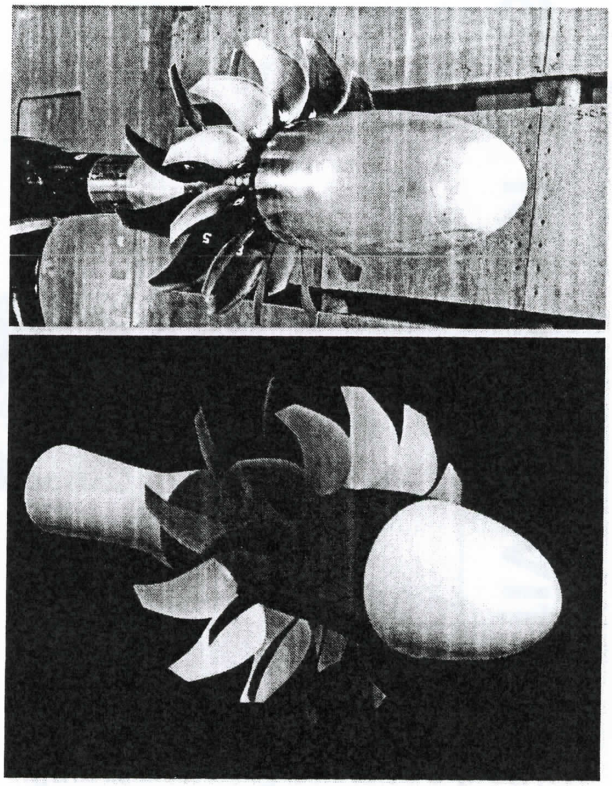
National Aeronautics and Space Administration

Open Rotor Noise Prediction – A Status Report



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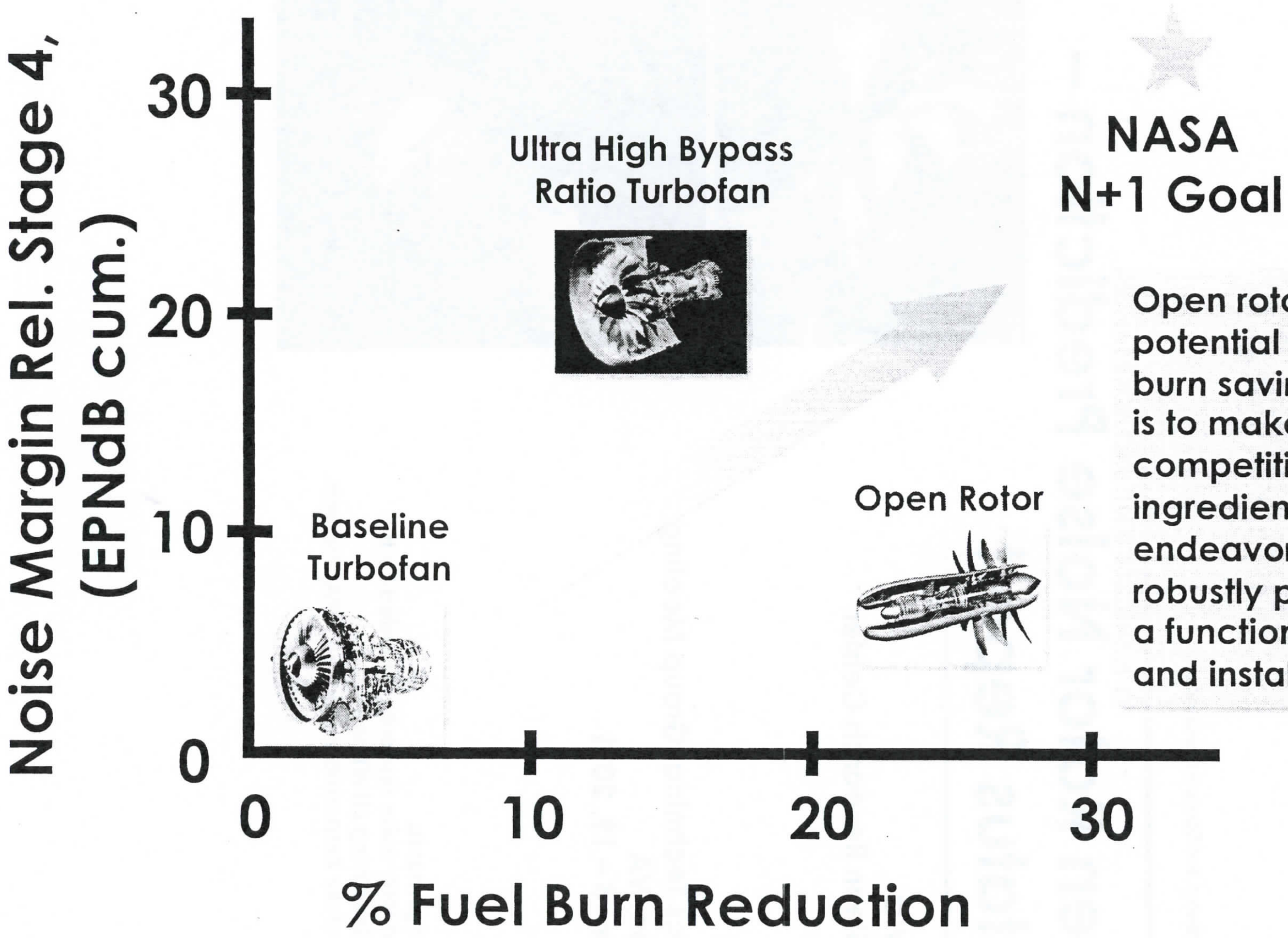
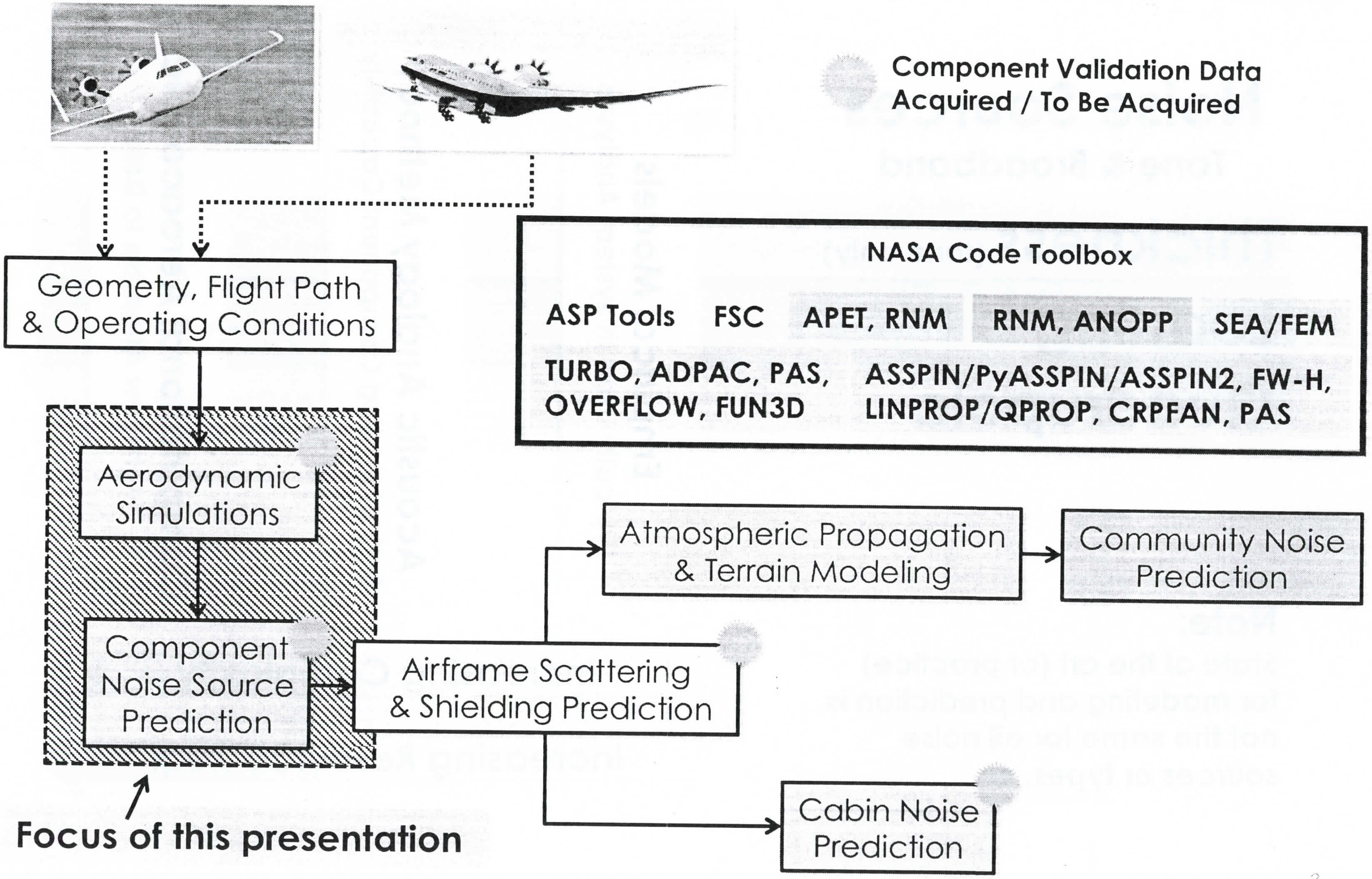
Motivation for This Work



