Broadband Noise Predictions Based on a New Aeroacoustic Formulation

J. Casper and F. Farassat

NASA Langley Research Center
Hampton, Virginia

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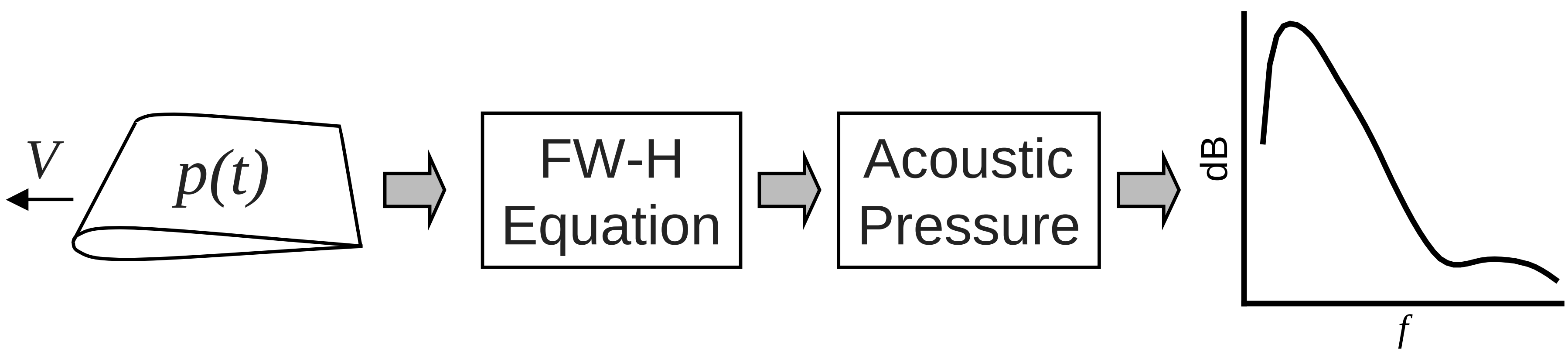
Outline

- Introduction / Motivation
- Acoustic Formulation
- Model Problems
  Surface Pressure from Thin Airfoil Theory
  Velocity Scaling Properties, Directivity
- Broadband Noise Prediction
  Incident Turbulence Noise
  Comparison with Experiment
  (Paterson and Amiet, 1976)

Introduction / Motivation

- Broadband Noise Prediction Tools
  - Airframe noise, ducted fan noise
  - Incident turbulence, TE noise
- Time Domain Approach
  - Acoustic Analogy
  - Ffowcs Williams – Hawkings equation
  - Decouples aerodynamics from acoustics
  - Input from CFD or experiment



