 22nd 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

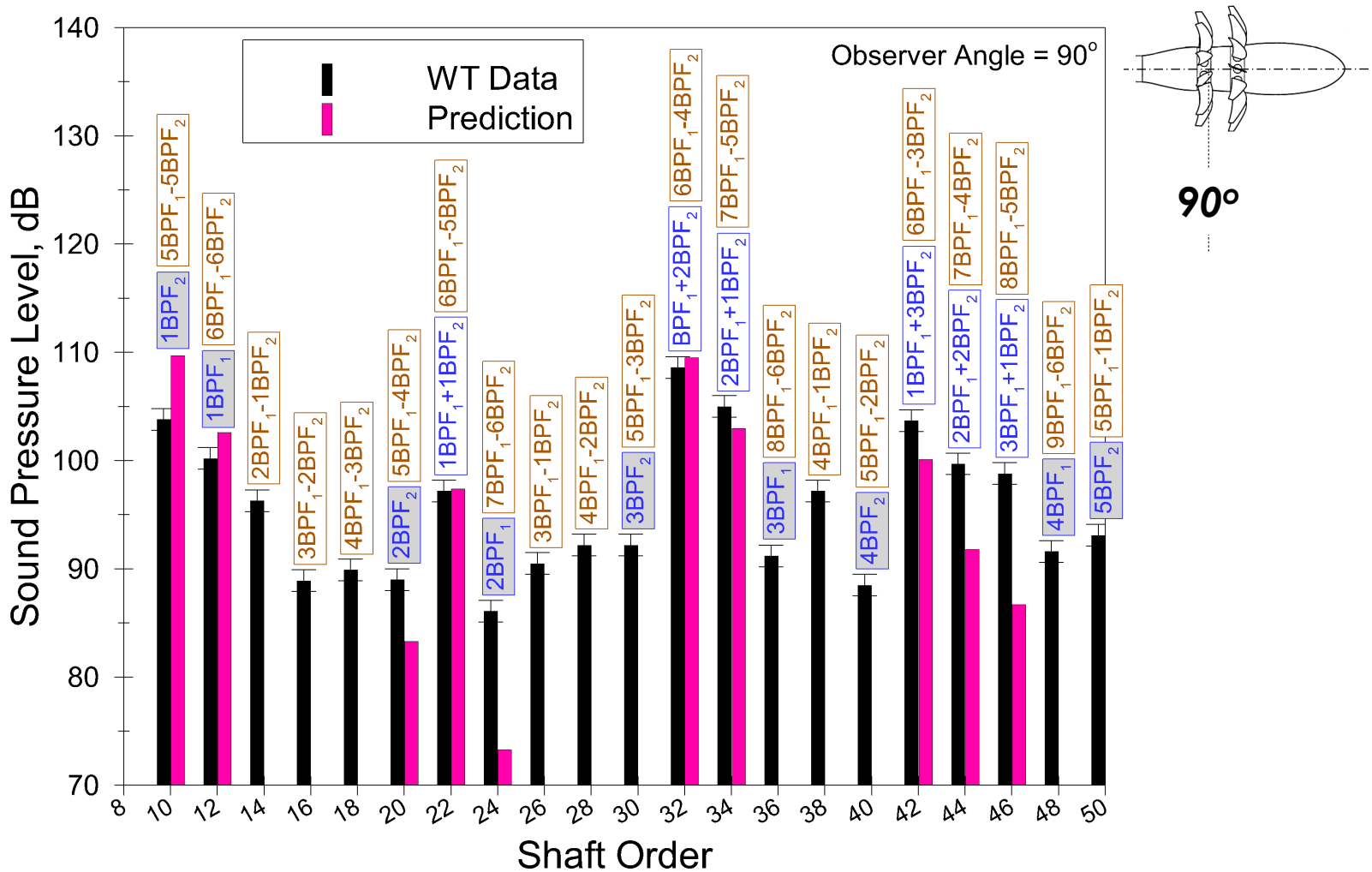


Aft Rotor 22Ω Wavefront @ z = 0



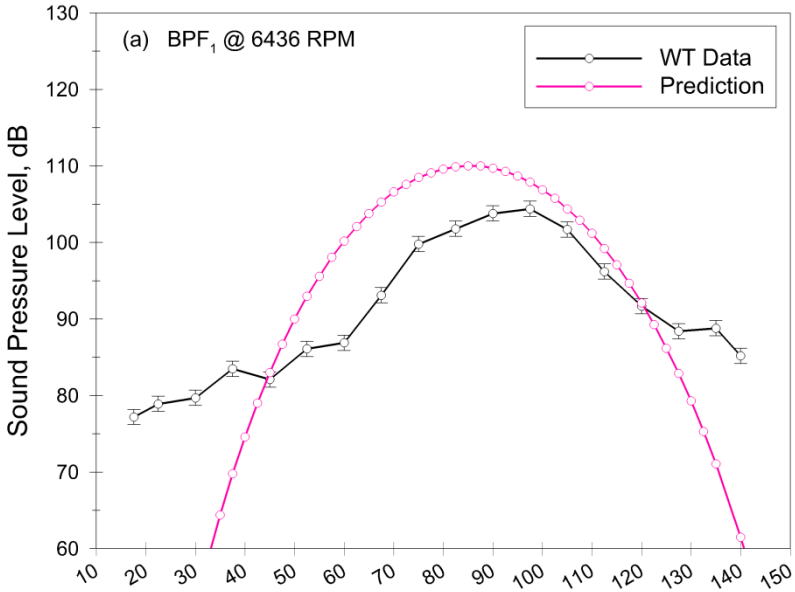
The aft rotor level is 10 times larger than the front rotor level and hence controls the overall 22Ω tone radiation pattern. Note that the radiation pattern of a tone is also a function of $|mB_1-kB_2|$.