Open rotors have the potential for significant fuel burn savings. The challenge is to make them acoustically competitive too. An essential ingredient of such an endeavor is the ability to robustly predict their noise as a function of design changes and installation effects.

Icons represent notional numbers based on published information

Acoustic Prediction Framework



Modeling Methodologies

Noise Sources

Tone & Broadband

Thickness (tone only)

Loading

Quadrupole

Empirical Models
Typically Used in System Analyses

Acoustic Analogy Methods
Bulk of Existing Component Capability

Computational Aeroacoustics
Very Few Attempts to Date

Increasing Complexity

Increasing Resource Req.

Note:
State of the art (or practice) for modeling and prediction is not the same for all noise sources or types.

Acoustic Analogy

Aerodynamic Calculation Step

Steady/Unsteady Aerodynamic Simulations
Used to Define Acoustic Source Strength Distribution

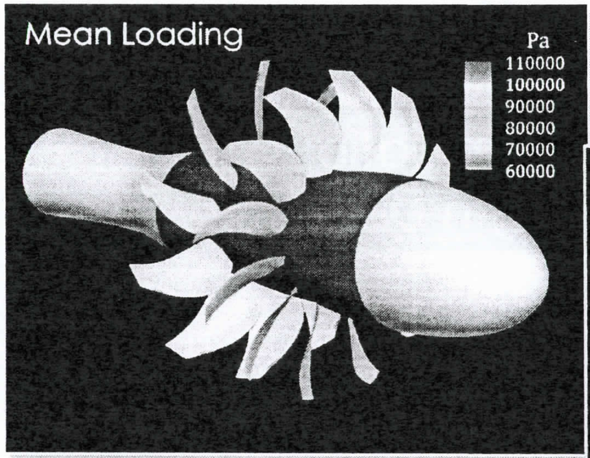
Acoustic Calculation Step

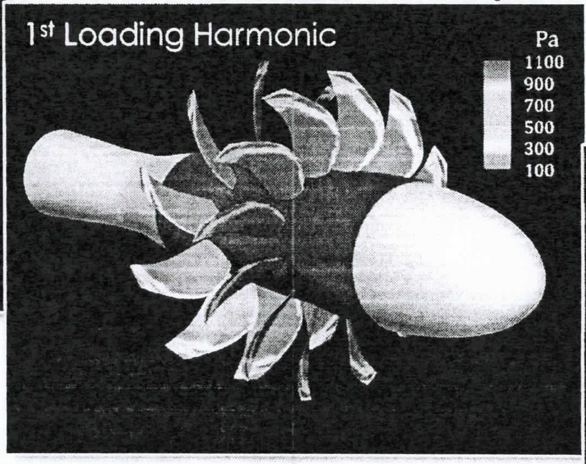
- Accuracy of the acoustics results is strongly influenced by the underlying aerodynamic input.
- Need efficient computational methods and strategies for computing aerodynamic input.

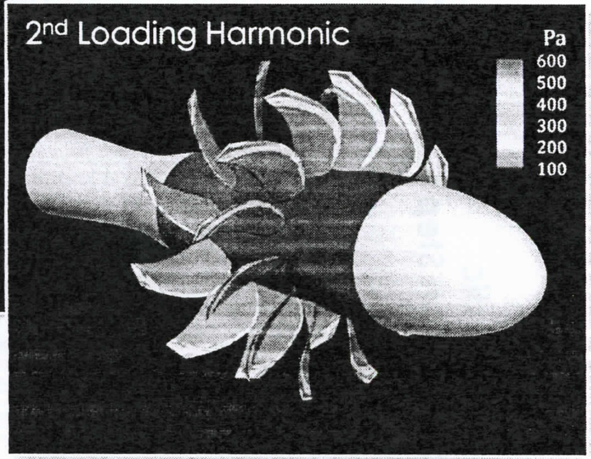
A team comprised of NASA GRC and OSU researchers has been tackling the aerodynamic analysis of open rotors. Currently using TURBO code (NASA & OSU) and Numeca's FINE/Turbo code (NASA) to compute the aerodynamics.

