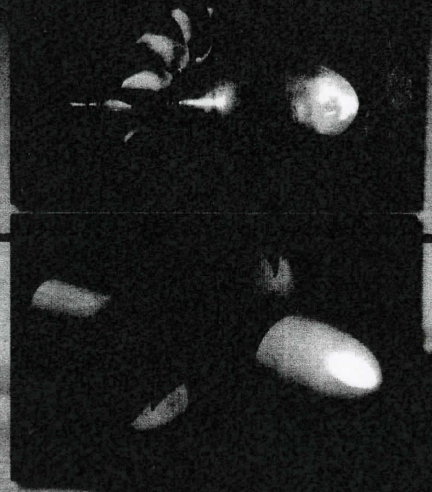
National Aeronautics and Space Administration

Open Rotor Noise Prediction



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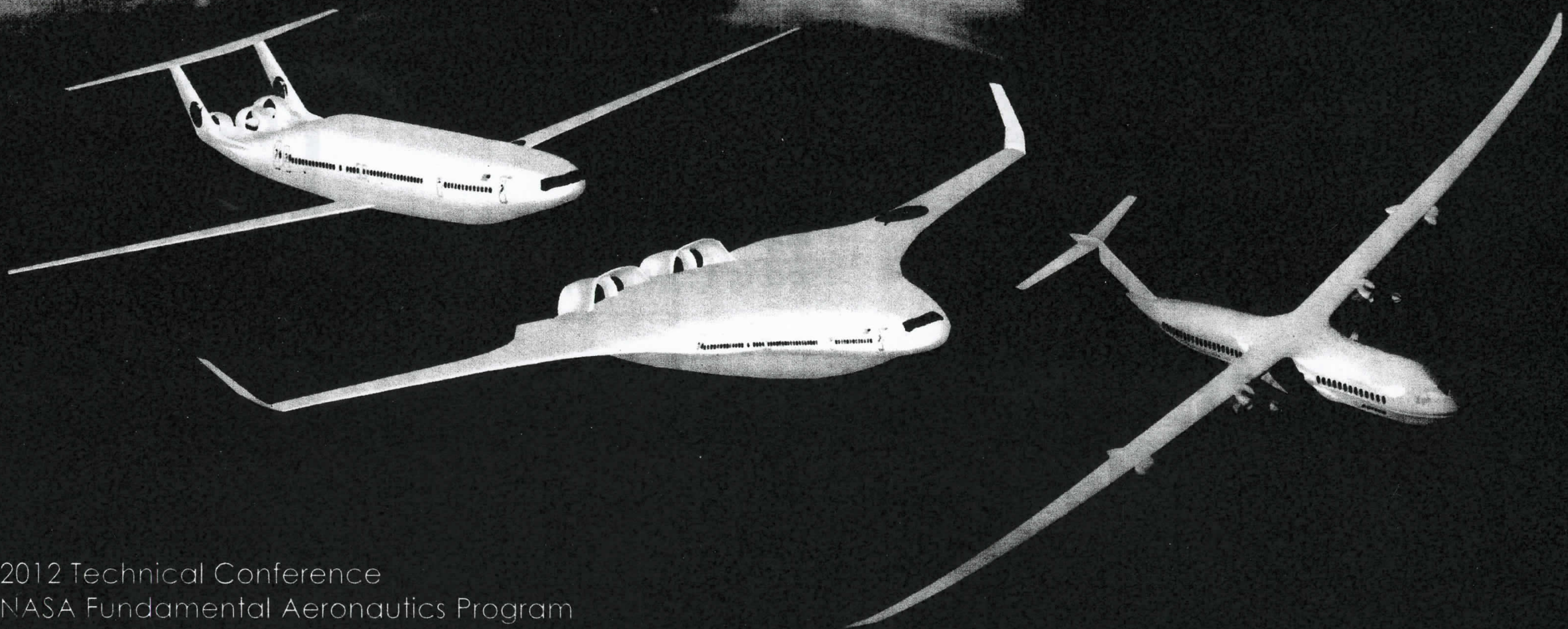

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NASA Fundamental Aeronautics Program
Subsonic Fixed Wing Project
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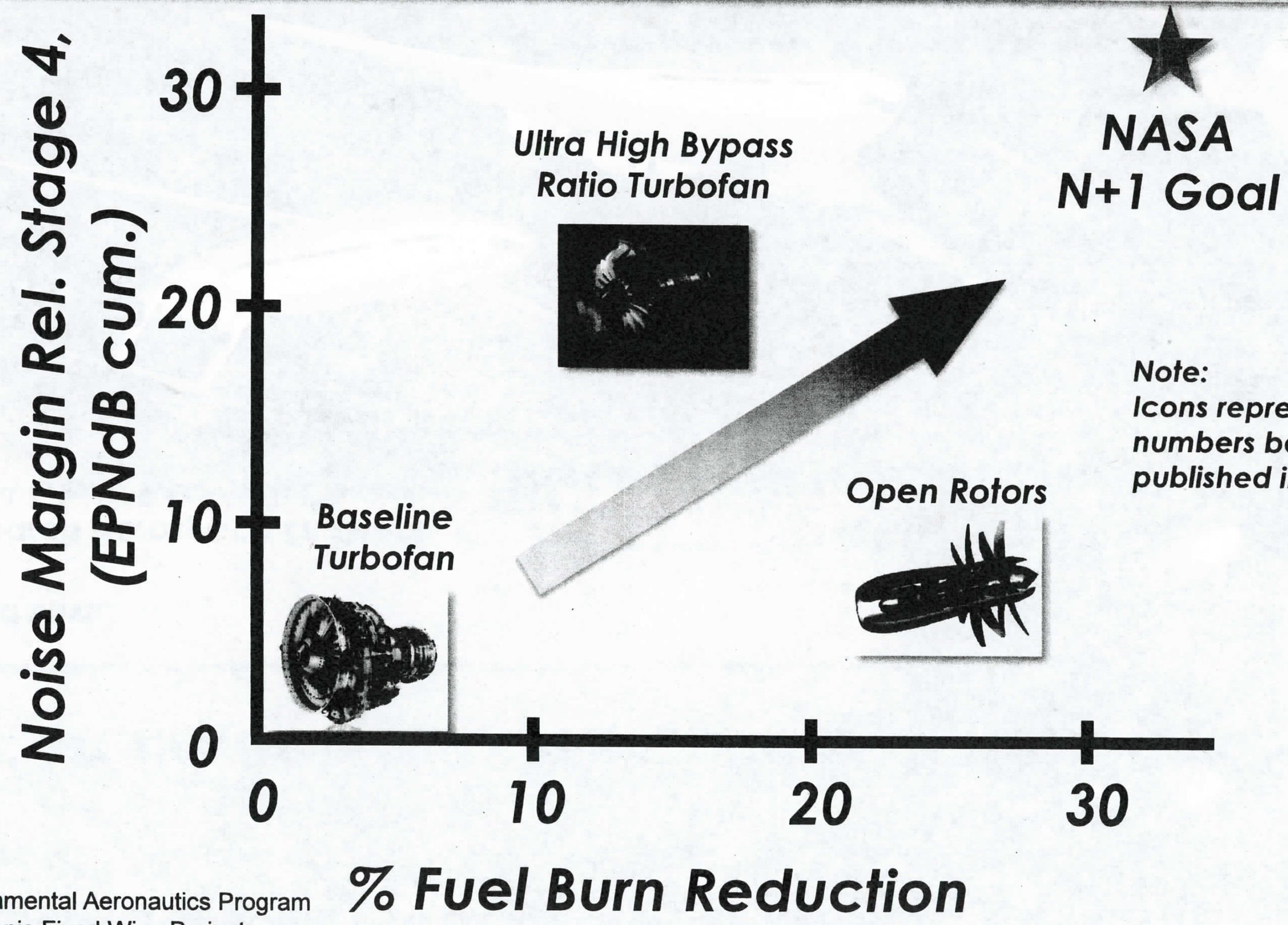
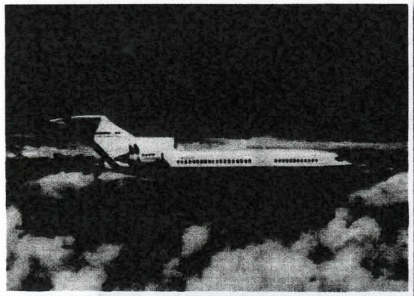
Why Open Rotors?