Acoustic Formulation

$\tilde{f} \geq 0$: surface geometry

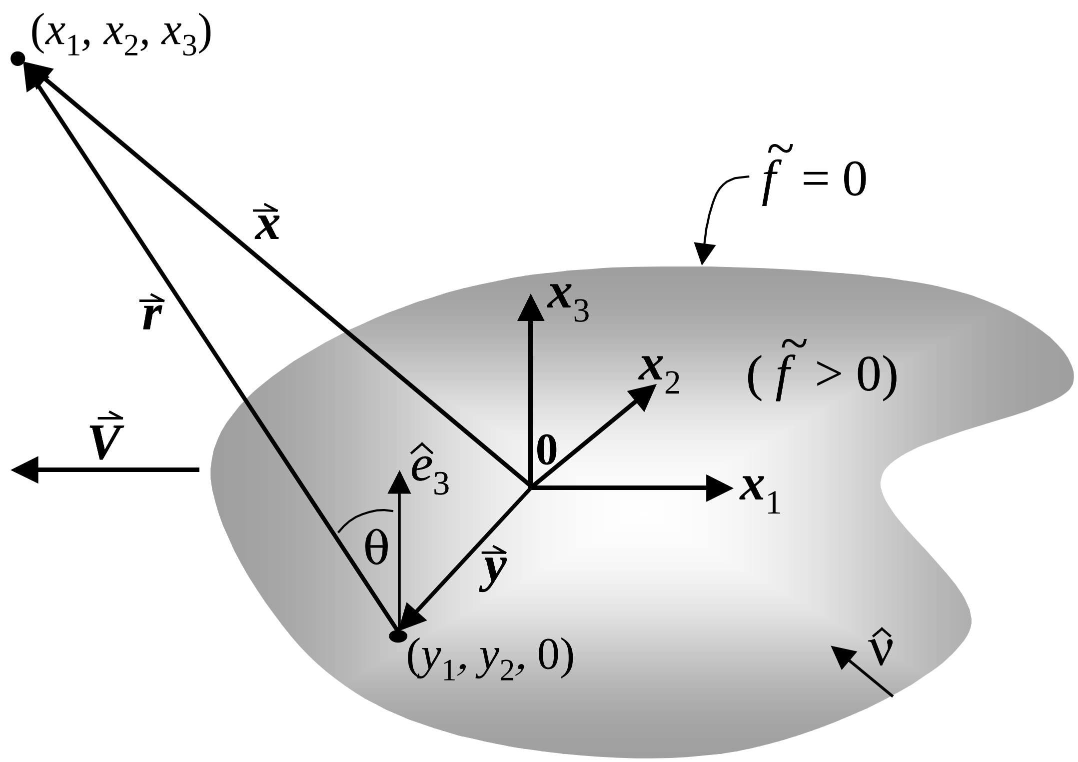
$\hat{\nu} =$ geodesic normal

$\vec{x} =$ observer position

$\vec{y} =$ source position

$$\vec{r} = \vec{x} - \vec{y}$$

$$\cos\theta = \vec{r} \cdot \hat{e}_3 / r$$



The only restriction on the velocity vector is that it lie in the same plane as the surface.

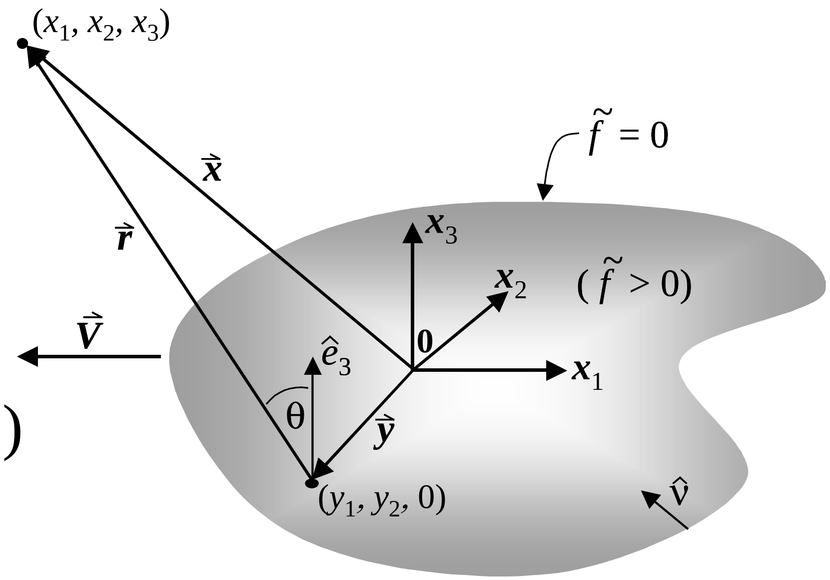
Acoustic Formulation

<u>Ffowcs Williams - Hawkings Equation</u>

Loading Noise (Dipole)

$$\frac{1}{c_0^2}\frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = -\vec{\nabla}\cdot\left[p\,\hat{n}\,H(\tilde{f})\,\delta(x_3) \right]$$

$$= -p(x_1, x_2, t)\,H(\tilde{f})\,\delta'(x_3)$$



<u>Solution</u>:

$$4\pi\, p'(\vec{x}, t) = -\int_{-\infty}^{t}\int_{R^3} \frac{\delta(g)}{r}\, p(y_1, y_2, \tau)\, H(\tilde{f})\,\delta'(y_3)\, d\vec{y}\, d\tau$$

Free-space Green's function: $\dfrac{\delta(g)}{4\pi\, r}$, $\quad g = \tau - t + \dfrac{r}{c_0}$

j.h.casper@larc.nasa.gov

Formulation 1B

$$4\pi p'(\vec{x},t) = \int_{\tilde{f}>0} \left[\frac{(\partial p/\partial\tau - V\partial p/\partial s)\cos\theta}{c_0\, r(1-M_r)} \right]_{\text{ret}} dS$$

$$+ \int_{\tilde{f}>0} \left[\frac{p\cos\theta}{r^2(1-M_r)} \right]_{\text{ret}} dS \; - \int_{\tilde{f}=0} \left[\frac{M_v\, p\cos\theta}{r(1-M_r)} \right]_{\text{ret}} d\ell$$

- Given $p(\vec{y},t)$ on the surface, this formula yields the loading noise at an observer $\vec{x}$ at time t.
- For $M \ll 1$, $r \gg \lambda$, the first integral dominates the signal.
- The contour integral vanishes at the trailing edge if the Kutta condition is satisfied.
- This formulation is valid for a rotating surface.