Aerodynamic Input

Example:
TURBO Unsteady RANS Simulation of F31/A31 at Nominal Takeoff Condition – Equal RPMs ($M_{tip\_Helical} \approx 0.66/0.64$)







12-Bladed Front Rotor 10-Bladed Rear Rotor		Measured*	Predicted
Thrust (lbf)	**Front Rotor**	303	304
	Rear Rotor	305	309
Torque (ft-lb)	**Front Rotor**	178	182
	Rear Rotor	171	177
Power (hp)	**Front Rotor**	225	230
	Rear Rotor	216	223

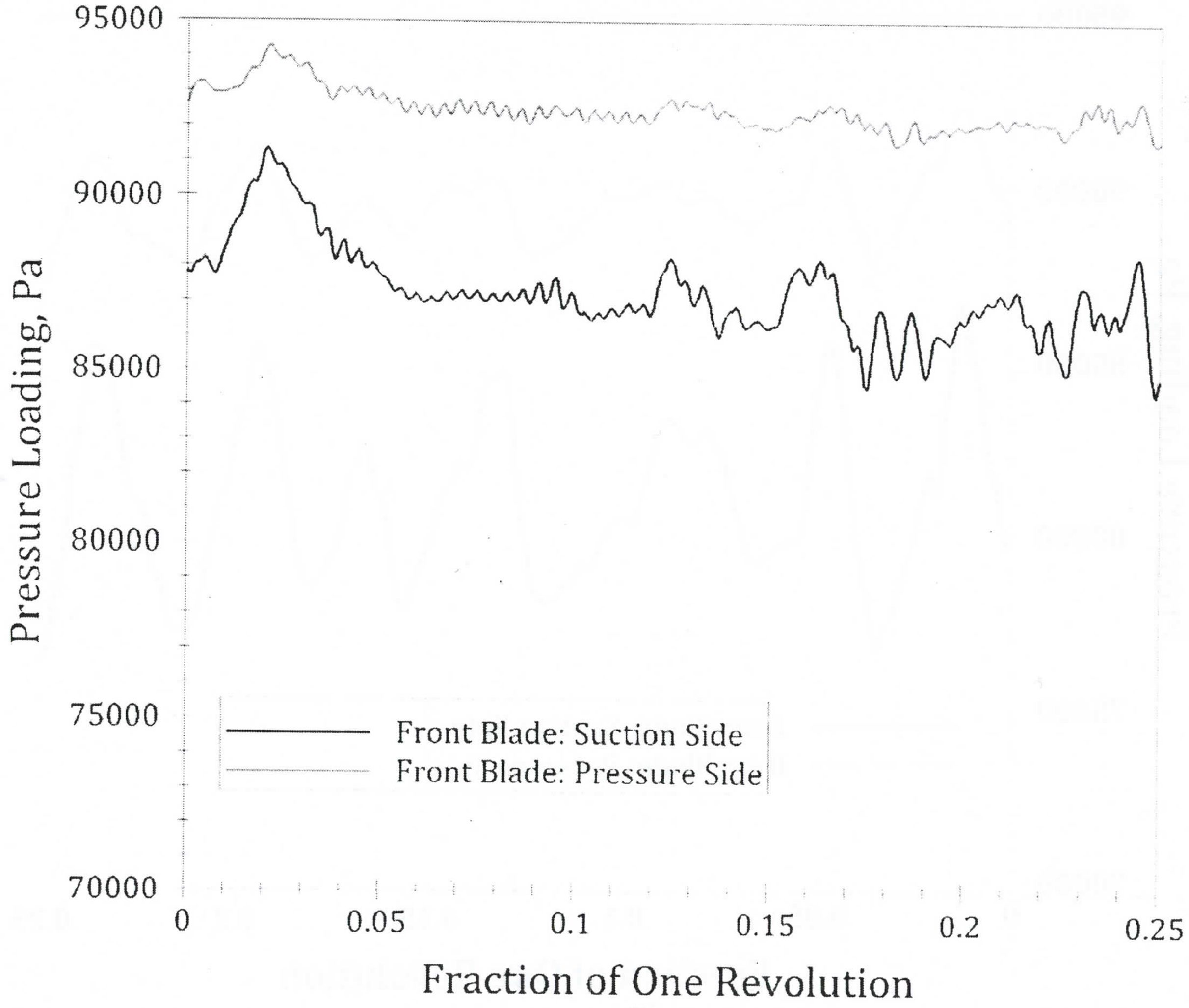
*Preliminary

Computed pressure distributions to be compared with pressure sensitive paint data.

Contour plots and integrated quantities shown here were computed from a simulation carried out at OSU by Trevor Goerig.