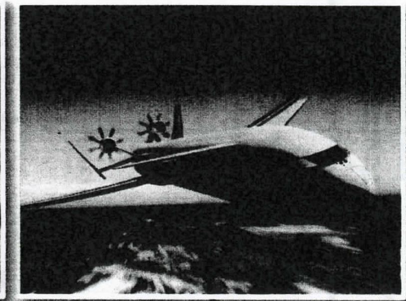
Advances in 3D aerodynamic design tools have made possible open rotor systems that can meet the current noise rules while maintaining their inherent fuel burn advantage. The goal is to make them acoustically competitive with the next generation turbofans. Acoustic design and prediction tools play an important role in that effort.



Note:
Icons represent notional numbers based on published information.

Acoustic Prediction Framework





NASA Tool Box of Aircraft Noise Prediction Codes

ASP Tools	FSC	APET, RNM	[redacted]	SEA/FEM
[redacted]	ANOPP (Modules), V072, RSI, LINFLUX, LINPROP, QPROP, ASSPIN, CRPFAN, ...			

Geometry, Flight Path & Operating Conditions

[redacted]ponent [redacted]e Source [redacted]diction

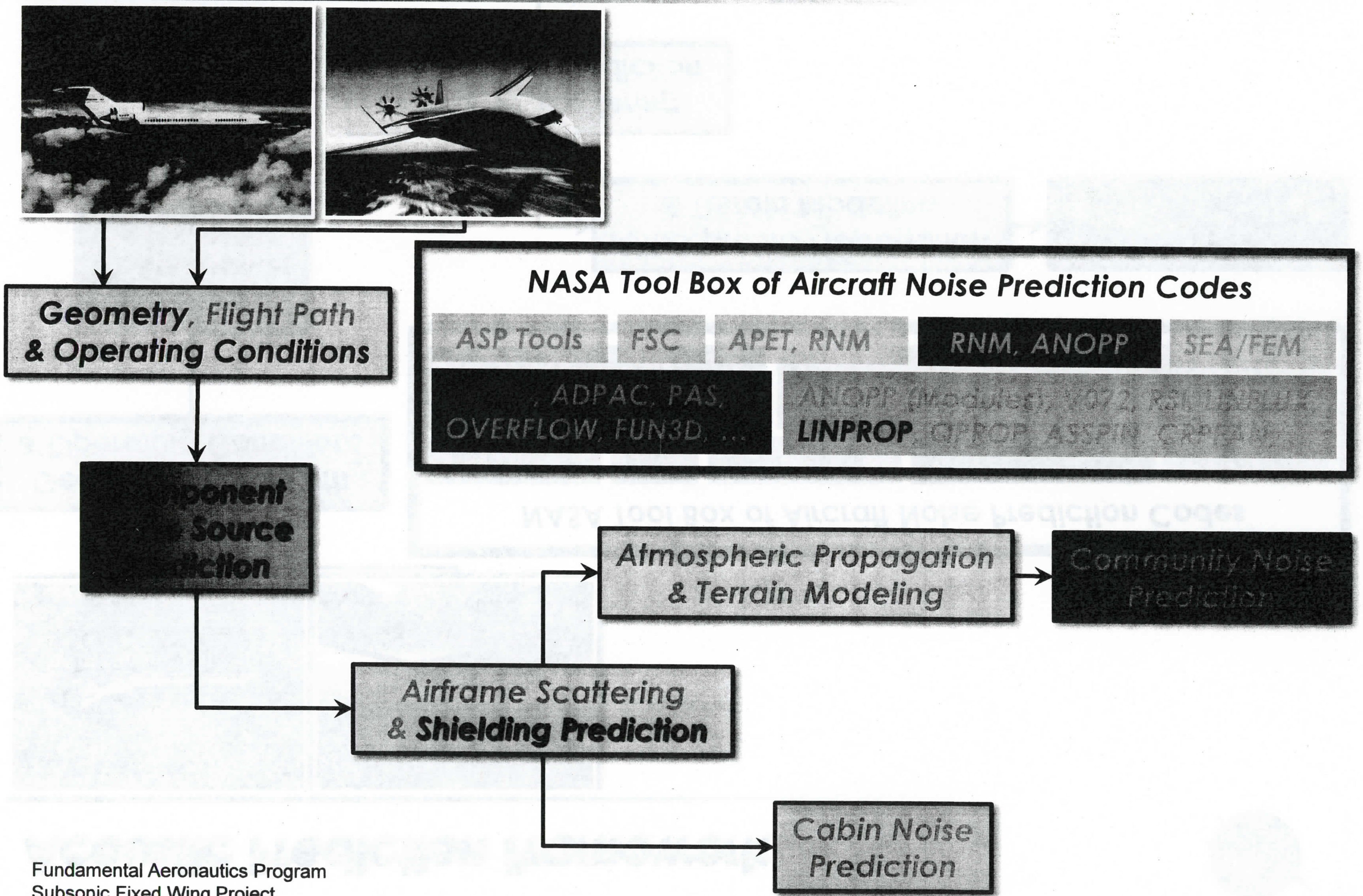
Airframe Scattering & Shielding Prediction

Atmospheric Propagation & Terrain Modeling

[redacted]

Cabin Noise Prediction

Acoustic Prediction Framework



Modeling Challenges & Strategy

- The fundamental challenge of aeroacoustic modeling and prediction is the large difference between the aerodynamic and acoustic scales; namely

$$p_{\text{acoustic}} \ll p_{\text{aerodynamic}}$$

- As an example, GE-90 produces the equivalent of roughly 27 MW of aerodynamic power at the sea level takeoff condition, while it is estimated to produce significantly less than 1 KW of radiated acoustic power.

- 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.

- In linearized methods, the mean flow and some aspects of the source description (e.g., amplitude, length/time scales, etc.) are specified, measured, or computed *a priori* and are introduced as boundary conditions or source terms in the equations governing the acoustics. CFD is most often used for that purpose.

LINPROP Open Rotor Tone Noise Prediction Code

$$p_{\text{acoustic}}(\vec{x},t)=\overbrace{\sum_{n=1}^{\infty}\left(\underbrace{A_{nB_1}}_{\text{Tone Amplitude}}e^{-inB_1\Omega_1 t}+\underbrace{A_{nB_2}}_{\text{Tone Amplitude}}e^{-inB_2\Omega_2 t}\right)}^{\text{Thickness Noise}}+$$

$$\overbrace{\sum_{m=1}^{\infty}\sum_{k=0}^{\infty}\underbrace{A_{mB_1,kB_2}}_{\text{Tone Amplitude}}e^{-i\overbrace{\left(mB_1\Omega_1+kB_2\Omega_2\right)}^{\text{Tone Frequency}}t}}^{\text{Loading Noise}}$$

B_1, Ω_1 and B_2, Ω_2 are the front and aft rotor blade counts and rotational frequencies, respectively. These parameters need not be the same for the front and aft rotors and they frequently are not.

