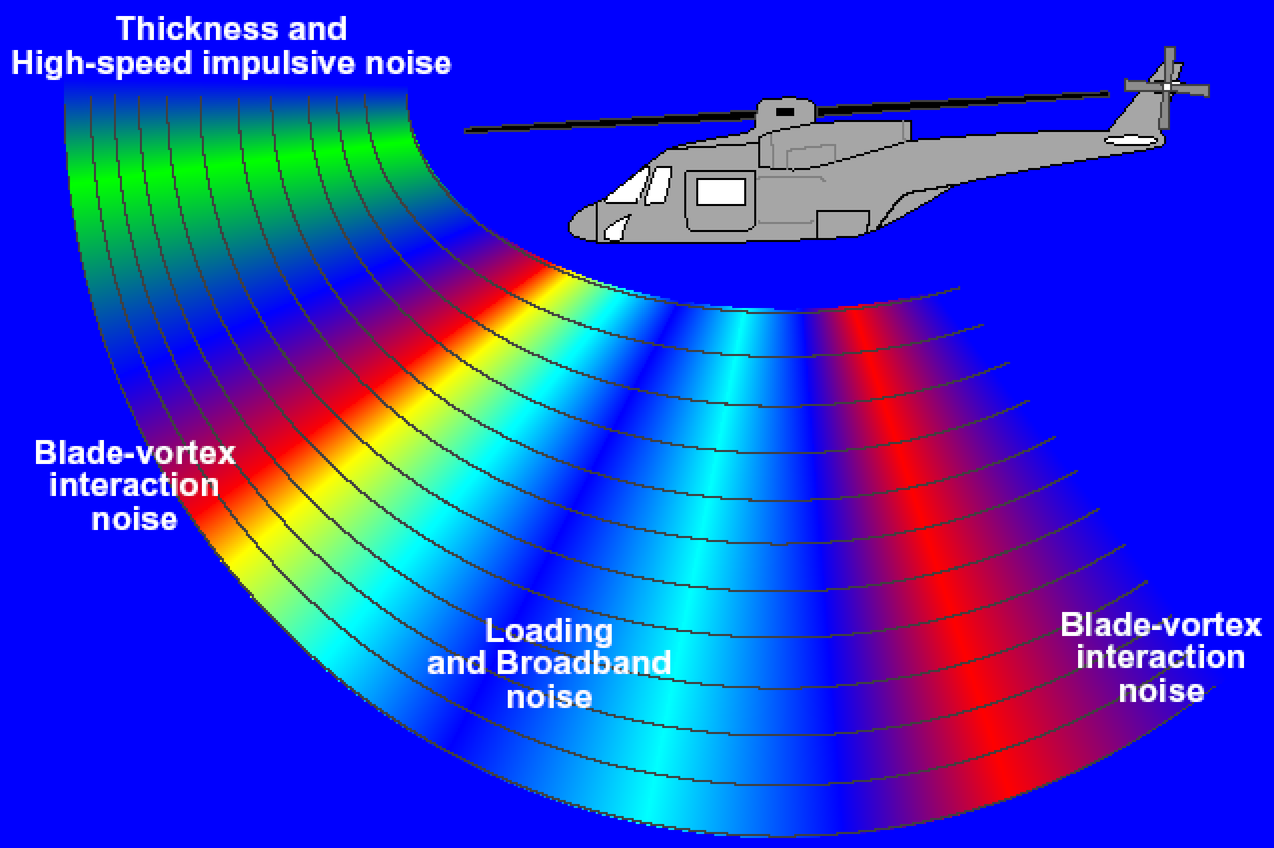
Rotorcraft Aeroacoustics

An Introduction

Preliminary Remarks

- Rotorcraft Noise is becoming an area of considerable concern to the community.
- United States and most European countries have stringent limitations of acceptable noise levels.
- Any new design must be done with these limitations, to avoid unpleasant surprises during certification time.

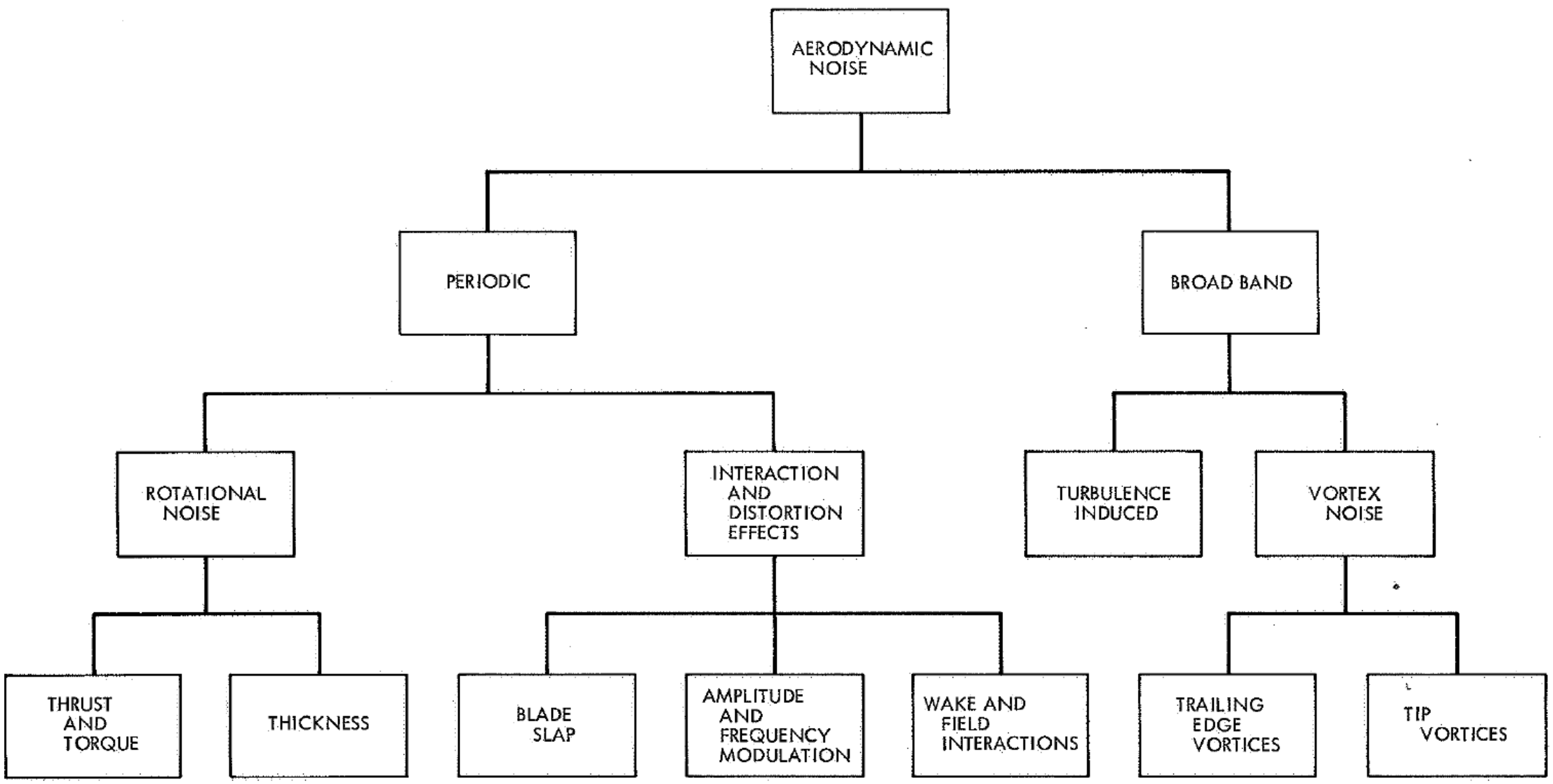
Rotor Source Noise



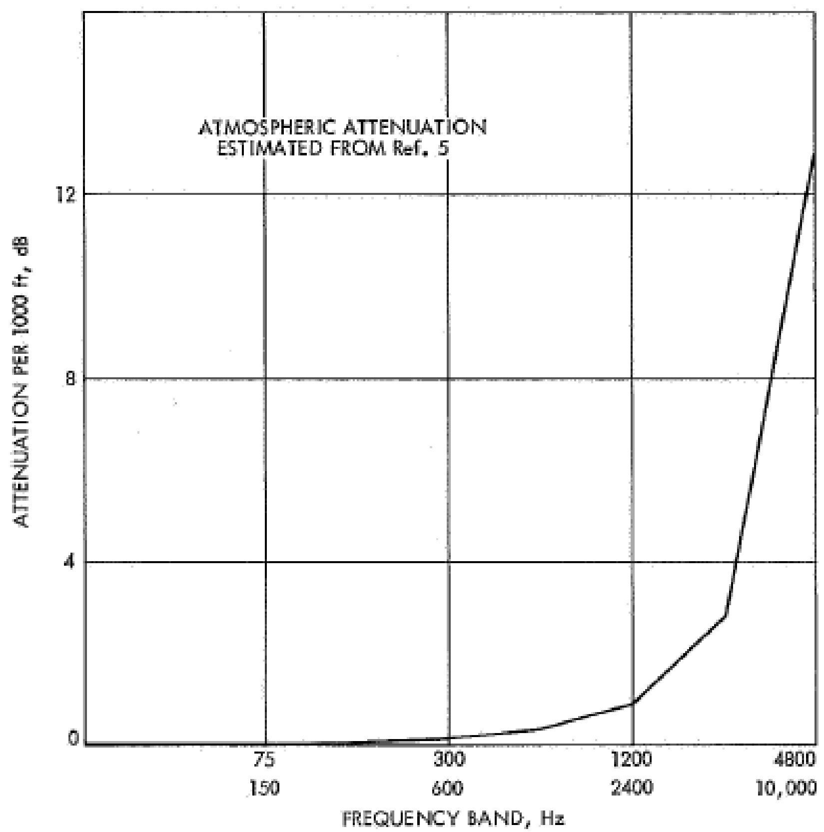
NASA Langley Research Center, Hampton, VA

K. S. Brentner

Sources of Noise
JPL Technical report 32-1462, 1970



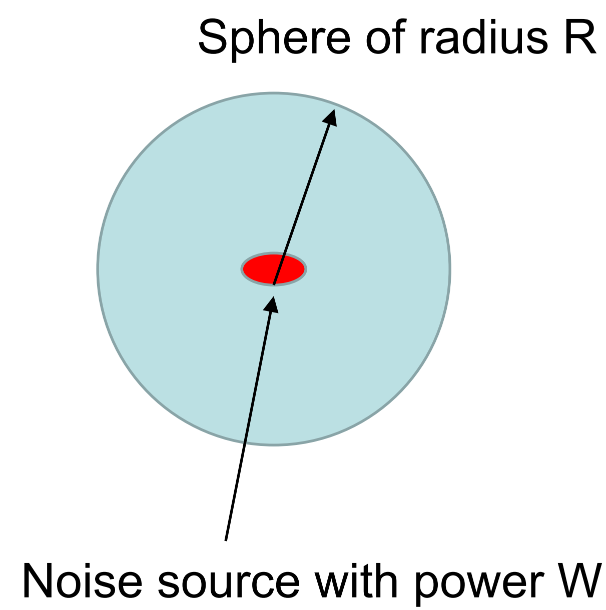
Atmospheric Attenuation



5. *Standard Values of Atmospheric Absorption as a Function of Temperature and Humidity for Use in Evaluating Aircraft Noise*, SAE Aerospace Recommended Practice ARP 866, New York, 1964.

