Contra-Rotating Open Rotor Tone Noise Prediction

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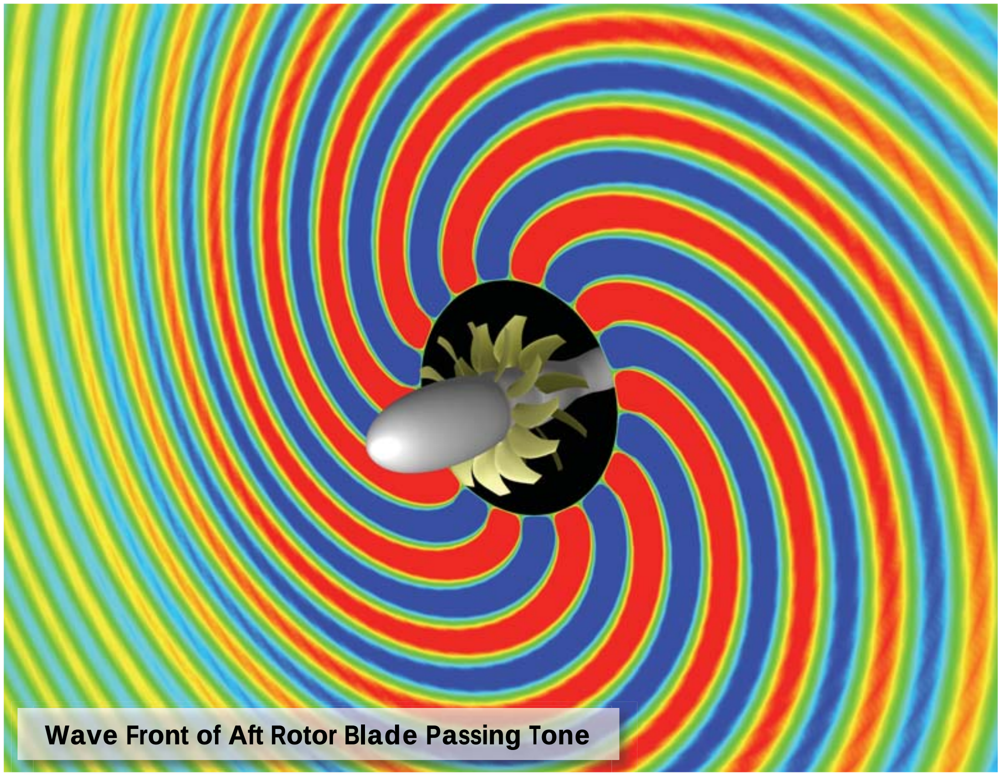
Presented at the 20th AIAA/CEAS Aeroacoustics Conference
Atlanta - June 18, 2014



Wave Front of Aft Rotor Blade Passing Tone

This work has been funded by the NASA Fixed Wing Project.

Background

❖ **Changes in design paradigm have made possible contra-rotating open rotor (CROR) propulsion systems that can retain their inherent fuel-efficiency advantage over turbofans while also be acoustically acceptable.**

GE Un-Ducted Fan (UDF) Engine (1980s)

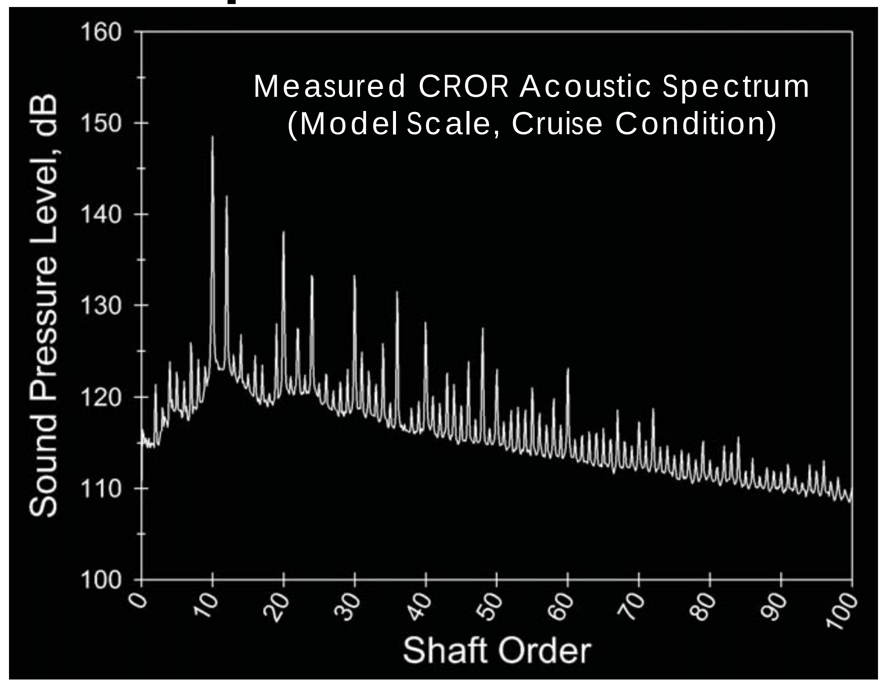
Snecma CROR Engine Concept (Present)

Lower tip speeds, increased rotor diameters & rotor-rotor spacing, unequal blade counts

Shift in Design Philosophy

Motivation

- Designing low-noise contra-rotating open rotor (CROR) propulsion systems that can meet both community noise regulations and cabin noise limits requires reliable aero/acoustic prediction tools.



- Since CROR noise spectra exhibit a preponderance of tones, predicting their tone content has been the focus of many past and current studies.

- In this study, a NASA open rotor tone noise model was assessed for its ability to predict CROR nearfield tone noise at cruise.

- The testbed is a benchmark GE model scale CROR blade set called F31/A31 for which extensive aero/acoustic data exist.

CROR Acoustic Modeling

- Acoustic Analogy ⟶ Ffowcs Williams Hawkings Eq.

$$p'_{\text{acoustic}} = \int_T \int_S \rho_0 v_n \frac{D_0 G}{D\tau}\, dS\, d\tau + \int_T \int_S f_i \frac{\partial G}{\partial y_i}\, dS\, d\tau + \int_T \int_V T_{ij} \frac{\partial^2 G}{\partial y_i \partial y_j}\, dV\, d\tau$$

Thickness Noise (Blade Normal Velocity: v_n)

Loading Noise (Blade Loading: f_i)

Quadrupole Noise (Lighthill Tensor: T_{ij}; Green's Function: G)

$$f_i = -\left(p - p_0\right) n_i, \qquad T_{ij} = \rho u_i u_j + \delta_{ij}\left[\left(p - p_0\right) - c_0^2\left(\rho - \rho_0\right)\right]$$

Owing to the linearity of the acoustic field, the acoustic contribution of each rotor can be calculated separately and the two contributions combined to estimate CROR noise field.