Formulation 1B

Test Cases

- Velocity Scaling Properties
- Directivity

Analytic Surface Pressure

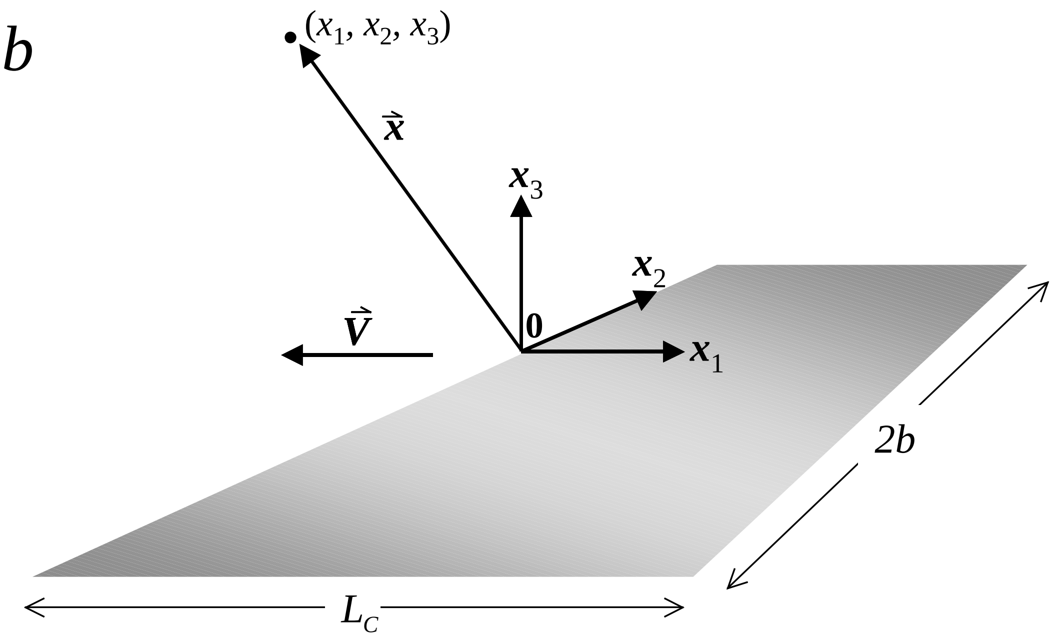
- Thin Airfoil Theory (Amiet, 1975-6)
- Periodic Gust – Constant Frequency
- Flat Plate in Uniform Rectilinear Motion