Geometric Attenuation

- If the observer is far away from the noise source, the sound intensity decreases, roughly as the inverse of distance squared.



Intensity $I = W/(4\pi R^2)$

Some Definitions

- Sound Pressure Level is measured in Decibels.

$$SPL = 20\log_{10}\left(\frac{p}{p_{\mathrm{Re}f}}\right) = 10\log_{10}\left(\frac{\langle p^2\rangle}{p_{\mathrm{Re}f}^2}\right)$$

where,

$$p_{\mathrm{Re}f} = 2\times10^{-5}\,\frac{N}{m^2}$$

$$\langle p^2\rangle = \text{Mean Square Pressure}$$

$$\langle p^2\rangle = \frac{1}{T}\int_0^T (p')^2\,dt$$

$$\cong \frac{1}{N}\sum_{i=1..N}(p')^2$$

Microphones capture p'

Computers do the summation

Definitions

Intensity :

$$I = \frac{\langle p' \rangle^2}{\rho c}$$ where is ρ density, c is speed of sound

Sound Power Level :

Overall Sound Pressure Level, OASPL

$$p(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \mathcal{P}(\omega) e^{-i\omega t} d\omega$$

$$\mathcal{P}(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} p(t) e^{i\omega t} dt$$

$$\mathcal{P}(\omega) = \frac{\Delta t}{2\pi} \sum_{n=1}^{N} p(n\Delta t) e^{-i\omega n\Delta t}$$

$$\mathrm{OASPL} = 10 \log_{10} \sum_{n} \left(\frac{\langle p^2 \rangle_n}{p^2{}_{ref}} \right) \qquad \mathrm{dB}$$

Weighting

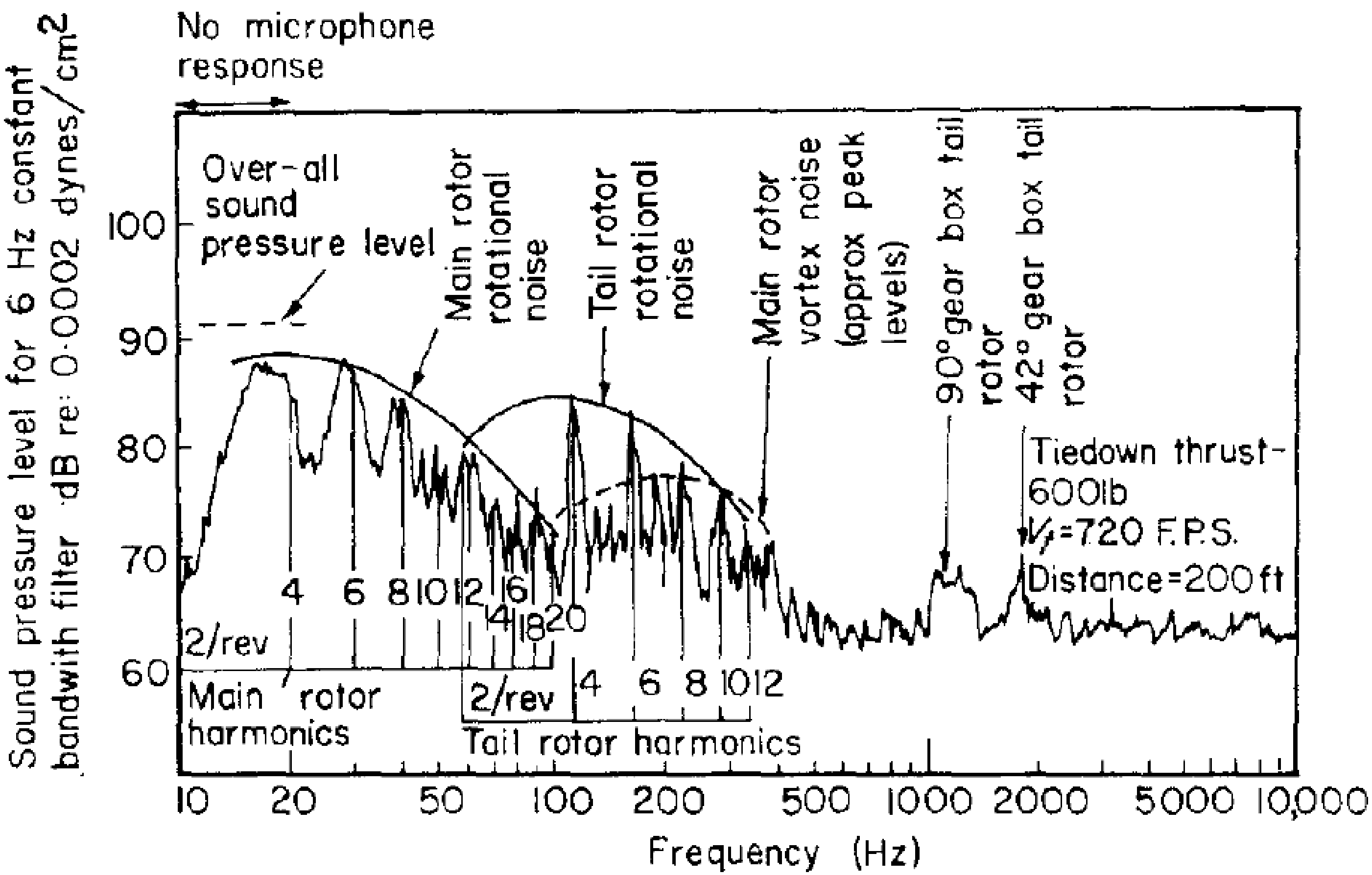
- A Weighting: Emphasizes sound frequencies that people here best.

- Perceived Noise Level (PNL) weighting: The most annoying frequencies are weighted more than others.

Typical dB Levels

- Hearing Threshold: 0 dBA
- Whisper : 20 dBA
- Quite Neighborhood: 40 dBA
- Normal Speech: 60 dBA
- Busy Office: 80 dBA
- Heavy Traffic: 100 dBA
- Discotheque 120 dBA

UH-1 Noise



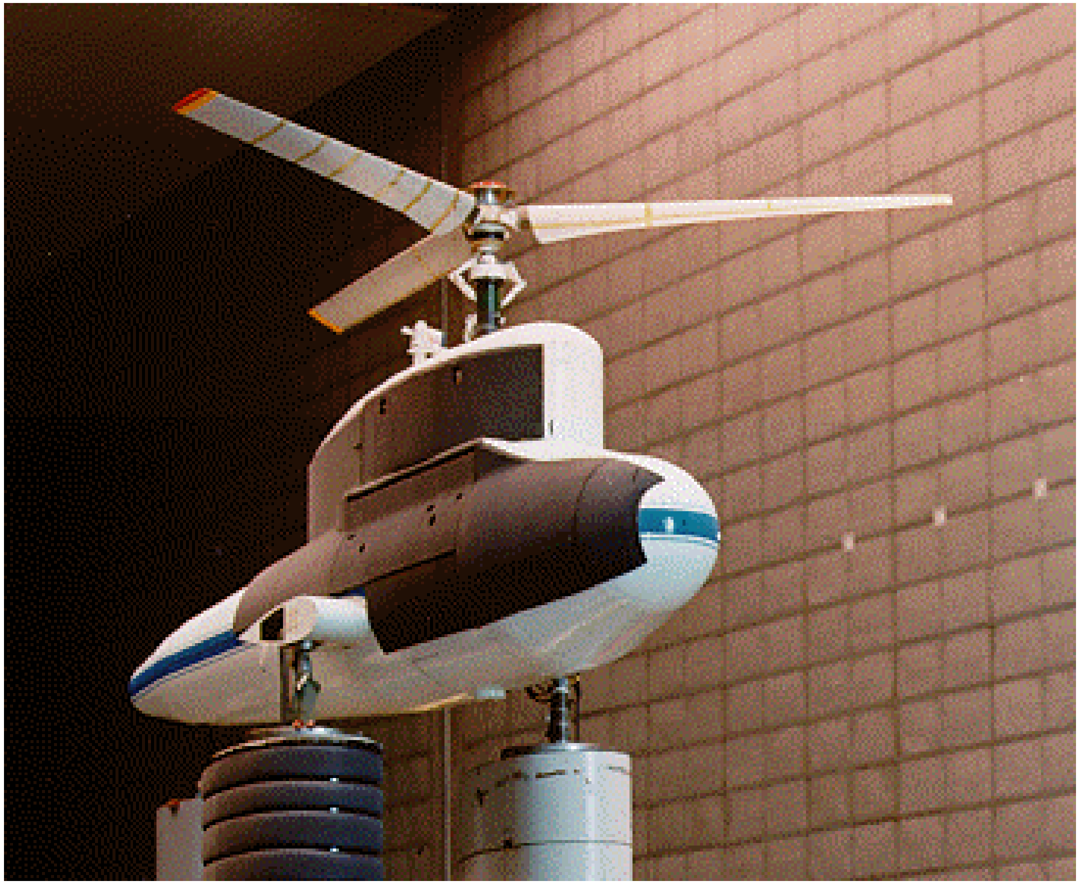
C. R. Cox and R. R. Lynn 1962 *TCREC Technical Report 62-73, U.S. Army Transportation Research Command, Fort Eustis, Virginia.* A study of the origin and means of reducing helicopter noise.

Flight Tests

Why Flight Tests?