CROR Tone Noise Model

❖Tonal acoustic field for front rotor

$$p'_{\text{acoustic}} = \overbrace{\sum_{m} \underbrace{p'_{T_m}}_{\text{Tone Amplitude}} e^{-i \overbrace{mB_1\Omega_1}^{\text{Tone Frequency}} t}}^{\text{Thickness Noise}} + \overbrace{\sum_{m}\sum_{k} \underbrace{p'_{L_{m,k}}}_{\text{Tone Amplitude}} e^{-i\overbrace{\left(mB_1\Omega_1 + kB_2\Omega_2\right)}^{\text{Tone Frequency}}t}}^{\text{Loading Noise}} +$$

$$\overbrace{\sum_{m}\sum_{k} \underbrace{p'_{Q_{m,k}}}_{\text{Tone Amplitude}} e^{-i\overbrace{\left(mB_1\Omega_1 + kB_2\Omega_2\right)}^{\text{Tone Frequency}}t}}^{\text{Quadrupole Noise}}$$

Acoustic Harmonic Index

$$mB_1\Omega_1 + kB_2\Omega_2 = m\text{BPF}_1 + k\text{BPF}_2$$

Unsteady aerodynamic Harmonic Index

Thickness noise is produced at the harmonics of the blade passing frequency of each rotor. Loading noise and quadrupole noise are produced at the harmonics of the blade passing frequency of each rotor as well as at the sum and difference combinations of the front and aft rotor blade passing frequencies.

CROR Tone Noise Model (Cont'd)

❖ **Tone amplitudes of various sources**

$$p'_{T_m} = \int_S \left[\int_0^{2\pi/\Omega_1} \underbrace{\rho_0 v_n}_{\substack{\text{Thickness Source} \\ \text{(geometric input)}}} \underbrace{\Theta_T(\tau)}_{\substack{\text{Source} \\ \text{Directivity}}} \underbrace{G(\tau)}_{\text{Propagation}} d\tau \right] dS$$

$$p'_{L_{m,k}} = \int_S \left[\int_0^{2\pi/\Omega_1} \underbrace{f_i(\tau)}_{\substack{\text{Loading Source} \\ \text{(aerodynamic input - CFD)}}} \underbrace{\Theta_{L_i}(\tau)}_{\substack{\text{Source} \\ \text{Directivity}}} \underbrace{G(\tau)}_{\text{Propagation}} d\tau \right] dS$$

The thickness and loading equations above are grouped under: LINPROP Code

$$p'_{Q_{m,k}} = \int_V \left[\int_0^{2\pi/\Omega_1} \underbrace{T_{ij}(\tau)}_{\substack{\text{Quadrupole Source} \\ \text{(aerodynamic input - CFD)}}} \underbrace{\Theta_{Q_{ij}}(\tau)}_{\substack{\text{Source} \\ \text{Directivity}}} \underbrace{G(\tau)}_{\text{Propagation}} d\tau \right] dV$$

The quadrupole equation above is marked: QPROP Code

Asymptotic approximations to integrals over source time τ yield efficient formulas of computing CROR tone amplitudes. Replace (B_1 & Ω_1) w. (B_2 & Ω_2) for aft rotor tones.

Aerodynamic Input

- ❖ Aerodynamic input for use in the acoustic model (i.e., blade loading and Lighthill tensor distributions) can be extracted or reconstructed from unsteady aerodynamic simulations.

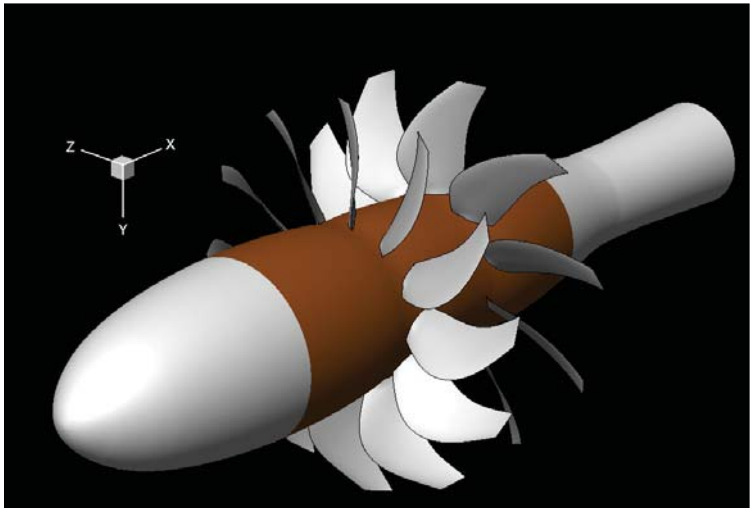
- ❖ In this work commercial CFD software package FINE/Turbo™ was used to generate the required unsteady aerodynamic inputs.

- ❖ The nonlinear harmonic (NLH) approximation was used to significantly reduce unsteady aerodynamic simulation times.

- ❖ Means plus three harmonics of the unsteady flow were considered in this study. For the dense grid used:
  - NLH CPU time ~ 5-6 x steady state solution time
  - Full unsteady CPU time ~100 x steady state solution time

