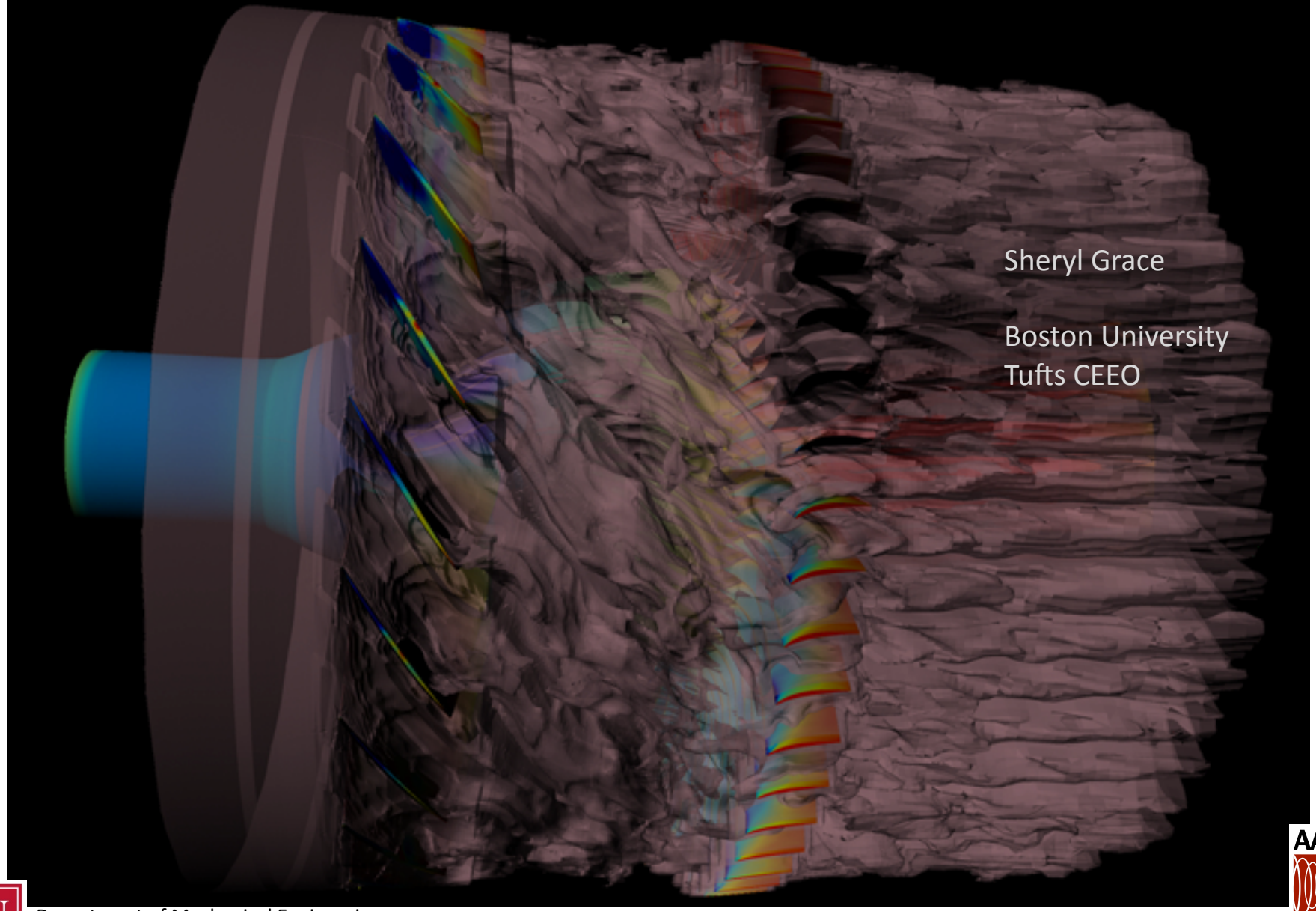
Predicting Turbofan Fan-Stage Noise



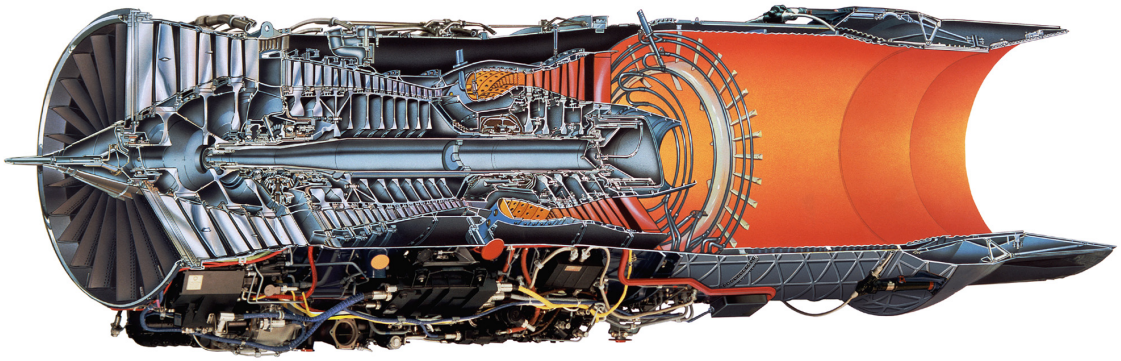
Sheryl Grace

Boston University
Tufts CEEO

Predicting Turbofan Fan-Stage Noise