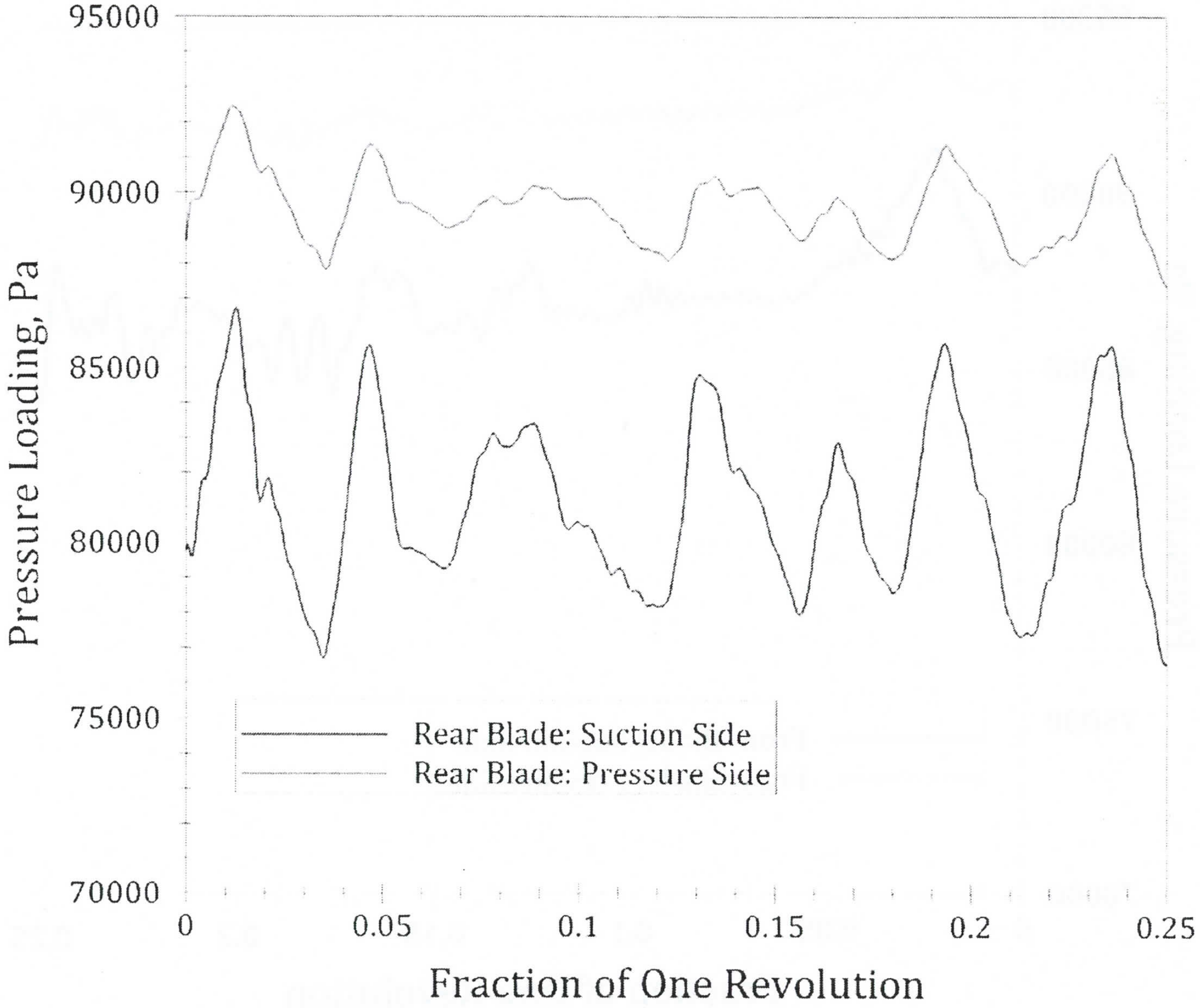
Computed Blade Loading Time Histories

Ex.: Front Rotor Time History at an Outboard Point on the Blade

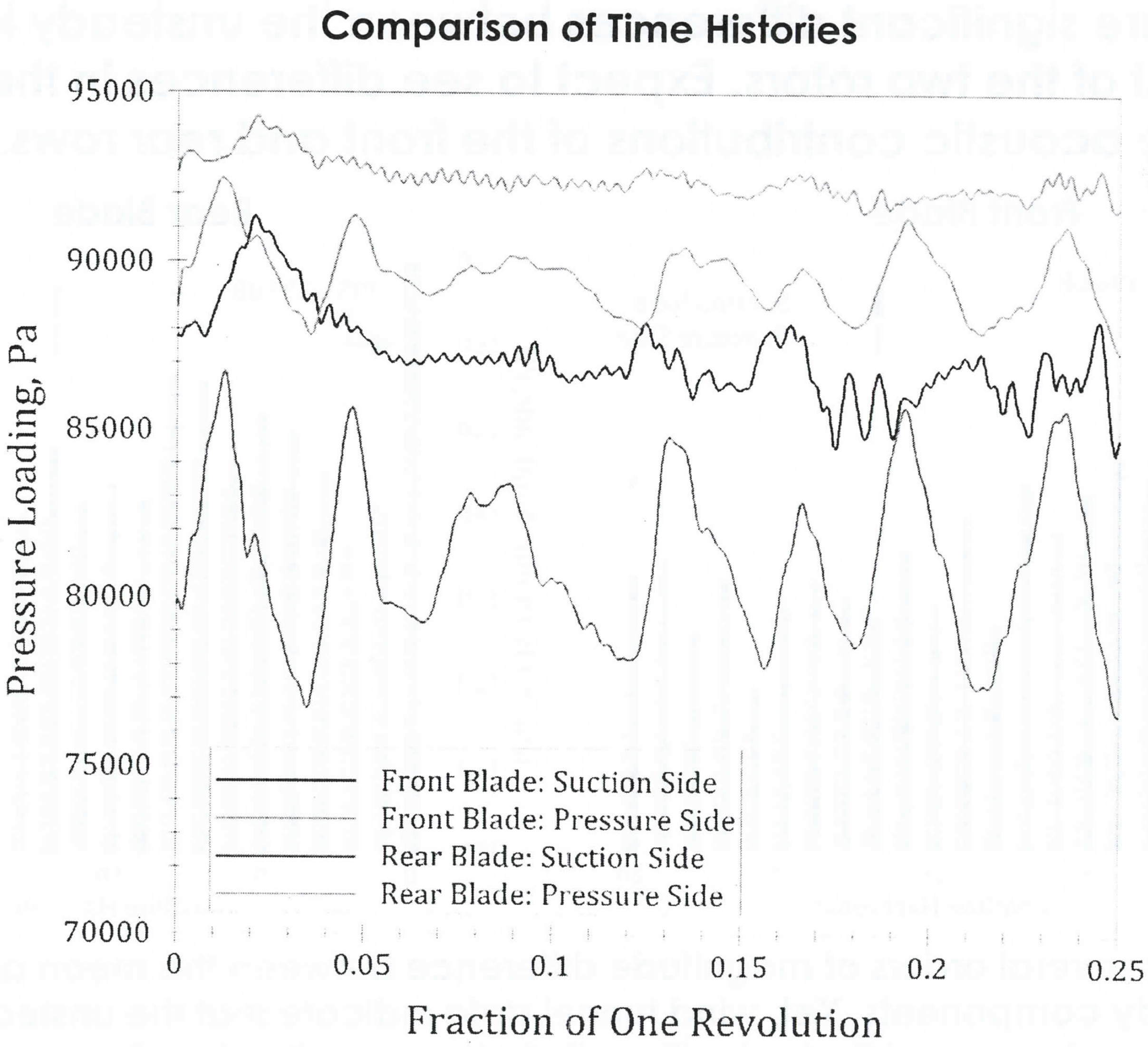


Computed Blade Loading Time Histories

Ex.: Rear Rotor Time History at an Outboard Point on the Blade



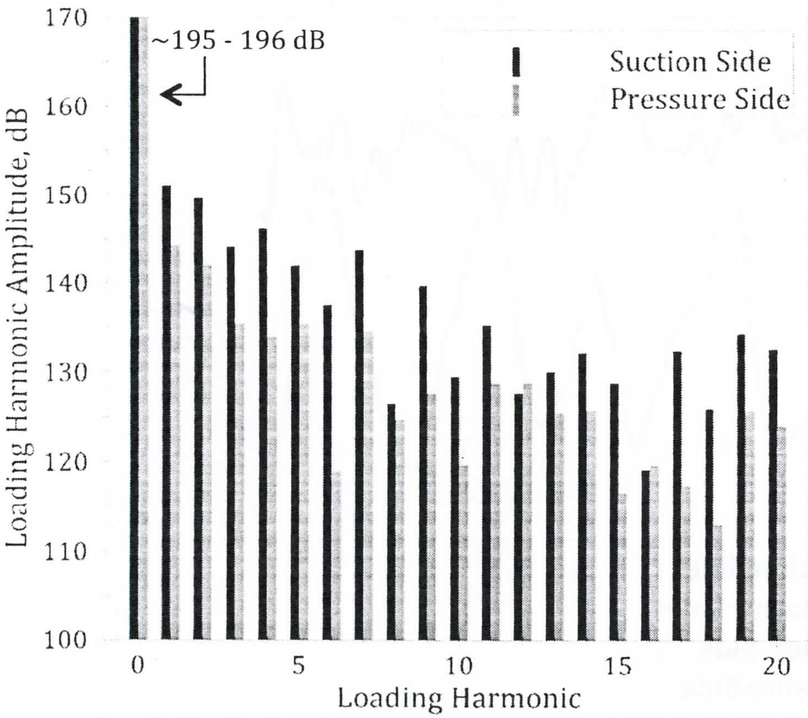
Computed Blade Loading Time Histories



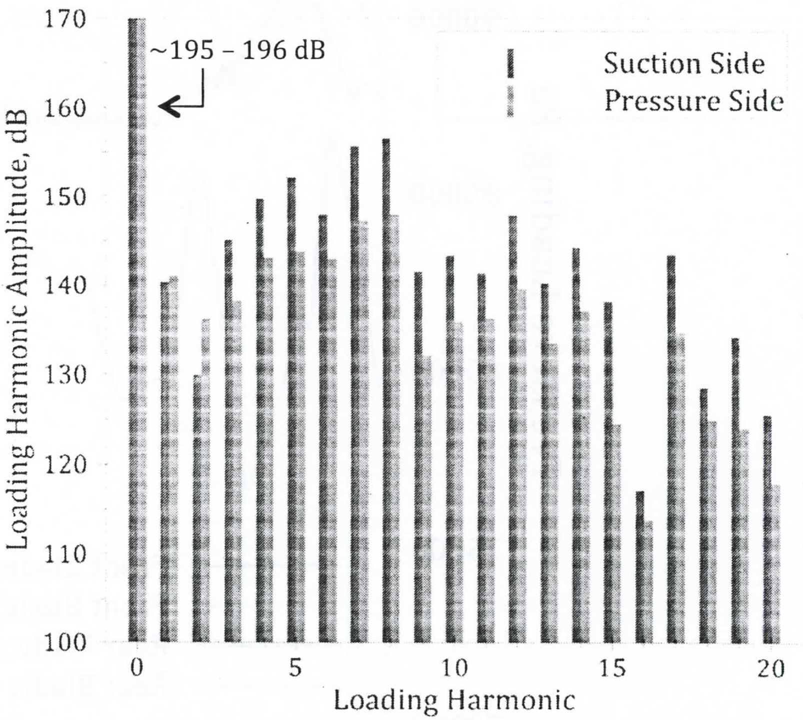
Computed Blade Loading Spectra

There are significant differences between the unsteady loading content of the two rotors. Expect to see differences in the relative acoustic contributions of the front and rear rows.