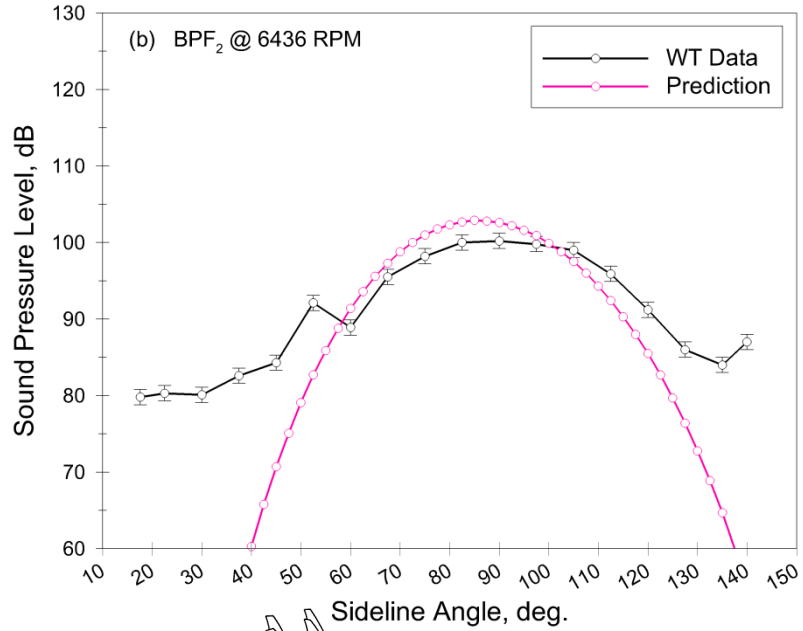
Data-Theory Comparisons (Tone Levels)

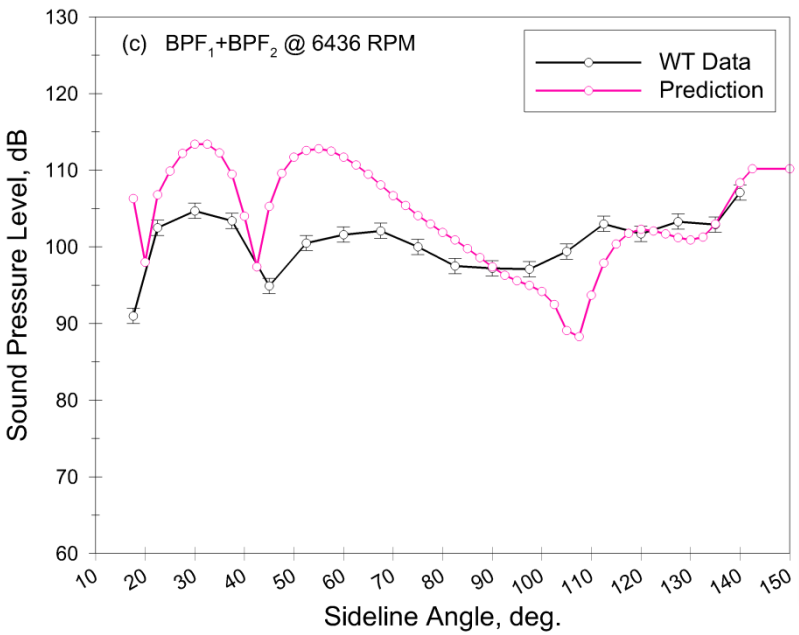


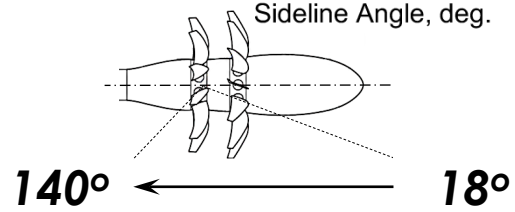
Primary interaction tone levels are reasonably well-predicted, but the harmonic fall off of rotor tones is not. Cause is likely related to imperfections in blade manufacture and installation which destroy the perfect phase relationships assumed in the theory.