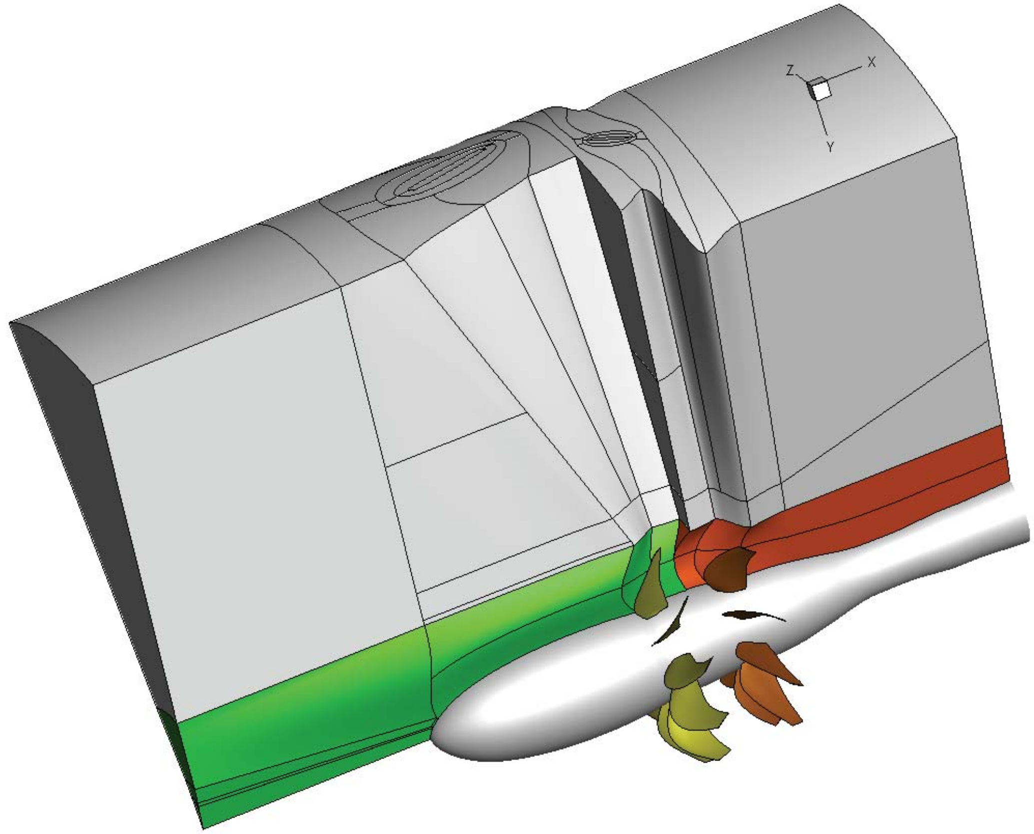
Aerodynamic Input (Cont'd)

- The NLH grid is comprised of 73 blocks and 27.1×10^6 mesh points. One passage each of the front and aft rotors plus ancillary regions like spinner, hub and farfield are included.



Sketch of GE Model Scale F31/A31 CROR

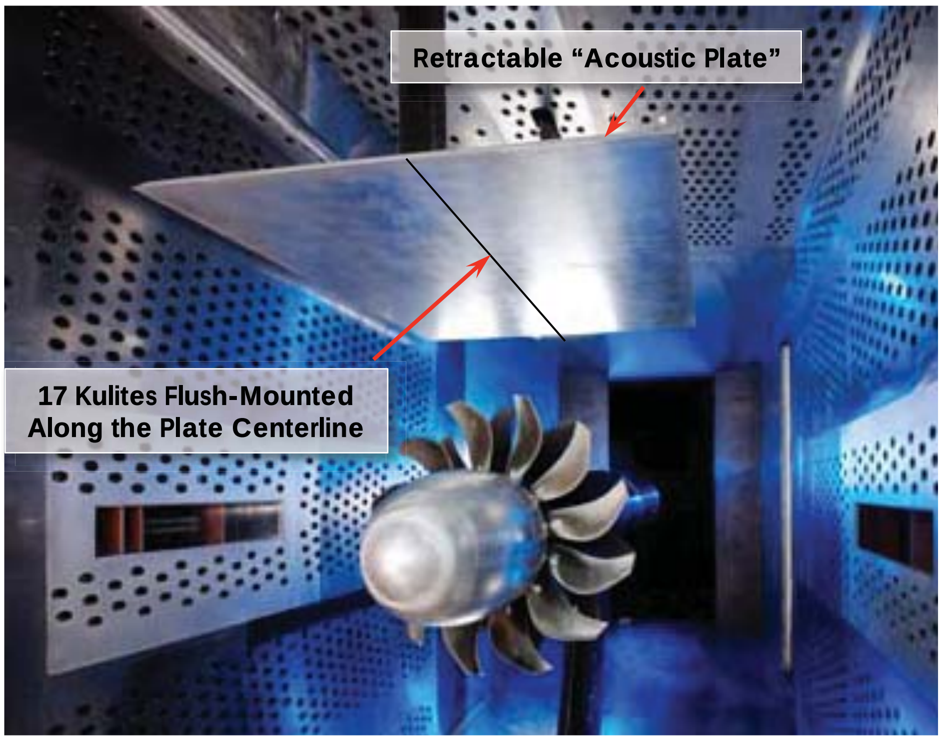
Front Rotor Blade Count	12
Aft Rotor Blade Count	10
Front Rotor Diameter	0.66m
Aft Rotor Diameter	0.63m
Rotor-Rotor Spacing	0.20m



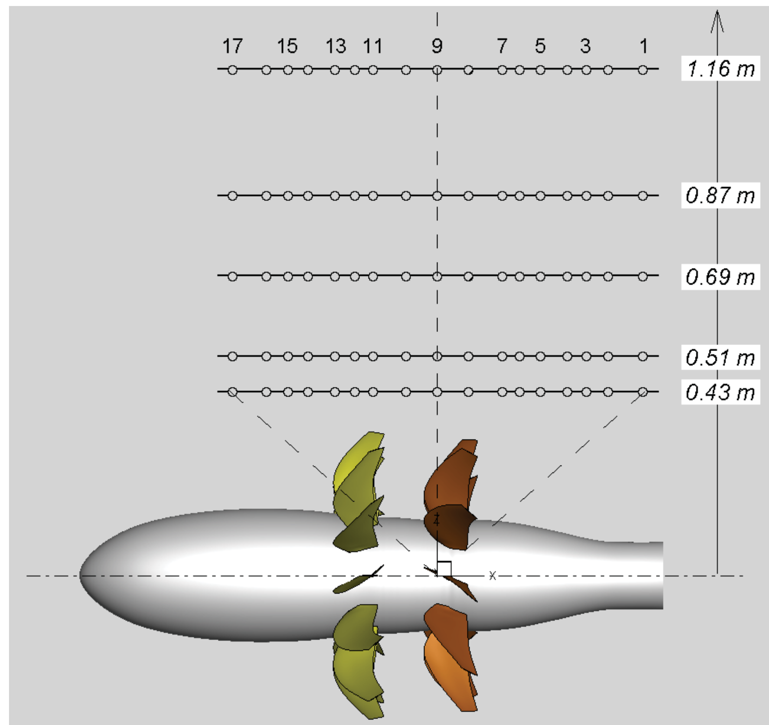
FINE/Turbo™ Computational Block (farfield blocks shown in gray)