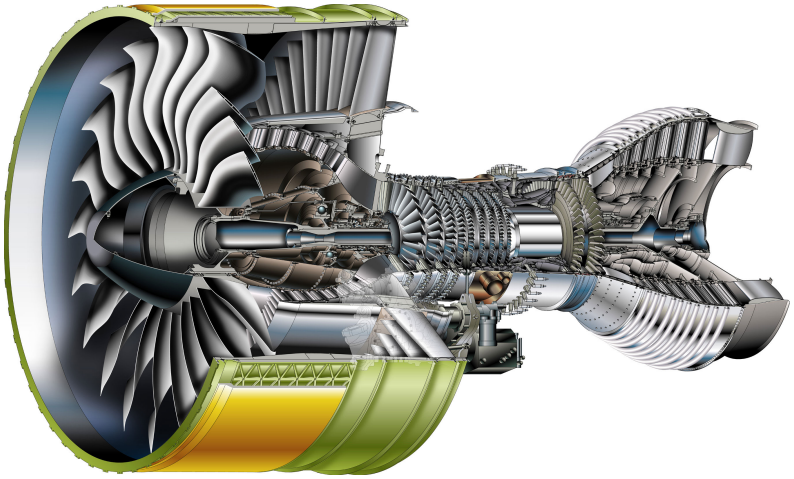
What is it?
Who cares?

Turbofans



Military
Low bypass
Multistage

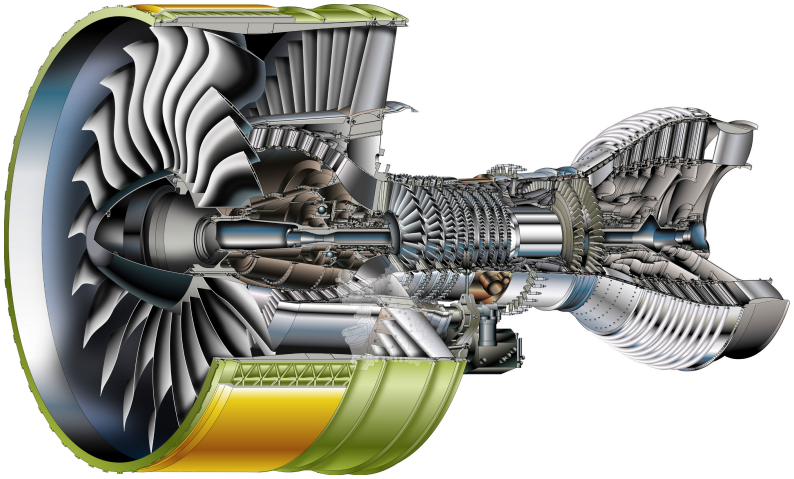
Commercial
High bypass
Single stage
Large axial gap