Analytic Surface Pressure

Rectangular Surface at Constant Velocity

$$0 \le x_1 \le L_C\ , \quad -b \le x_2 \le b$$

$$\vec{V} = [-U, 0, 0]^T$$



Upwash

$$w(x_1, t) = w_0\, e^{-ik(x_1 - Ut)}$$

Surface pressure

$$\Delta P(x_1, t) = \rho_0 U\, w_0\, g(x_1, k)\, e^{ikUt}$$

$k = \omega / U =$ constant, $\quad g(x_1, k)$ from thin airfoil theory

Directivity

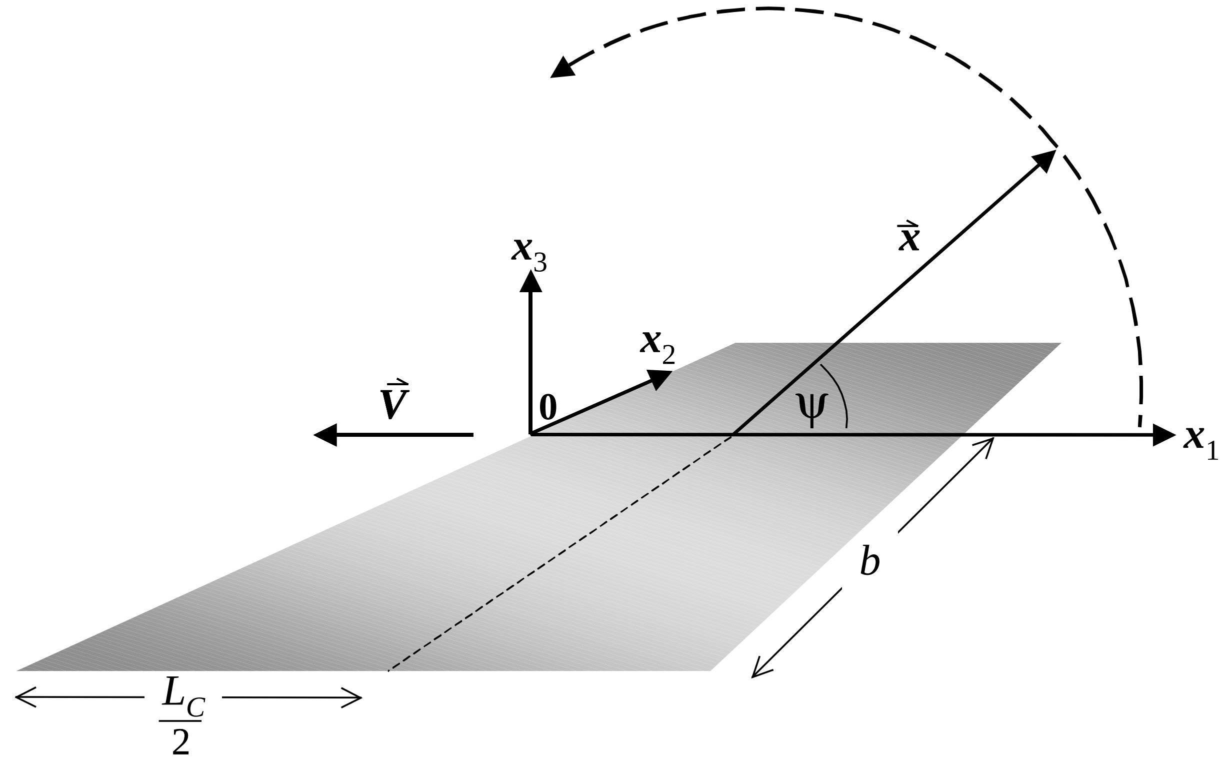
