Open Rotor Noise Prediction

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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.

**Why Open Rotors?**

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![Graph showing fuel burn reduction and noise margin improvement for Ultra High Bypass Ratio Turbofan vs. Baseline Turbofan and Open Rotors.](Note: Icons represent notional numbers based on published information.)

**NASA N+1 Goal**

- **Noise Margin Rel. Stage 4, (EPNdB cum.)**
  - 30
  - 20
  - 10
  - 0
  - Baseline Turbofan
  - Ultra High Bypass Ratio Turbofan
  - Open Rotors

- **% Fuel Burn Reduction**
  - 0
  - 10
  - 20
  - 30

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Acoustic Prediction Framework

Geometry, Flight Path & Operating Conditions

Component Source Prediction

Airframe Scattering & Shielding Prediction

Atmospheric Propagation & Terrain Modeling

Cabin Noise Prediction

NASA Tool Box of Aircraft Noise Prediction Codes

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

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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 \textit{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.
The complex noise function for an open rotor system is given by:

\[ P_{\text{acoustic}}(\vec{x},t) = \sum_{n=1}^{\infty} \left( A_{nB_1} e^{-inB_1\Omega_1 t} + A_{nB_2} e^{-inB_2\Omega_2 t} \right) + \sum_{m=1}^{\infty} \sum_{k=0}^{\infty} A_{mB_1,kB_2} e^{-i(mB_1\Omega_1 + kB_2\Omega_2) t} \]

**Thickness Noise**

**Loading Noise**

The parameters \( B_1, \Omega_1 \) and \( B_2, \Omega_2 \) 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)

\[
A_{nB_i} = \frac{2\pi/\Omega_i}{0} \int_{S_i} \int \rho_0 v_n Q_T G ds d\tau
\]

Blade Normal Velocity
Green's Function
Thickness Source (geometric input)
Propagation

\[
A_{mB_1,kB_2}^i = \frac{2\pi/\Omega_i}{0} \int_{S_i} \int F^i_j n_j Q_L G ds d\tau
\]

Blade Loading
Loading Source (aerodynamic input - CFD)
Propagation

Asymptotic approximations to these expressions yield efficient means of computing the tone amplitudes in LINPROP code.
Typical Open Rotor Narrowband Acoustic Spectrum

Open rotors have a preponderance of tones in their acoustic spectra.

\[ B_1 = 12, \quad B_2 = 10 \]

BPF: Blade Passing Frequency

nBPF₁ and nBPF₂ tones are generated by the blade mean loading. Interaction tones are produced by the blade unsteady loading.
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.
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.
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.

**Sideline Microphone Traverse Track**

**Barrier Wall**
*(Aft Position)*

**Short & Long Barriers in Aft Position**
Aerodynamic Input

Unsteady RANS Simulation of F31/A31 at Nominal Takeoff Condition

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

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

**LINPROP Free-Field Acoustic Predictions**

Wind Tunnel Data (Extracted Tones)
LINPROP (Aft Rotor Harmonics)
LINPROP (Front Rotor Harmonics)
LINPROP (Interaction Harmonics)

Power Spectral Density, dB

- BPF₁
- BPF₁+BPF₂
- BPF₁+2BPF₂
- 2BPF₁+BPF₂
- 3BPF₁
- 2BPF₁+2BPF₂
- 3BPF₁+BPF₂
- 4BPF₁
- 2BPF₂
- 3BPF₂
- 4BPF₂
- 5BPF₂

Shafte Order
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.

![Graph showing power spectral density vs. shaft order for different harmonic tones.](image-url)
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.

![Graph showing LINPROP Acoustic Shielding Predictions]

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Data – Theory Comparisons (Shielding Benefits)

![Graph showing data and trend lines for BPF₂](image)

- **BPF₂**

- **Trend Lines**

- **Sideline Angle, deg.**

- **Tone Level Reduction, dB**

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Data – Theory Comparisons (Shielding Benefits)

Barrier wall acoustic data serve as benchmarks for assessing shielding/scattering prediction codes.
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.
Placement of the open rotors relative to a U-tail can be tailored to reduce noise in a particular direction.

**BPF_1 + 3BPF_2**

![Graph showing data and theory comparisons for shielding benefits.](image-url)
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.