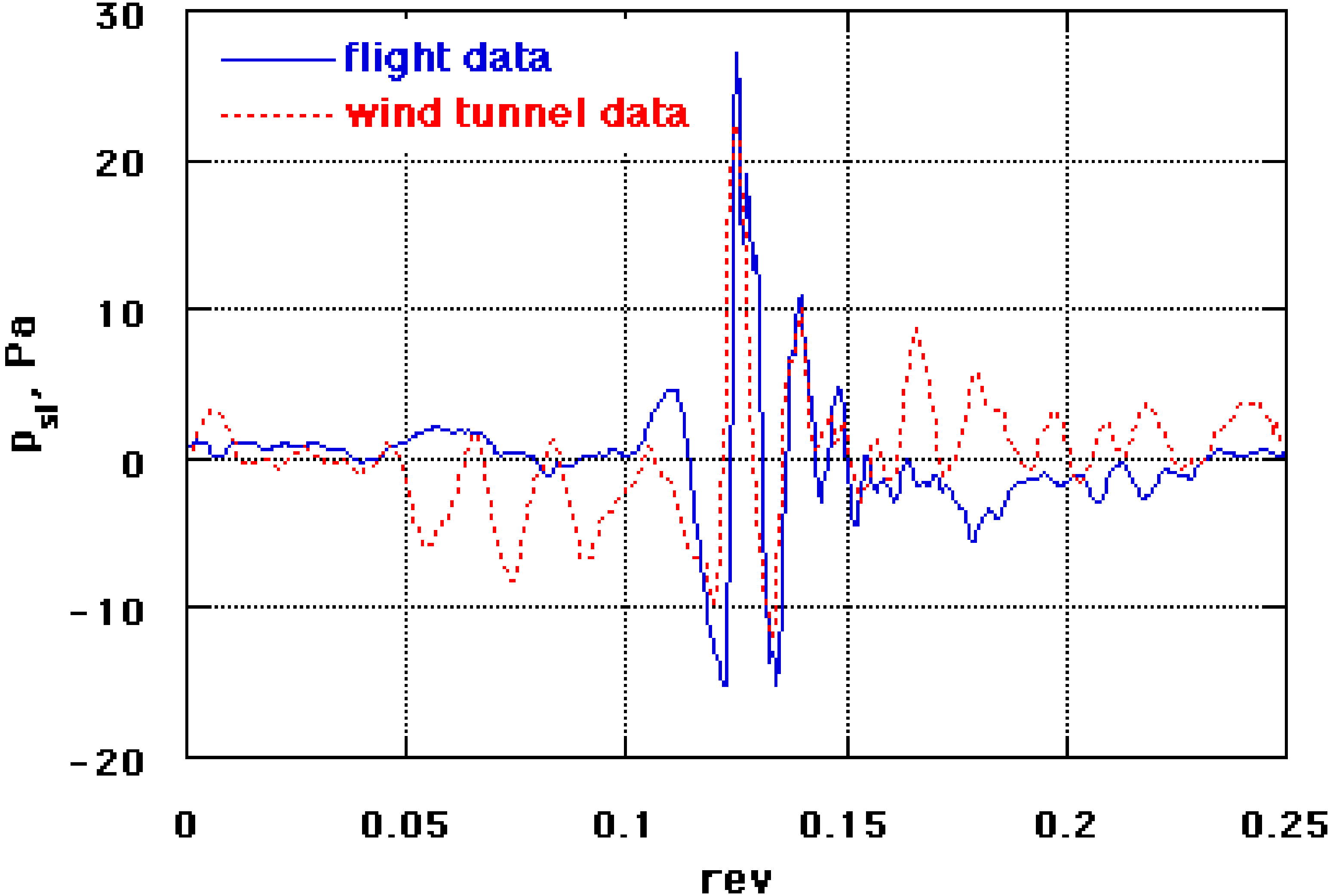
- **Why Flight Test?** Wind-tunnel tests provide precise, repeatable control of rotor operating conditions, but accurate noise measurements are difficult for several reasons:
- Wall effects prevent the rotor wake from developing exactly as it does in free flight. This is crucial because an important contributor to rotor noise is the interaction between the rotor and its own wake (such as blade-vortex interaction).
- In many wind-tunnel tests, the rotor test stand is not the same shape as the helicopter fuselage, hence aerodynamic interference between the test stand and rotor is different than in flight.
- The wind-tunnel walls cause reflections that may corrupt the acoustic signals.
- The wind tunnel has its own background noise, caused by the wind-tunnel drive and by the rotor test stand. (The YO-3A aircraft is actually quieter than many wind tunnels.)
- The wind tunnel turbulence level is rarely the same as in flight.
- The rotor is frequently trimmed differently in a wind-tunnel test than in flight.

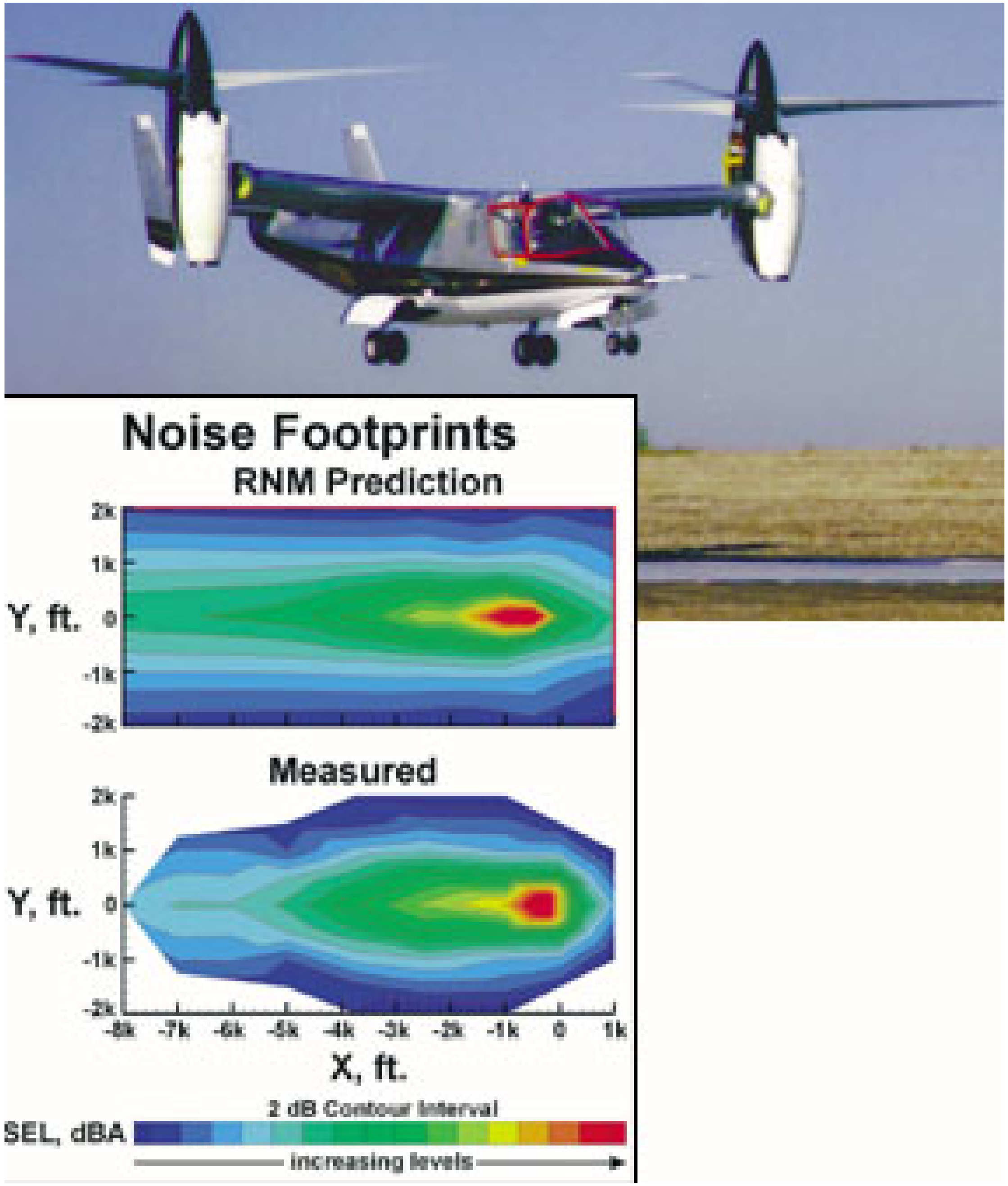
Wind Tunnel Tests



http://halfdome.arc.nasa.gov/research/IRAP-intro.html

Flight Test vs. Wind Tunnel Tests

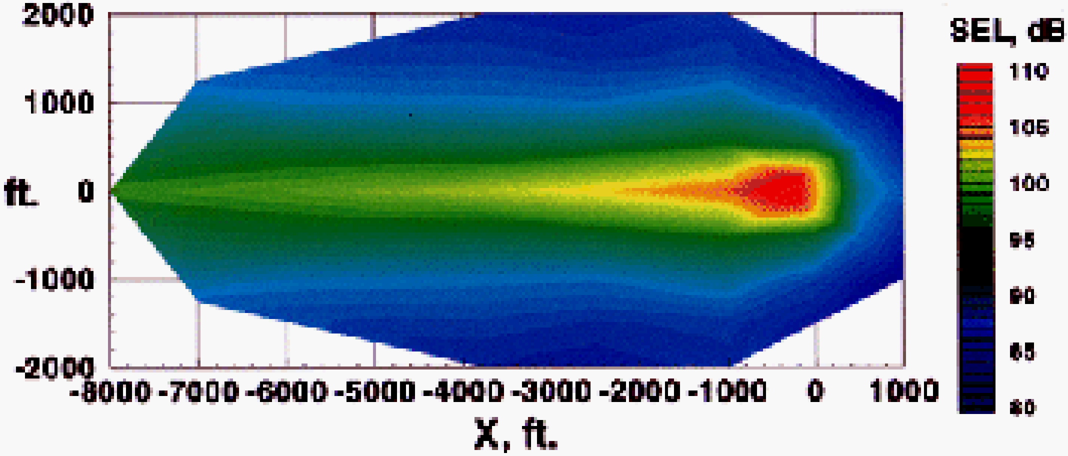


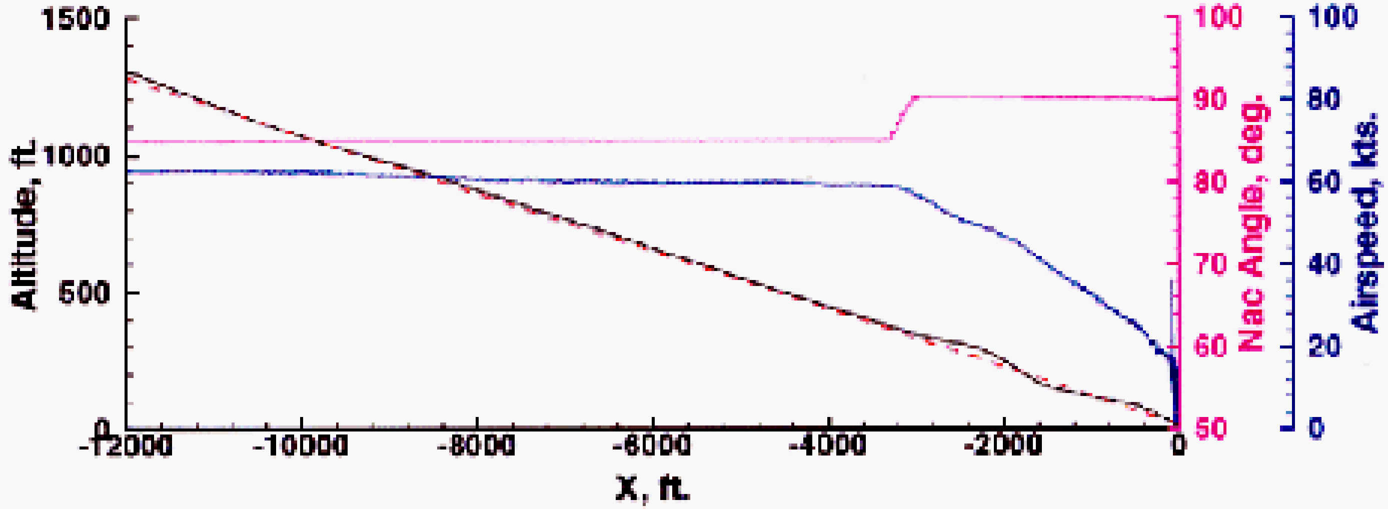


Noise Footprints
RNM Prediction
Measured
Y, ft.
X, ft.
2k
1k
0
-1k
-2k
-7k
-6k
-5k
-4k
-3k
-2k
-1k
1k
2 dB Contour Interval
SEL, dBA
increasing levels