Wind Tunnel Data

❖ **Aerodynamic/Acoustic data used for comparisons in this study were acquired in the NASA 8' x 6' high speed wind tunnel. Aerodynamic data include thrust and torque measurements, and acoustic data include nearfield sideline measurements.**



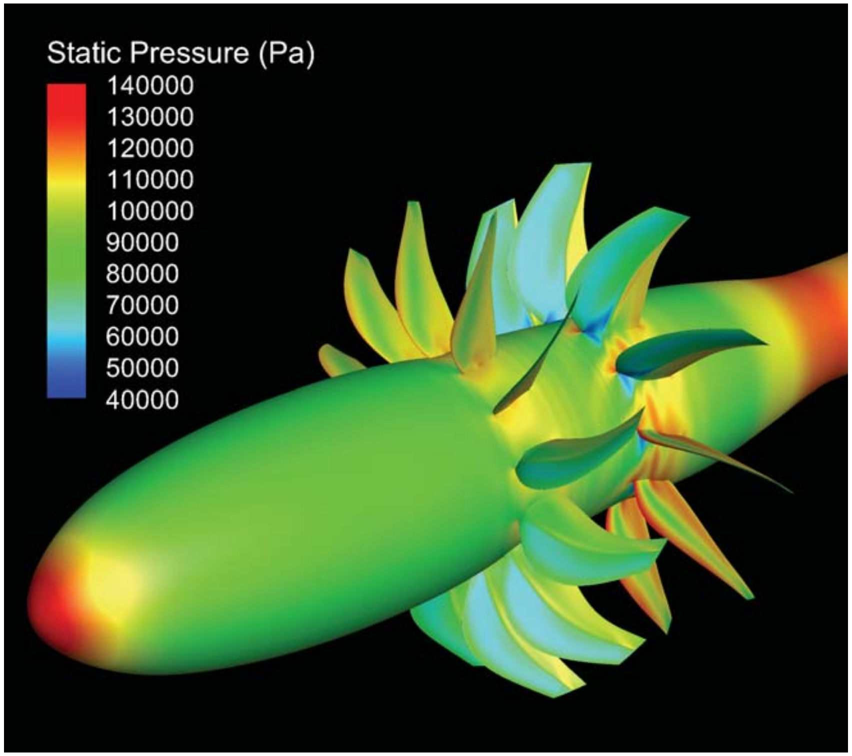
Model Scale GE F31/A31
Installed in NASA 8' x 6' WT



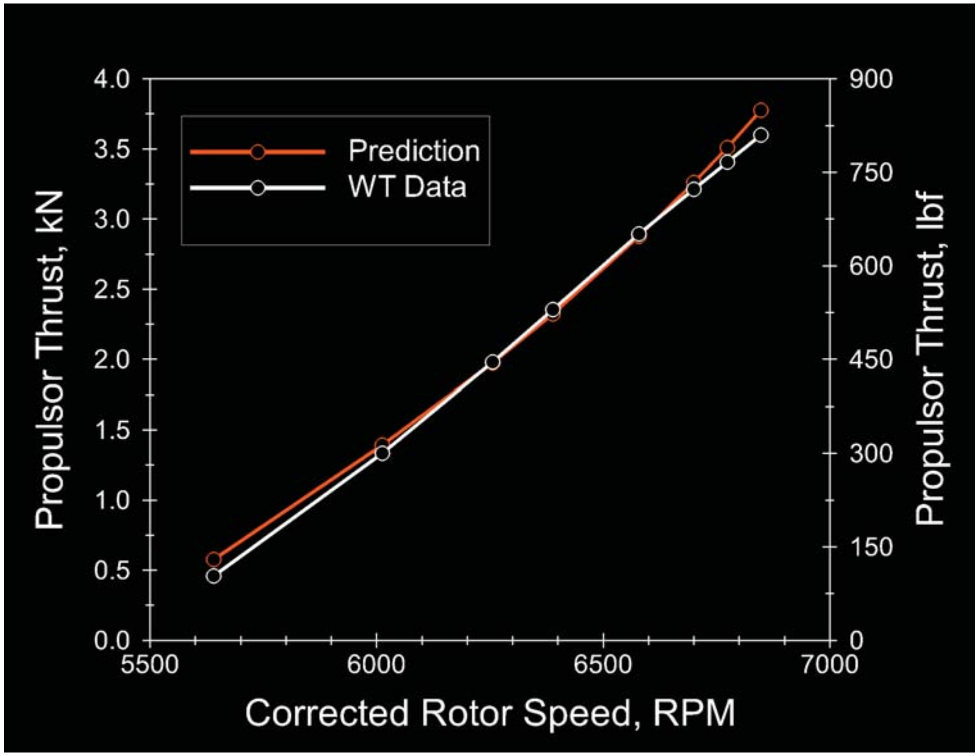
Vertical Positions of the Plate
Relative to Open Rotor Axis

Aerodynamic Predictions

❖ In total eight tip speed conditions were simulated. The front and aft rotor speeds were equal for all cases though neither the aero nor the acoustic model is restricted to equal RPM cases.