$$L_C = 0.5 \text{ m}$$

$$2b = 2.0 \text{ m}$$

$$M = 0.2$$

$$U = 68.6 \text{ m/s}$$

$$w_0 = 0.05\,U$$

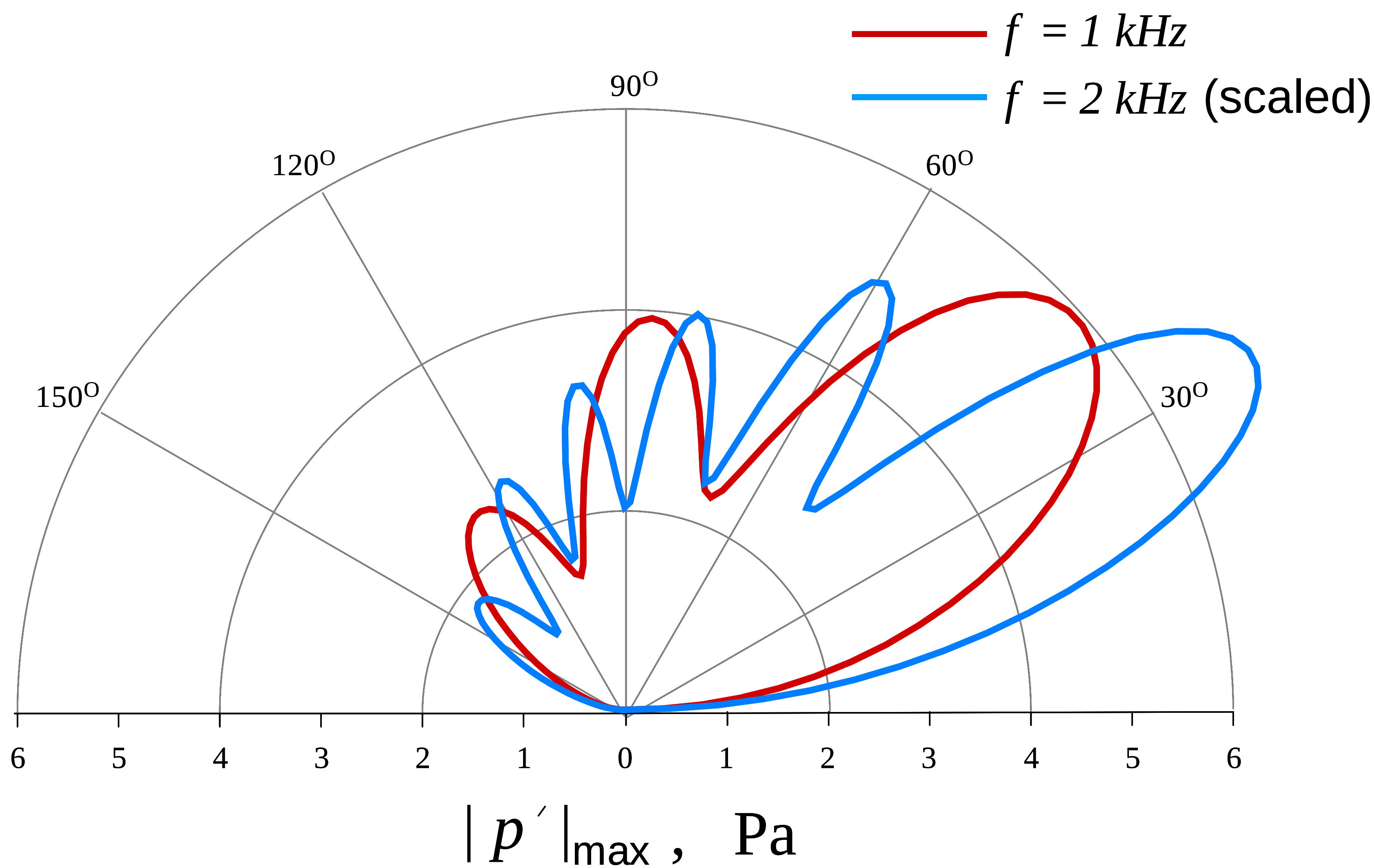


<u>Test Cases</u>

$$\vec{x} : (r, \psi)\,,\ \ r = 3 \text{ m}\,,\ 0 \le \psi \le \pi$$

$$f_1 = 1 \text{ kHz}\,,\ \ f_2 = 2 \text{ kHz}$$

Directivity



Incident Turbulence Noise

Experiment: Paterson and Amiet (1976)