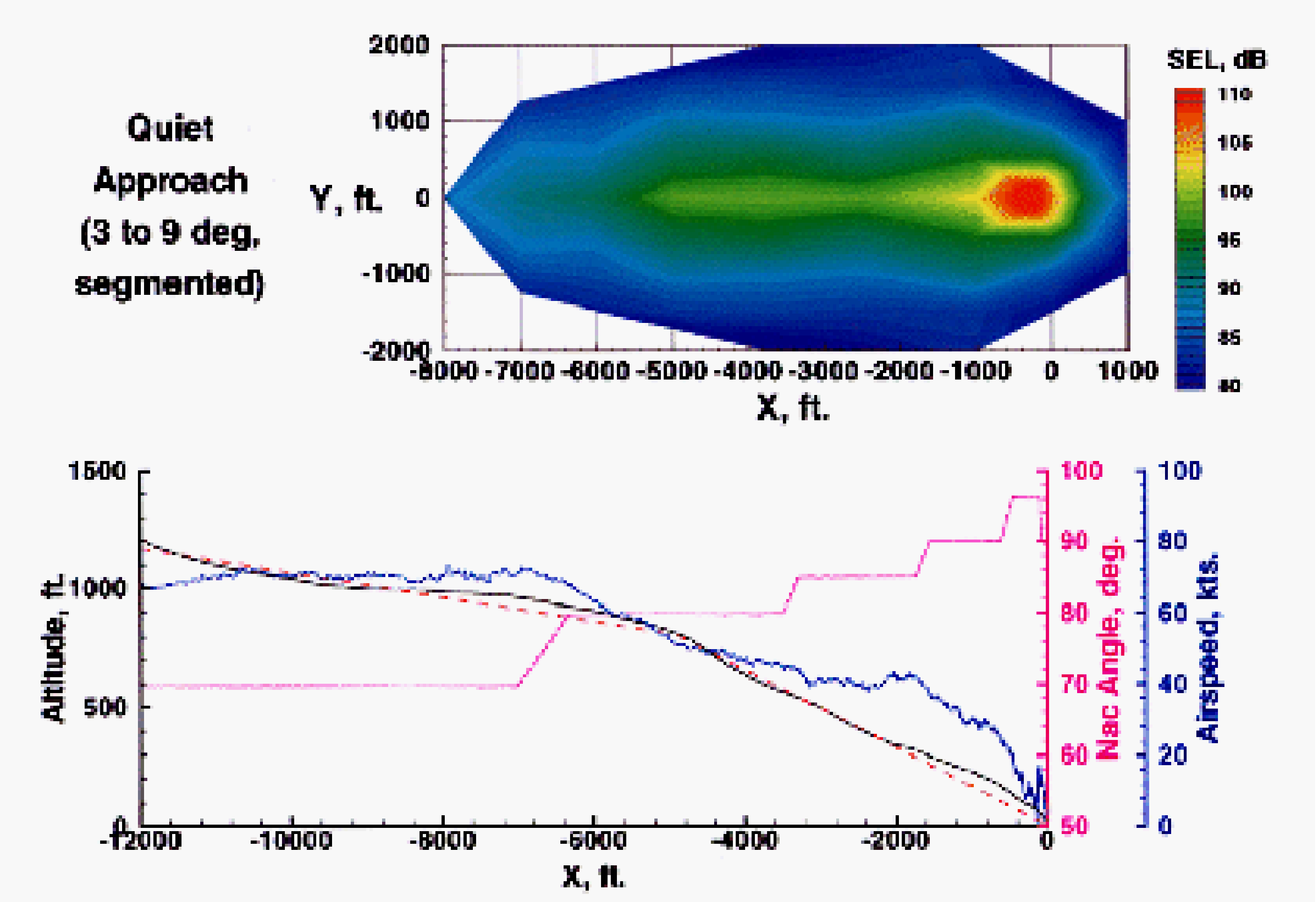
Baseline Approach; 70 kts, 85 deg. nacelle; flare into IGE hover

Baseline Approach
(6 deg, straight-in)





Noise Abatement: Quite Approach



Lighthill's Formulation

- **Idea: rearrange governing equation into a wave equation**

$$\frac{\partial}{\partial t}\left\{\frac{\partial \rho}{\partial t}+\frac{\partial \rho u_i}{\partial x_i}\right\}=0$$ continuity

$$-\quad \frac{\partial}{\partial x_i}\left\{\frac{\partial\, \rho u_i}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_i u_j+P_{ij})\right\}=0$$ momentum (N-S)

$$\frac{\partial^2 \rho}{\partial t^2}=\frac{\partial^2}{\partial x_i \partial x_j}\left(\rho u_i u_j+P_{ij}\right)$$

form wave equation

$$\boxed{\frac{\partial^2 \rho}{\partial t^2}-c_o\,\frac{\partial^2 \rho}{\partial x_i \partial x_i}=\frac{\partial^2 T_{ij}}{\partial x_i \partial x_j}}$$

where $T_{ij}=\rho u_i u_j+P_{ij}-c_o \rho \delta_{ij}$

Kirchoff Formulation

- **define generalized pressure perturbation:**

$$\tilde{p}' = \begin{cases} p' & f > 0 \\ 0 & f < 0 \end{cases}$$

f(x,y,z,t):Rotor Surface

- **use generalized derivatives**
- **generalized wave equation is Kirchhoff governing equation:**

$$\Box^2 p'(\vec{x},t) = -\left(\frac{\partial p'}{\partial t}\frac{M_n}{c} + \frac{\partial p'}{\partial n}\right)\delta(f) - \frac{\partial}{\partial t}\left(p'\frac{M_n}{c}\delta(f)\right) - \frac{\partial}{\partial x_i}\left(p'\hat{n}_i\delta(f)\right)$$

$$\equiv Q_{kir}$$

$$\frac{\partial^2 p'}{\partial t^2} - c^2\nabla^2 p' = Q_{Kirchoff}$$

Ffowcs Williams-Hawkings Formulation

- **Embed exterior flow problem in unbounded space**
  - **define generalized functions valid throughout entire space**
  - **interpret derivatives as generalized differentiation**

$$\tilde{\rho} = \begin{cases} \rho & f > 0 \\ \rho_o & f < 0 \end{cases}$$

$$\rho\tilde{u}_i = \begin{cases} \rho u_i & f > 0 \\ 0 & f < 0 \end{cases}$$

$$\tilde{P}_{ij} = \begin{cases} P_{ij} & f > 0 \\ 0 & f < 0 \end{cases}$$

- **Generalized conservation equations:**

$$\frac{\bar{\partial}\tilde{\rho}}{\partial t} + \frac{\bar{\partial}\rho\tilde{u}_i}{\partial x_i} = (\rho' \frac{\bar{\partial} f}{\partial t} + \rho u_i \frac{\bar{\partial} f}{\partial x_i})\delta(f) \qquad \text{continuity}$$

$$\frac{\bar{\partial}\rho\tilde{u}_i}{\partial t} + \frac{\bar{\partial}\rho\tilde{u}_i\tilde{u}_j}{\partial x_j} + \frac{\bar{\partial}\tilde{P}_{ij}}{\partial x_j} = (\rho u_i \frac{\partial f}{\partial t} + (\rho u_i u_j + P_{ij})\frac{\partial f}{\partial x_i})\delta(f) \qquad \text{momentum}$$

FWH Formulation (Continued)

- **Numerical solution of the FW–H equation**

$$\Box^2 p'(\bar{x},t) = \frac{\partial}{\partial t}[\rho_0 \mathrm{v}_n \delta(f)] - \frac{\partial}{\partial x_i}[l_i \delta(f)] + \frac{\partial^2}{\partial x_i \partial x_j}[T_{ij} H(f)]$$

- **Three source terms**
  - **thickness source (monopole)**
    - **requires blade *geometry* and *kinematics***
  - **loading source (dipole)**
    - **requires blade geometry, kinematics, and *surface loading***
  - **quadrupole source**
    - **requires *flow field* (i.e., T_{ij}) around the blade (volume integration)**

FWH Formulation (Continued)

- **Retarded-time solution to FW–H equation** (neglecting quadrupole)

$$4\pi p'(\vec{x},t) = \frac{\partial}{\partial t}\int_{f=0}\left[\frac{Q}{r(1-M_r)}\right]_{ret} dS + \frac{\partial}{\partial x_i}\int_{f=0}\left[\frac{L_i}{r(1-M_r)}\right]_{ret} dS$$

where $Q = \rho v_n$ and $L_i = P_{ij}\hat{n}_j$

Stress Tensor that includes pressure,
Comes from a CFD analysis

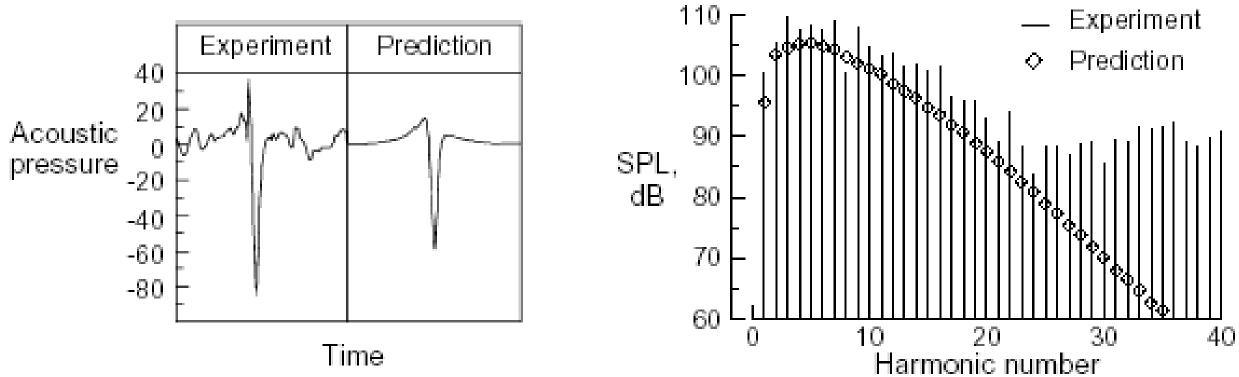
Integration is over rotor surface

M_r is Mach number of a source on the blade along r
R: distance between point on the blade and observer

