The Effect of Blade Thickness and Angle of Attack on Broadband Fan Noise

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Work Supported by ONR,
Prog. Manager: Dr. Ron Joslin

Authors would like to thank Ed Envia for providing additional slides

Sources of Broadband Fan Noise

Rotor Alone

- Trailing Edge Noise
- Blade Tip Gap Noise
- Duct Wall BL Inflow Noise

Rotor/Stator Interaction

- Inflow Noise
  - Rotor Turbulence
  - Rotor Tip Vortices
  - Duct Wall BL
- Self Noise

AIAA Papers No: 93-4402, 98-2316

Comparison of Predicted R/S Interaction Noise and Measurements

for the SDT Fan Rig (Envia et al, 2008)

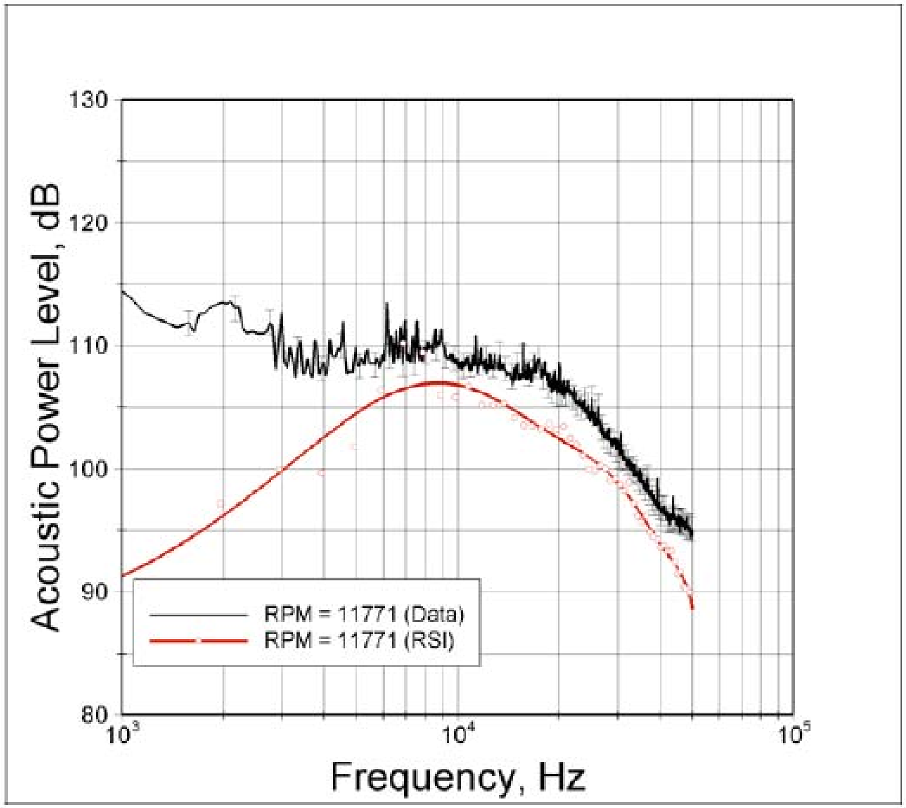


Figure A27. Comparisons of predicted (RSI) and measured narrowband sound power level for SDT at 11,771 RPM.

Envia et al AIAA paper no 2008-2991

Prediction of R/S Interaction Noise with Rotor Alone Noise Added

for the SDT Fan Rig (Envia et al, 2008)

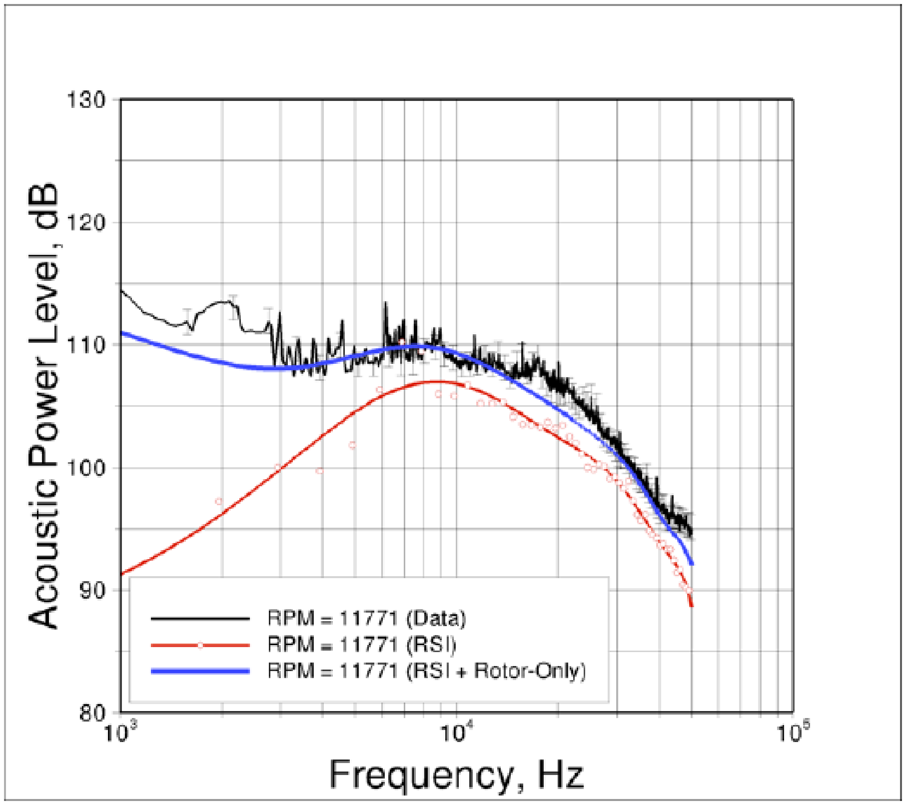


Figure 24. Comparison of augmented RSI prediction and measured narrowband PWL for SDT at 11,771 RPM.

Envia et al AIAA paper no 2008-2991

Outline of Talk

- **Rotor Alone Noise**
- Predicting Trailing Edge Noise Sources
- Blade Surface Pressure Spectra and AoA
- Recent Developments
- **Rotor Stator Interaction Noise**
- Review of Existing Studies
- Physics of Leading Edge Noise AoA and Thickness Effects
- Wind Tunnel Measurements Of Leading Edge Noise
- **Conclusions**

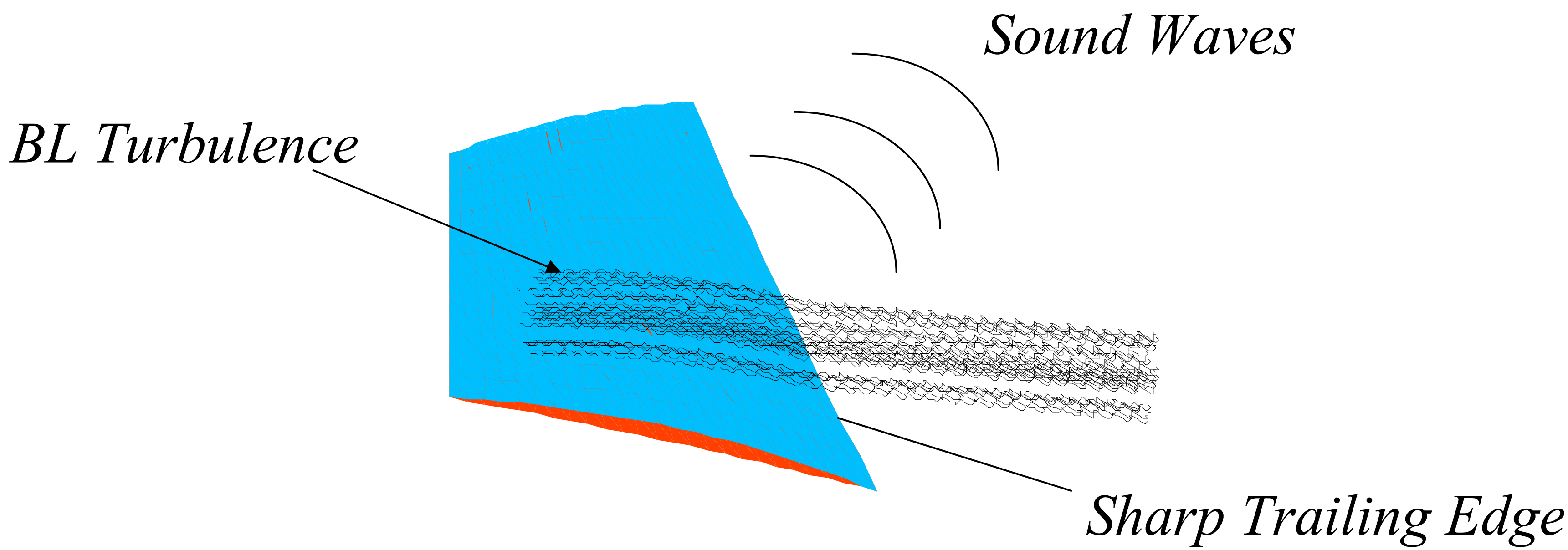
Rotor Alone Noise

Sources of Rotor Alone Noise

- **Tip Flows** – may dominate for low speed fans with large tip gaps and low AR
- **Wall BL Inflow Noise** -typically BL is very thin and source is not important
- **Trailing Edge Noise** -assumed to dominate for moderate AR blades with small tip gaps

Predicting TE Noise

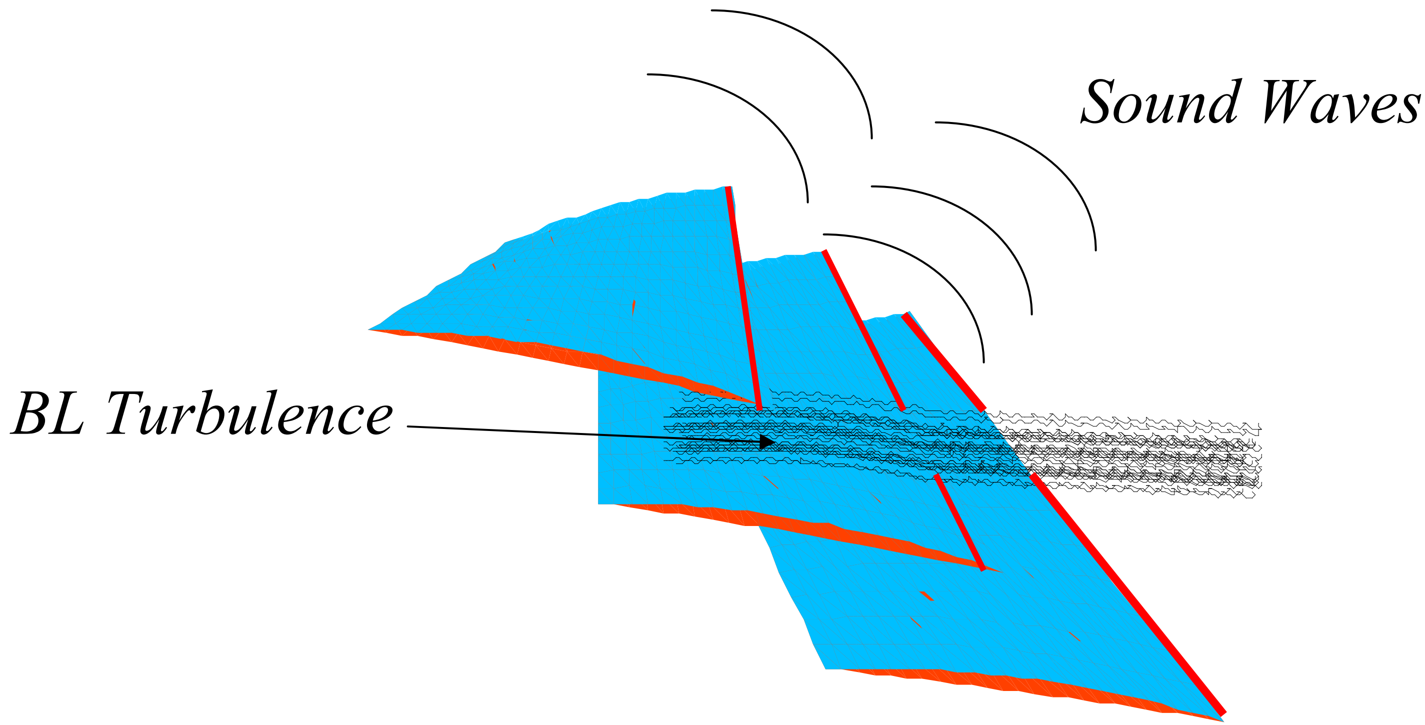
Trailing Edge Noise
Single Blade



- **Scattering of BL pressure fluctuations causes propagating acoustic waves**
- **Kutta condition is assumed at the trailing edge**