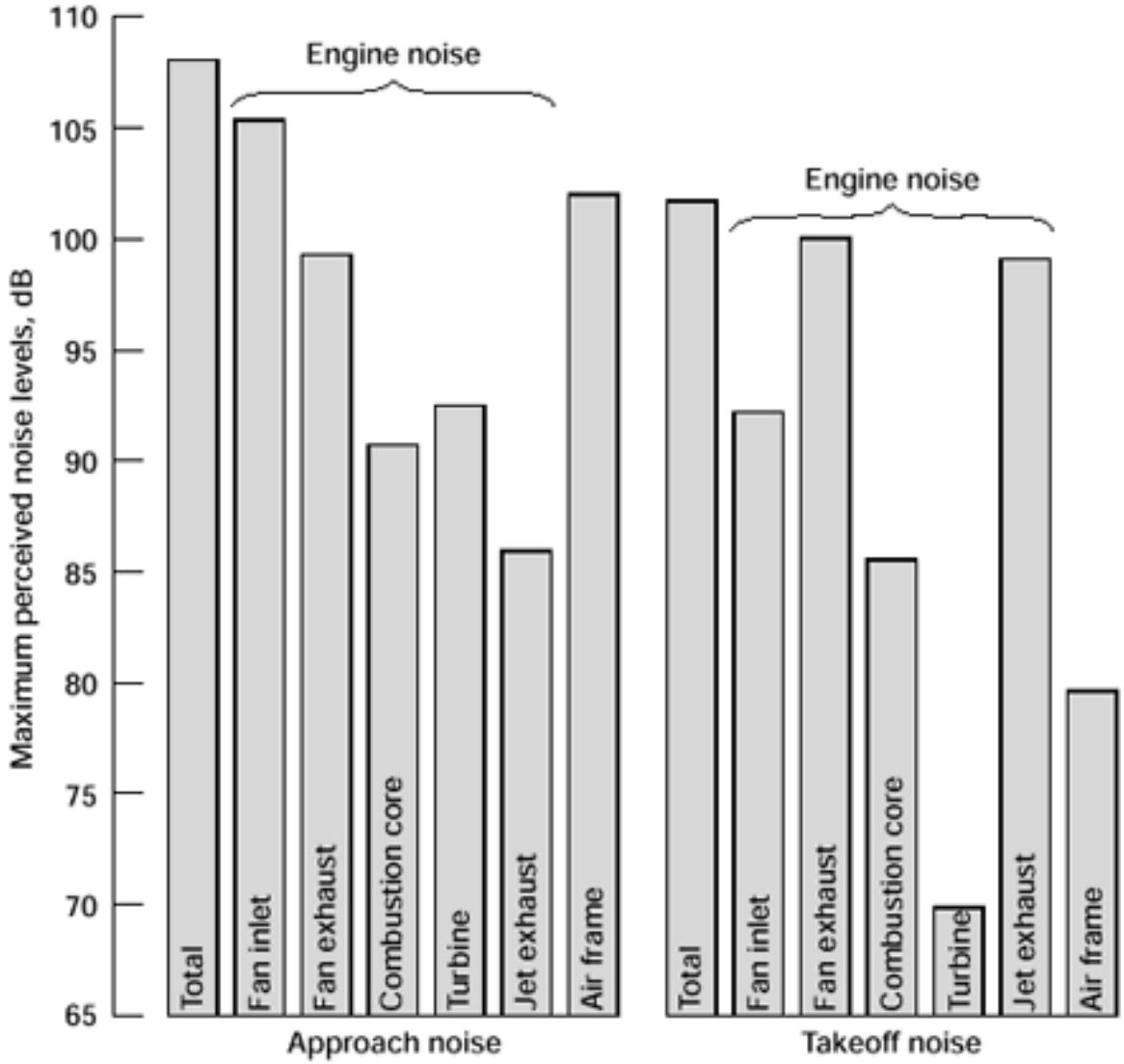


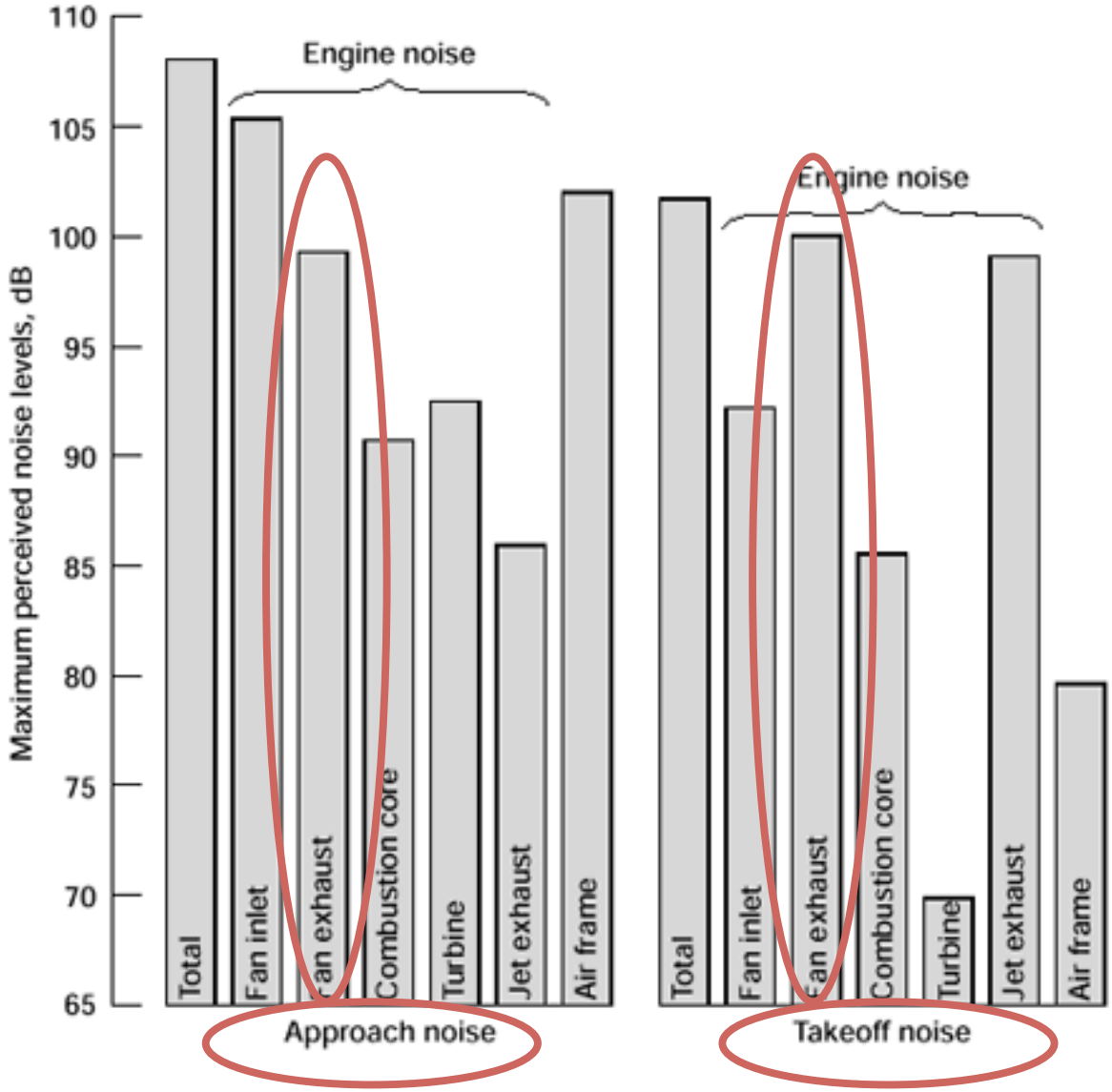
Turbofans

Strict noise regulations
Getting stricter

Commercial
High bypass
Single stage
Large axial gap




Maximum perceived noise levels, dB
110
105
100
95
90
85
80
75
70
65
Engine noise
Engine noise
Total
Fan inlet
Fan exhaust
Combustion core
Turbine