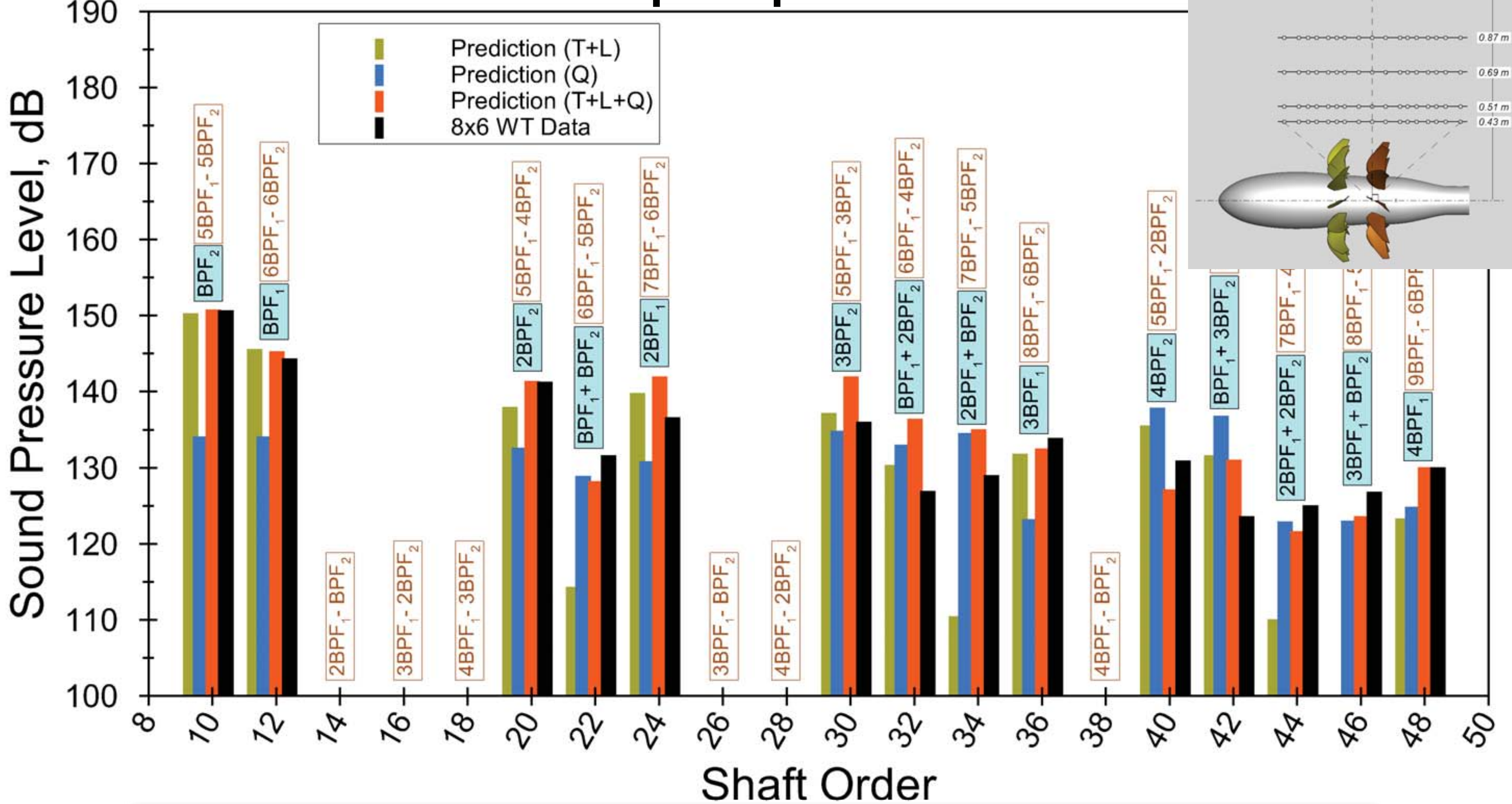
Mean Pressure Distribution at Highest Speed



Predicted & Measured Propulsor Thrust as a Function of Rotor Corrected Speed

Acoustic Predictions

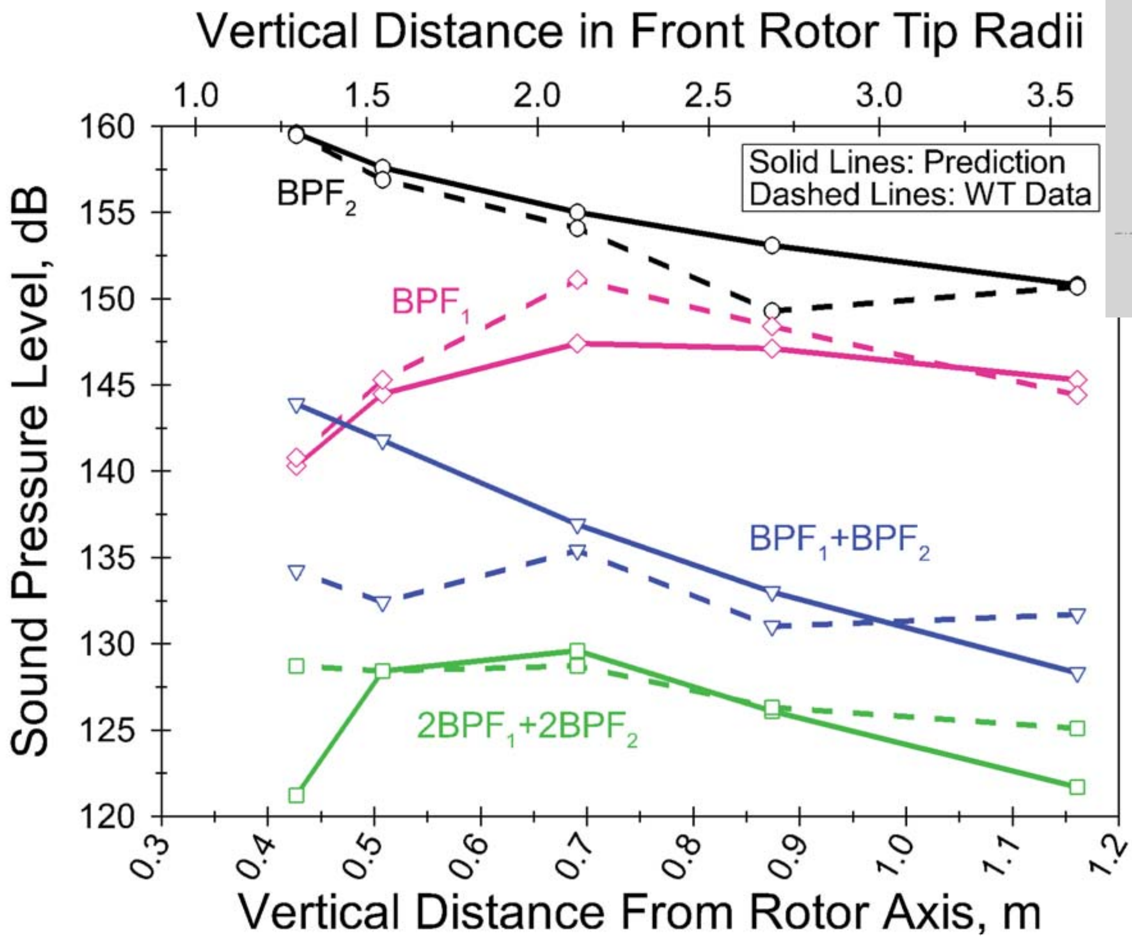
❖ **Tone spectral comparisons at the highest tip speed broadside to the aft rotor for farthest plate position.**

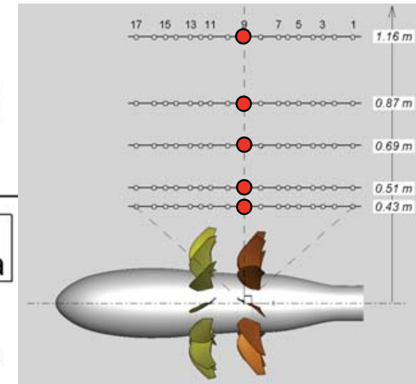


Typically, rotor tones are well-predicted using thickness & loading sources only, but interaction tones require the inclusion of quadrupole source for better agreement.