Ret: Retarded time, that is time at which noise left the rotor

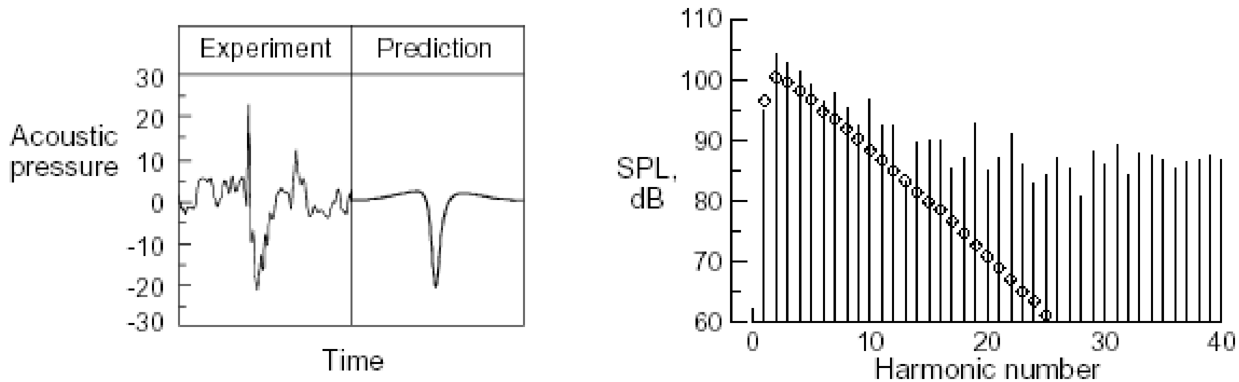
Thickness and Loading Noise

- **Predictions accurately reflect design changes**



a) Rectangular planform

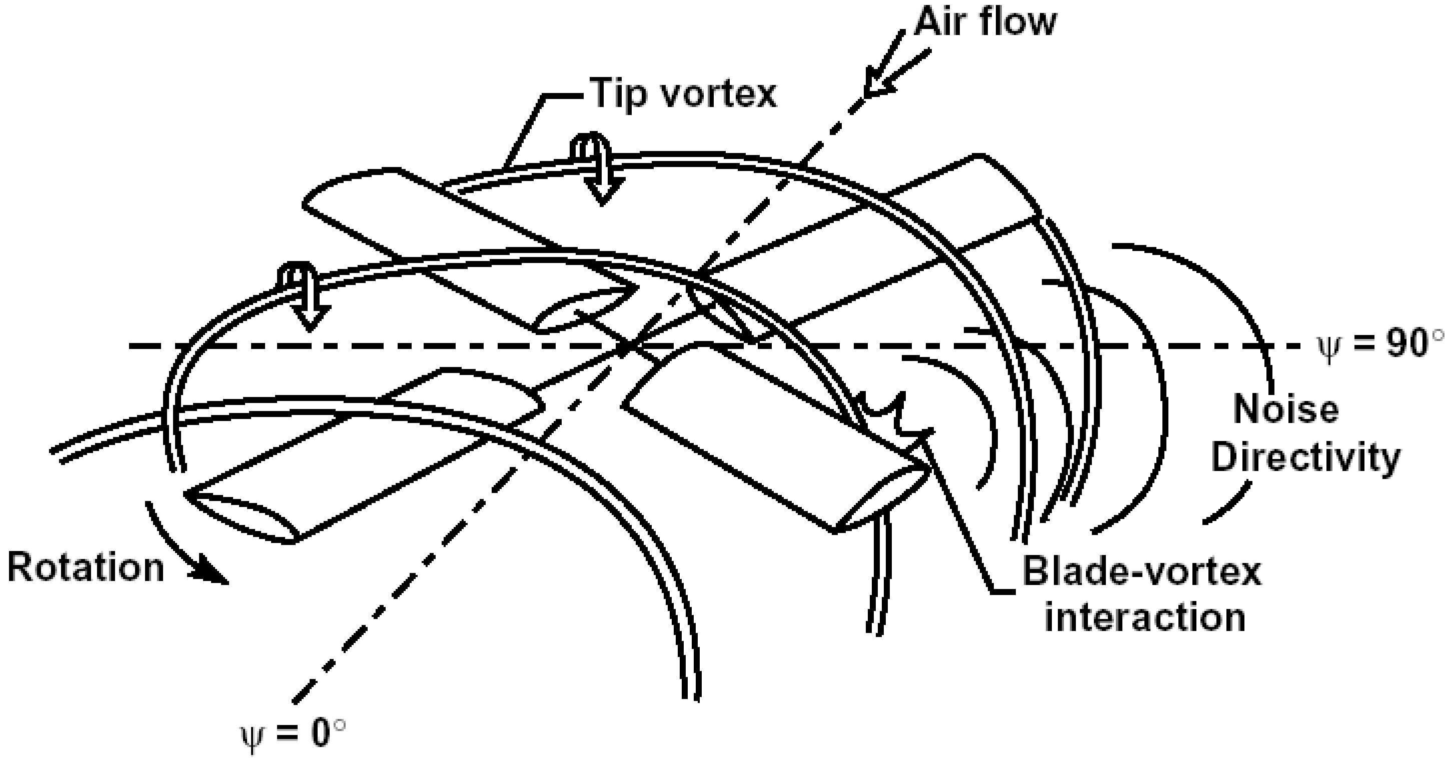
V_∞ = 110 kts
upstream mic in TPP
on advancing side



b) Tapered planform

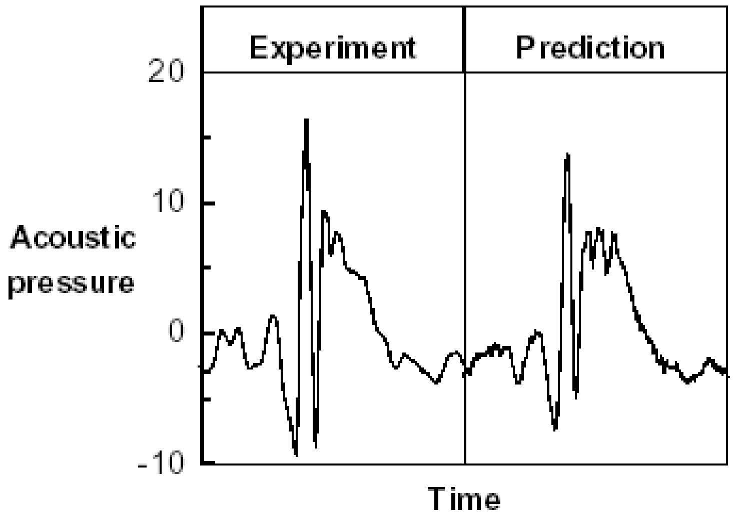
ref: Brentner 1987

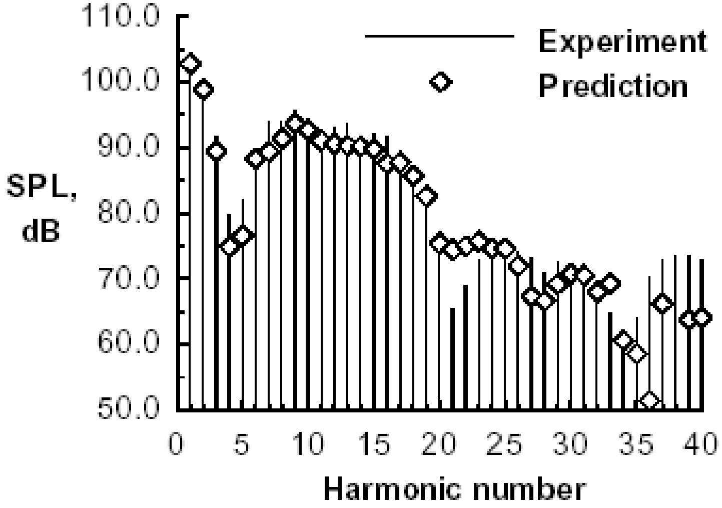
Blade-Vortex Interaction (BVI)



BVI Noise Prediction: *with measured airloads*

- Amplitude, waveform, and spectra predicted well
- High temporal and spatial resolution of blade loads essential