Front Blade



Rear Blade



There is several orders of magnitude difference between the mean and the unsteady components. Yet, wind tunnel data indicate that the unsteady component can contribute significantly to the overall noise of an open rotor.

Acoustic Solution – FW-H Equation

Blade Normal Velocity

Green's Function

$$p(\vec{x},t) = \int_{-T}^{T}\int_{S(\tau)} \underbrace{\rho_0 v_n}_{\substack{\text{Thickness Source} \\ \text{(geometric input)}}} \underbrace{\frac{D_0 G}{D\tau}}_{\text{Propagation}} \, ds \, d\tau \; +$$

Blade Loading

$$\int_{-T}^{T}\int_{S(\tau)} \underbrace{F_j}_{\substack{\text{Loading Source} \\ \text{(aerodynamic input)}}} \underbrace{\frac{\partial G}{\partial y_j}}_{\text{Propagation}} \, ds \, d\tau \; +$$

Linear Sources

Lighthill Stress

$$\int_{-T}^{T}\int_{V(\tau)} \underbrace{T_{jk}}_{\substack{\text{Quadrupole Source} \\ \text{(aerodynamic input)}}} \underbrace{\frac{\partial^2 G}{\partial y_j \partial y_k}}_{\text{Propagation}} \, ds \, d\tau$$

Nonlinear Source

Frequency-Domain Solution

Solution for Isolated Rotor (Valid for All Source Types)

Ref.: E. Envia, AIAA Journal, Vo. 32, No. 2, February 1994

$$p(\vec{x},t) = \sum_{m=-\infty}^{\infty} \underbrace{\left(p_{mB}^{(T)}(\vec{x}) + p_{mB}^{(L)}(\vec{x}) + p_{mB}^{(Q)}(\vec{x})\right)}_{\text{Tone Amplitude}} e^{-i\overbrace{mB\Omega}^{\text{Tone Frequency}}t}$$

B Blade Count

Ω Rotational Speed

Airy Function & Its Derivative

$$p_{mB}^{(T,L,Q)}(\vec{x}) = \int_{S_0,V_0} e^{-imB\Psi} \underbrace{\left\{ d_0^{(T,L,Q)} \frac{Ai\left[(mB)^{2/3}\gamma^2\right]}{(mB)^{1/3}} + d_1^{(T,L,Q)} \frac{Ai'\left[(mB)^{2/3}\gamma^2\right]}{(mB)^{2/3}} \right\}}ds$$

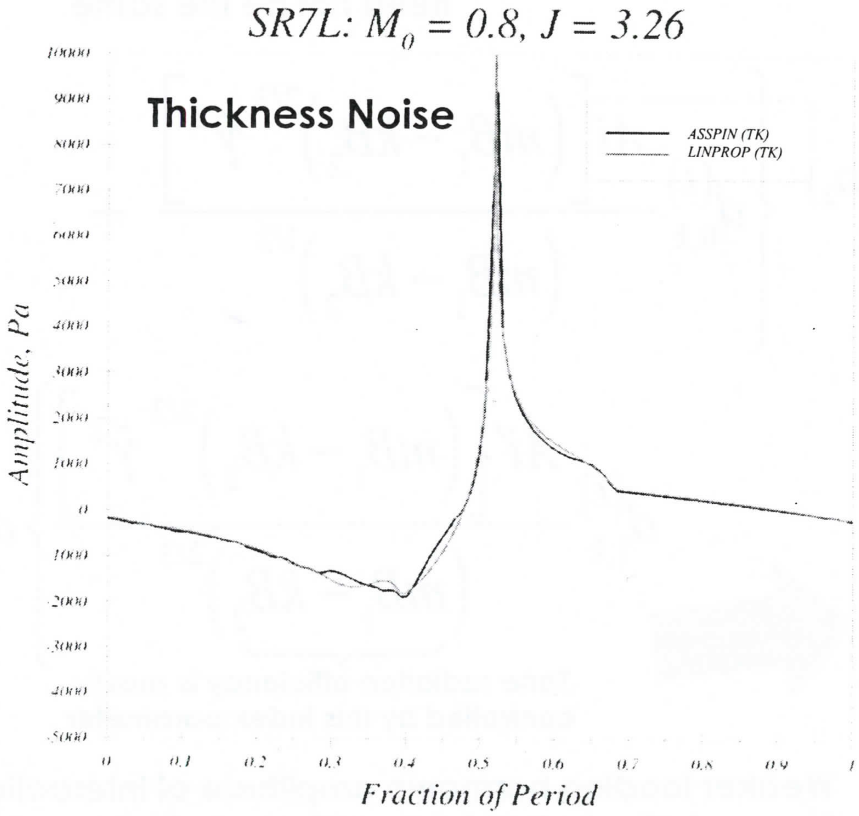
Surface or Volume Integral Computed Using Quadrature

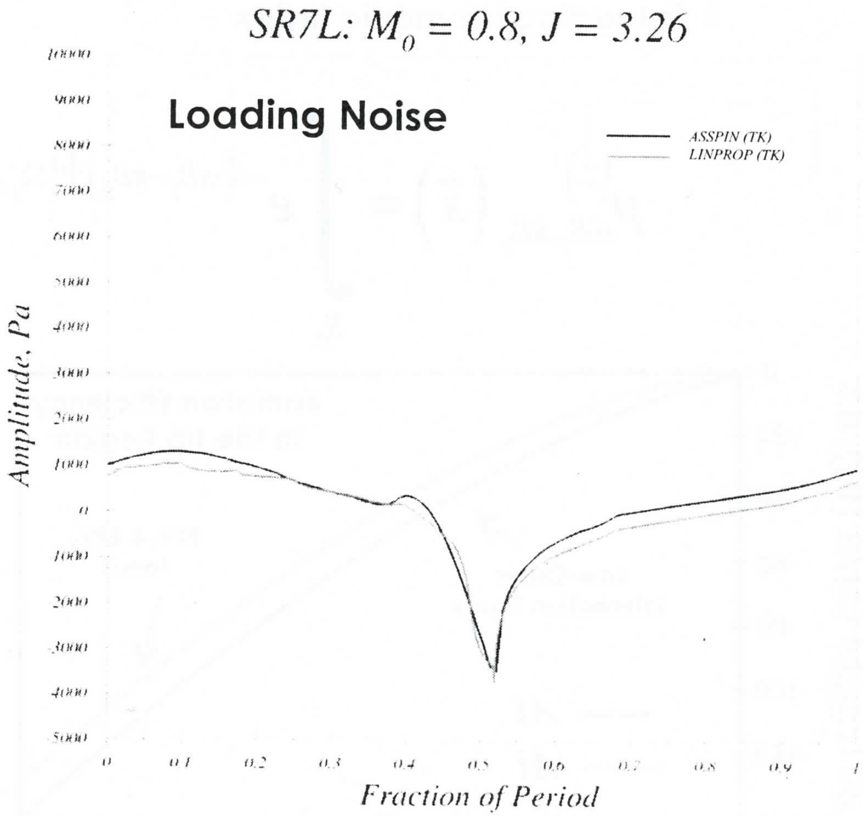
Uniform Asymptotic Approximation to Radiation Efficiency Integral (i.e., integration over τ). This formula is much more efficient than carrying out the integration numerically when the parameter *mB* is large.