LINPROP Code (Cont'd)

❖ **Expressions for tone amplitudes (Thickness & Loading Sources)**

Blade Normal Velocity **Green's Function**

$$A_{nB_i} = \int_0^{2\pi/\Omega_i} \int_{S_i} \underbrace{\rho_0 v_n}_{\substack{\text{Thickness Source} \\ \text{(geometric input)}}} \underbrace{Q_T\, G}_{\text{Propagation}}\, ds\, \mathrm{d}\tau$$

Blade Loading

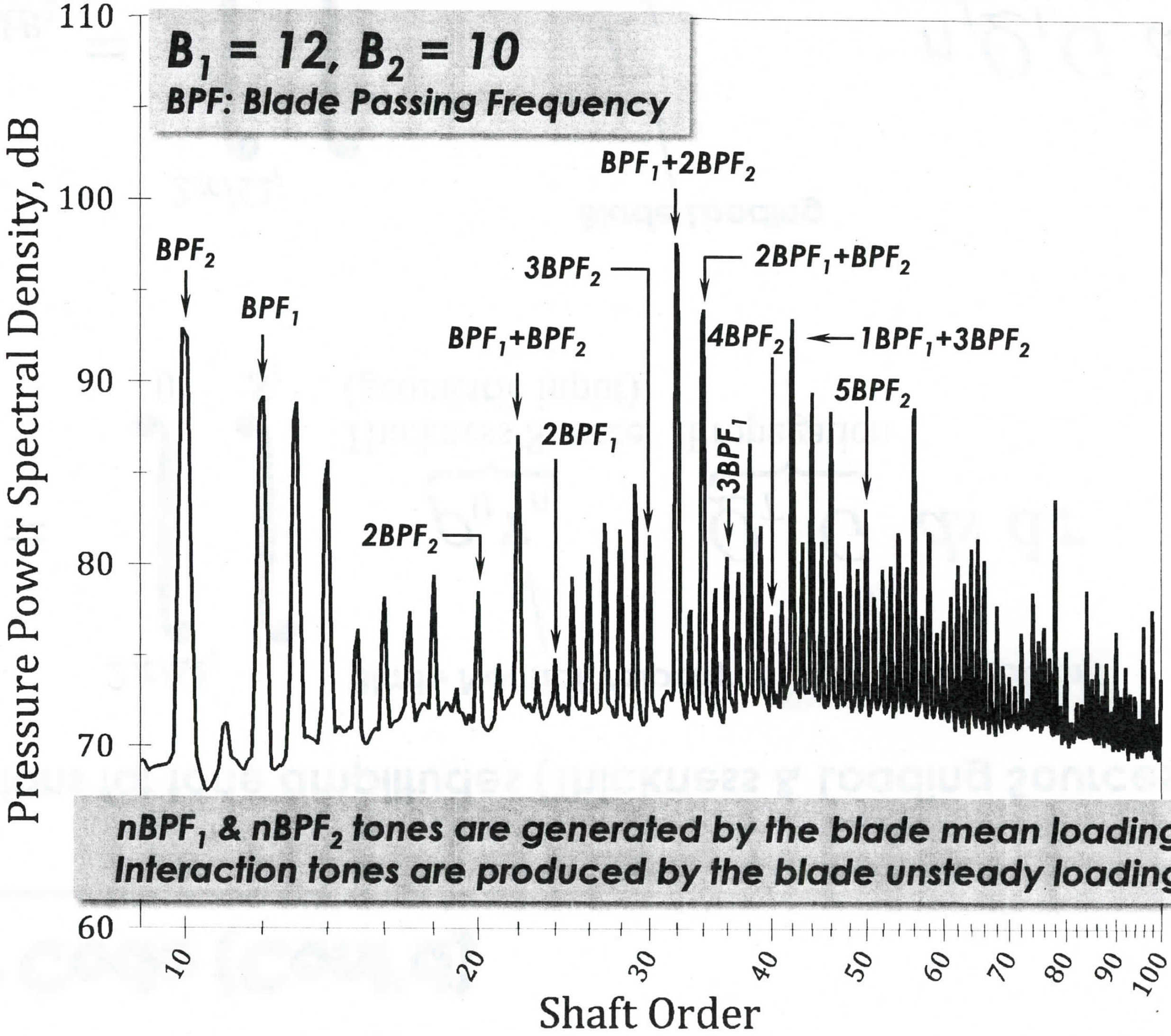
$$A^i_{mB_1,kB_2} = \int_0^{2\pi/\Omega_i} \int_{S_i} \underbrace{F^i_j}_{\substack{\text{Loading Source} \\ \text{(aerodynamic input - CFD)}}} \underbrace{n_j Q_L G}_{\text{Propagation}}\, ds\, d\tau$$

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

Open Rotor Noise Spectrum

Typical Open Rotor Narrowband Acoustic Spectrum
Open rotors have a preponderance of tones in their acoustic spectra.

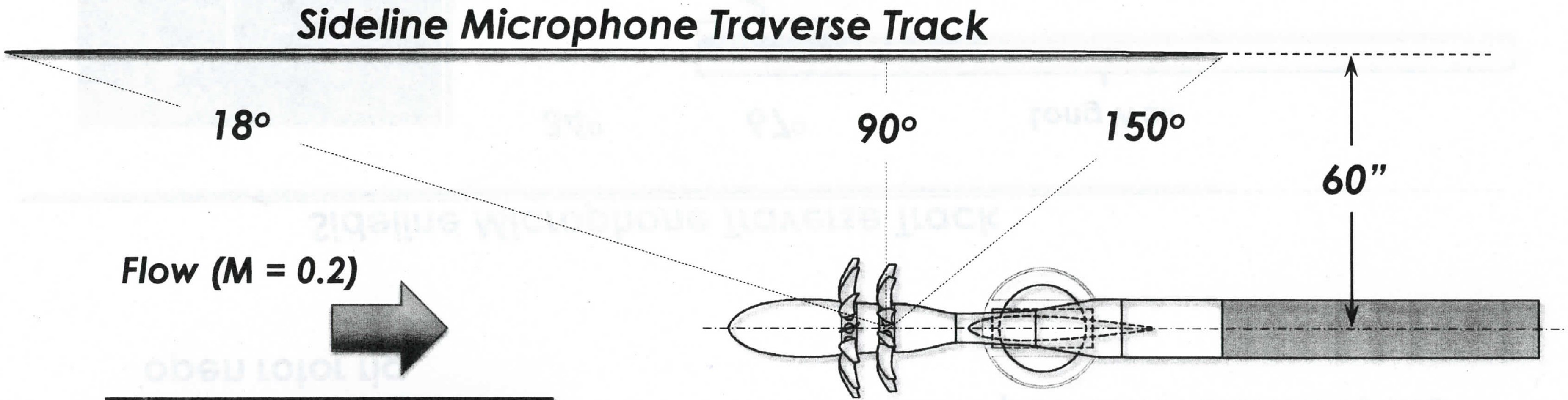
$B_1 = 12$, $B_2 = 10$
BPF: Blade Passing Frequency

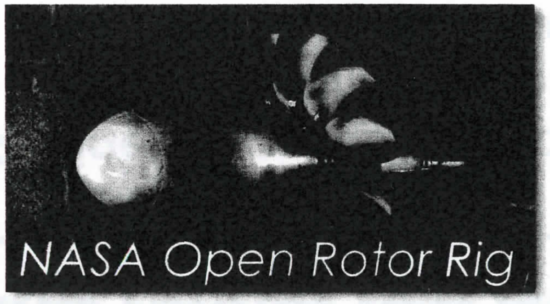


$nBPF_1$ & $nBPF_2$ tones are generated by the blade mean loading.
Interaction tones are produced by the blade unsteady loading.

Open Rotor Wind Tunnel Test Campaign

❖ In a collaborative effort between NASA and GE, diagnostic data including benchmark sideline acoustic measurements were acquired for a scale model open rotor configuration called F31/A31.