Acoustic Predictions (Cont'd)

❖ **Select tone SPLs at the highest tip speed broadside to the aft rotor for all plate positions.**

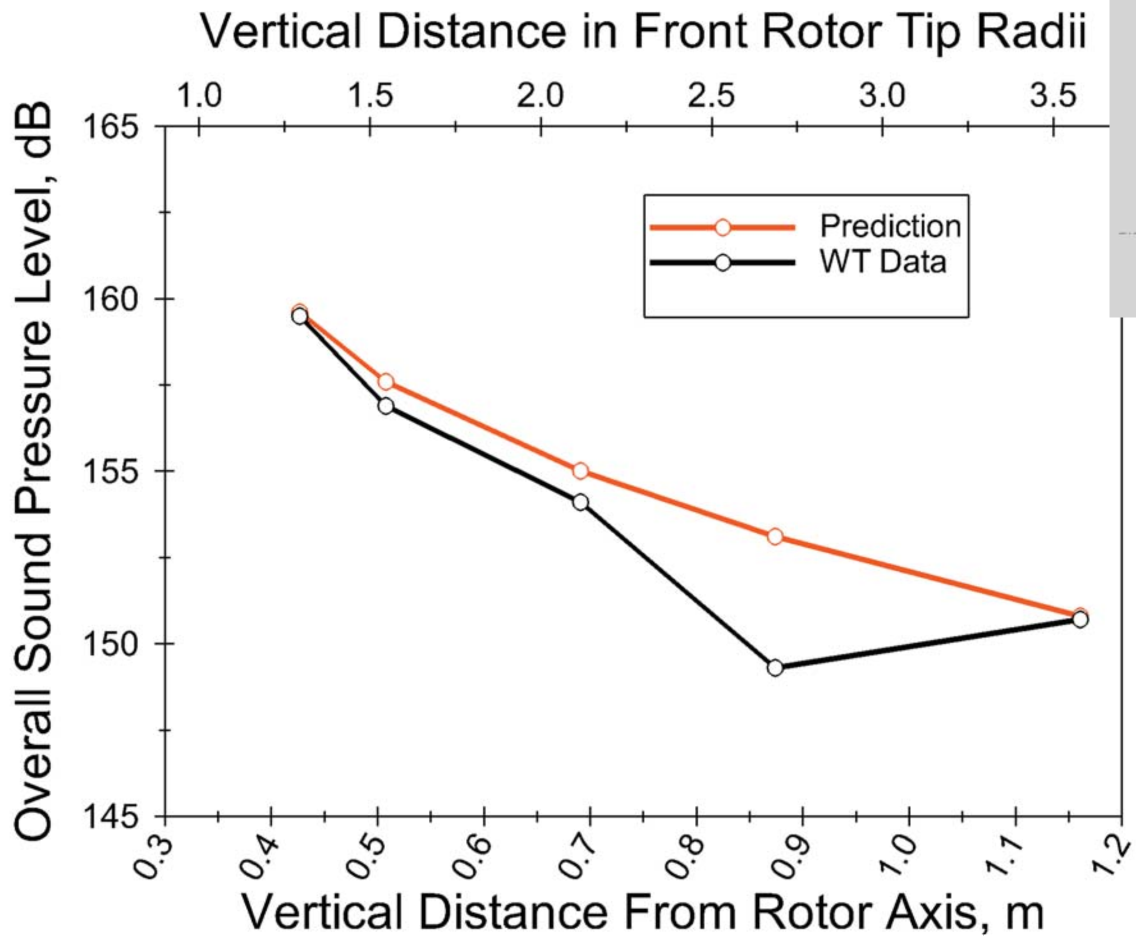


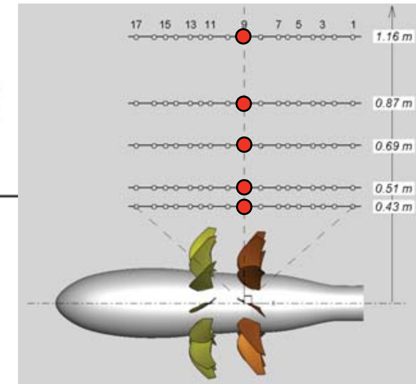


Absolute level of rotor tones are generally well-predicted (avg. Error = 1dB).
The agreement for the interaction tones is fair (avg. Error ≤ 3dB).

Acoustic Predictions (Cont'd)

❖ **Tone OASPL at the highest tip speed broadside to the aft rotor for all plate positions.**