The representation is valid across the tip speed regime (subsonic to supersonic) and applicable to any observer position (near- or far-field). The code based on that solution for thickness & loading sources is called LINPROP and that for quadrupole source is called QPROP. The Data-theory comparisons for single rotation rotor configurations for both codes can be found in the cited reference.

Comparison to Time-Domain Codes

More Recent Single Rotation Example
SR7 Propfan Noise Predicted Using LINPROP & ASSPIN Codes





Ext. of LINPROP/QPROP to Open Rotors

* Only loading term needs to be modified

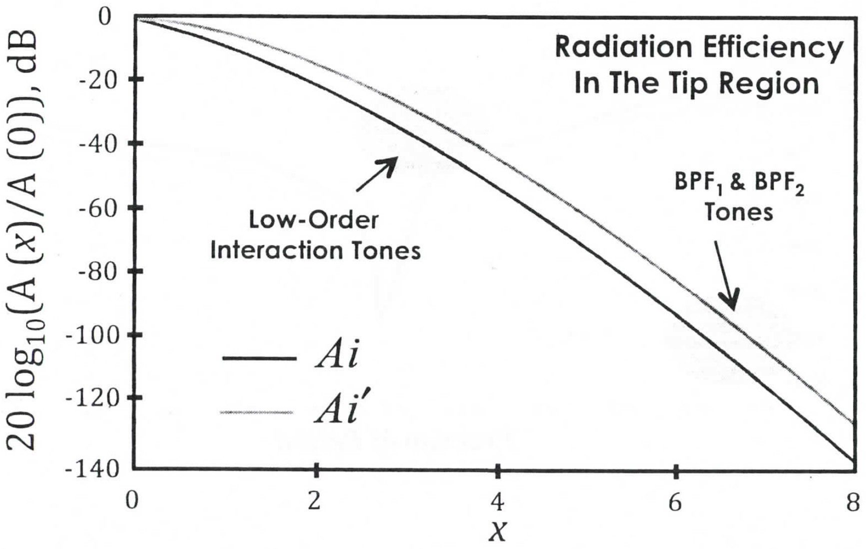
$$p^{(L)}(\vec{x},t) = \sum_{m=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} \underbrace{p^{(L)}_{mB_1,kB_2}(\vec{x})}_{\text{Tone Amplitude}} e^{-i\overbrace{(mB_1\Omega_1 + kB_2\Omega_2)}^{\text{Tone Frequency}}t}$$

Blade counts and rotational speeds need not be the same

m is noise harmonic index
k is loading harmonic index

$$p^{(L)}_{mB_1,kB_2}(\vec{x}) = \int_{S_0} e^{-i(mB_1-kB_2)\tilde{\Psi}(\Omega_1,\Omega_2)} \left\{ d^{(L)}_{0,k} \frac{Ai\left[(mB_1-kB_2)^{2/3}\tilde{\gamma}^2\right]}{(mB_1-kB_2)^{1/3}} + d^{(L)}_{1,k} \frac{Ai'\left[(mB_1-kB_2)^{2/3}\tilde{\gamma}^2\right]}{\underbrace{(mB_1-kB_2)}^{2/3}} \right\} ds$$

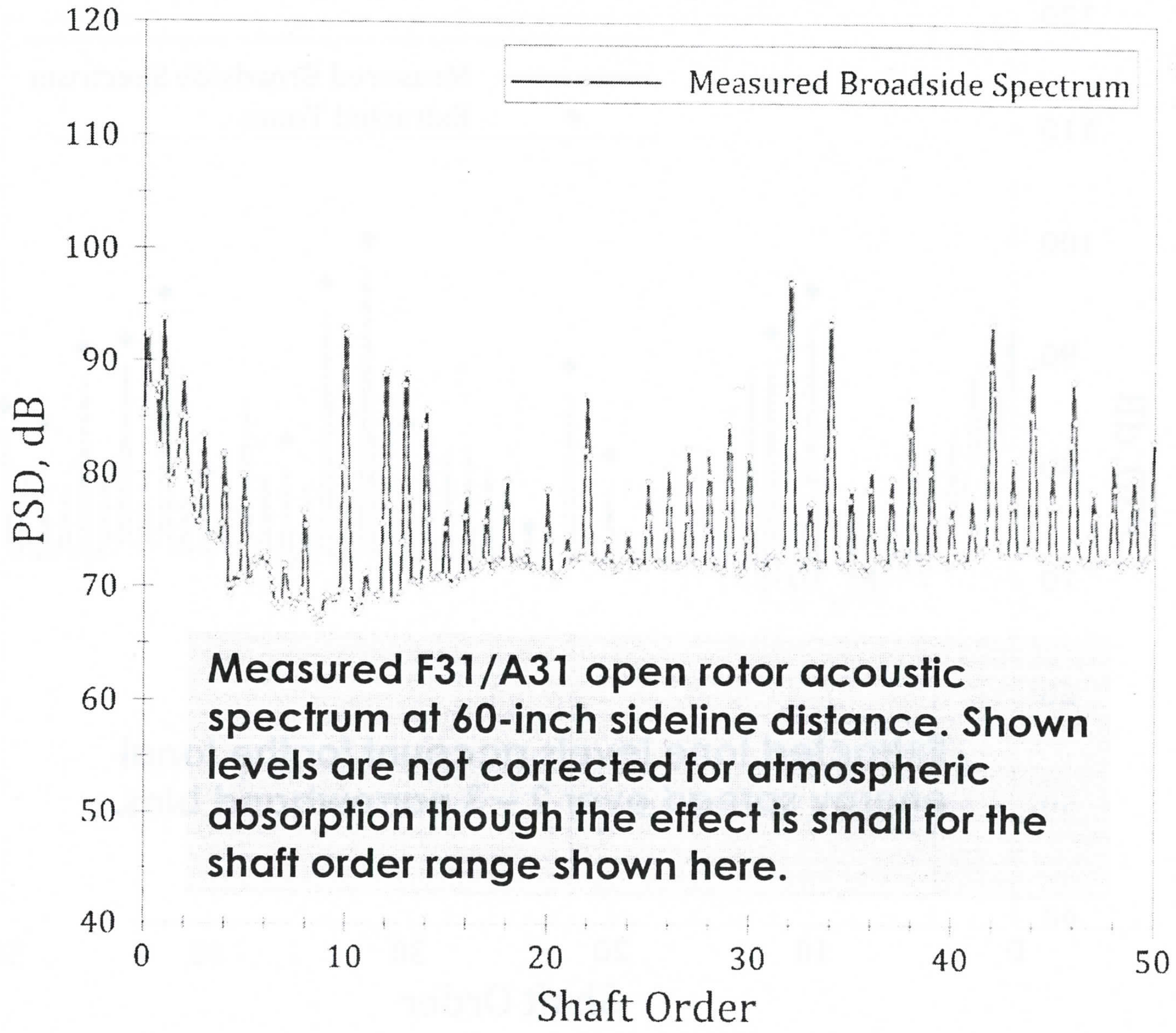
Tone radiation efficiency is mostly controlled by this index parameter



Weaker loading harmonic amplitude of interaction tones relative to that for the primary rotor tones is offset by their much higher radiation efficiency.