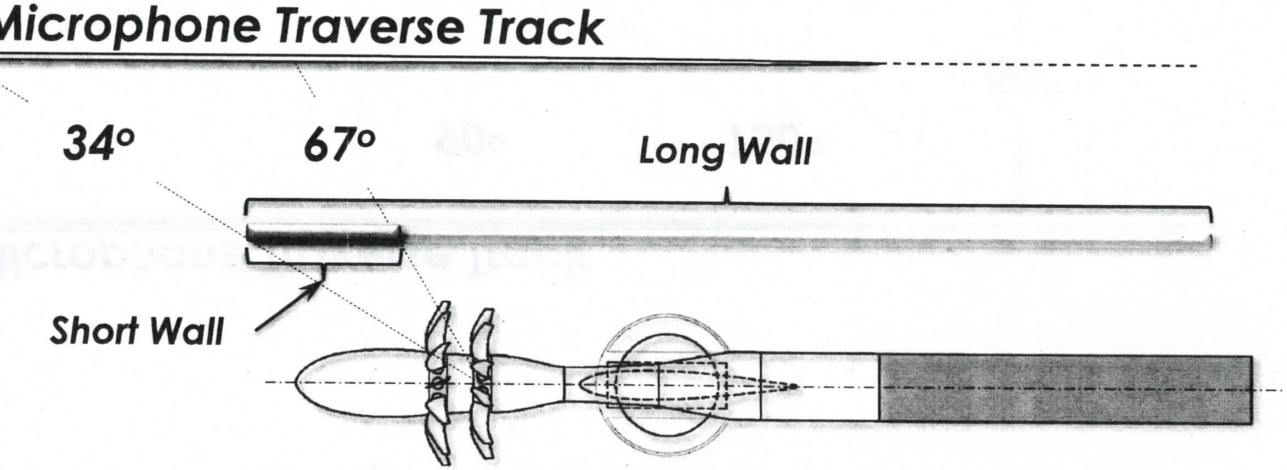


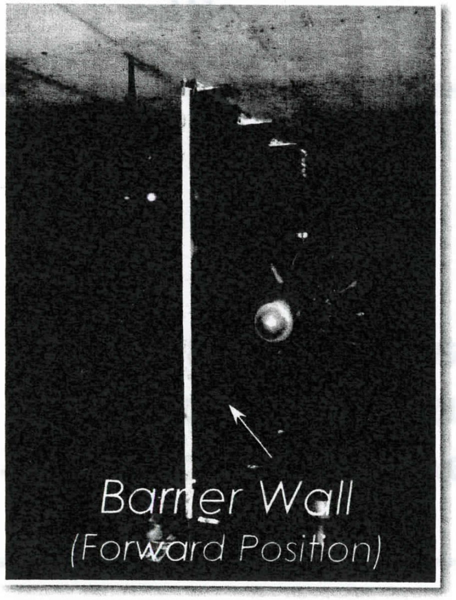


Plan View of the Free-Field F31/A31 Open Rotor Installation in the 9'x15' Acoustic Wind Tunnel

Wind Tunnel Test Acoustics Data

❖ Sideline acoustic measurements were also acquired for four basic shielding configurations using short and long barrier walls. One set included the barrier walls in a forward axial positions relative to the open rotor rig,

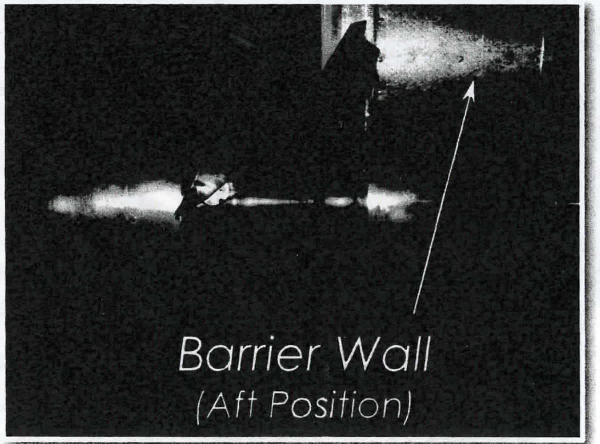


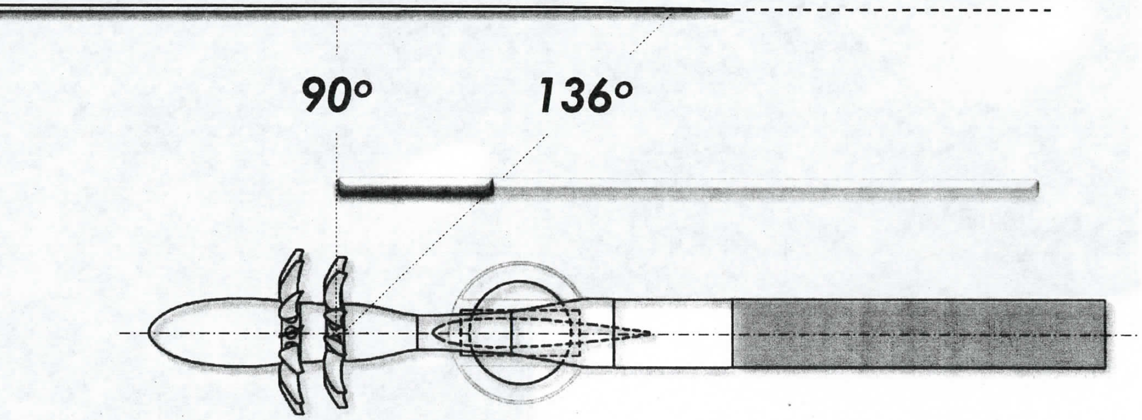


Short & Long Barriers in Forward Position

Wind Tunnel Test Acoustics Data (Cont'd)

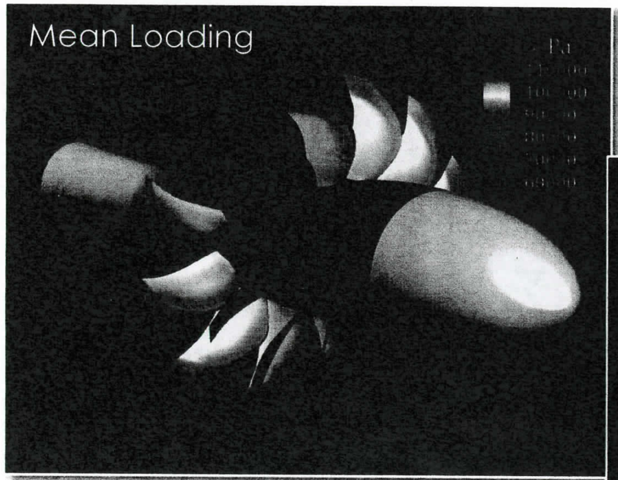
- ... and the other set with the barrier walls in the aft position relative to the open rotor rig.