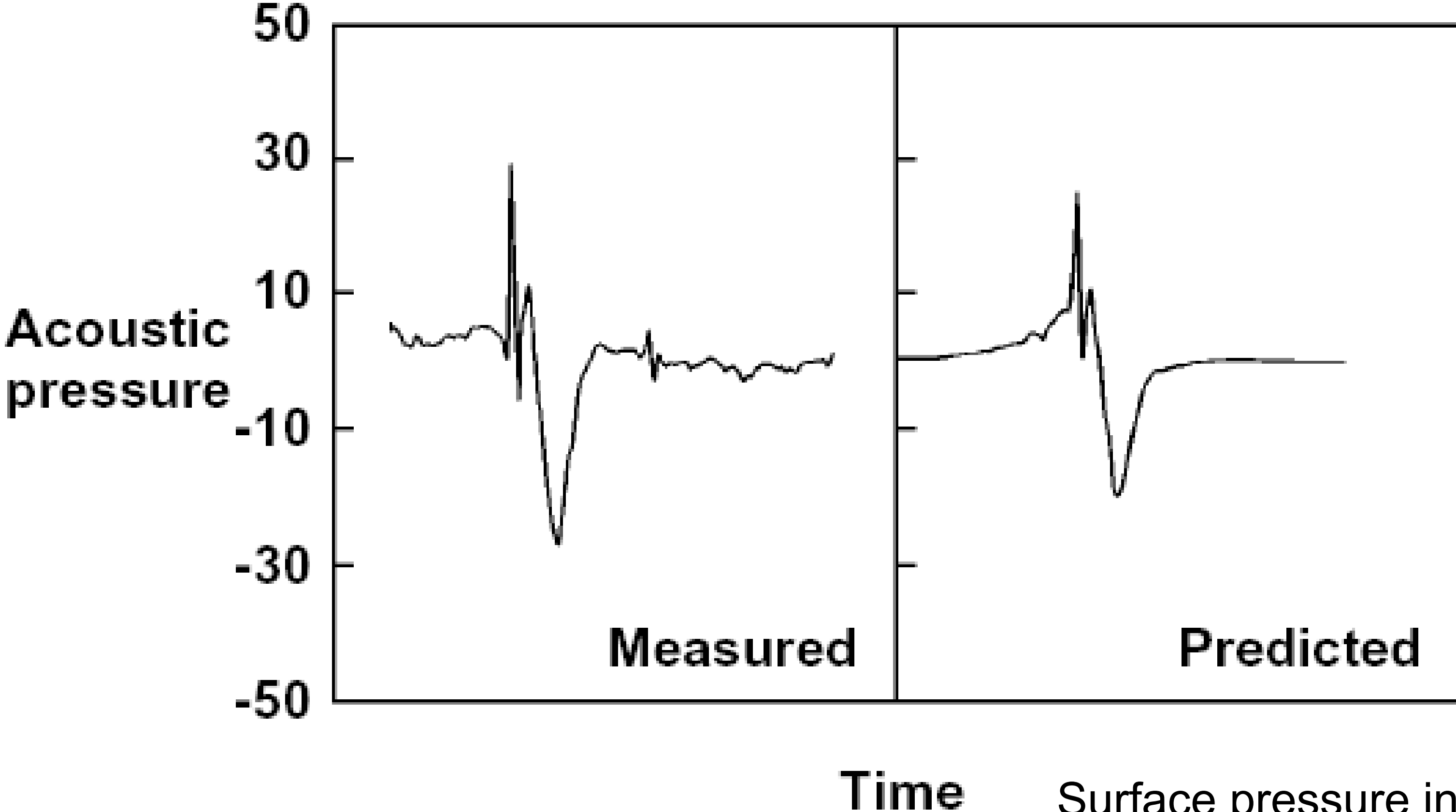


- microphone located upstream of rotor on advancing side, 25 deg. below TPP

$\mu = 0.152, \quad C_T / \sigma = 0.07,$ decent condition

Ref: Brentner et al. 1994, Visintainer et al. 1993

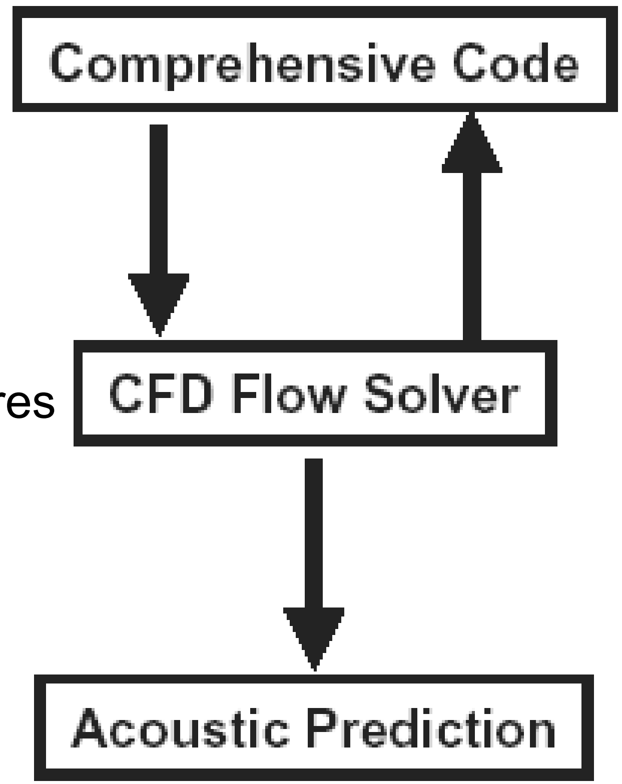
BVI Noise Predictions with Computed Loads



Surface pressure input
From RFS2BVI – a code
Jointly developed at Ga Tech
And Boeing Mesa.

Coupling of Acoustics Solver to CFD Codes and Comprehensive Codes

Provides trim,
Blade dynamics,
Elastic deformations

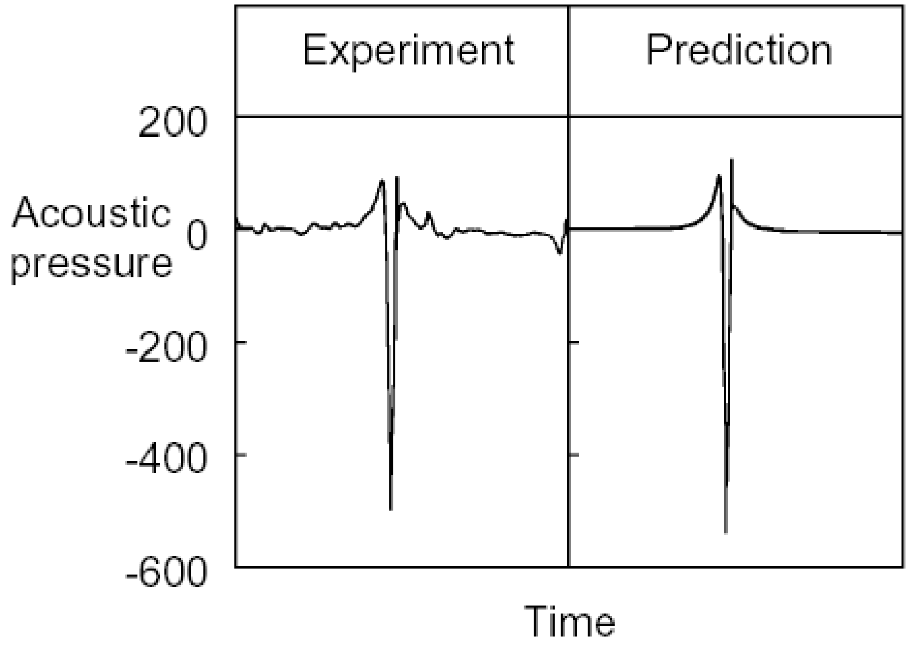


Provides surface Pressures
As a function of time all
Over the blade surface

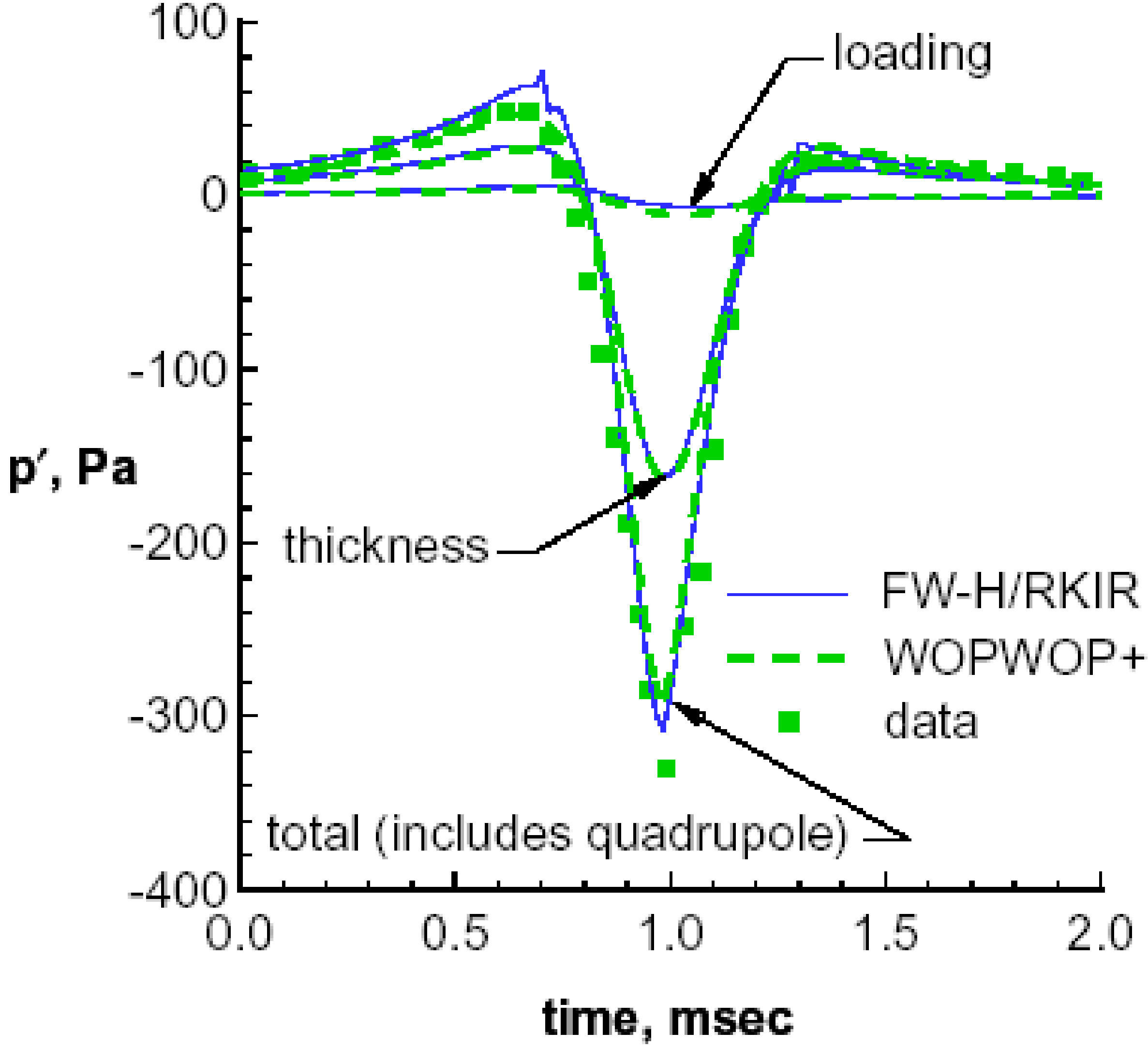
High-Speed Impulsive Noise

- Prediction by approximate quadrupole calculation
  - ➤ Measured blade pressures and computed flow field used in prediction

M_H = 0.9
hovering rotor
mic in TPP

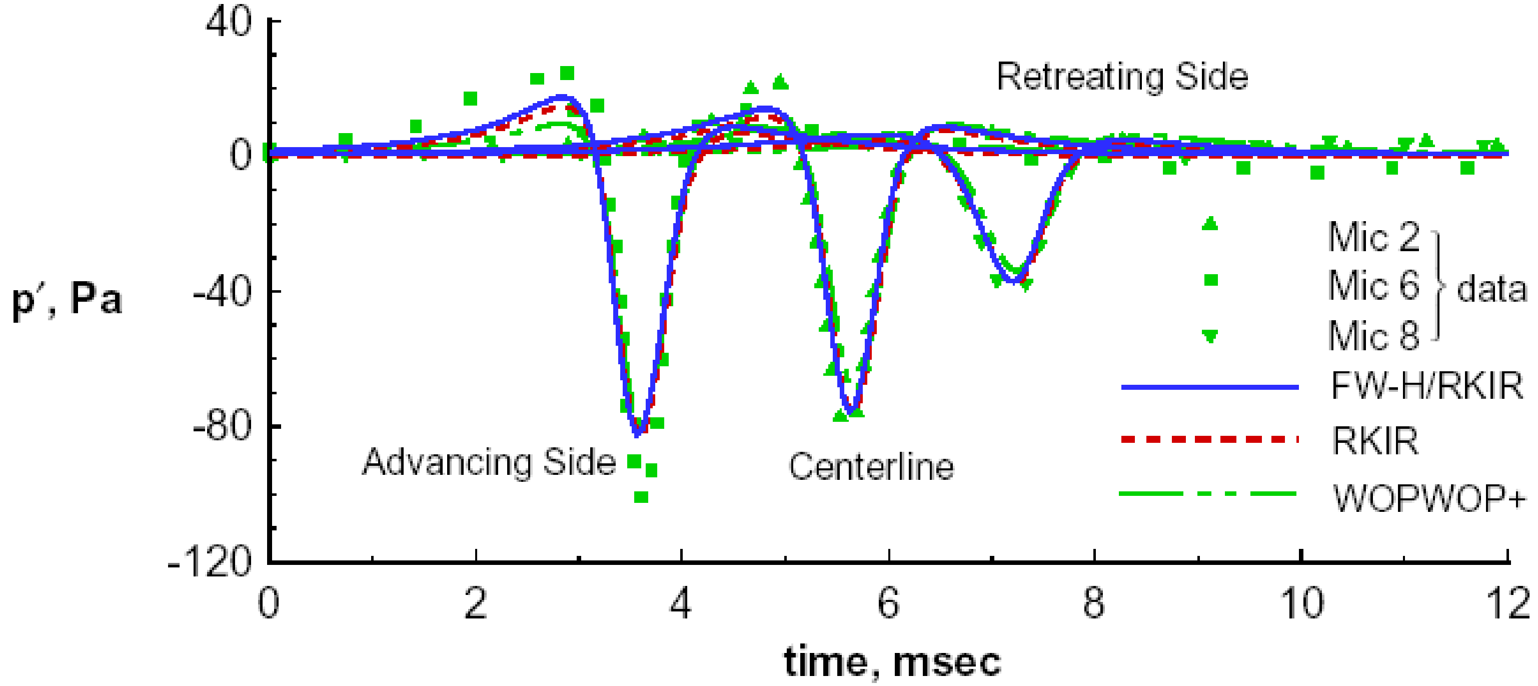


ref: Schultz and Splettstoesser 1987



loading
thickness
total (includes quadrupole)
FW-H/RKIR
WOPWOP+
data
p′, Pa
time, msec
100
0
-100
-200
-300
-400
0.0
0.5
1.0
1.5
2.0