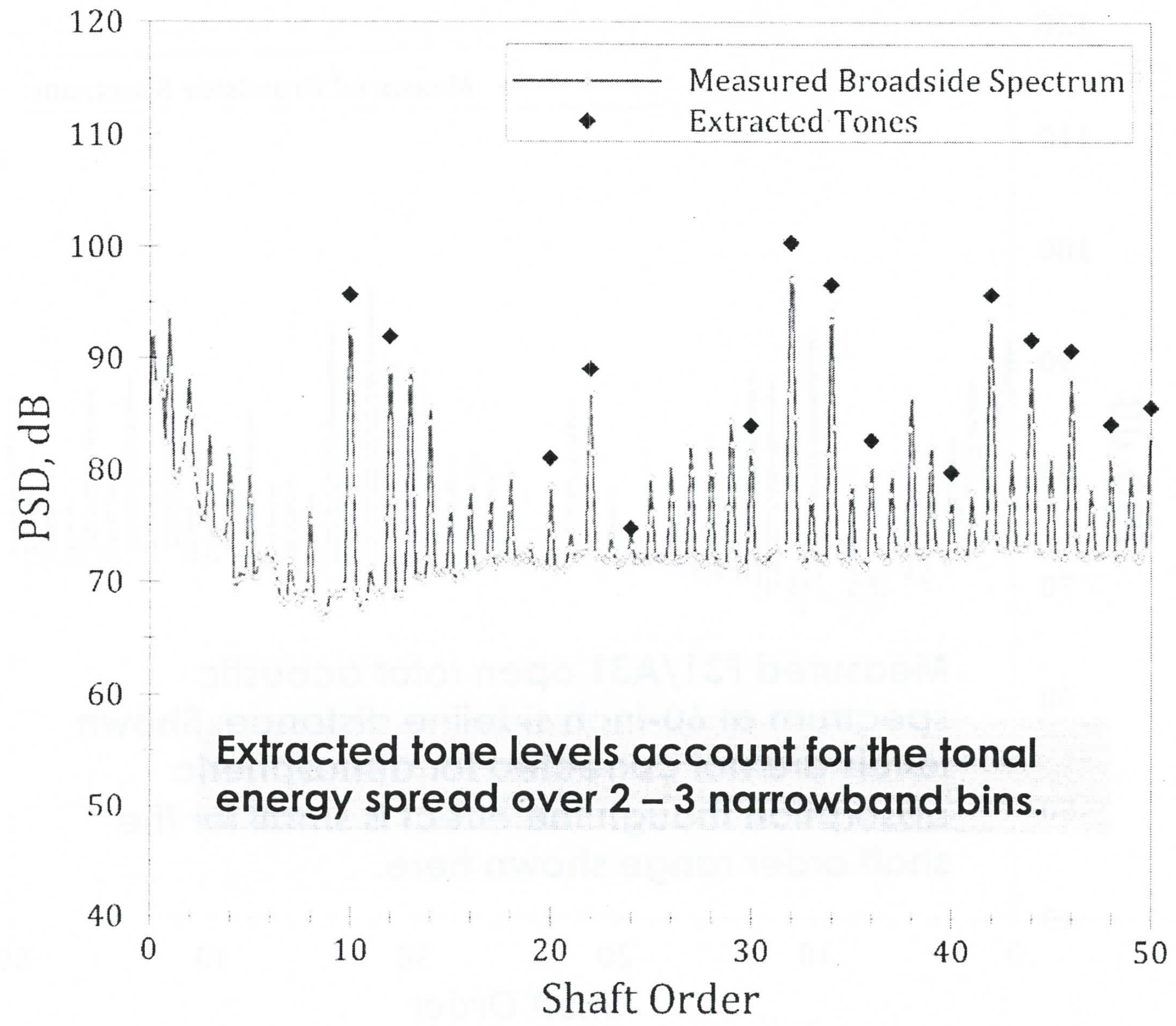
Preliminary Acoustic Predictions

Measured Sideline Narrowband Acoustic Spectrum at Broadside Position



Preliminary Acoustic Predictions

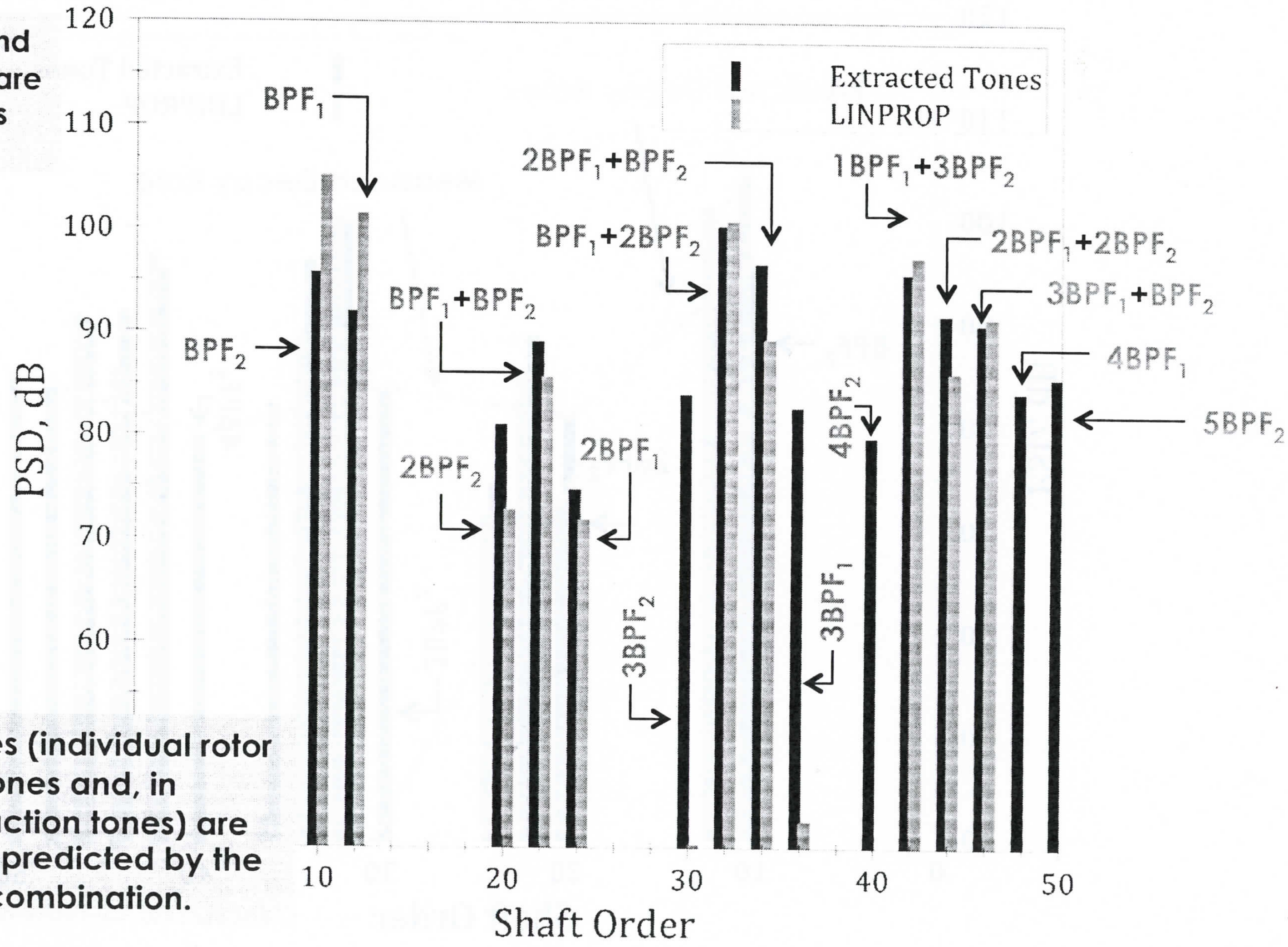
Tone Extraction from Narrowband Spectrum