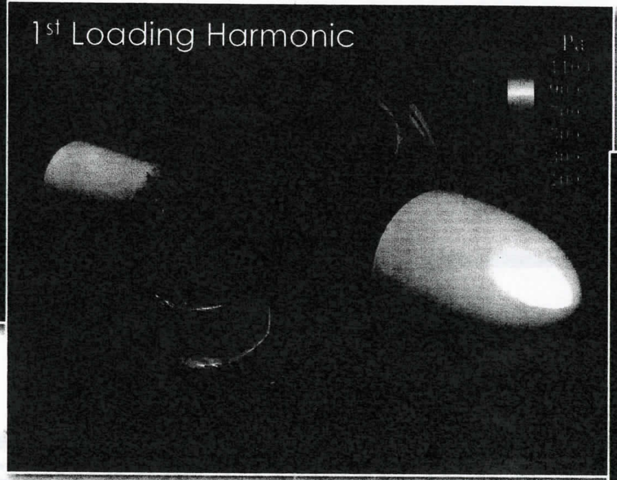


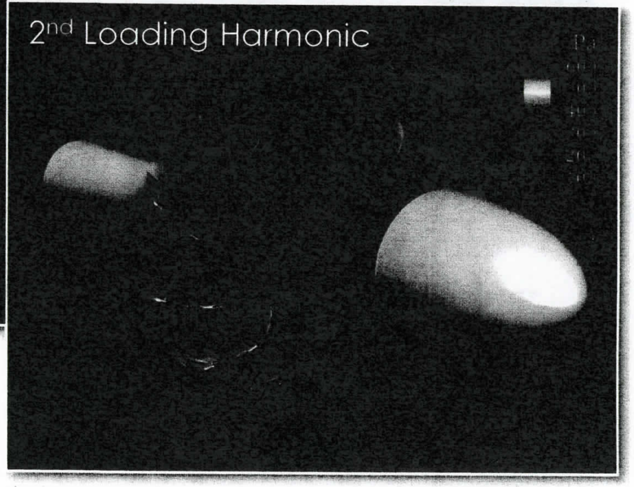
Short & Long Barriers in Aft Position

Aerodynamic Input



Unsteady RANS Simulation of F31/A31 at Nominal Takeoff Condition





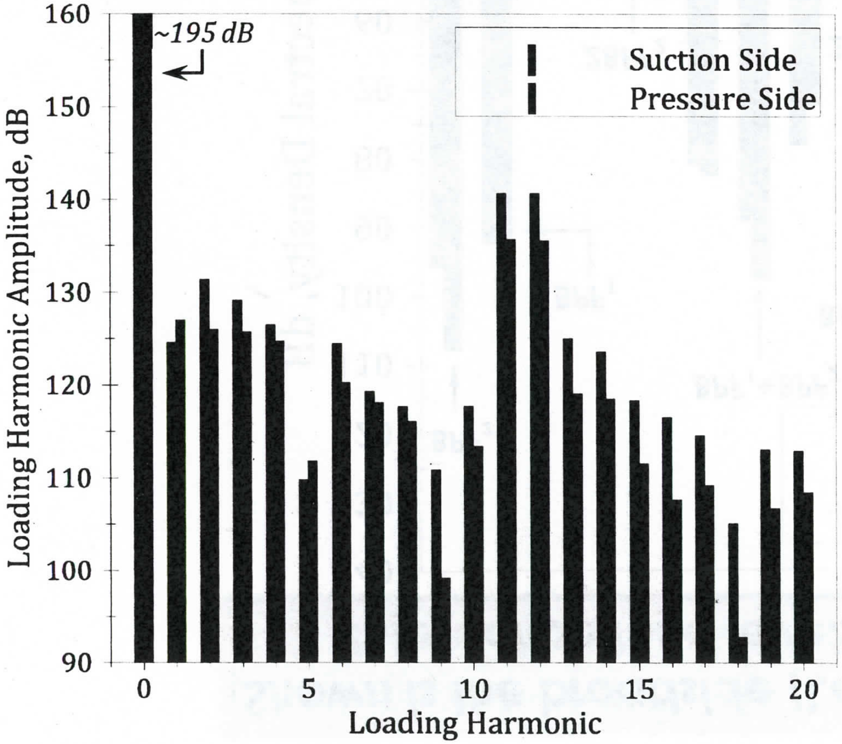
Thrust (lbf)	Front Rotor	303	304
	Aft Rotor	305	309
Torque (ft-lb)	Front Rotor	178	182
	Aft Rotor	171	177
Power (hp)	Front Rotor	225	230
	Aft Rotor	216	223

Contour plots and integrated quantities shown here were computed from a simulation carried out at Ohio State University by Trevor Goerig using the TURBO code.

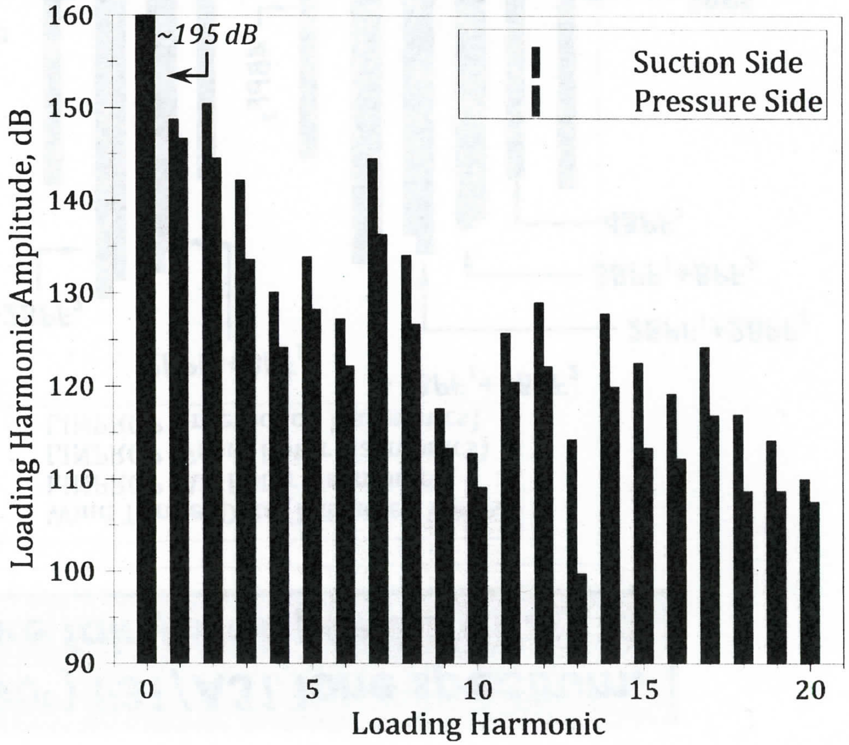
Blade Loading Spectra (CFD)

There are several orders of magnitude difference between the mean and unsteady loading components. Yet, wind tunnel data indicate that the noise due to the unsteady loading component can contribute significantly to the overall noise of an open rotor. This has to do with the much higher radiation efficiency of the interaction tones compared with the individual rotor tones.