(Amiet (1977), Brooks(1984), Howe (1998)

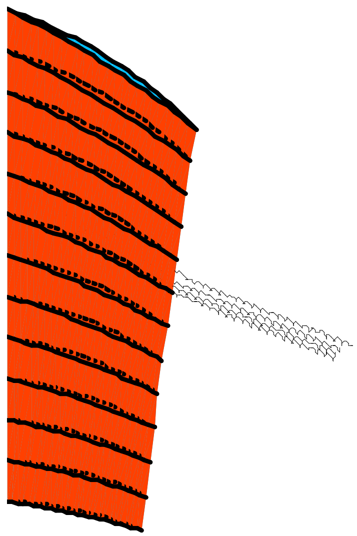
Trailing Edge Noise
Blade Row



In a blade row there is acoustic scattering from multiple blades

AIAA Jnl Vol 36(9) 1998

TE Noise Prediction



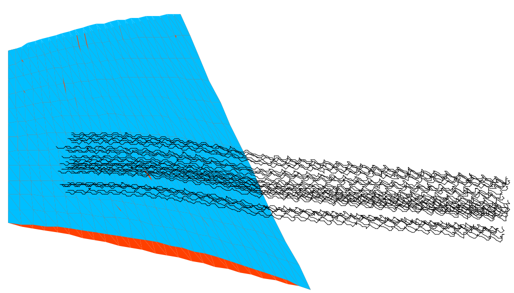
- Blade is broken down into sections
- Surface pressure wavenumber spectrum defined at each blade section
- Coupled Duct/ 3D TE Scattering Response defined for each blade section
- Spanwise wavenumber varies with radius
- Assumes small spanwise correlation lengthscale

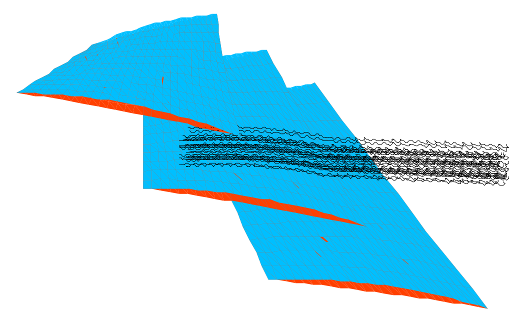
Blade Surface Pressure → **Blade Row Scattering** → **Duct Mode Amplitudes**

AIAA Jnl Vol 36(9) 1998

Properties of the Surface Pressure

Assume that the boundary layer on a single blade has the same surface pressure spectrum as a blade in a cascade if *U* and δ^* are the same





AIAA Jnl Vol 36(9) 1998

Deducing the Surface Pressure Spectrum

*for a given U and δ**

Single Blade

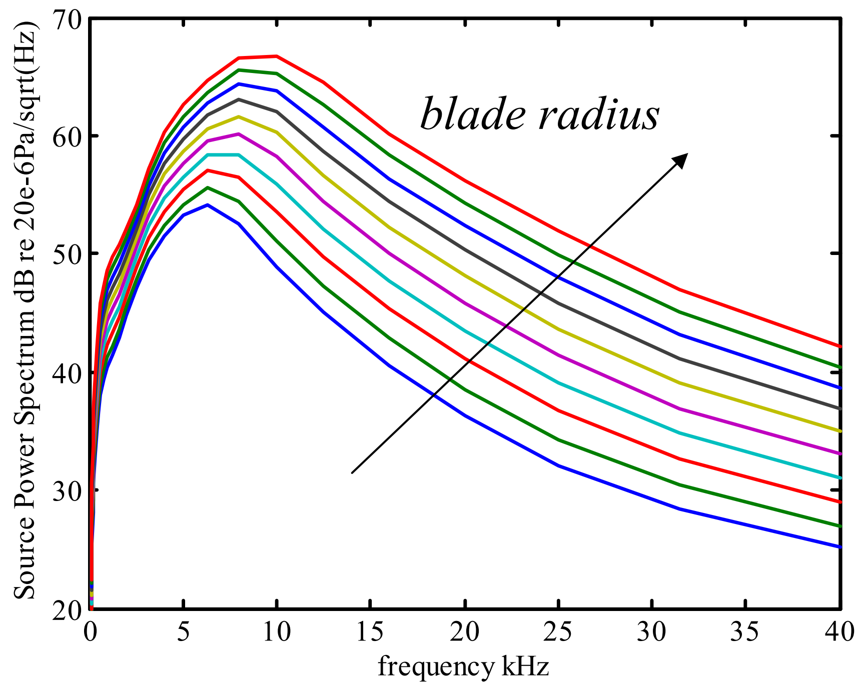
Blade Surface Pressure * TE Scattering (Known) = Far Field Sound (Brooks)

Blade Row

Blade Surface Pressure * Blade Row Scattering (Known) = Duct Mode Amplitudes

AIAA Jnl Vol 36(9) 1998

Source Spectra at Different Radii



Constant AoA of 7 deg

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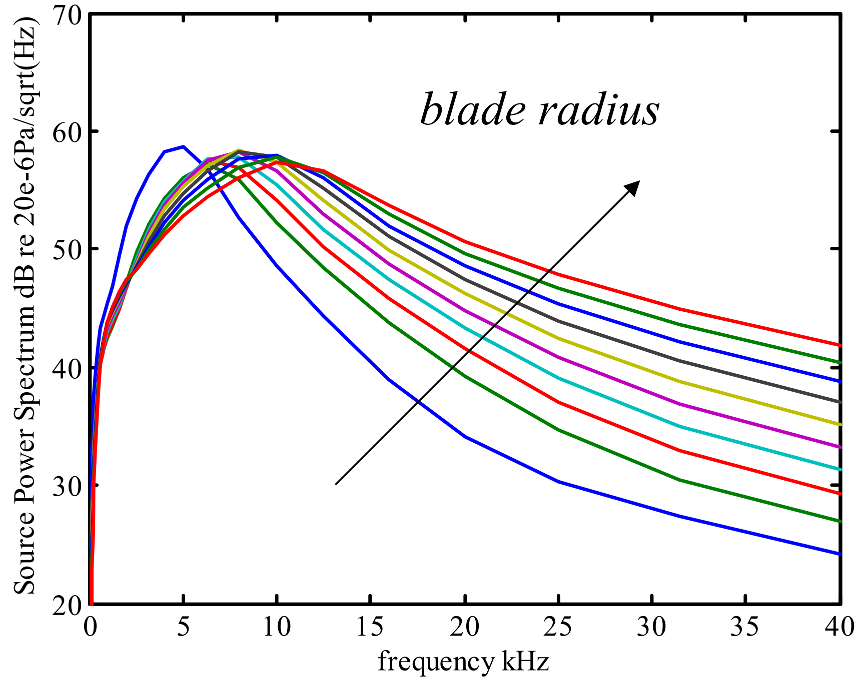
Source Spectra at Different Radii



AoA is 8 deg at hub and 4 deg at tip

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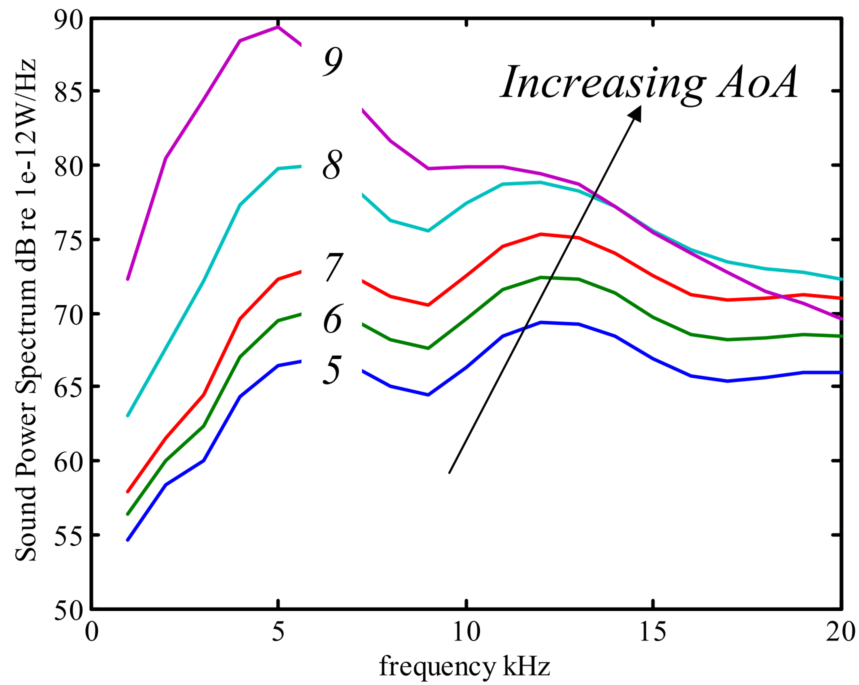
Effect of Increasing AoA on Sound Power Output



AoA constant from hub to tip

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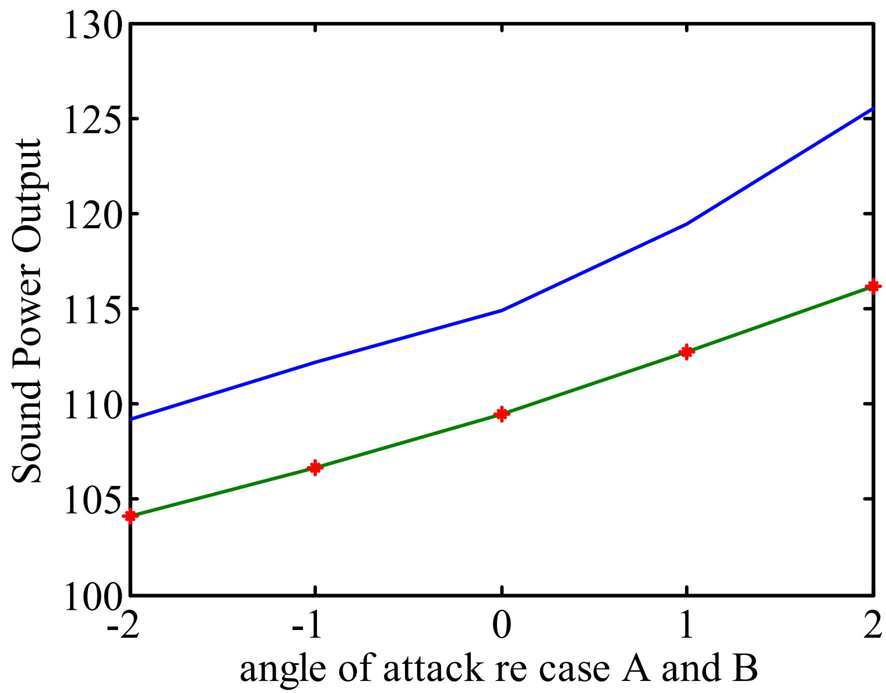
Effect of AoA on Total Sound Power