Preliminary Acoustic Predictions

Data-Theory Comparisons Using LINPROP Predictions

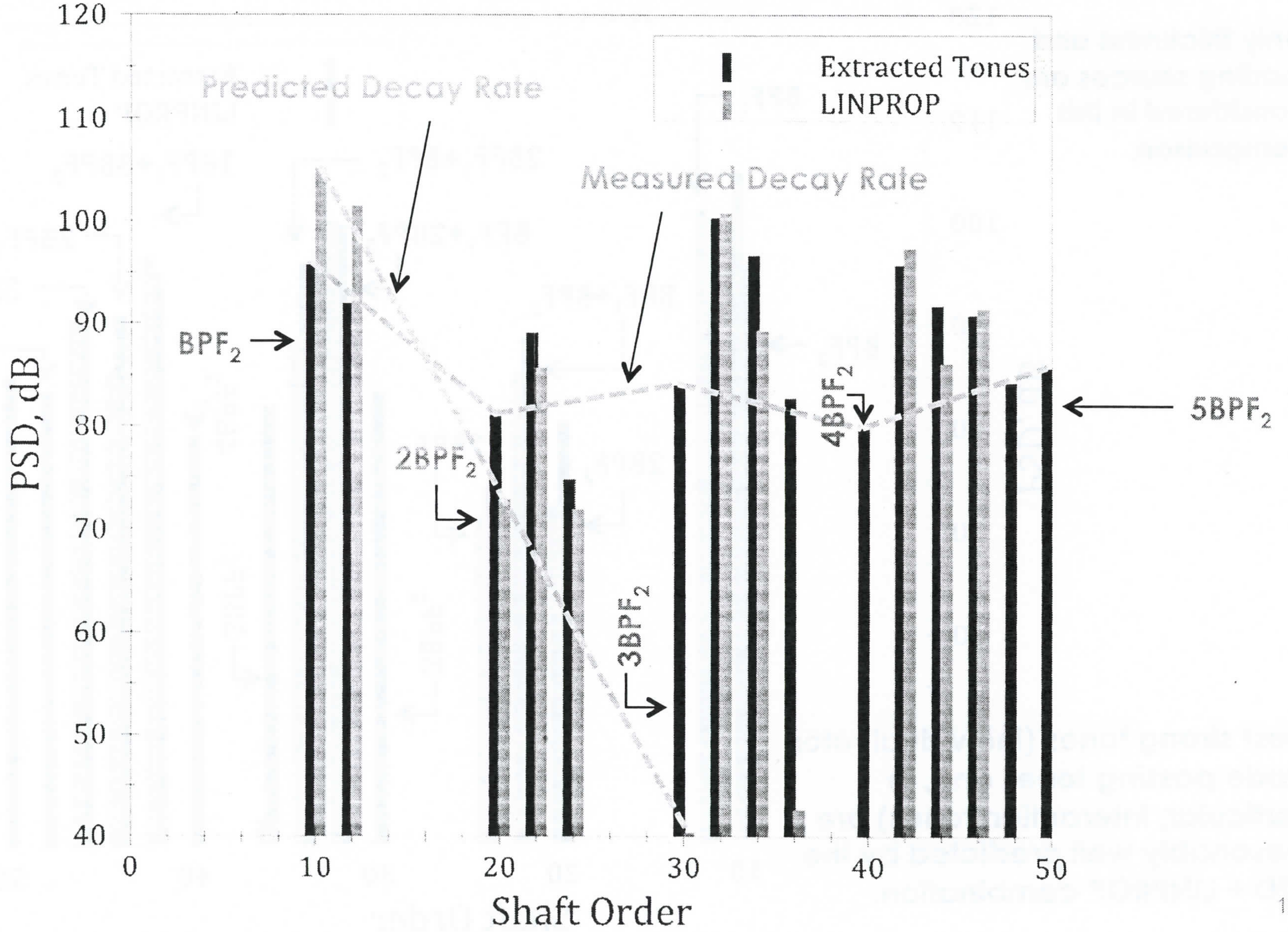
Only thickness and loading sources are considered in this comparison.



Most strong tones (individual rotor blade passing tones and, in particular, interaction tones) are reasonably well predicted by the CFD + LINPROP combination.

Preliminary Acoustic Predictions

Decay rates of measured individual rotor harmonics (i.e., $nBPF_1$ & $nBBF_2$) do not conform to the expected behavior at subsonic helical tip speeds. Culprit may be either nonlinear propagation effects in the nearfield (likely) or contribution from the quadrupole source (not very likely).



Summary

- An effort has been underway at NASA to assess and improve NASA open rotor noise prediction tools. LINPROP and QPROP are among the NASA codes for source noise prediction that have been extended and are being evaluated for handling open rotor configurations.

- A critical element of the noise prediction process is the computation of the unsteady aerodynamic input needed by these codes.

- Preliminary results suggest that LINPROP can predict open rotor interaction tone noise reasonably well, but additional improvements may be necessary to better match the measured individual rotor harmonics ($nBPF_1$ and $nBBF_2$) in the nearfield. Given the preponderance of tones in open rotor spectra, the highly efficient asymptotic approach incorporated into LINPROP (and QPROP) makes it quite suitable for this type of analysis. The bottleneck is the CFD input generation process.

- Concurrent efforts at NASA and OSU have been focused on making the aerodynamic prediction element more efficient using both fully coupled TURBO and "selectively" coupled FINE/Turbo CFD approaches.

- Further analysis and data-theory comparisons are underway to establish the accuracy and robustness of the LINPROP and QPROP codes in particular, and the FW-H approach in general.