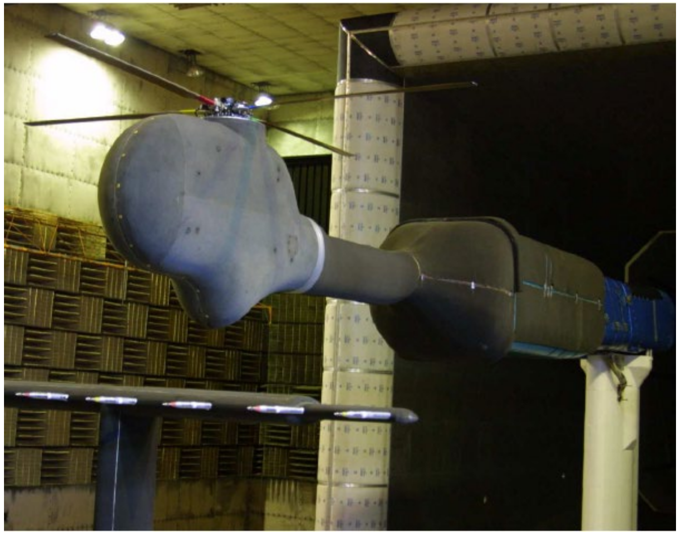
Numerical Comparison: Forward Flight Case



Validation of the Georgia Tech Solvers for HART-II BVI

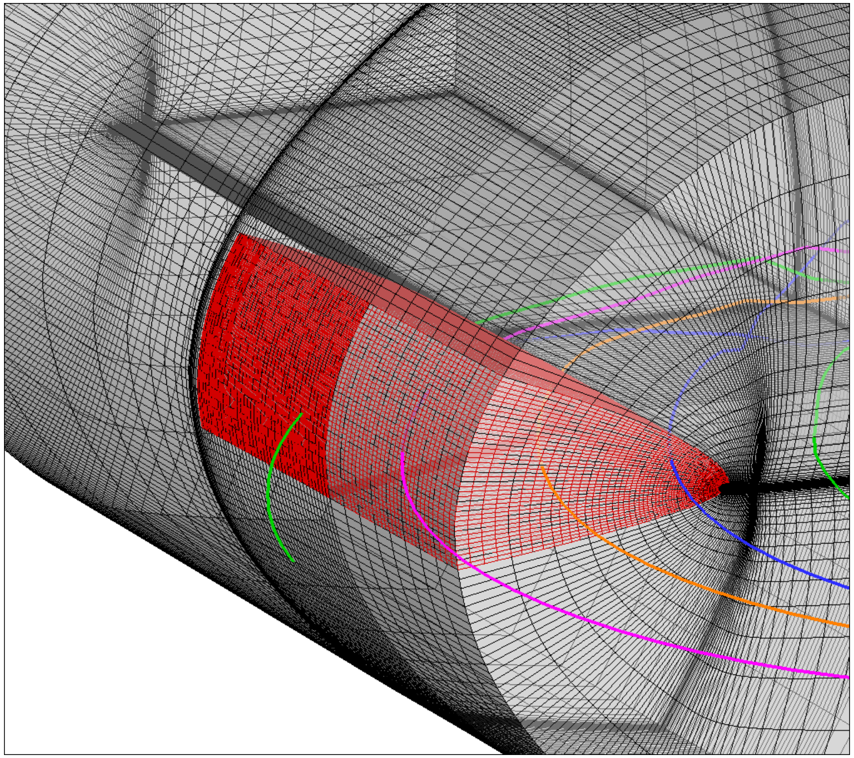
- HART-II (Higher harmonic control Aeroacoustics Rotor Test) model
  - 40% Mach scaled hingeless Bo105 model rotor (4 blades)
    - NACA23012 airfoil with 5.4mm trailing edge tab of 0.8mm thickness
    - Rectangular blade with -8 deg. linear twist (zero twist at 75%R)
    - Radius: 2m, Chord length: 0.121m
    - Precone anlge: 2.5 deg.
  - Well-documented noise data are publicly available.
  - Test condition includes a maximum BVI condition at a descent mode.

	Baseline Test Condition
α_{shaft}	**5.3° aft.**
μ, M_{tip}	**0.15, 0.64**

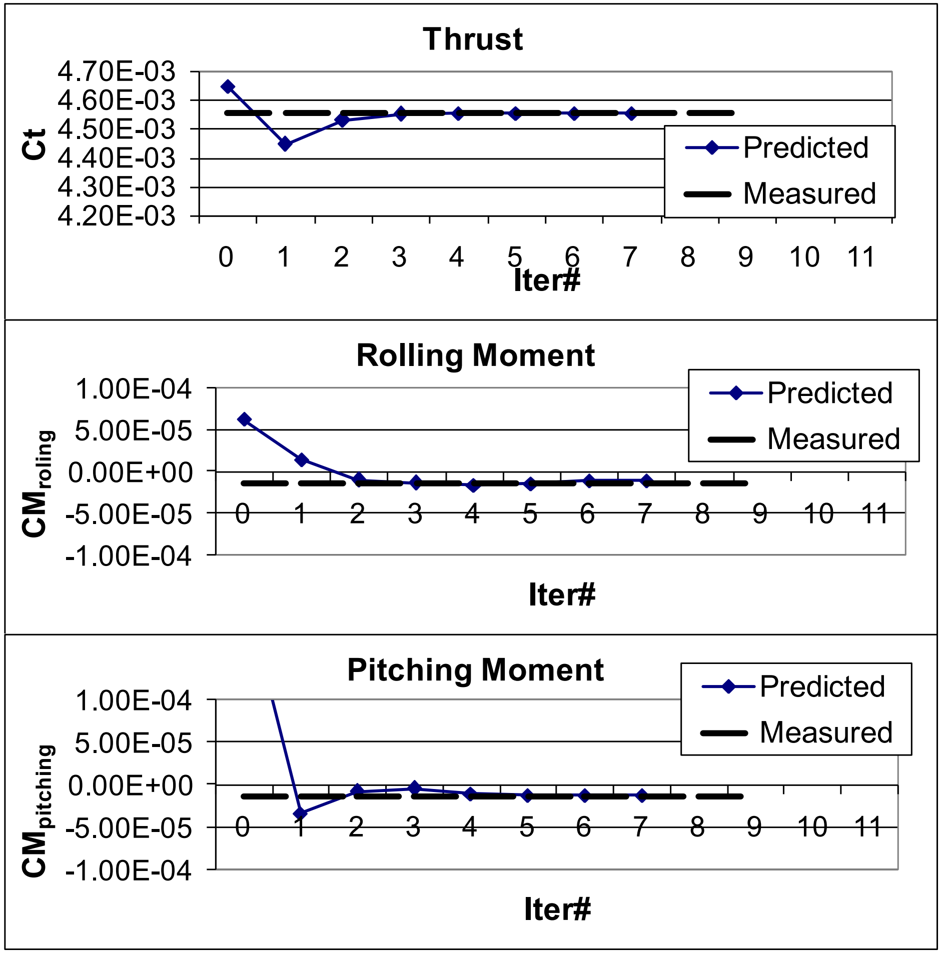


Coupled Analysis of the Baseline Rotor

- **CFD coupled to an elastic analysis (DYMORE) was carried out for baseline rotor.**

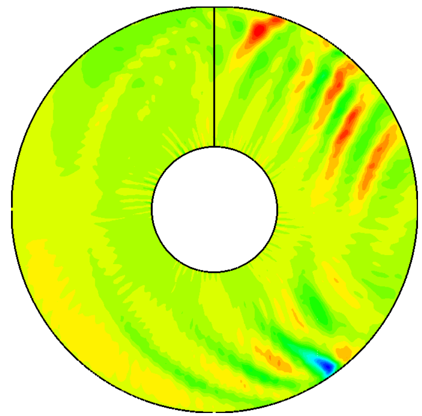


Baseline Grid with Embedded Grid

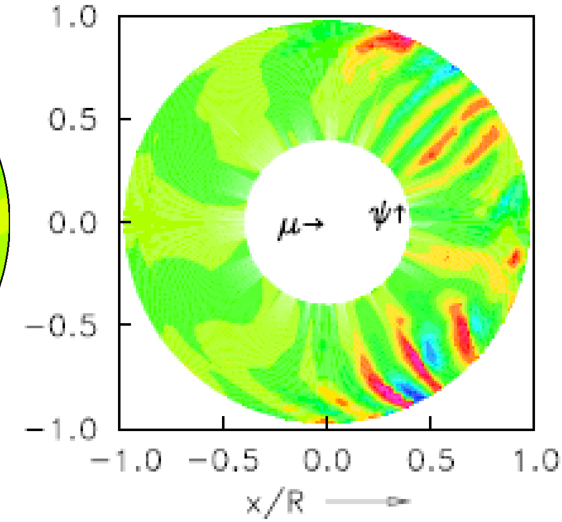


Predicted and Measured BVI events

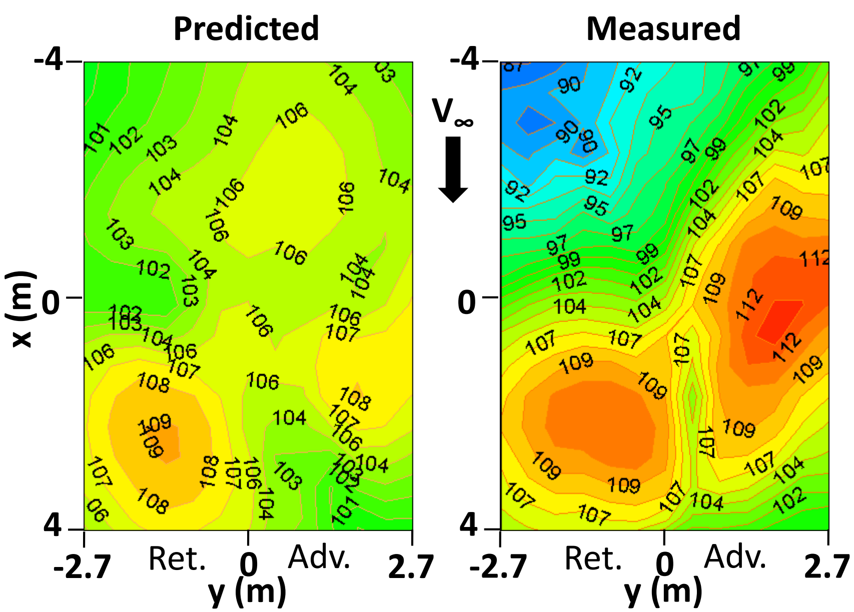
- BVI patterns over the 1st and 4th quadrants are reasonably well captured.
- Noise was under-estimated and additional hot spot was appeared in front disk area.