Front Blade

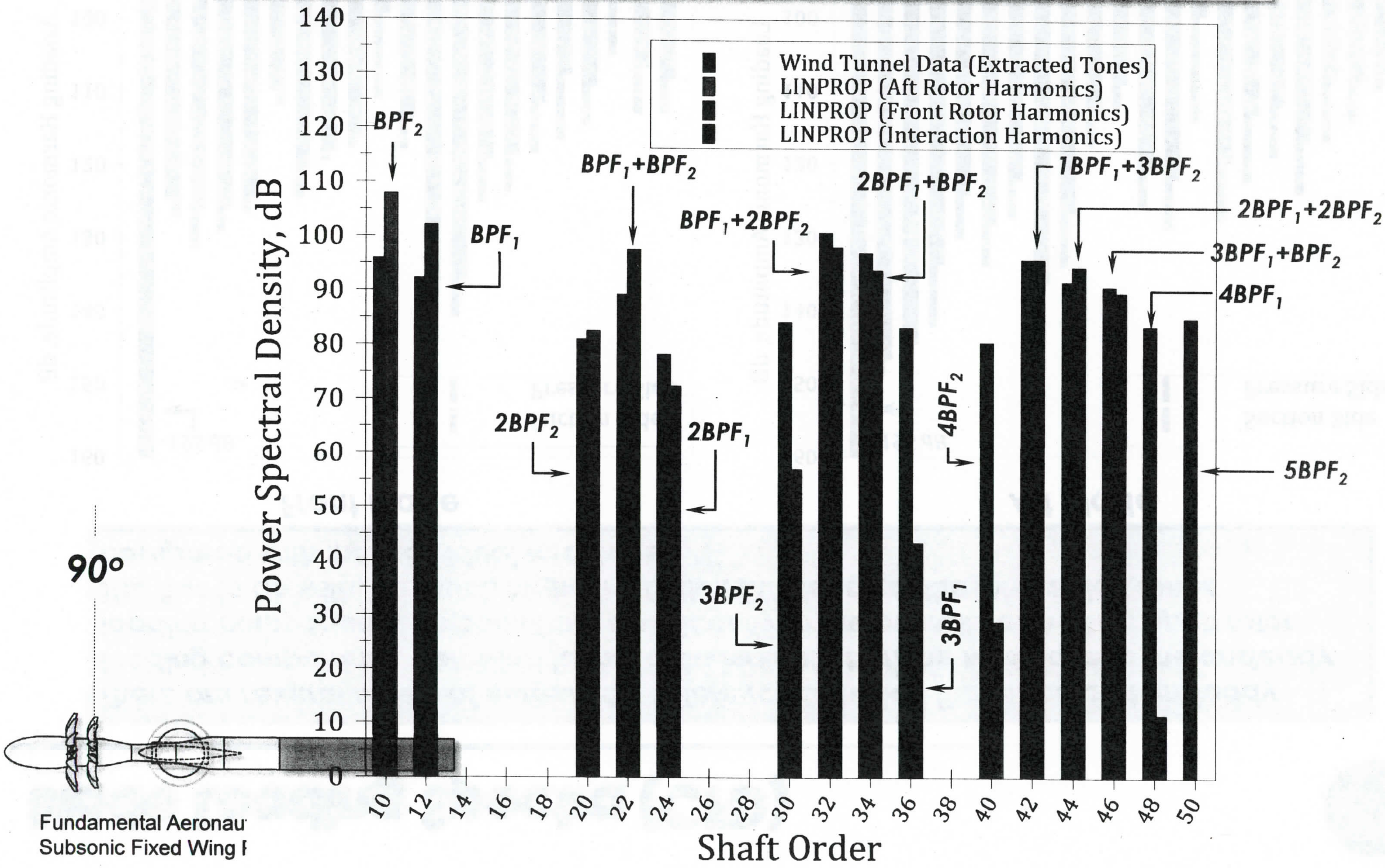


Aft Blade



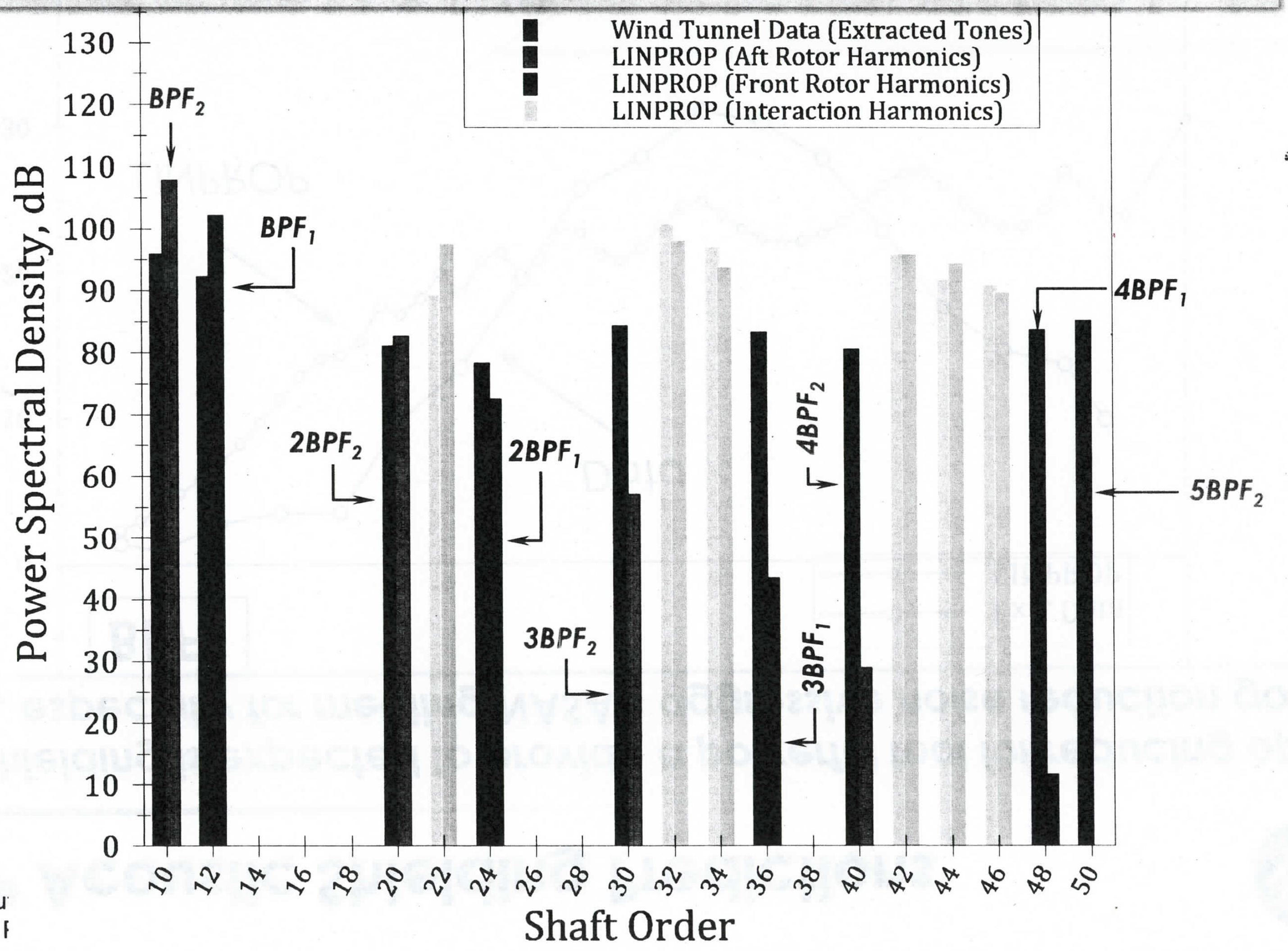
LINPROP Free-Field Acoustic Predictions

Shown is the broadside (i.e. 90°) F31/A31 tone spectrum. Interaction tone levels are fairly well predicted.



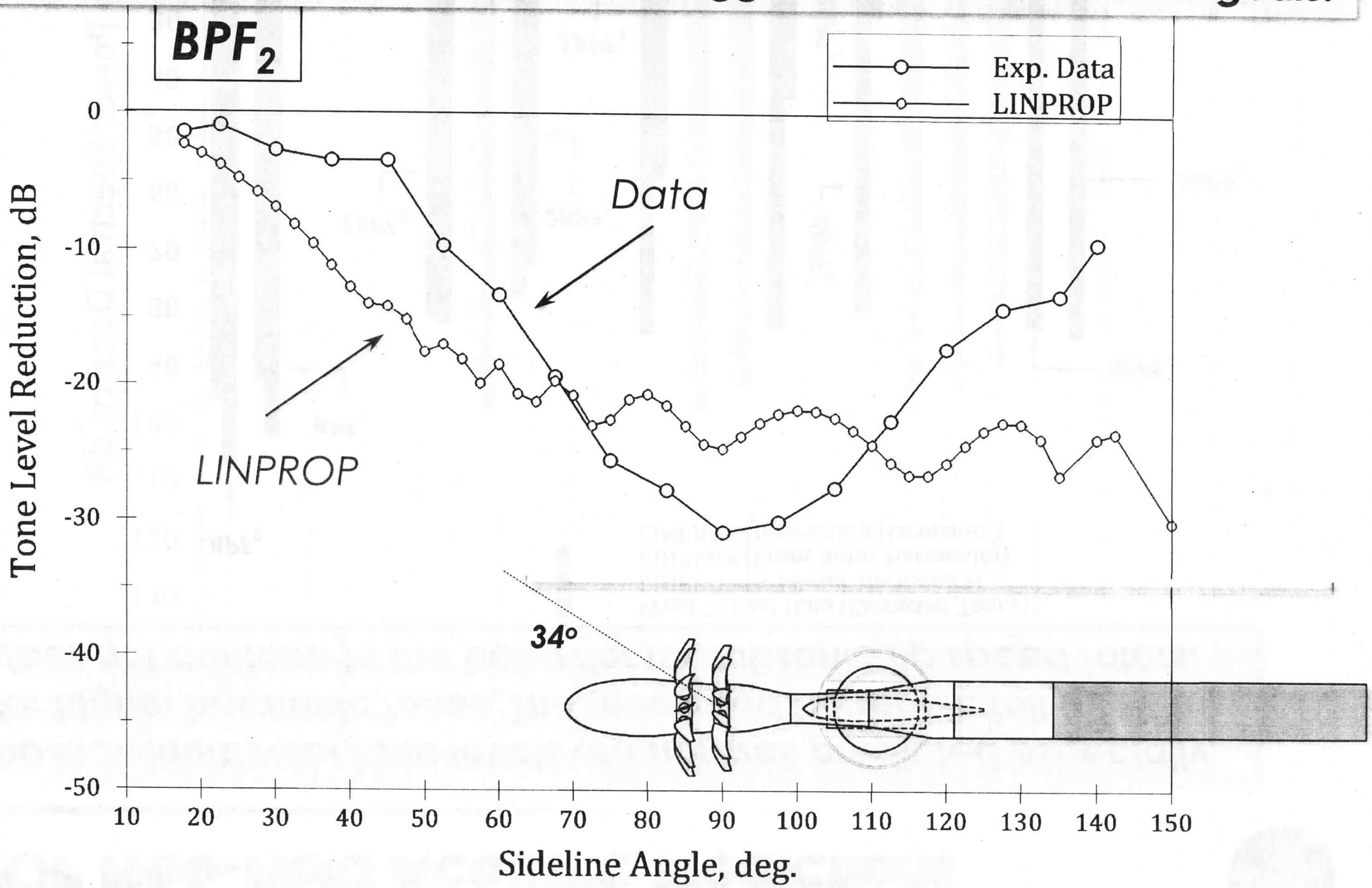
LINPROP Free-Field Acoustic Predictions

The individual rotor tone levels are not well predicted especially for higher harmonic tones. The measured harmonic fall off rate does not conform to the behavior for subsonic tip speed rotors.