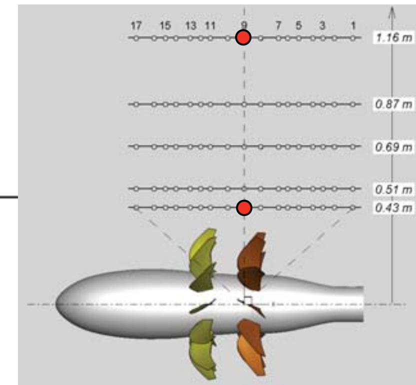


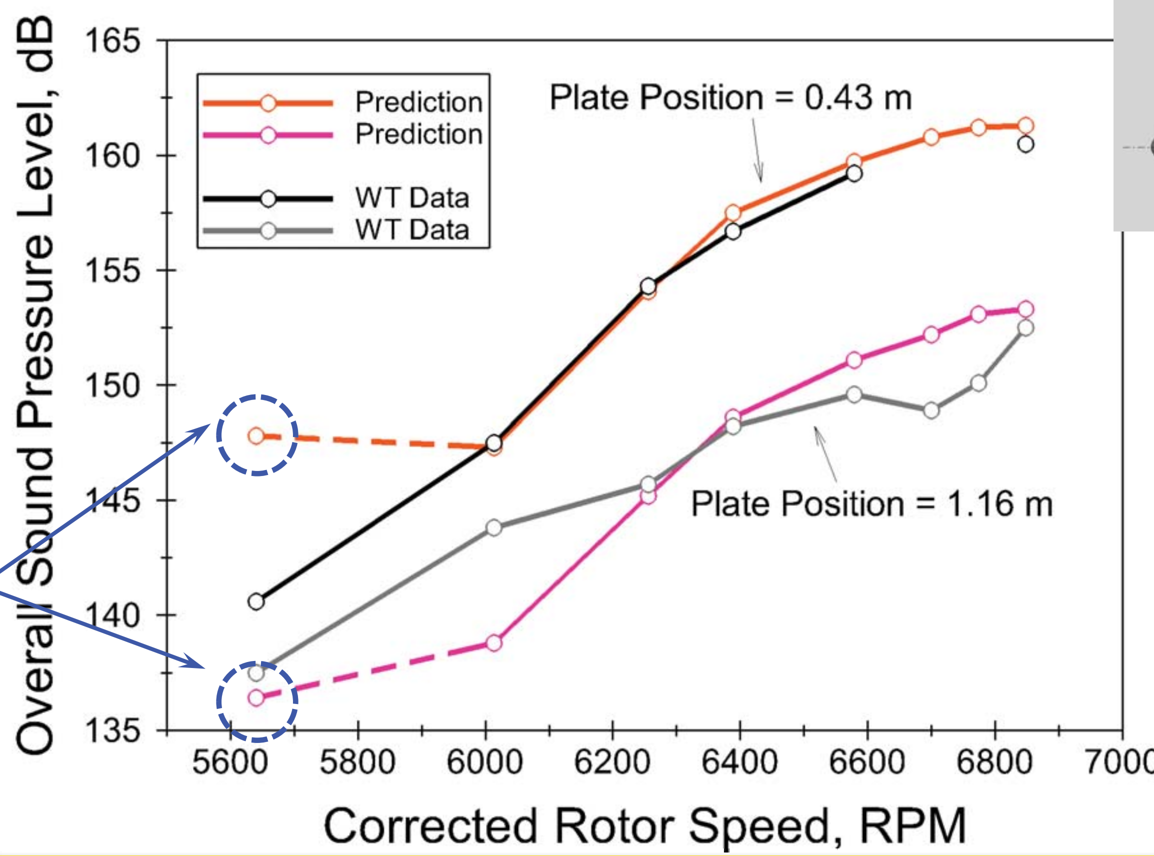


Tone OASPL is extremely well-predicted in all but one plate position. The predicted trend with plate distance is less erratic than the measured trend.

Acoustic Predictions (Cont'd)

❖ **Tone OASPL as a function of tip speed broadside to the aft rotor for two plate positions.**



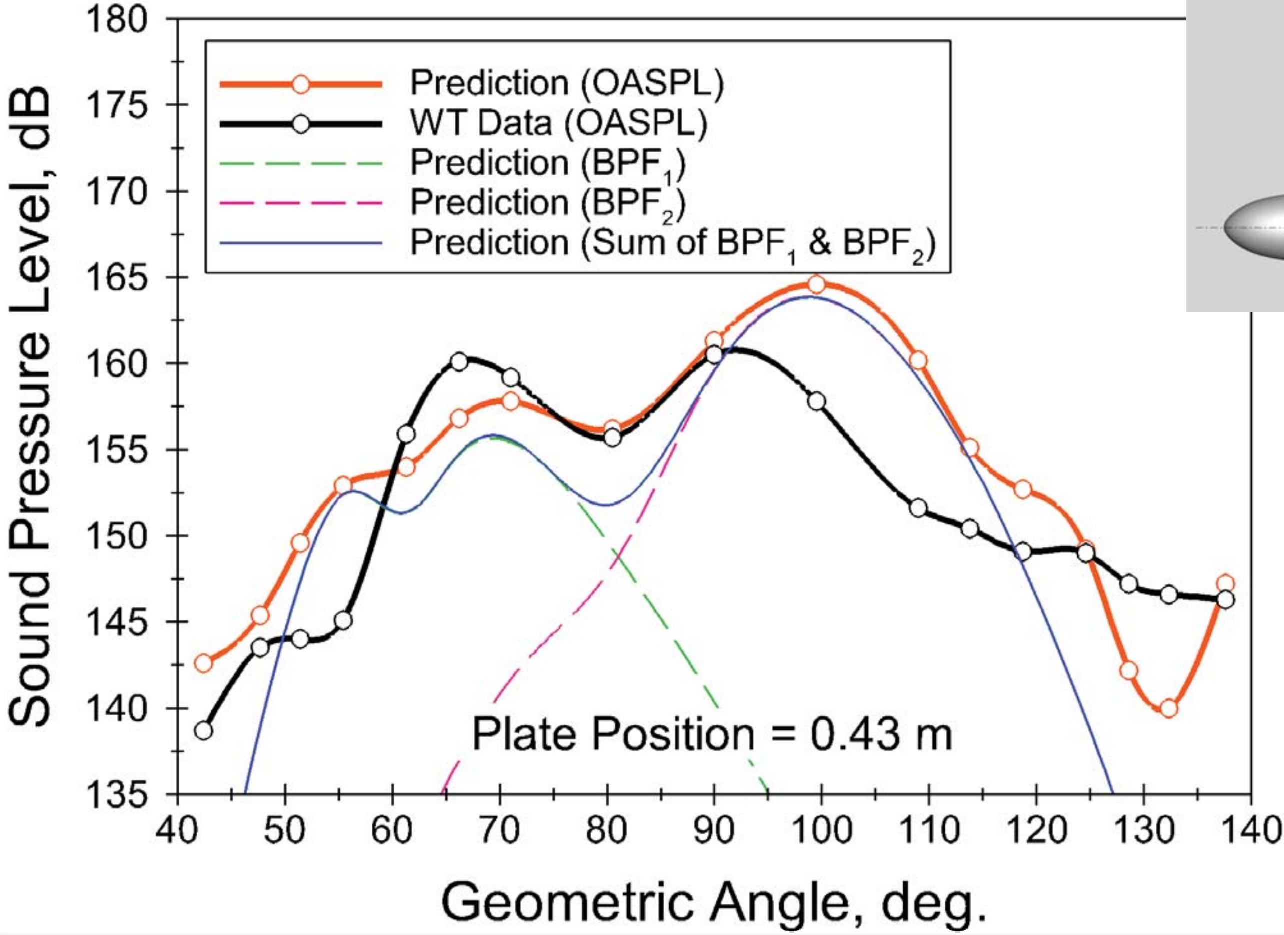


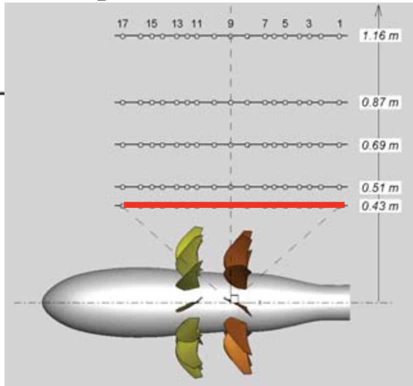
Measurements indicate aft rotor is near windmill at this speed. Predicted aft rotor thrust more than twice the measured thrust.