Sound power increases as ~2.4 dB per degree

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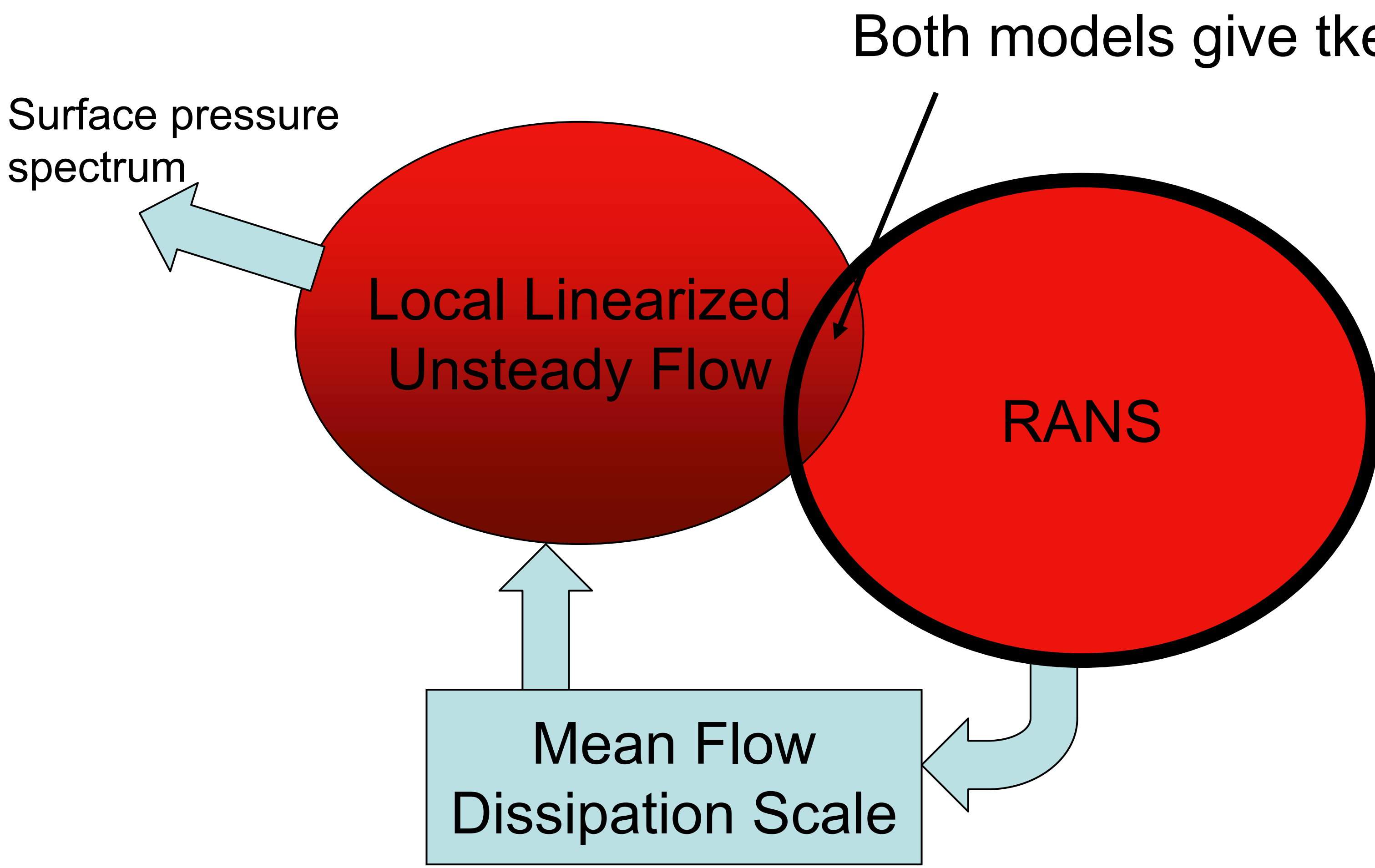
Recent Developments

In collaboration with Bruce Morin, Oliver Attasi and Ramon Reba

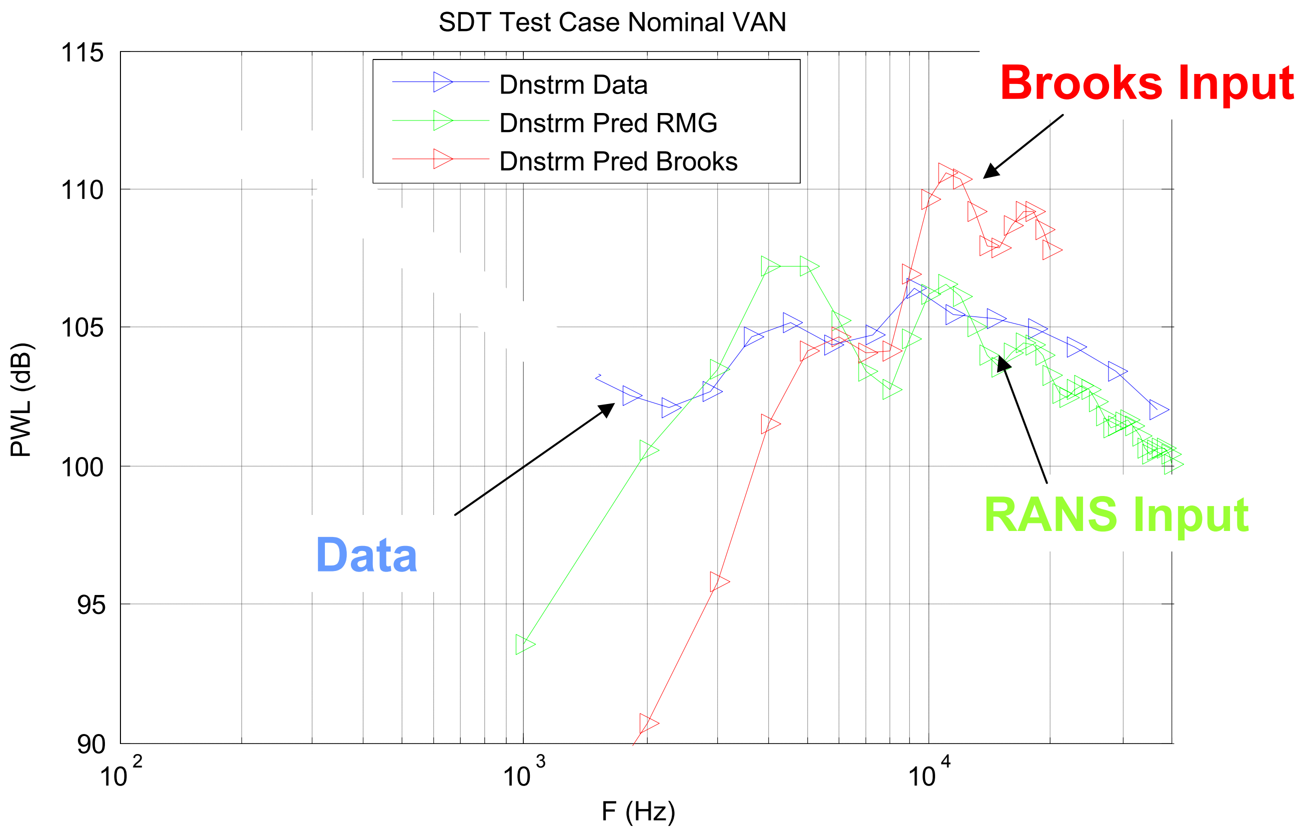
AIAA paper no 2008-2993

Using RANS
to get surface pressure spectrum



AIAA paper no 2008-2993

SDT Test Comparison
Rotor Alone Noise



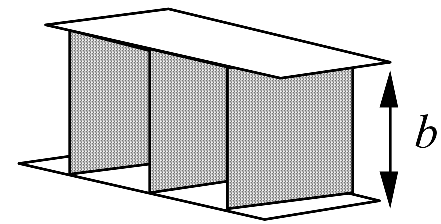
The downstream sound power radiated from the fan blade versus frequency. The blue curve corresponds to the measured data, the green curve is the prediction based on the current model and the red curve is the prediction using the Brooks et al (1989) self noise database.

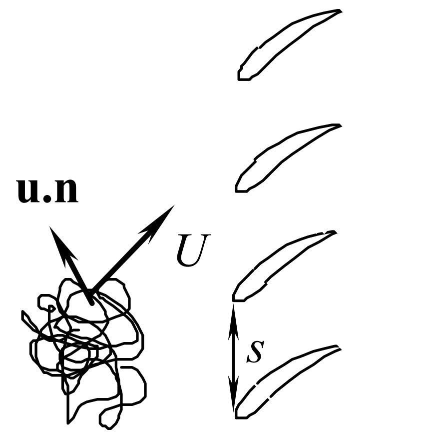
AIAA paper no 2008-2993

Rotor Stator Interaction Noise

Rotor/Stator Interaction Noise

- Hanson and Horan (AIAA 98-2319)
- Glegg and Walker (AIAA 99-1888)
- Evers and Peake (JFM v.43, 2002)
- Nallasamy and Envia (JSV v. 283, 2005)
- Cheong et al (JASA 119, 2006)
- Attasi and Vinogradov (AIAA 2007-3691)





Rotor/Stator Interaction Noise
Effect of AoA

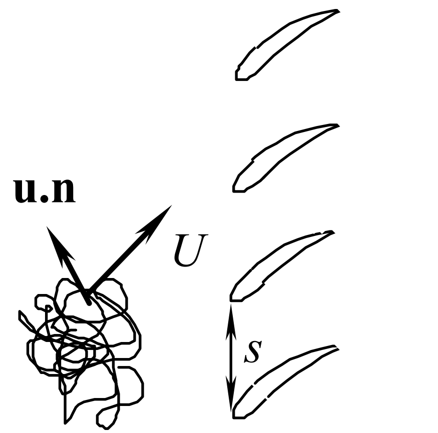
Evers and Peake

(JFM v.43, 2002)

Gave a high frequency analysis of loaded cascade,

Showed effects of AoA for tonal noise from blade wakes was large ~10dB

However only a small effect ~2dB was found on broadband noise for a homogeneous turbulent inflow



Rotor/Stator Interaction Noise
Fully Loaded Rotor

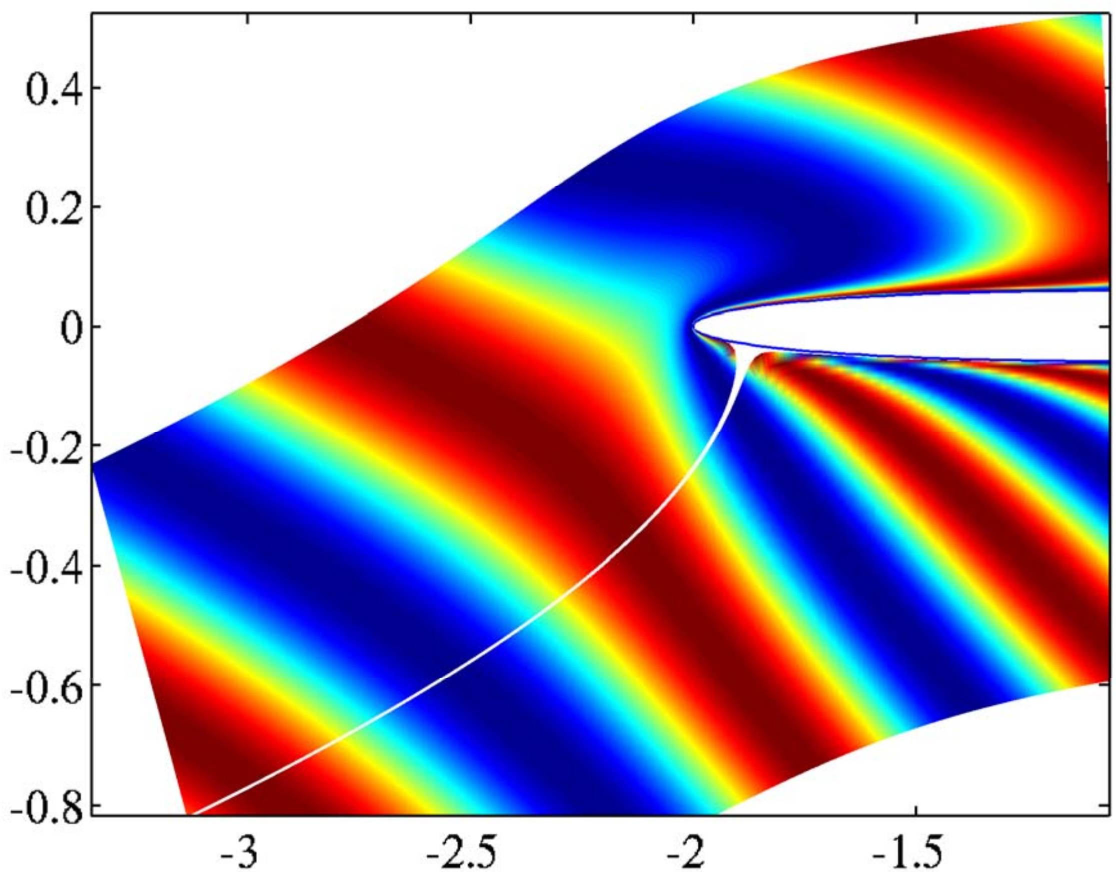
Attasi and Vinogradov (AIAA 2007-3691)

- *Gave a complete analysis of loaded set of stator vanes in a circular duct*
- *Showed up to 3-4dB of real blade effects on broadband noise*
- *Predictions were similar to flat plate results at high frequencies*
- *Verified predictions using experimental data*

Concluded that real blade effects were small, but what is the physics??