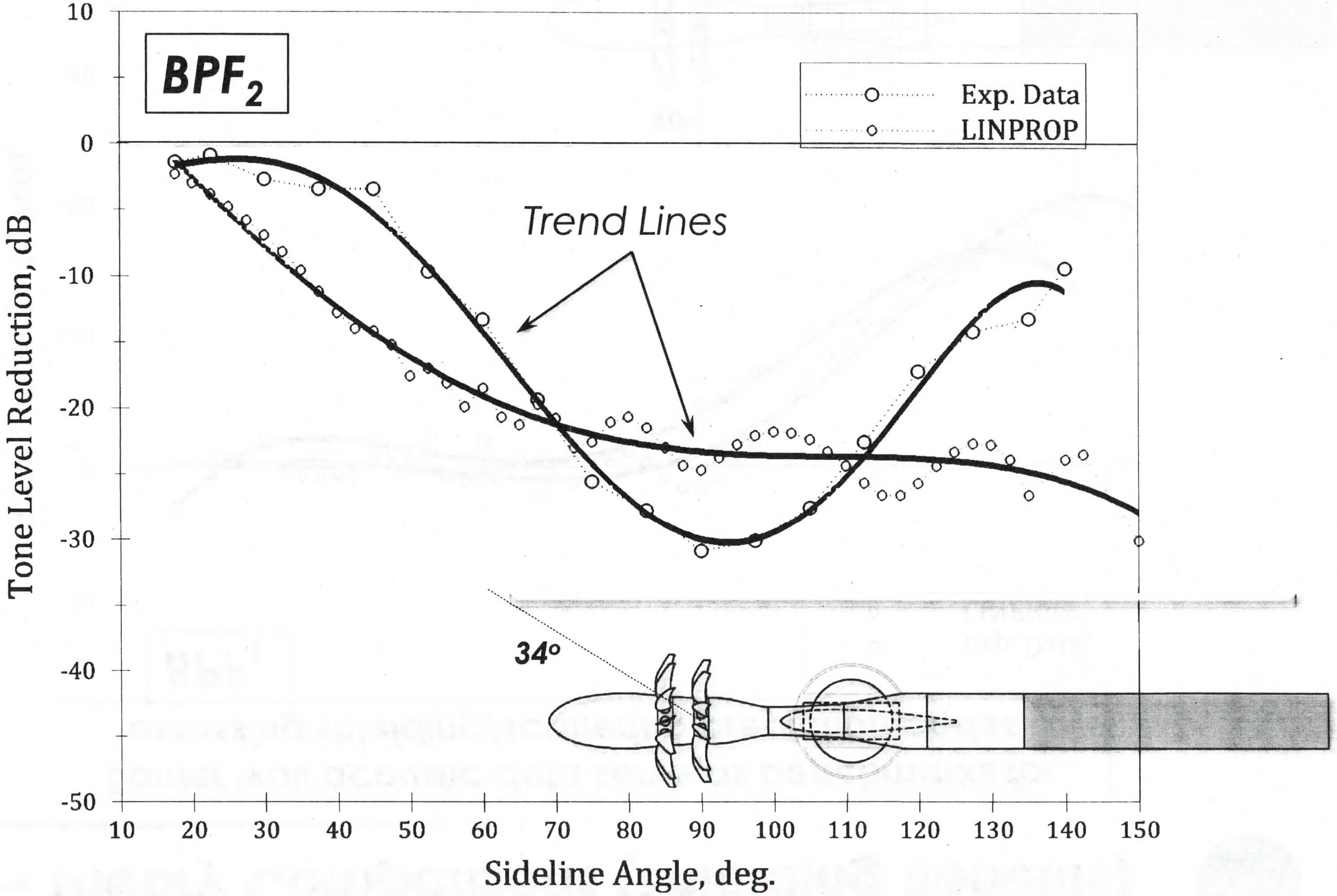


LINPROP Acoustic Shielding Predictions

Acoustic shielding is expected to provide a powerful tool for reducing open rotor noise, especially for meeting NASA's aggressive noise reduction goals.

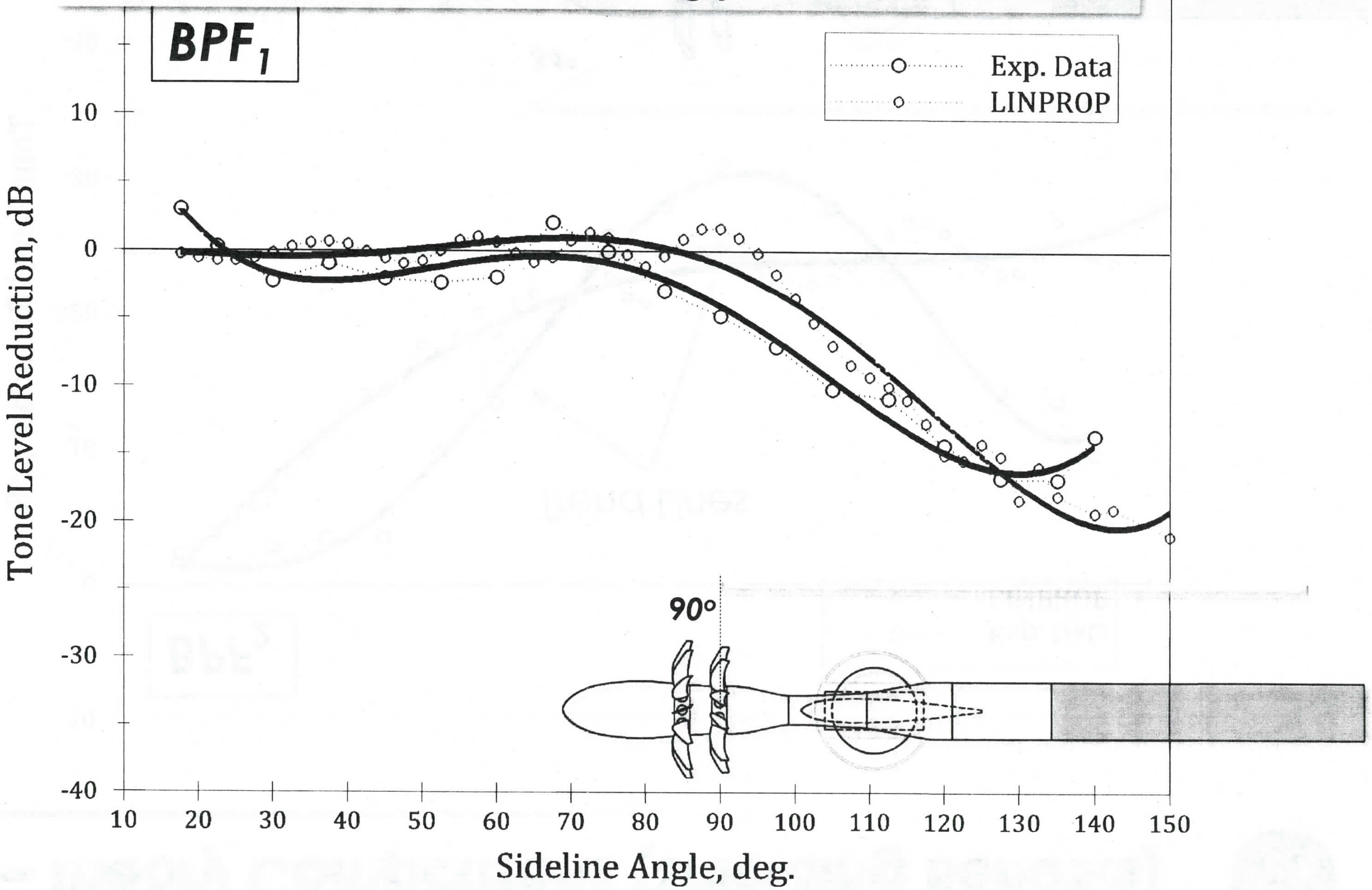


Data – Theory Comparisons (Shielding Benefits)