Data-Theory Comparisons (Tone Directivity)



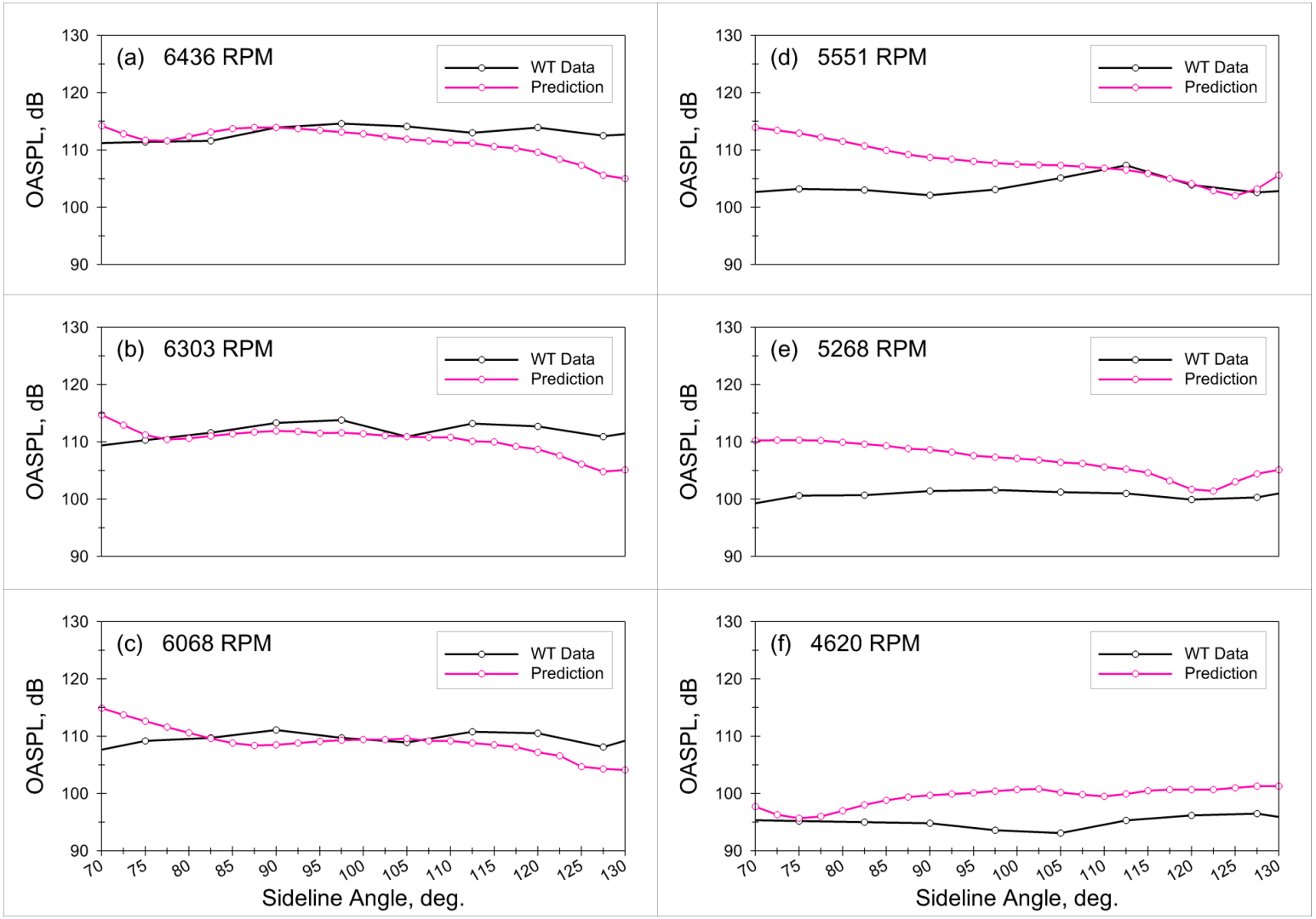






Basic trends are predicted, but not the absolute levels. The predicted fall off of rotor tone directivities is consistent with single rotation data. It is not clear why would the measured tone directivities level off or roll up at far upstream and far downstream angles.

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 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 tone noise trends can be reasonably well predicted, the <u>absolute tone levels</u> 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.

- It may be possible to conduct theoretical parametric studies in which prescribed small 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?