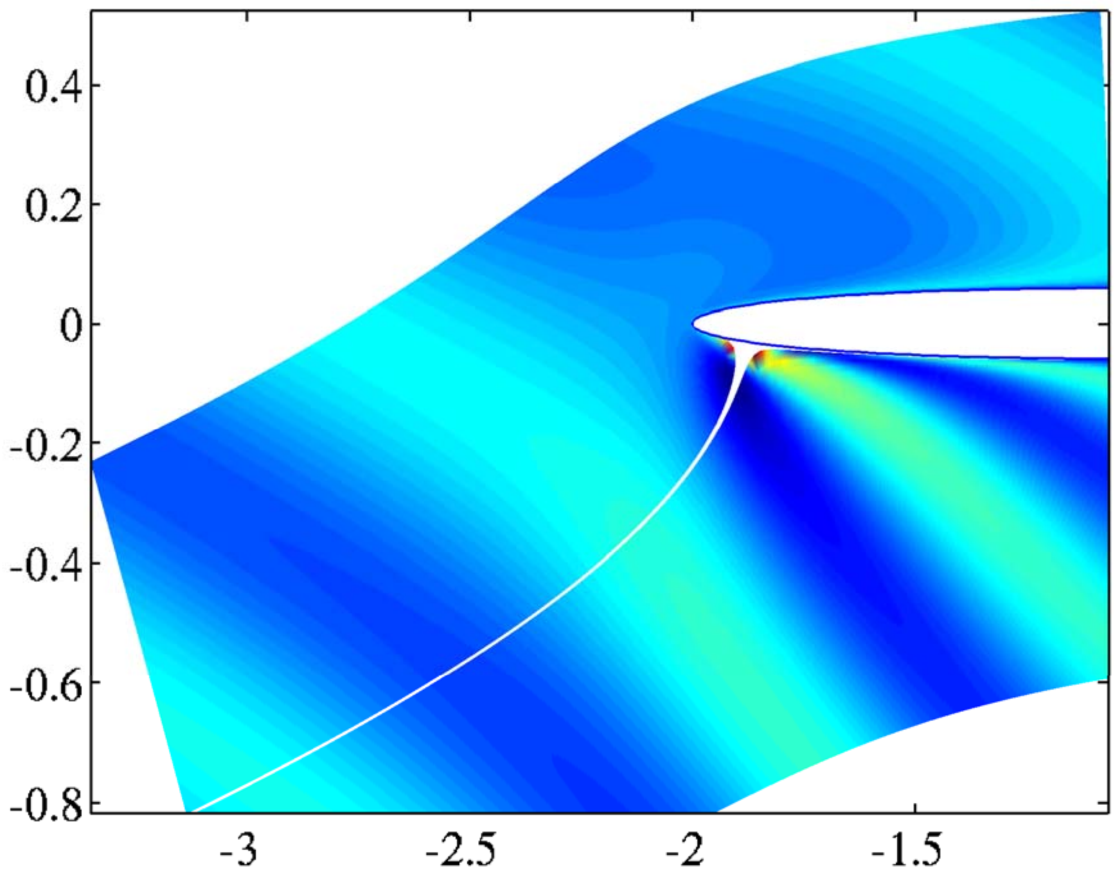
Leading Edge Noise

Phase of a Vortical Gust



AIAA paper no 2006-2424

Streamwise Component of Goldstein's Gust

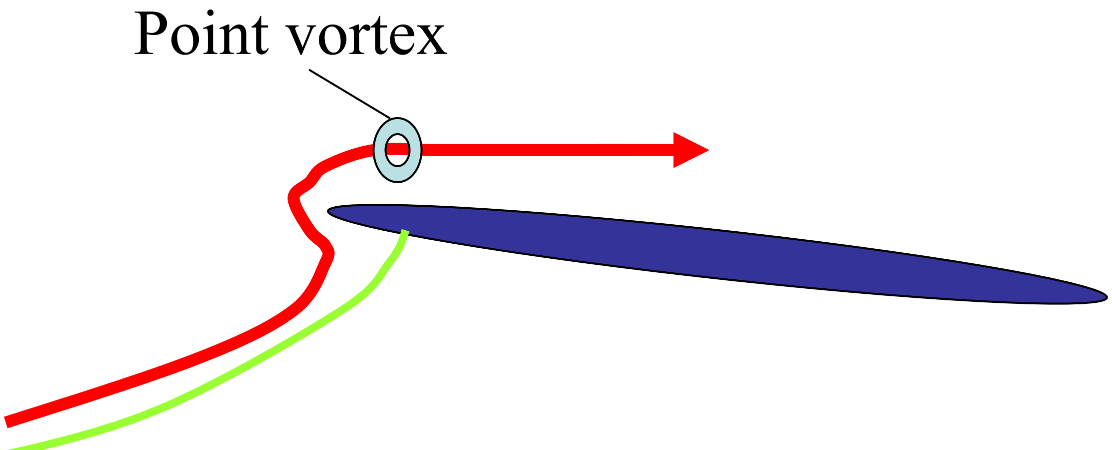


AIAA paper no 2006-2424

Time Domain Methods

- **Calculate the unsteady loading from a blade vortex interaction and hence the noise**

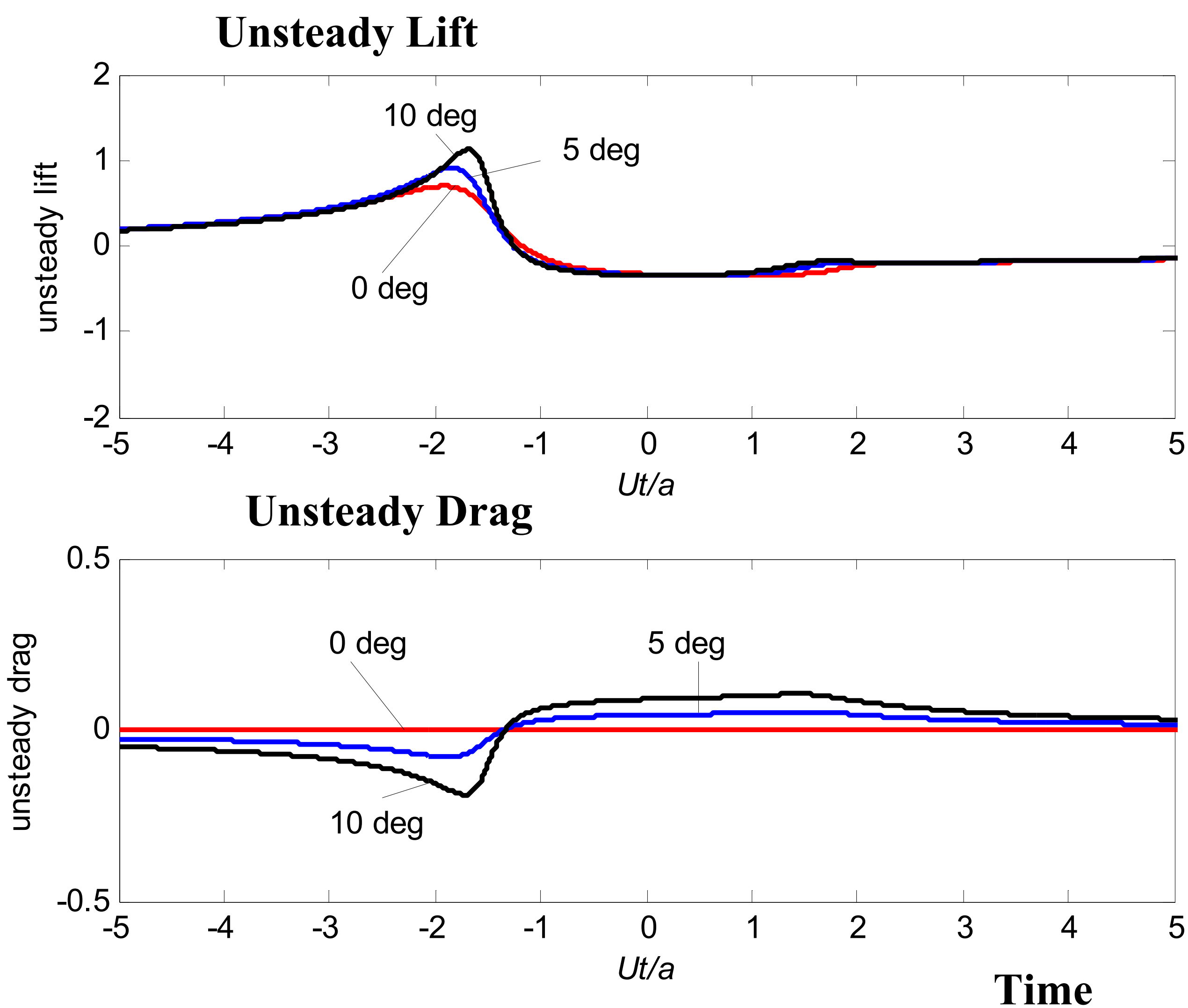
- **Arbitrary gust is modeled by multiple vortices**