NACA 0012 Airfoil

Chord = 0.23 m

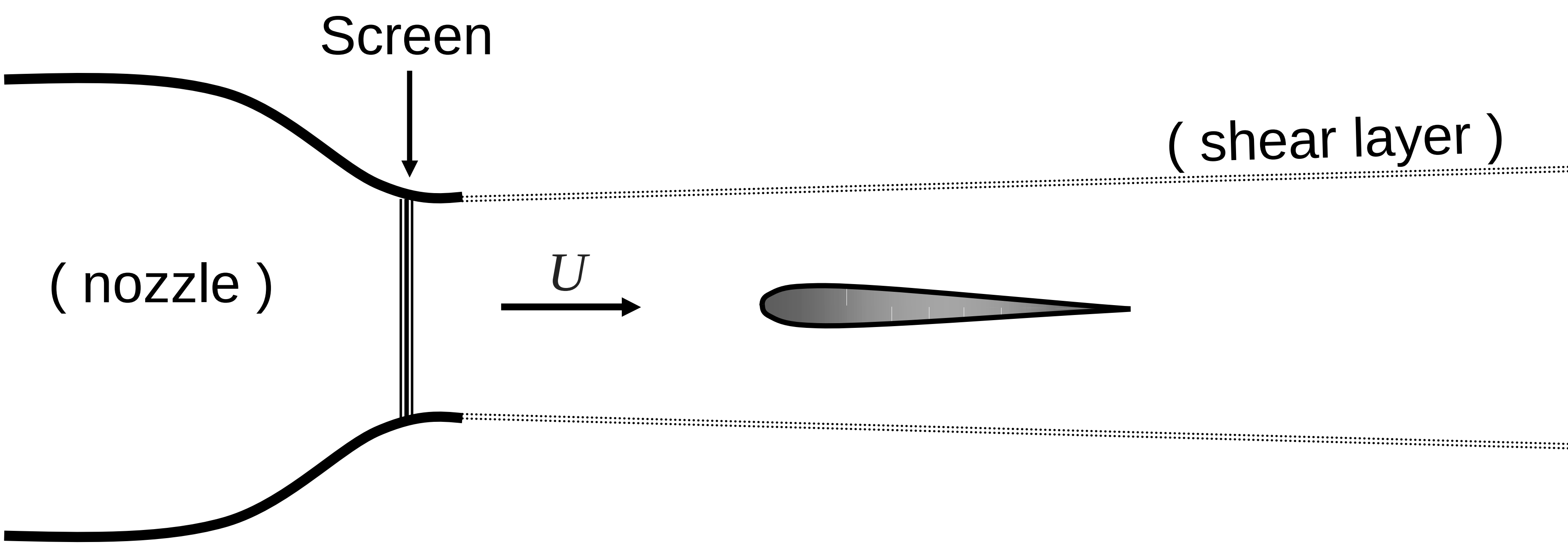
Span = 0.53 m

$\alpha = 0$ degrees

Microphone:

$r = 2.25$ m,

$\theta = 90$ degrees



2D Periodic Gust

Upwash

$$w(x_1, x_2, t) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \hat{\hat{w}}(k_1, k_2)\, e^{-i[k_1(x_1 - Ut) + k_2 x_2]}\, dk_1 dk_2$$

Surface pressure

$$\Delta P(x_1, x_2, t) = \rho_0 U \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \hat{\hat{w}}(k_1, k_2)\, g(x_1, k_1, k_2)\, e^{i(k_1 Ut - k_2 x_2)} dk_1\, dk_2$$

Amiet (1975)
Skewed gusts contribute little to the sound received by an observer in the plane $x_2 = 0$ (mid-span), *i.e.* $k_2 = 0$ is the only spanwise wave number to consider.

Broadband Surface Pressure

$$\Delta P(x_1, t) \approx \rho_0 U \sum_{n=-N}^{N} A_{n,0}\, g(x, k_{1,n}, 0)\, e^{i\left(k_{1,n} U t + \Phi_n\right)}$$

$$A_{n,0} = \left[S_{ww}(k_{1,n}, 0)\, \Delta k_1 \Delta k_2 \right]^{1/2}$$

$S_{ww}(k_1, k_2) =$ power spectral density of w

$\Phi_n =$ random phase angle on $[0, 2\pi]$

Without explicit spanwise integration, this formulation can be expected to require amplitude scaling in the far field, but the spectral shape of the noise will be unaffected.