Jet exhaust
Air frame
Total
Fan inlet
Fan exhaust
Combustion core
Turbine
Jet exhaust
Air frame
Approach noise
Takeoff noise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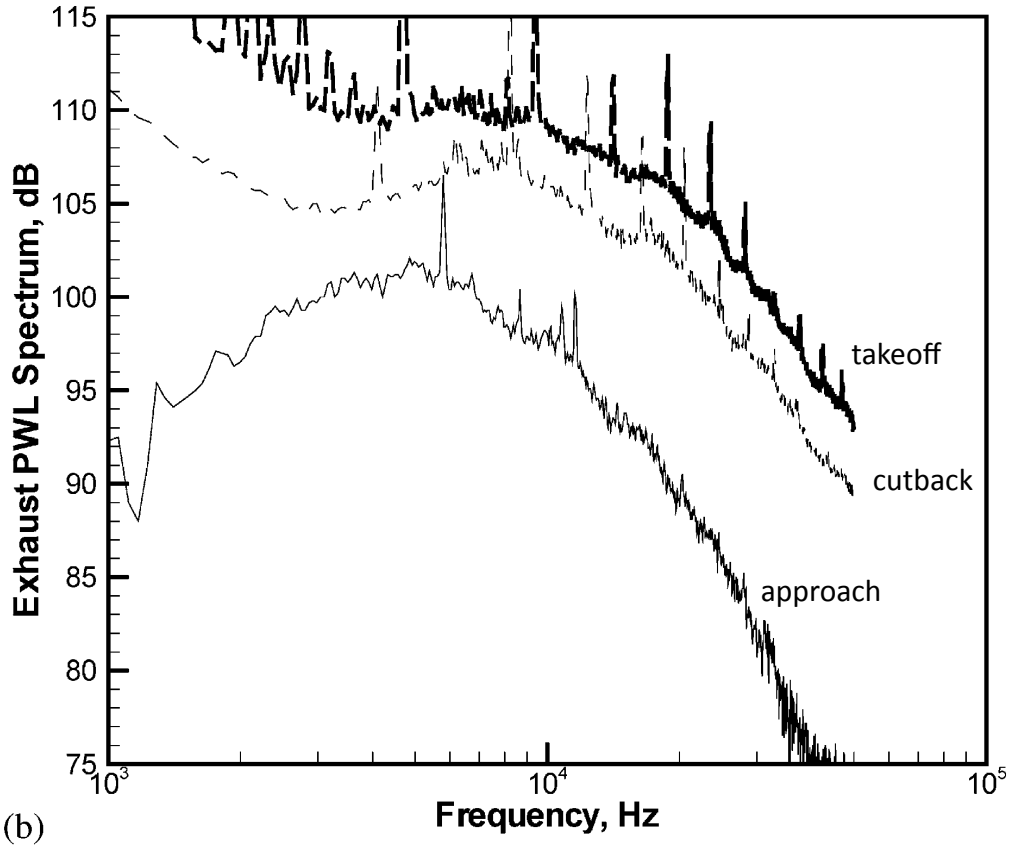
Turbine
Jet exhaust
Air frame
Total
Fan inlet
Fan exhaust
Combustion core
Turbine
Jet exhaust
Air frame
Approach noise
Takeoff noise