Works well for problems which can be reduced to 2D

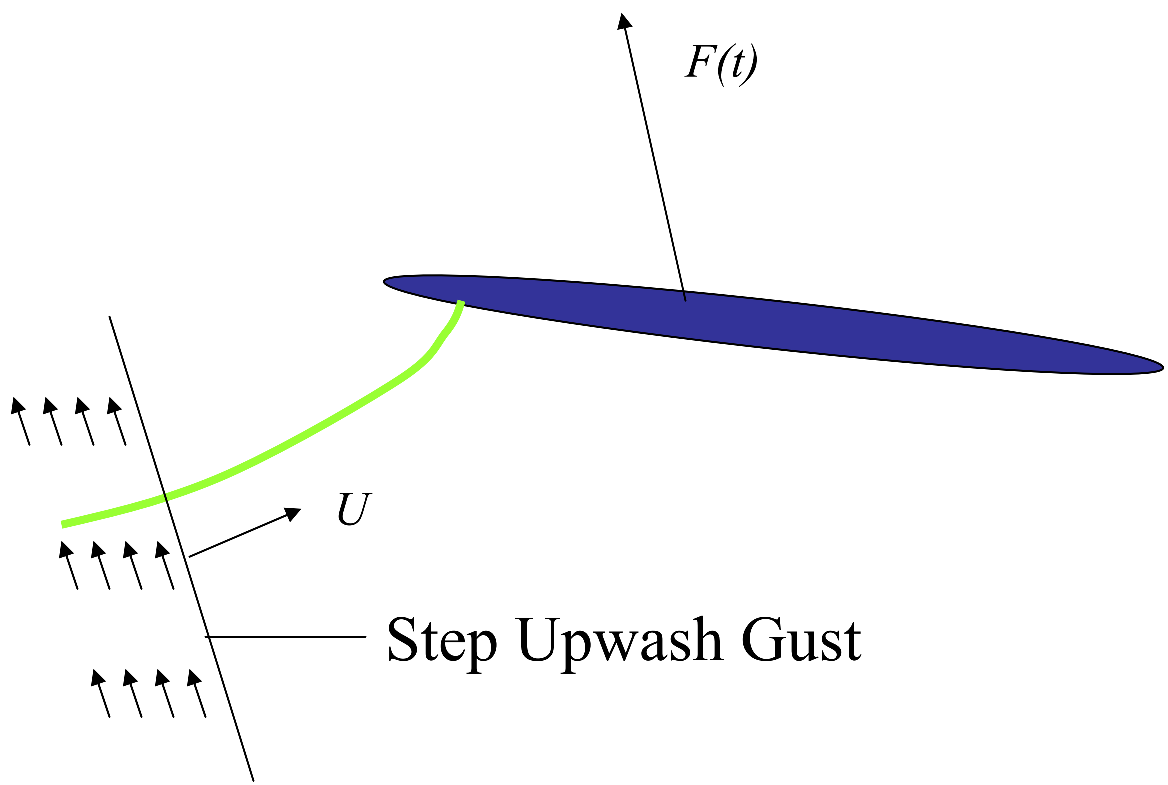
Glegg and Devenport JSV 2008

Unsteady Loading from a BVI



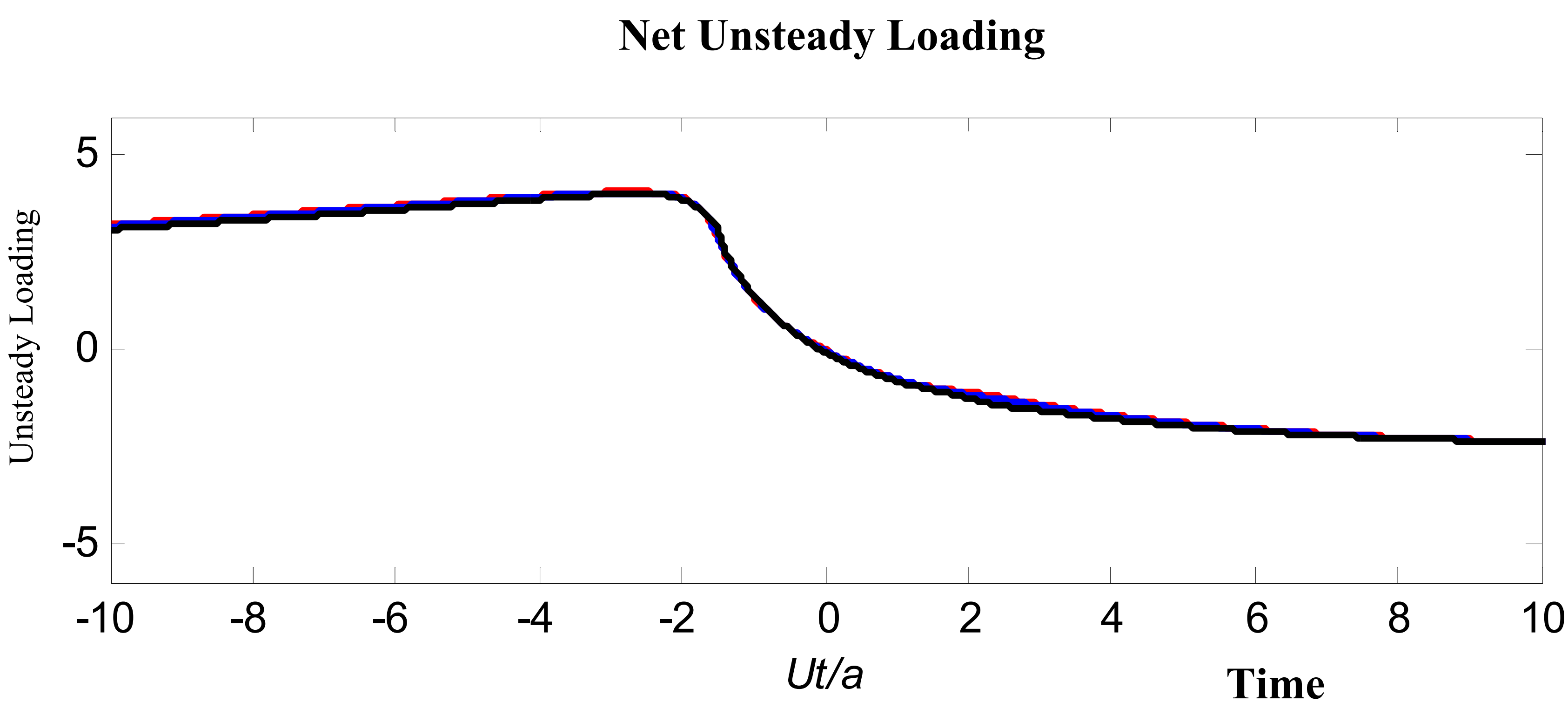
Glegg and Devenport JSV 2008

Response to Step Upwash Gust



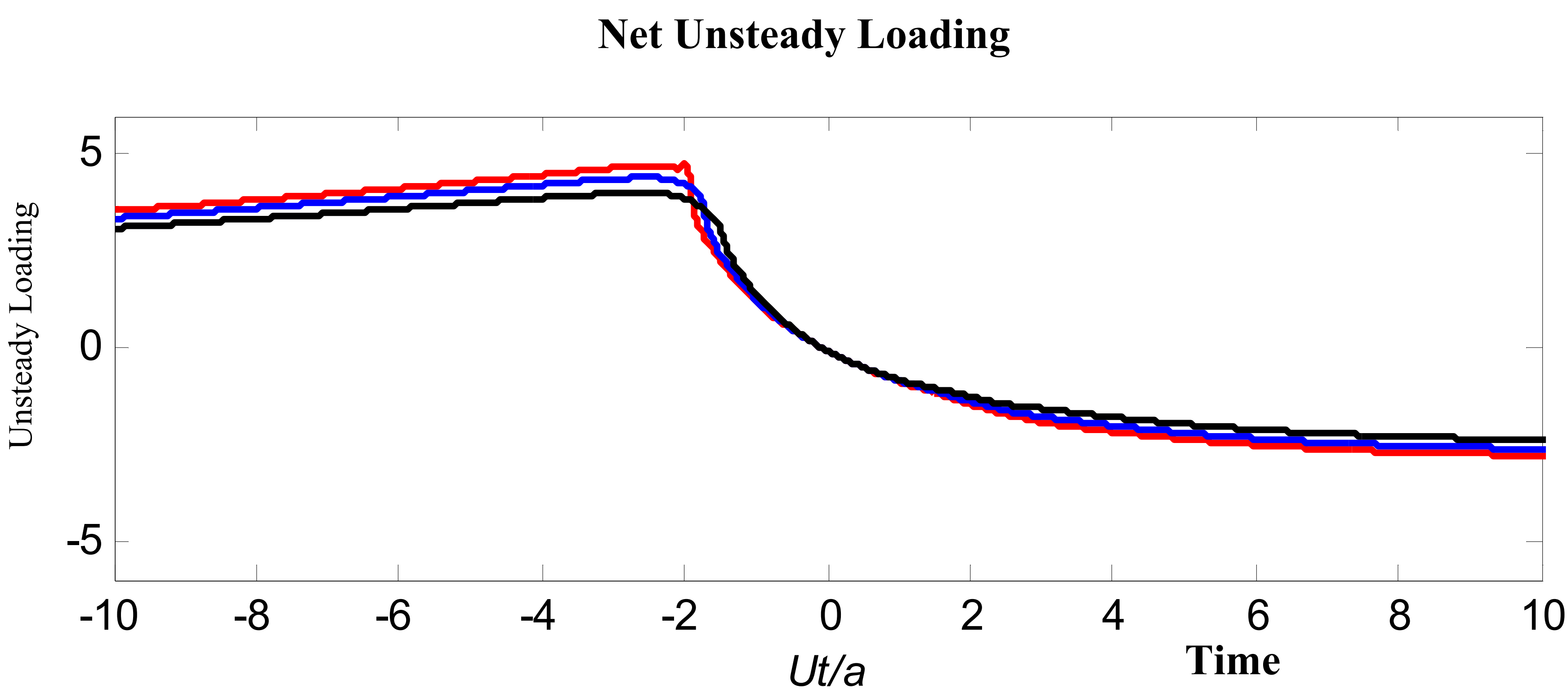
Glegg and Devenport JSV 2008

Unsteady Loading from a Step Gust
for 0,5,10 deg AoA



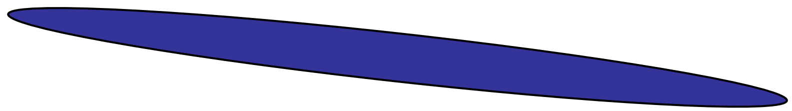
Glegg and Devenport JSV 2008

Unsteady Loading from a Step Gust
for thickness to chord ratios 0.001,0.06,0.15

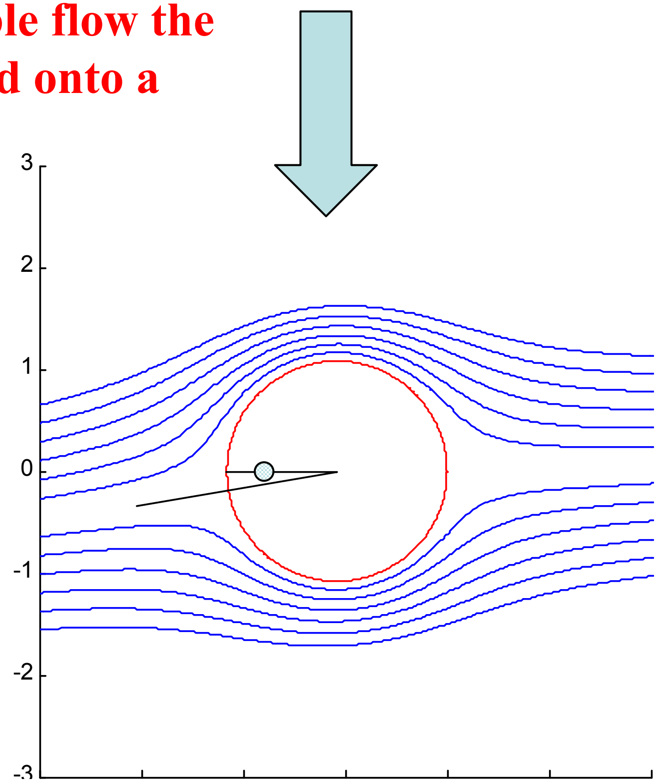


Glegg and Devenport JSV 2008

Conformal Mapping



For 2D incompressible flow the airfoil can be mapped onto a circle



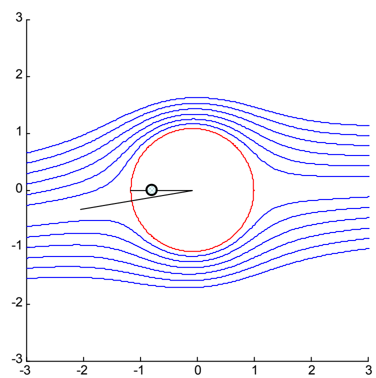
Unsteady loading depends on the distance of the vortex from the singular point

Location of the singular point depends on airfoil thickness

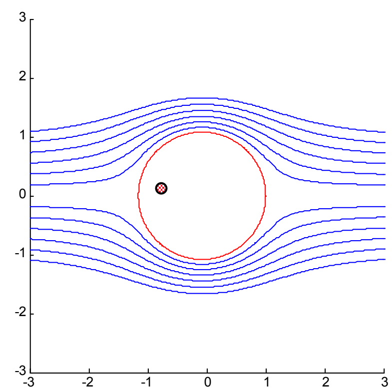
Glegg and Devenport JSV 2008

Conformal Mapping

(a) Streamlines at an AoA α deg

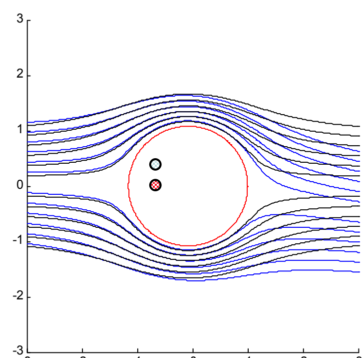


(b) Streamlines at zero AoA



After rotation streamlines are overlaid

Increased levels from vortices in upper plane cancels reduced level from vortices in lower plane



Overlay of (b) onto (a) rotated clockwise by 2α deg

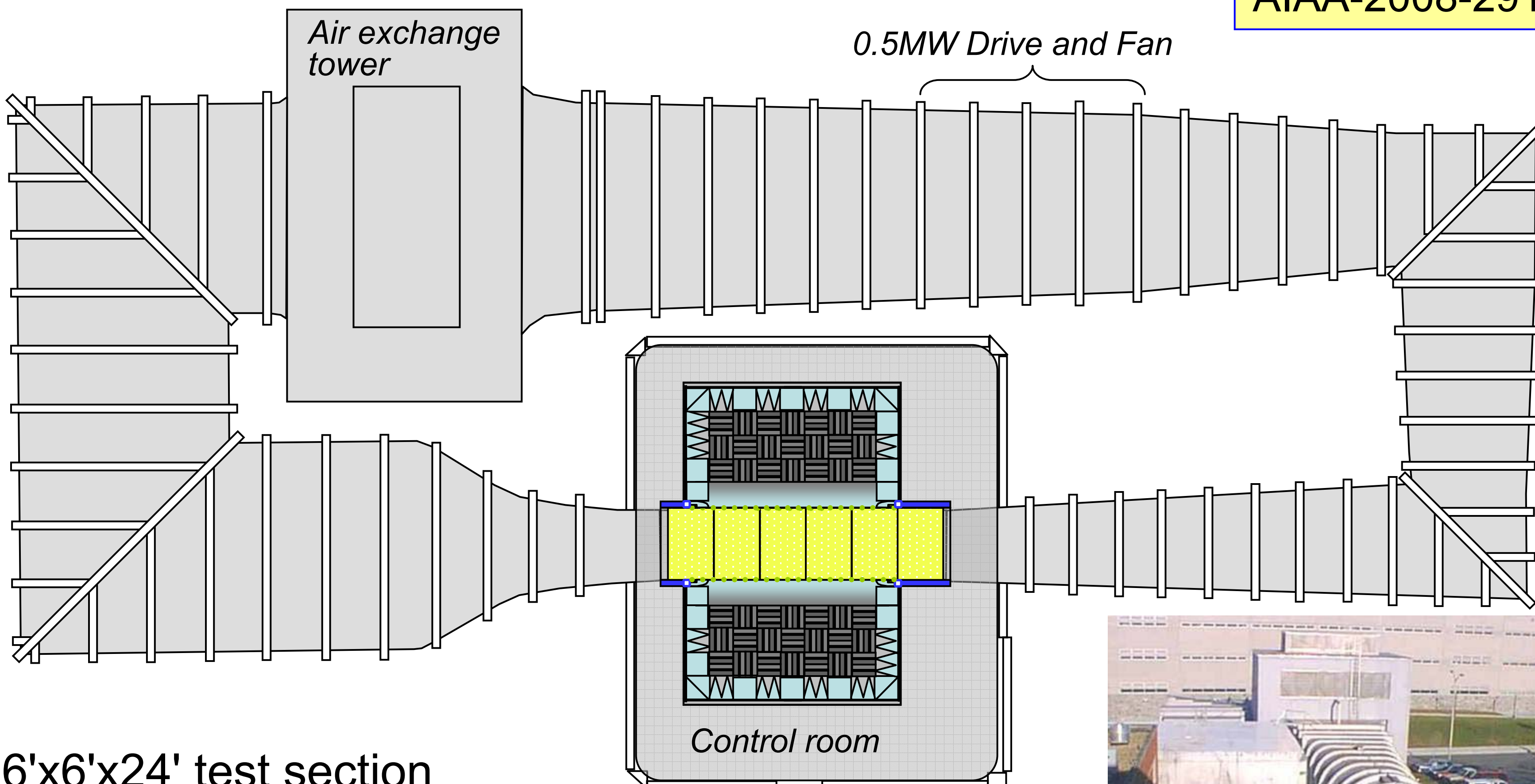
Glegg and Devenport JSV 2008

Experimental Verification

Experiments carried out at Virginia Tech in collaboration with William Devenport and Joshua Staubs