Predicted $\partial(C_n M^2)/\partial\psi$



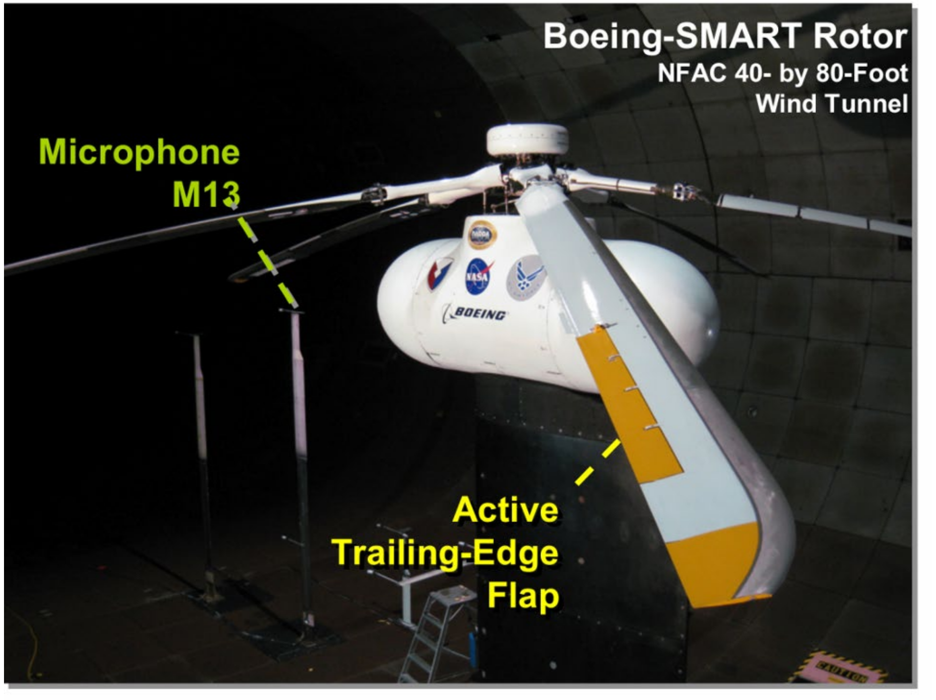
Measured ΔP_{LE}



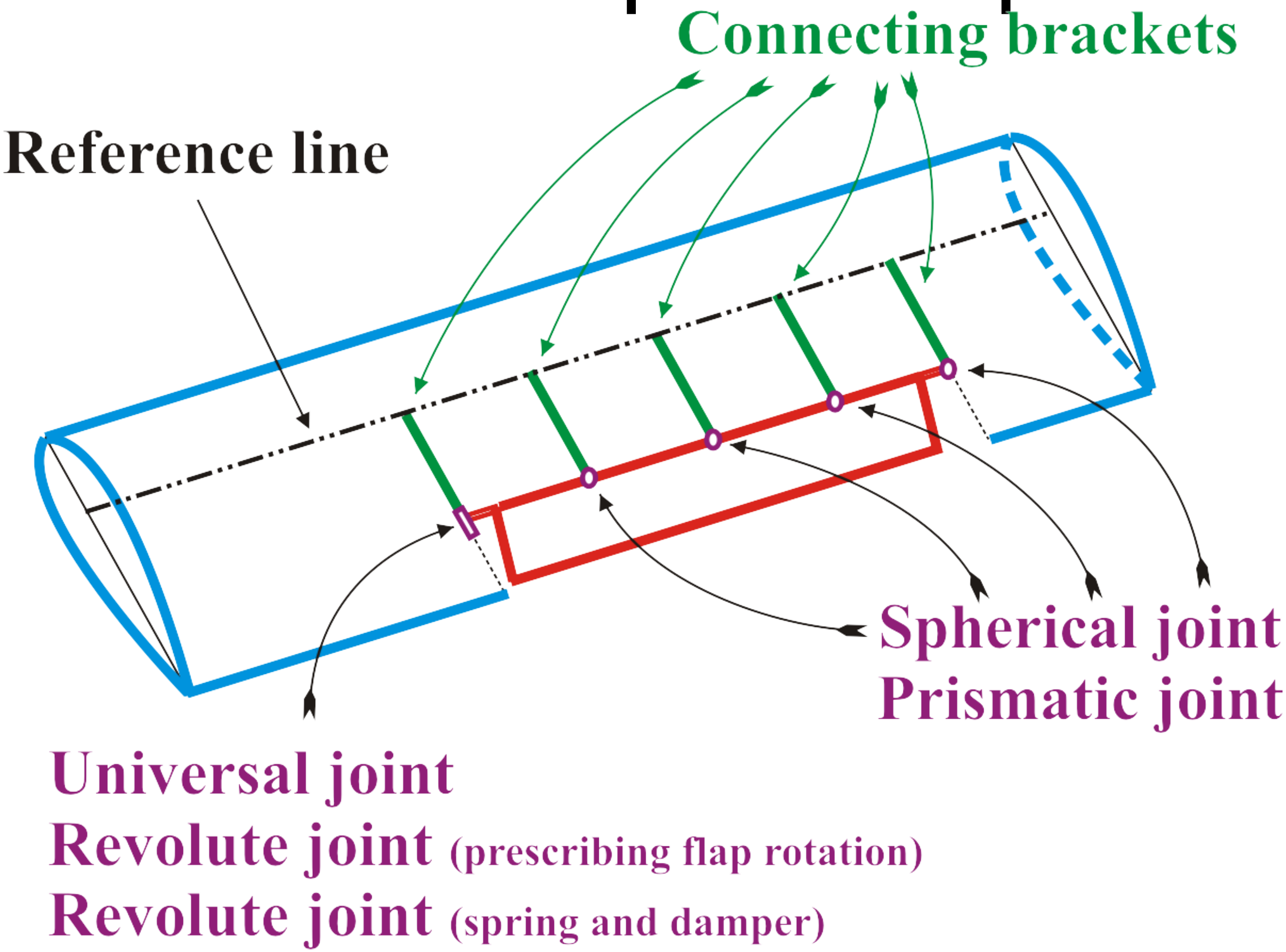
Noise Contour (BVISPL, z=-2.215m)

Smart Rotor

- The Boeing Active Flap SMART Rotor
- Blind Runs prior to wind tunnel entry in early 2008.

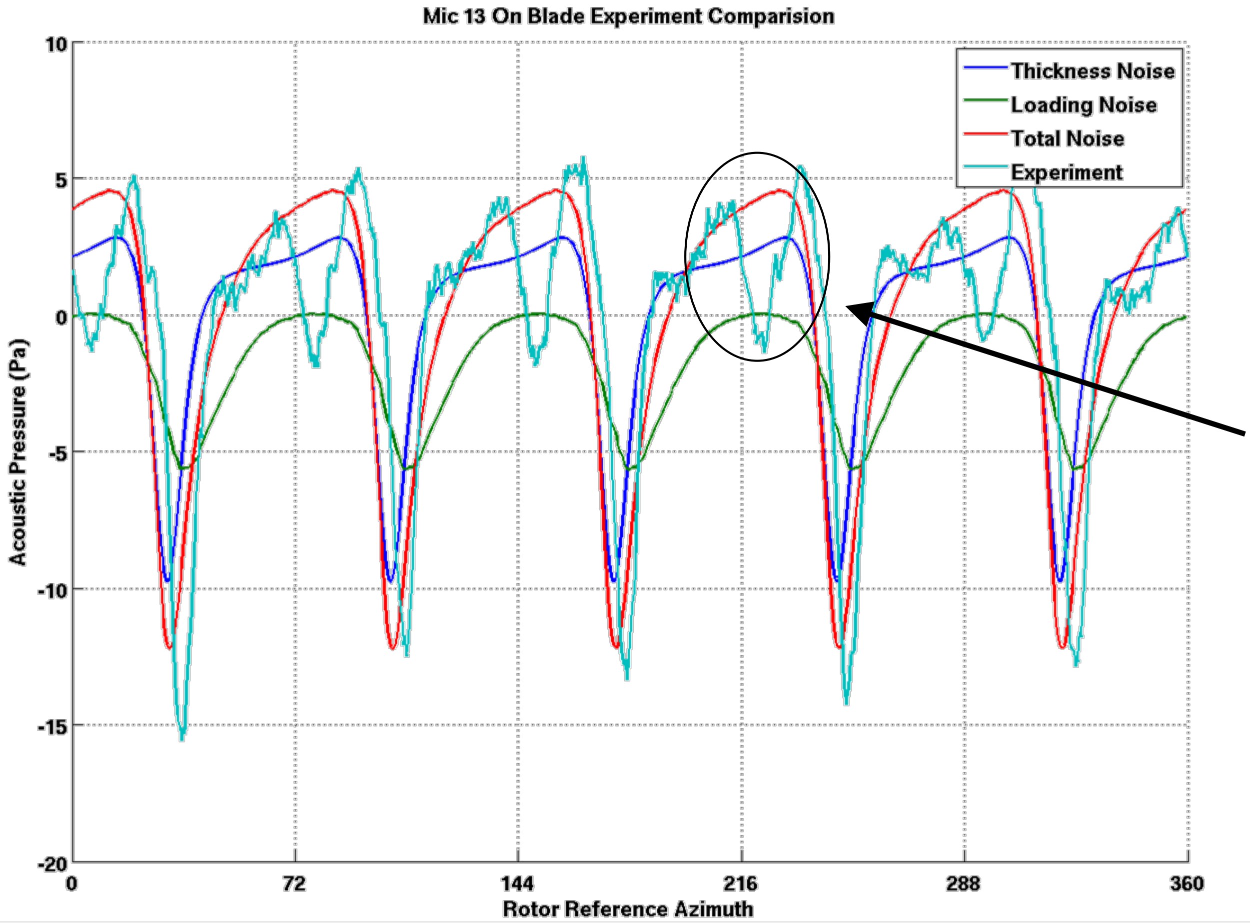


SMART Flap Description



SMART Rotor Results

- No Flap Deflection Case



This is likely due to Wind Tunnel wall reflections and is currently being researched in conjunction with

NASA and AFDD

Concluding Remarks

- Outputs from CFD codes (or even lifting line/blade element theory) can be input into aeroacoustic codes, that solve the wave equation in integral form.
- Satisfactory agreement is obtained for thickness, lift, and shock noise sources with these approaches.