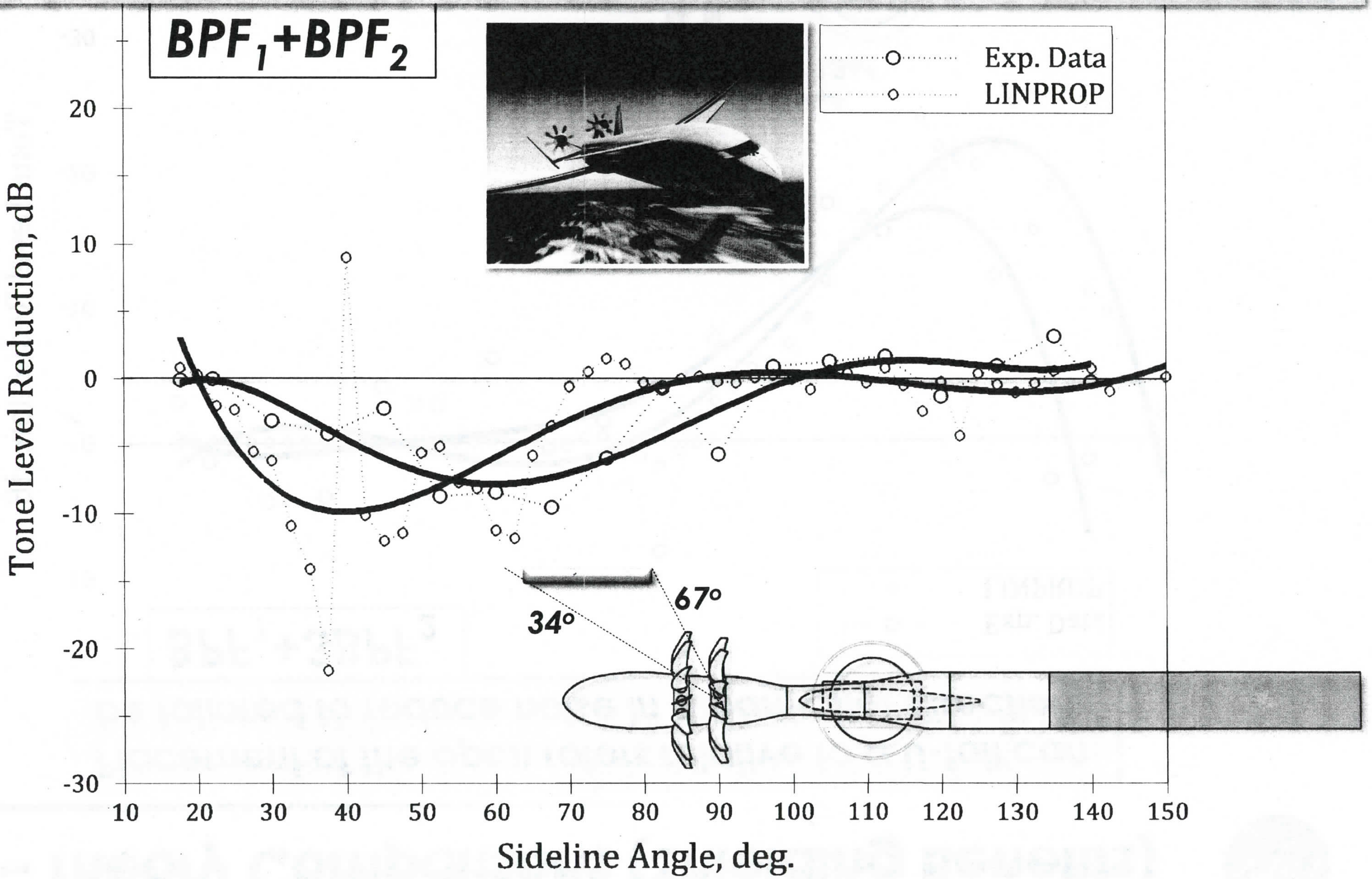
Data – Theory Comparisons (Shielding Benefits)

Barrier wall acoustic data serve as benchmarks for assessing shielding/scattering prediction codes.



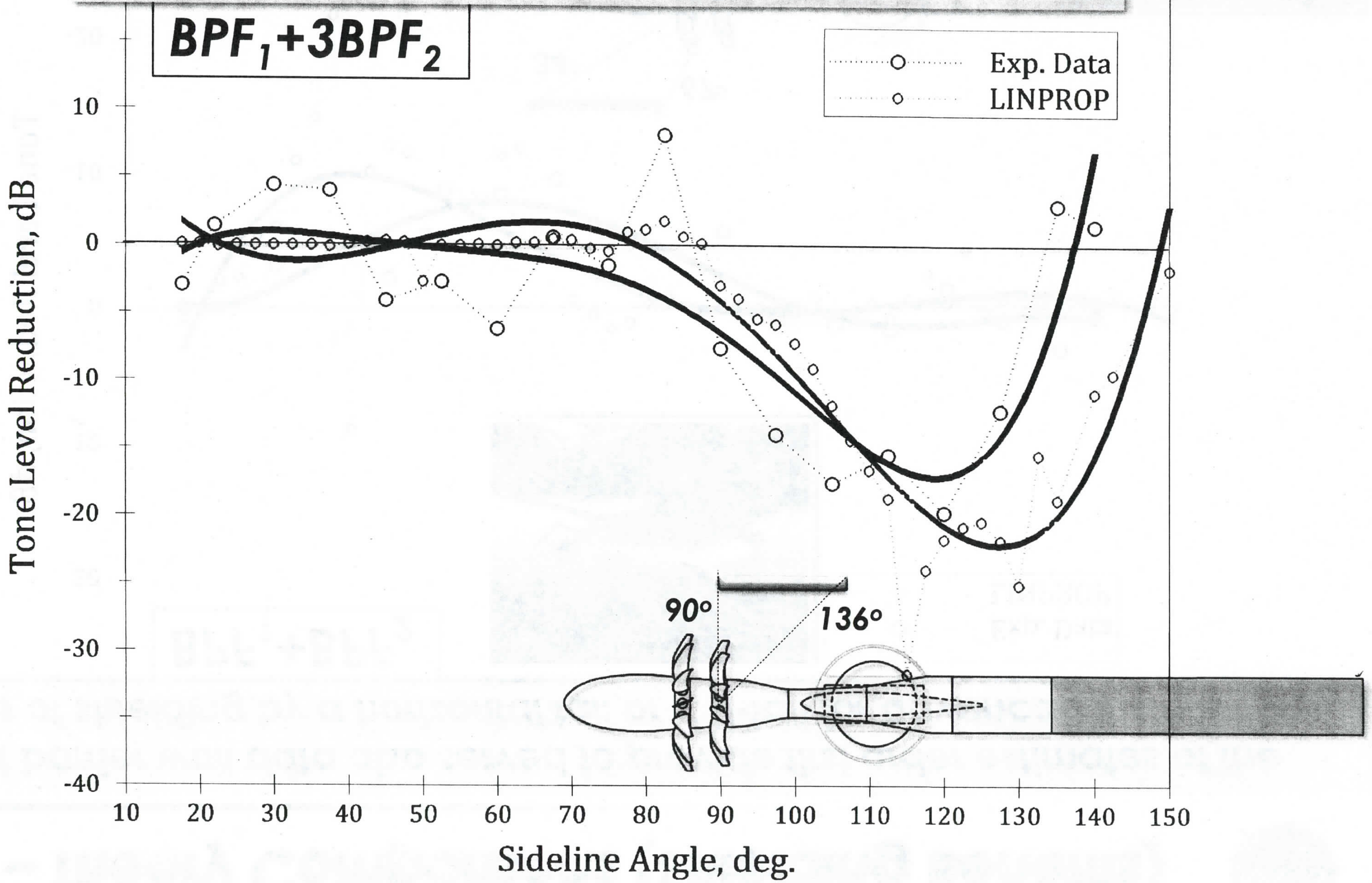
Data – Theory Comparisons (Shielding Benefits)

Short barrier wall data also served to provide first order estimates of the benefits of shielding by a horizontal tail or a U-tail for advanced installations.



Data – Theory Comparisons (Shielding Benefits)

Placement of the open rotors relative to a U-tail can be tailored to reduce noise in a particular direction.



Some Observations

- Linearized methods (e.g., LINPROP code) can predict the interaction tone levels reasonably well, but improvements may be necessary to better match the individual rotor harmonic tone levels.

- Changes in noise levels due to configuration changes can also be fairly well predicted by linearized methods (at least as far as trends are concerned) providing a good capability for acoustic design optimization.

- A critical and time consuming element of the linearized noise prediction methods is the computation of the unsteady aerodynamic input.

- For acoustic design purposes, more efficient CFD based aerodynamic tools are needed to reduce the analysis cycle times.

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