VT Stability Wind Tunnel

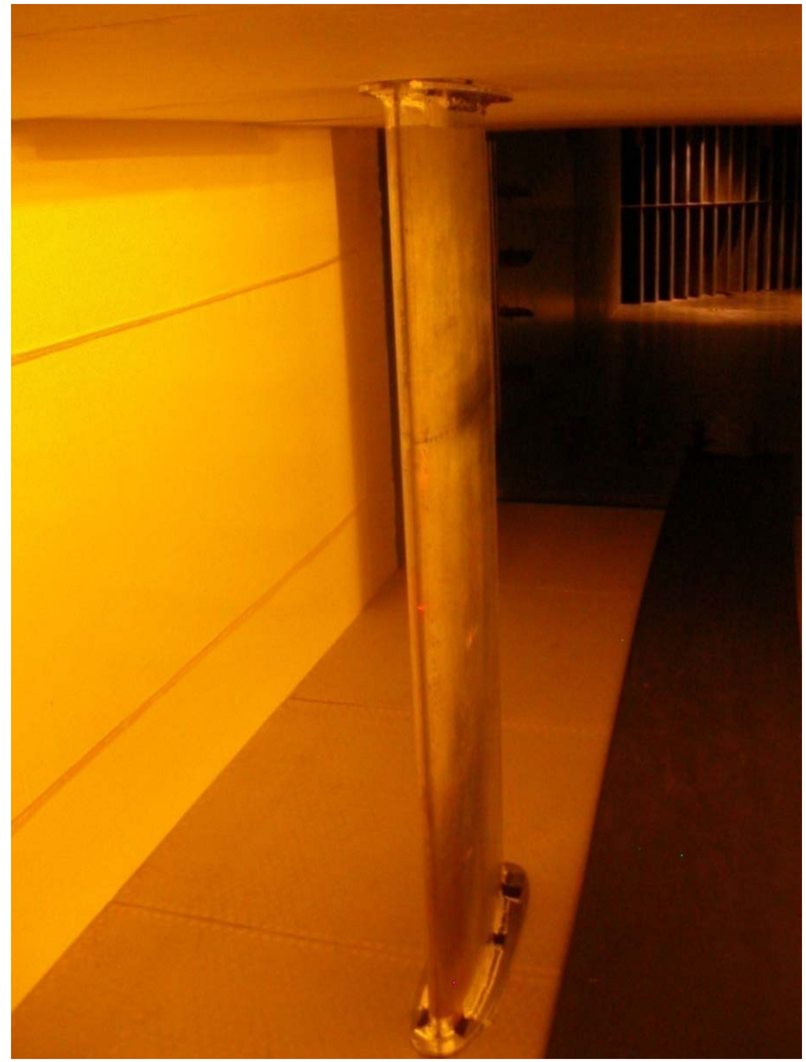
AIAA-2008-2911

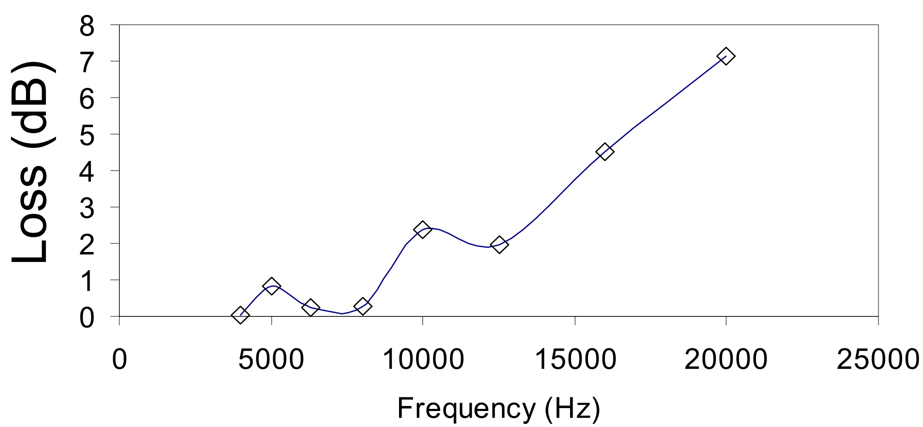


- 6'x6'x24' test section
- 15' dia., 600 h.p. fan produces flow speeds to 80m/s (Re > 5000000 per meter)

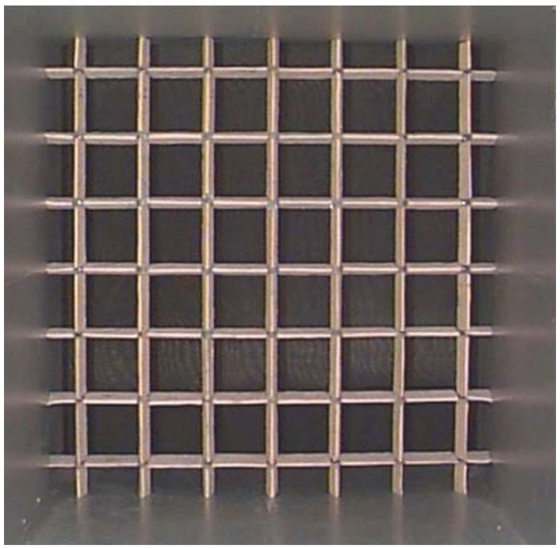
Anechoic system installed in control room area

From Inside

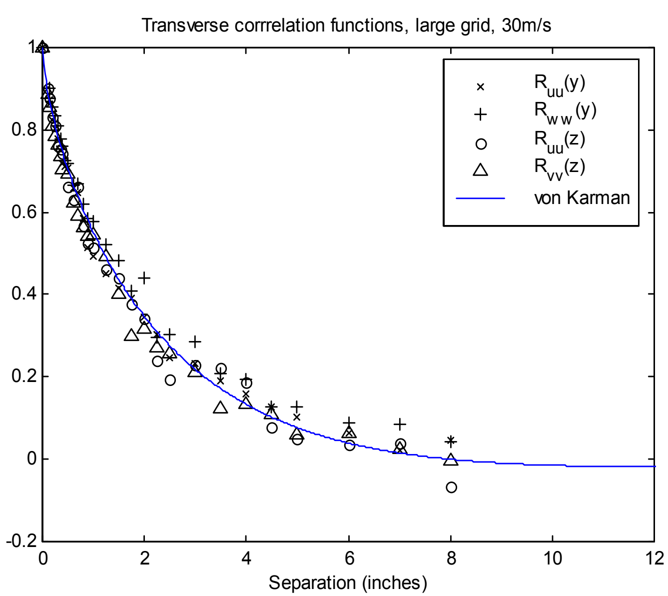


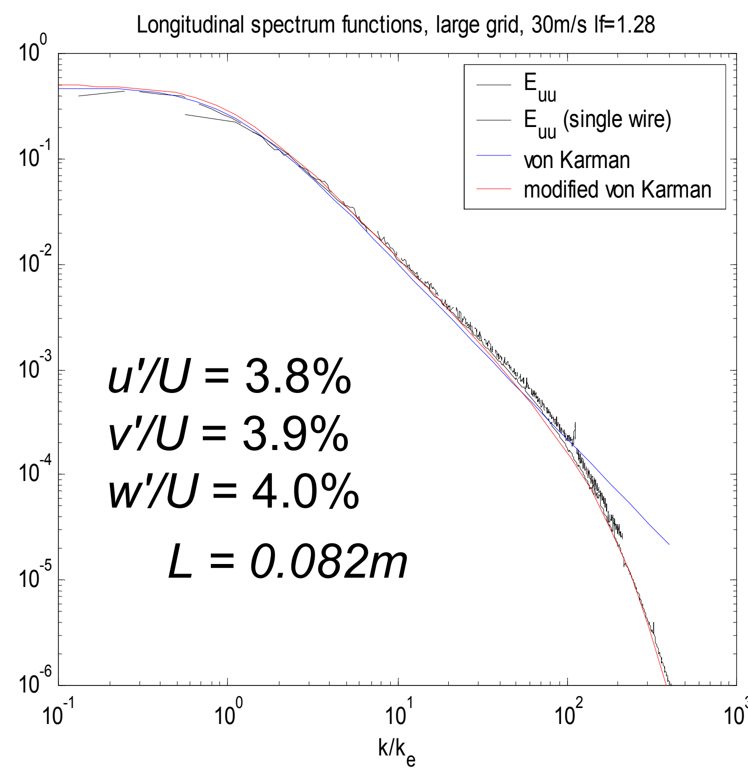

Loss (dB)
8
7
6
5
4
3
2
1
0
0
5000
10000
15000
20000
25000
Frequency (Hz)

Turbulence Grid



- 5cm bars on 30cm centers
- 69.4% open area ratio
- In contraction (area 32% larger than test section)
- 19.5 mesh sizes ahead of airfoils