For nearest plate position tone OASPL is extremely well-predicted at all but the lowest speed. For the farthest plate position the agreement is fair.

Acoustic Predictions (Cont'd)

❖ **Tone OASPL directivity for highest tip speed for nearest plate position.**

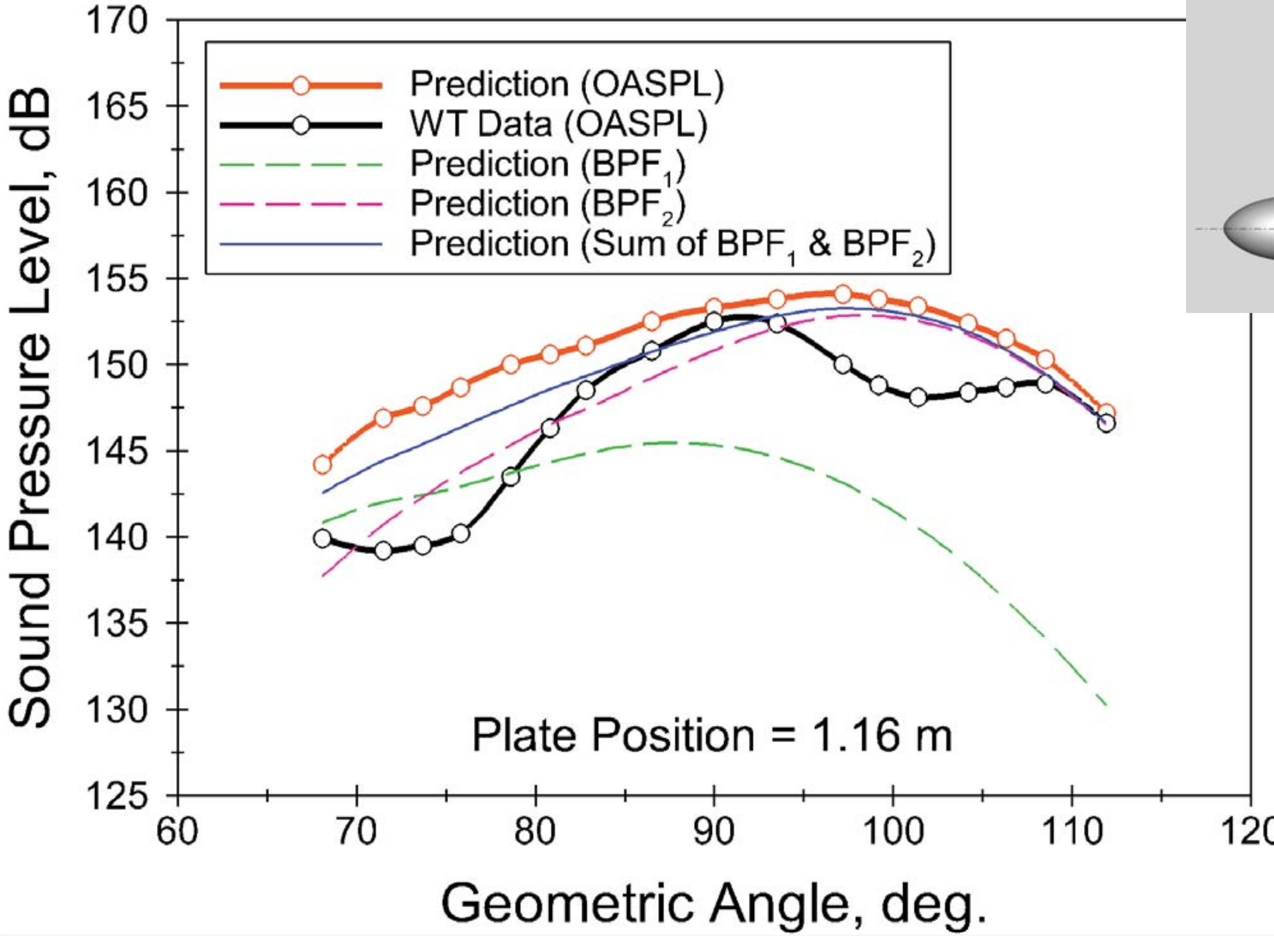


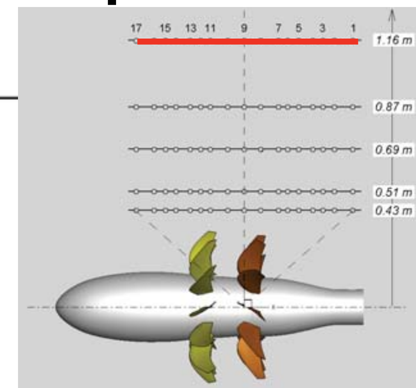


The data-theory agreement for the basic features and trends of tone OASPL directivity is good. In the neighborhood of the broadside location the levels are well-predicted.

Acoustic Predictions (Cont'd)

❖ **Tone OASPL directivity for highest tip speed for farthest plate position.**





The data-theory agreement for the basic features and trends of tone OASPL directivity is fair. In the neighborhood of the broadside location the levels are well-predicted.

Summary

- Assessment of a NASA acoustic analogy based open rotor noise prediction model has been carried out using nearfield acoustic data acquired for a model scale open rotor at cruise condition.
- Comparisons indicate that the strongest tones as well as tone OASPL are well predicted for the broadside locations for which plate boundary layer and end-effect corrections are relatively small.
- The quadrupole source does not influence the levels of rotor tones, but is crucial in determining the interaction tone levels.
- Not unexpectedly, the aft rotor contribution is more significant than the front rotor's.
- Thickness and loading source levels contribute roughly equally for the front rotor tones, but for the aft rotor tones the loading noise is entirely dominant.

Questions?