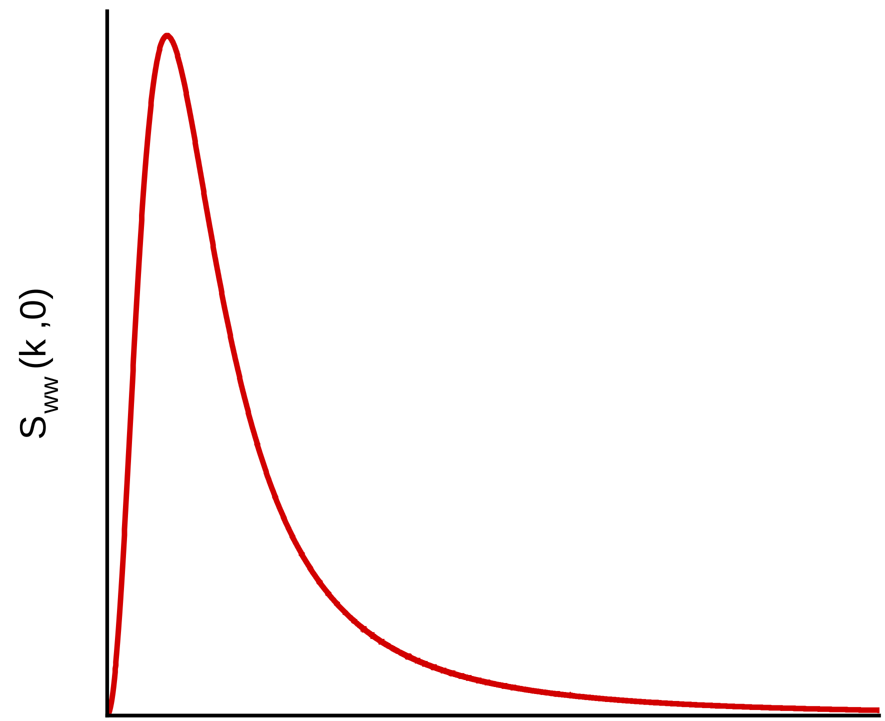
Turbulence PSD

2-Component von Karman Formula

$$S_{ww}(k_1,k_2)=\frac{4}{9\pi}\frac{u^2}{k_e^2}\frac{\hat{k}_1^2+\hat{k}_2^2}{\left[1+\hat{k}_1^2+\hat{k}_2^2\right]^{7/3}}$$

$$\hat{k}_i=\frac{k_i}{k_e}\,,\quad k_e=\frac{\sqrt{\pi}}{L_1}\frac{\Gamma(5/6)}{\Gamma(1/3)}$$

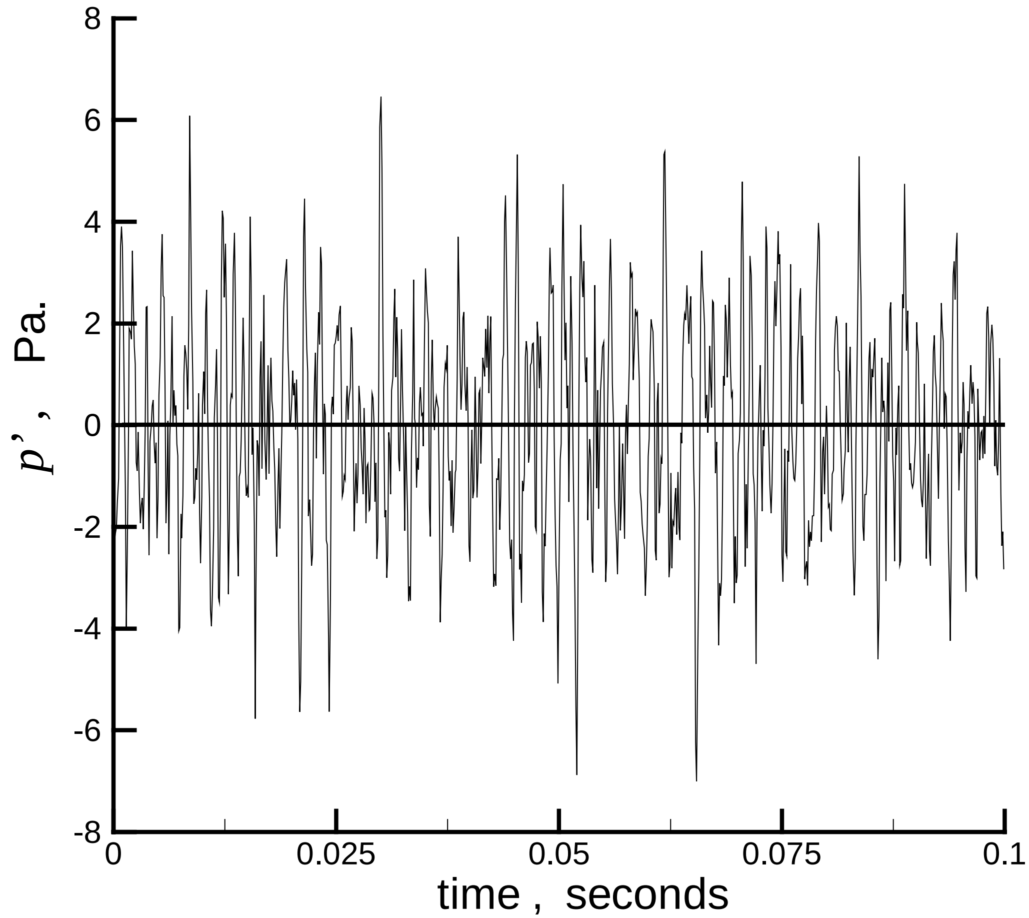
L_1 and u^2 determined by experimental measurement