$u'/U = 3.8\%$

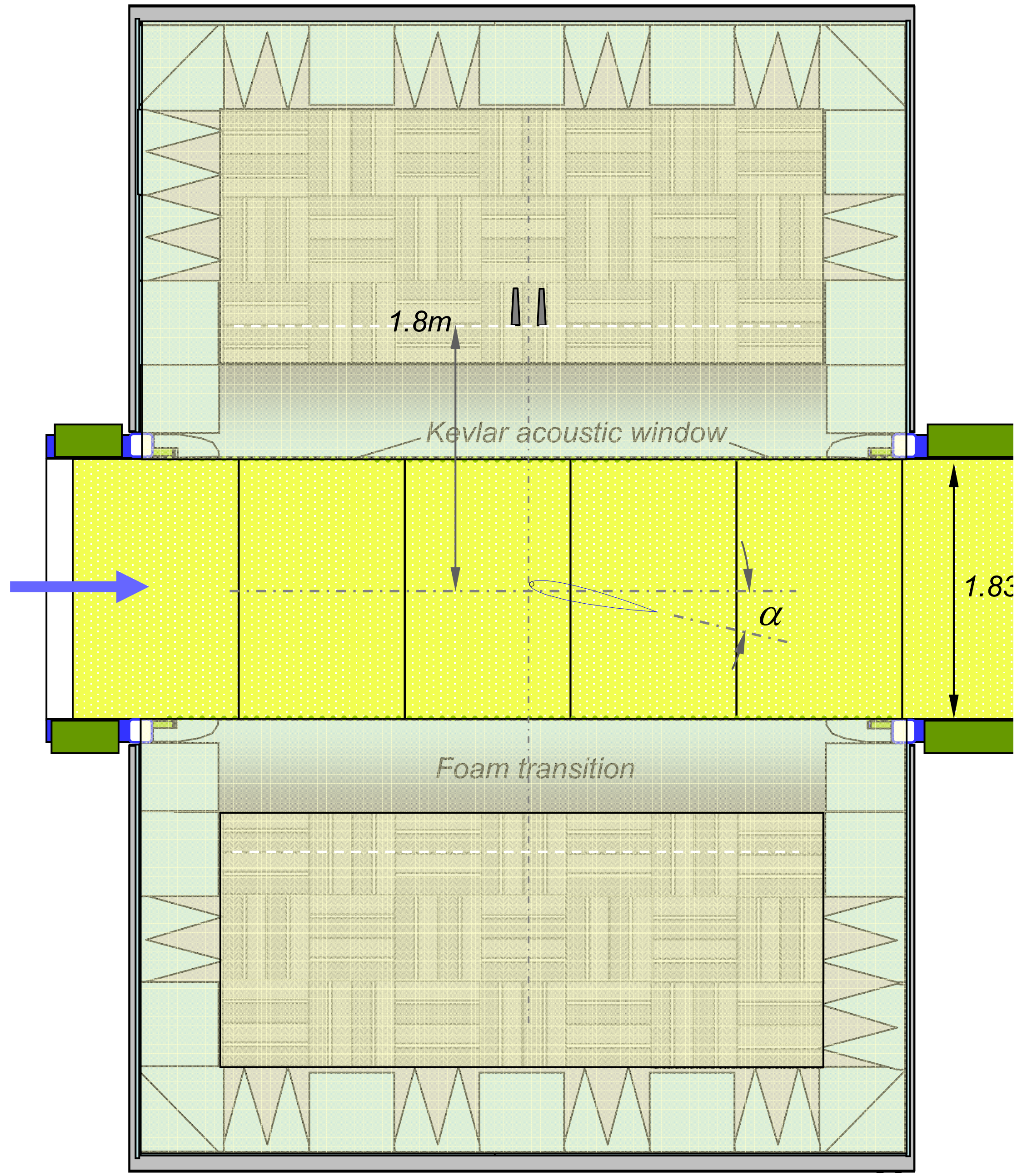
$v'/U = 3.9\%$

$w'/U = 4.0\%$

$L = 0.082m$

Measurement locations and conditions

	c	α^o
NACA 0012	0.2m	-12,-8,-4,0,4,8,12
NACA 0015	0.6m	0,2,4,6,8,10,12
NACA 0012	0.9m	0,2,4,6,8,10,12
DU96	0.9m	0,2,4,6,8,10
S831	0.9m	0,2,4,6,8,10



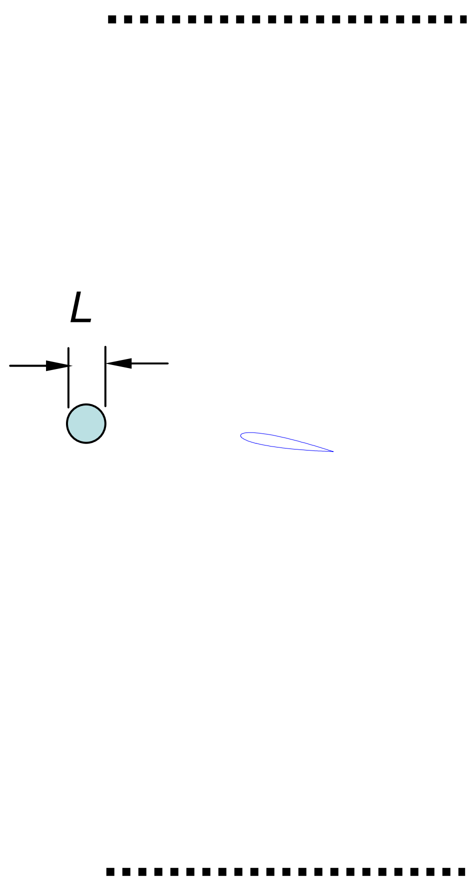
- All measurements at 30m/s (additional at 40m/s not shown)

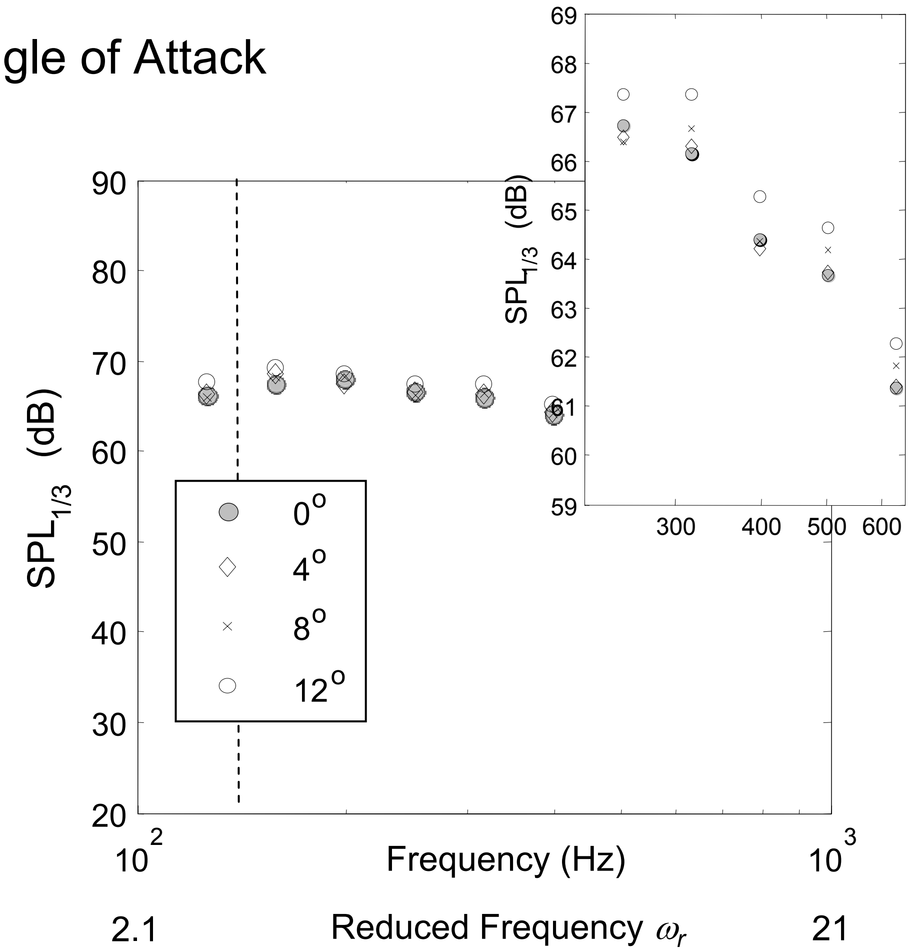
AIAA paper no 2008-3018

WJD1

0.2-m NACA 0012

Effects of Angle of Attack





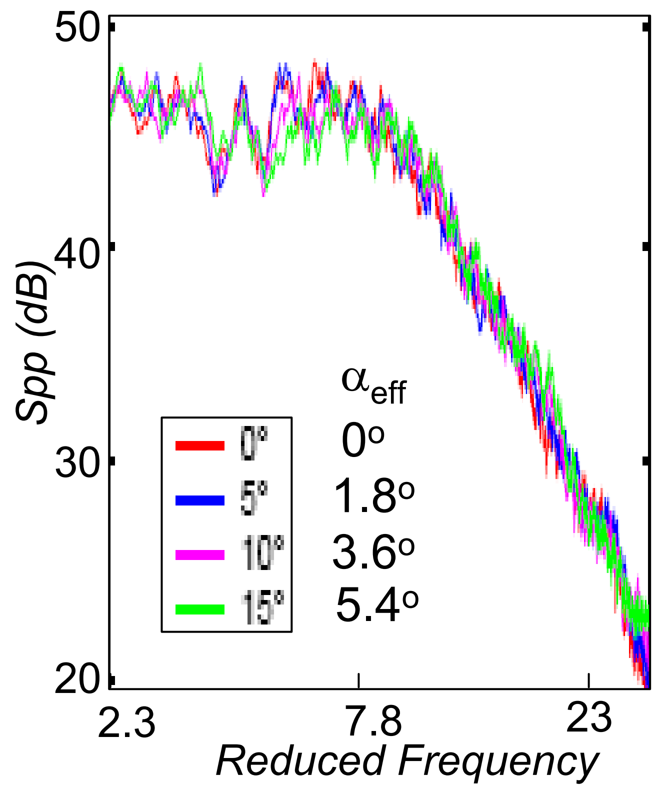
AIAA paper no 2008-3018

Diapositiva 40

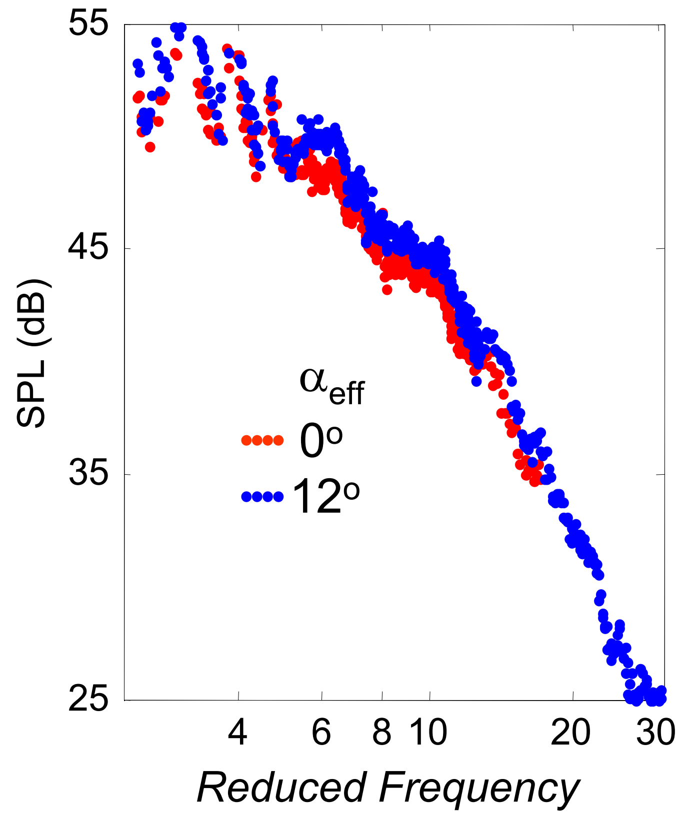
WJD1 Sync animation
change Gershfeld to Howe
William Devenport; 06/05/2008

0.2-m NACA 0012

AIAA paper no 2008-3018



Moreau *et al.* (2005)
NACA 0012 *h/c=1.3* (jet)
L=6.6%c u'/U=5% U=40m/s



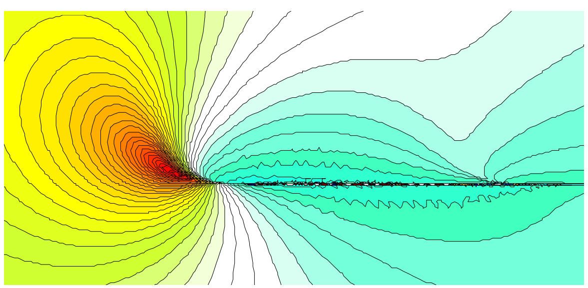
NACA 0012, 0.2-m *h/c=9*
L=40%c u'/U=3.9% U=30m/s

Noise Calculations

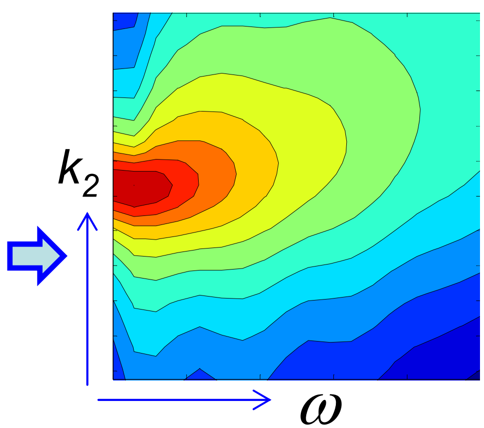
- Glegg, Devenport and Staubs (2008) Theory.

Von Karman

$$S_{pp}(\omega) = \frac{\pi\omega^2 U R_3}{r^2 c_0^2} \int_{-\infty}^{\infty} \Omega_{33}(-\omega/U, k_2, 0) \left| \frac{\hat{L}(\omega, k_2)}{2R_3} \right|^2 dk_2$$

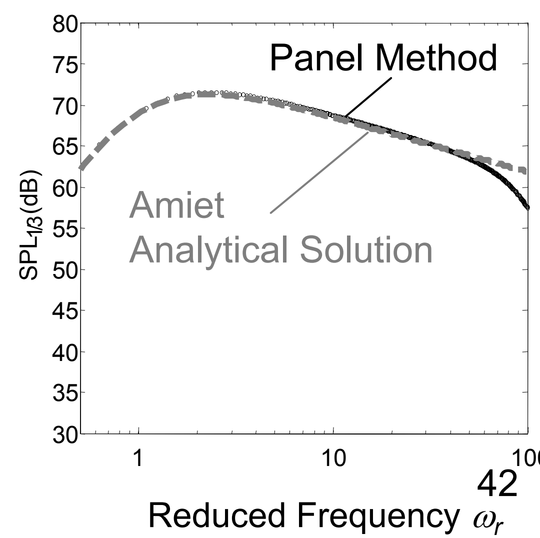


Drift coordinates



Wavenumber space

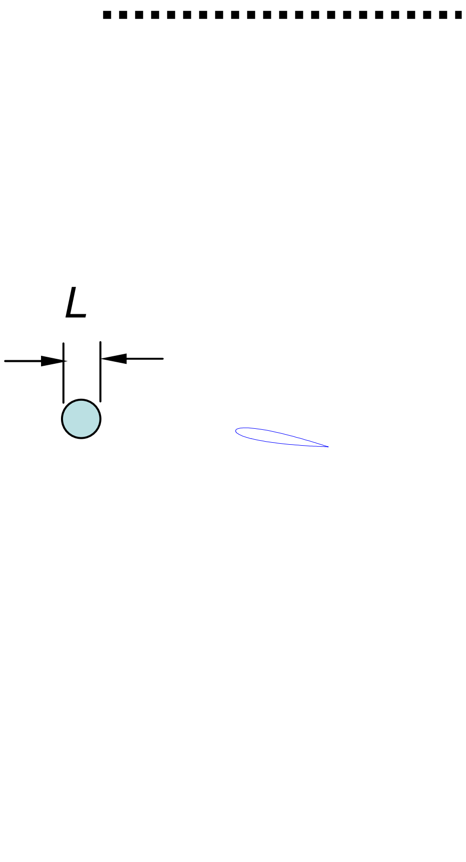
Sound from a flat plate

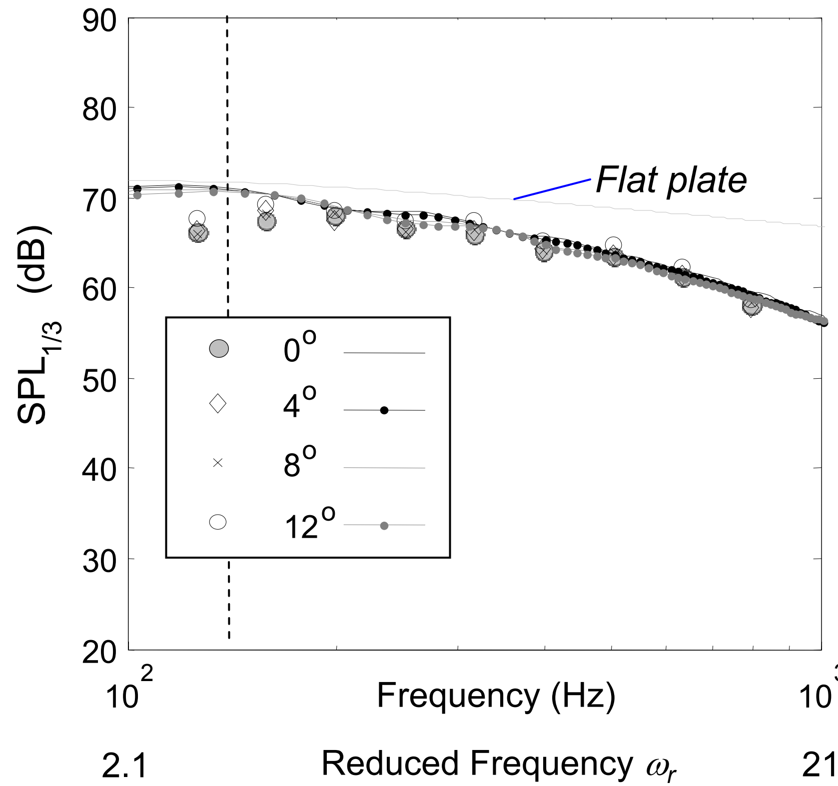


WJD2

0.2-m NACA 0012

Effects of Angle of Attack with predictions



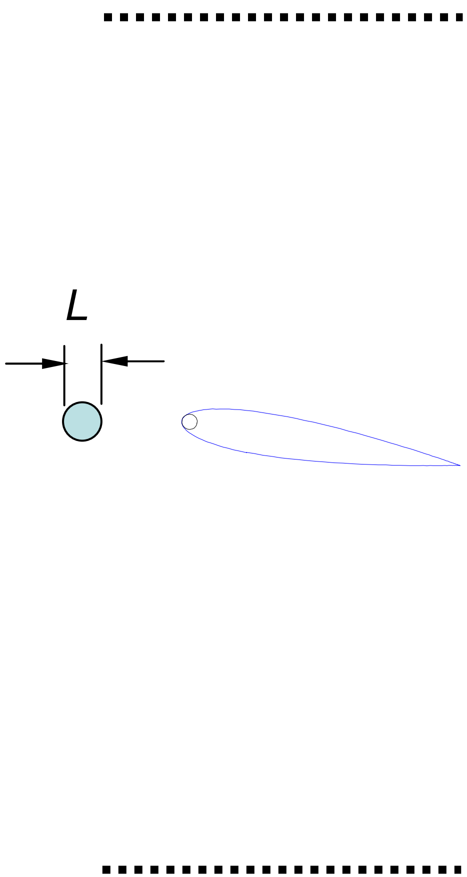


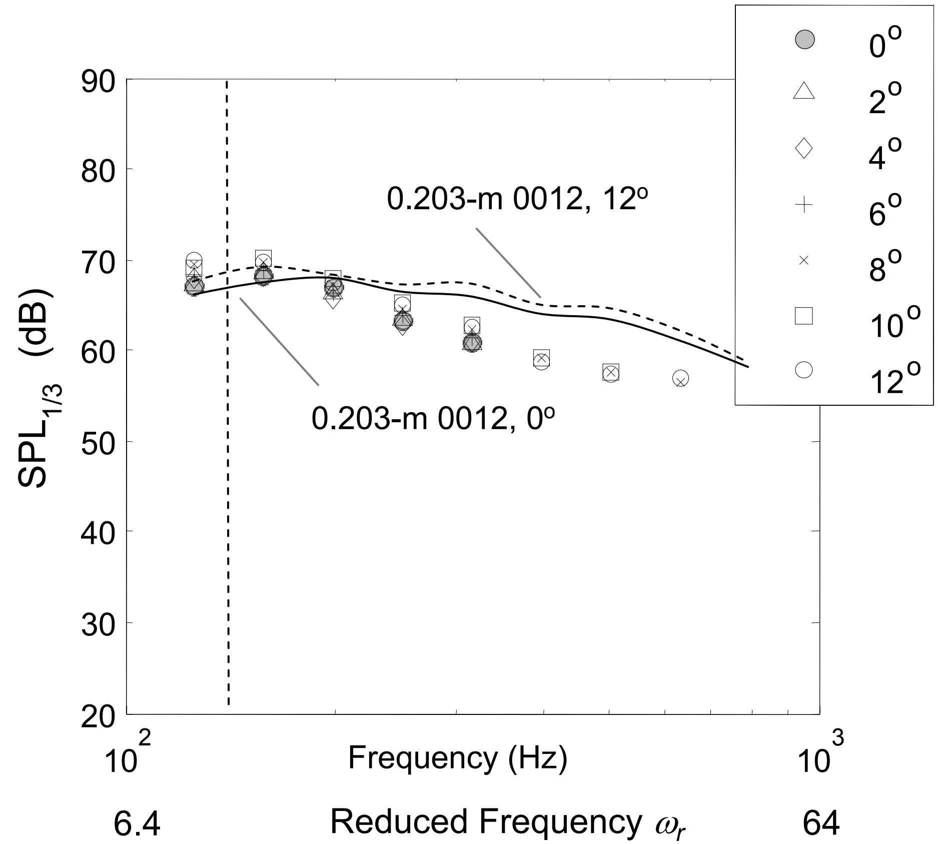
AIAA paper no 2008-3018

WJD2 Sync animation
change Gershfeld to Howe
William Devenport; 06/05/2008

0.6-m NACA 0015

Effects of Angle of Attack



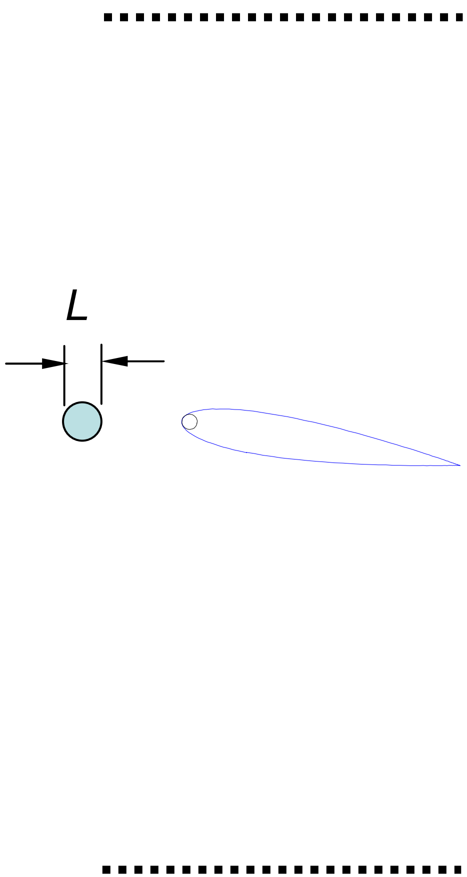


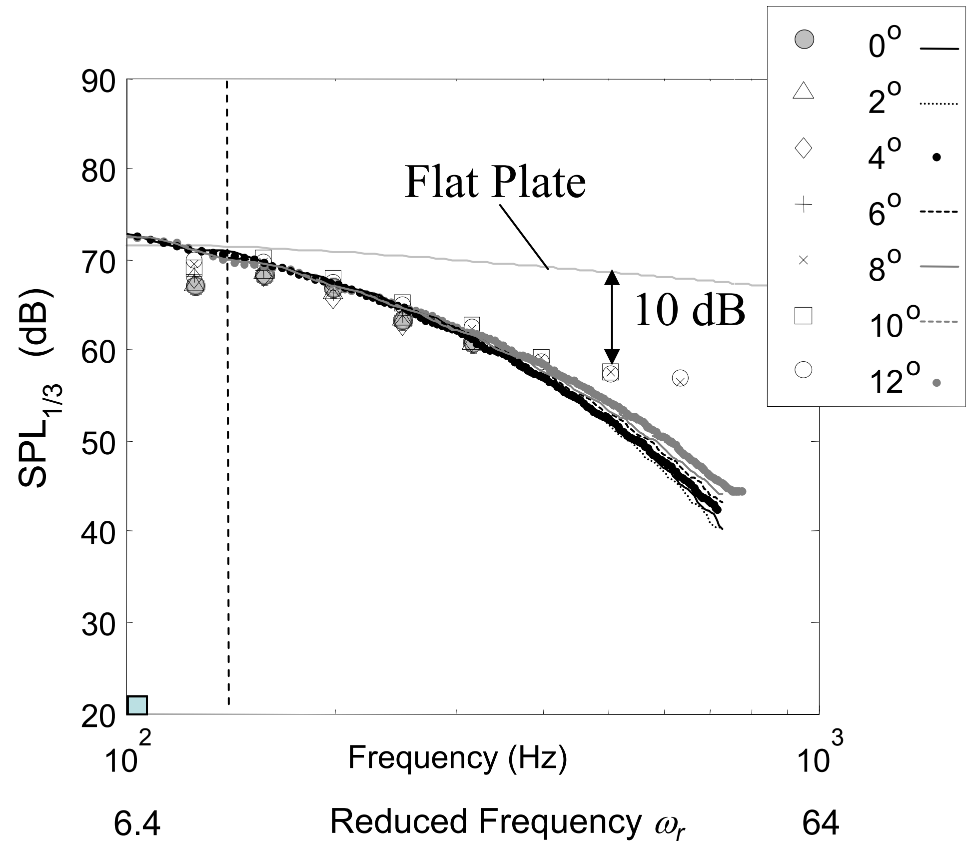
NACA 0015, 0.6-m *h/c=3*
L=13%c u'/U=3.9% U=30m/s

AIAA paper no 2008-3018

0.6-m NACA 0015

Effects of Angle of Attack with predictions





AIAA paper no 2008-3018

Conclusions

- Rotor alone noise and rotor stator interaction noise are equally important
- Trailing edge noise can be predicted from calculations of the blade surface pressure spectrum
- Blade stall dramatically increases trailing edge noise
- Angle of attack effects on blades in isotropic turbulence are small (but not necessarily for anisotropic turbulence and asymmetric blades)
- Blade thickness can significantly reduce high frequency noise (but the details of the blade shape are important)