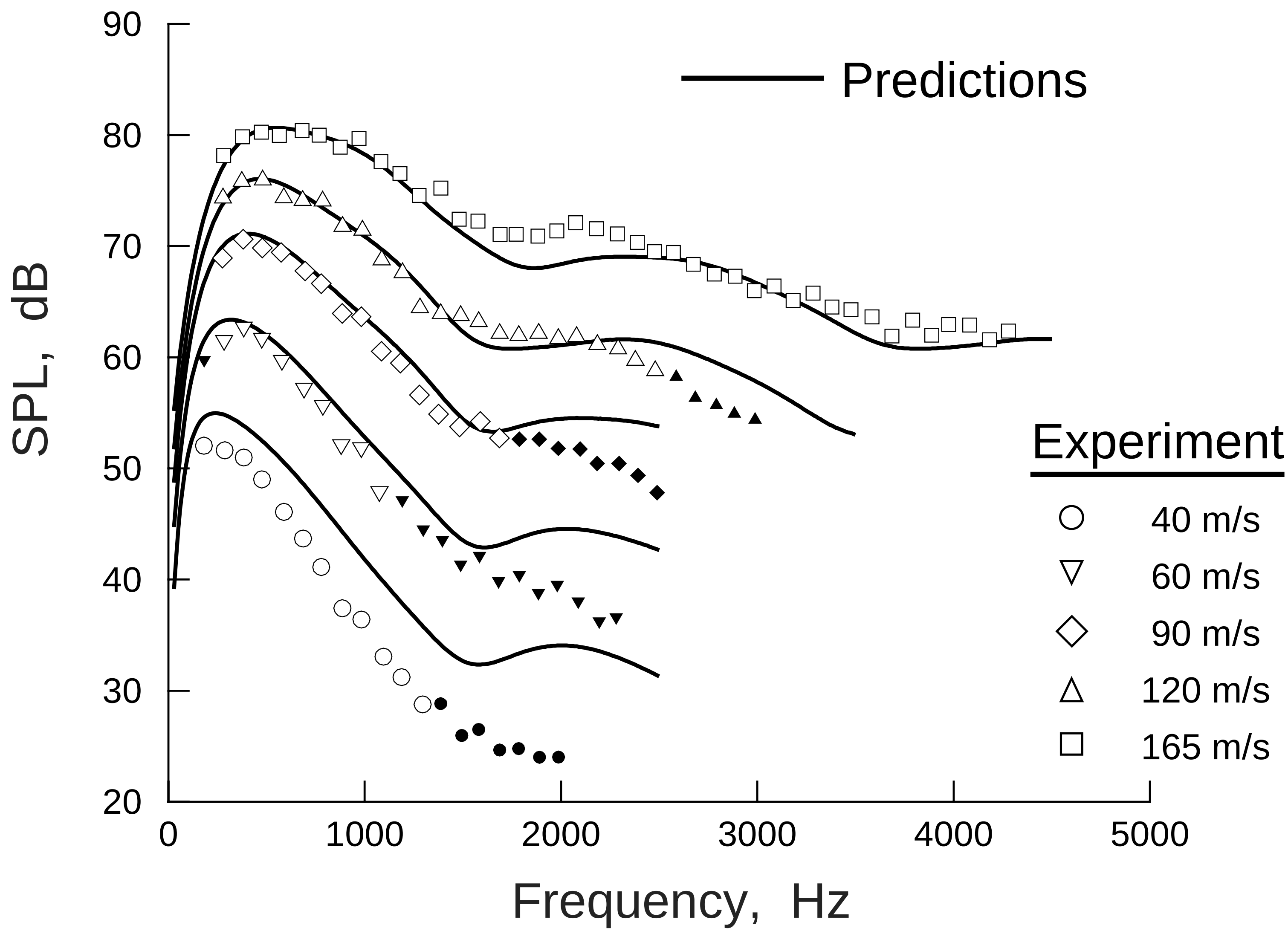
Broadband Prediction in Time

- Surface pressure input to Formulation 1B
- Five tunnel speeds: U = 40, 60, 90, 120, 165 m/s
- Directivity and amplitude corrected for refraction through shear layer
- Acoustic pressure Fourier analyzed to convert to spectral density

Predicted Signal
U = 165 m/s



Far Field Noise Spectrum



Concluding Remarks

- A new solution to the FW-H equation provides a useful formulation for loading noise predictions.
- Although simple in form, Formulation 1B is applicable to rotating surfaces.
- A broadband noise prediction was shown to agree well with experimental measurement.
- The formulation's simplicity lends itself well to statistical analysis of broadband noise.
- Future research will include the application of the statistical formulation to trailing edge noise.