Types of noise from fan stage

Tonal

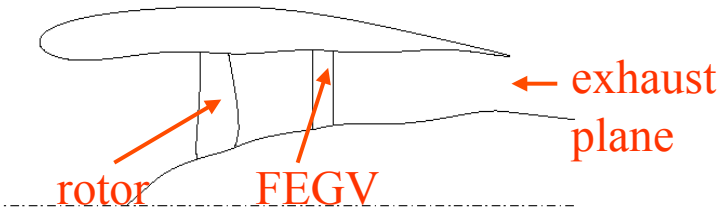
Broadband

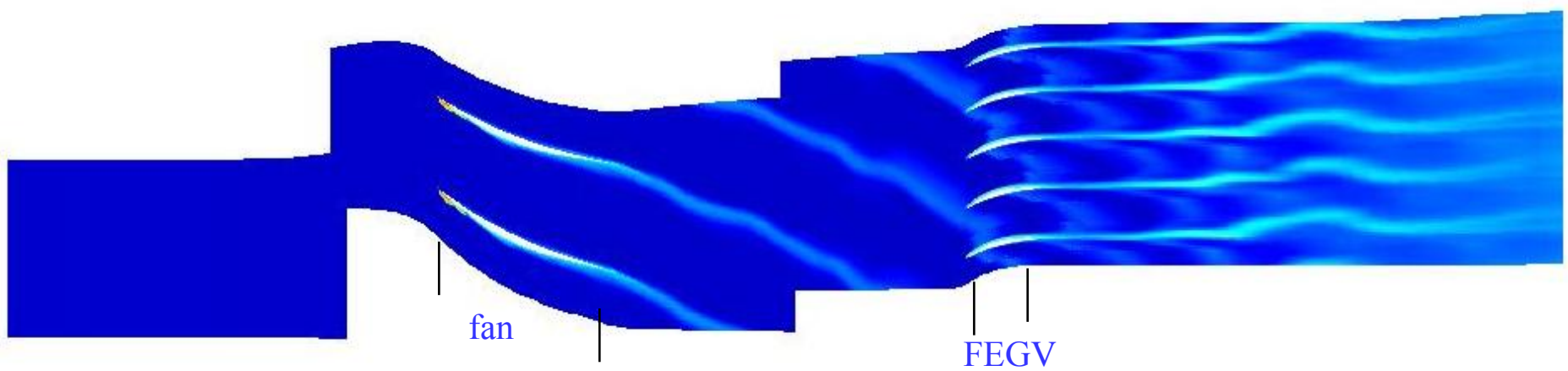


(b)

Nallasamy and Envia, JSV, 2005

Fan-stage tonal noise, explained

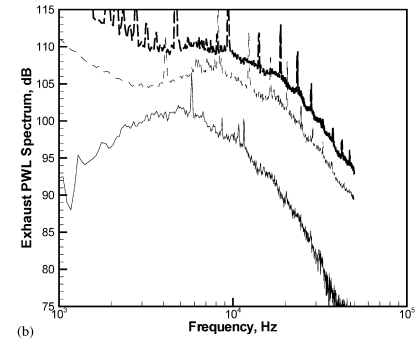


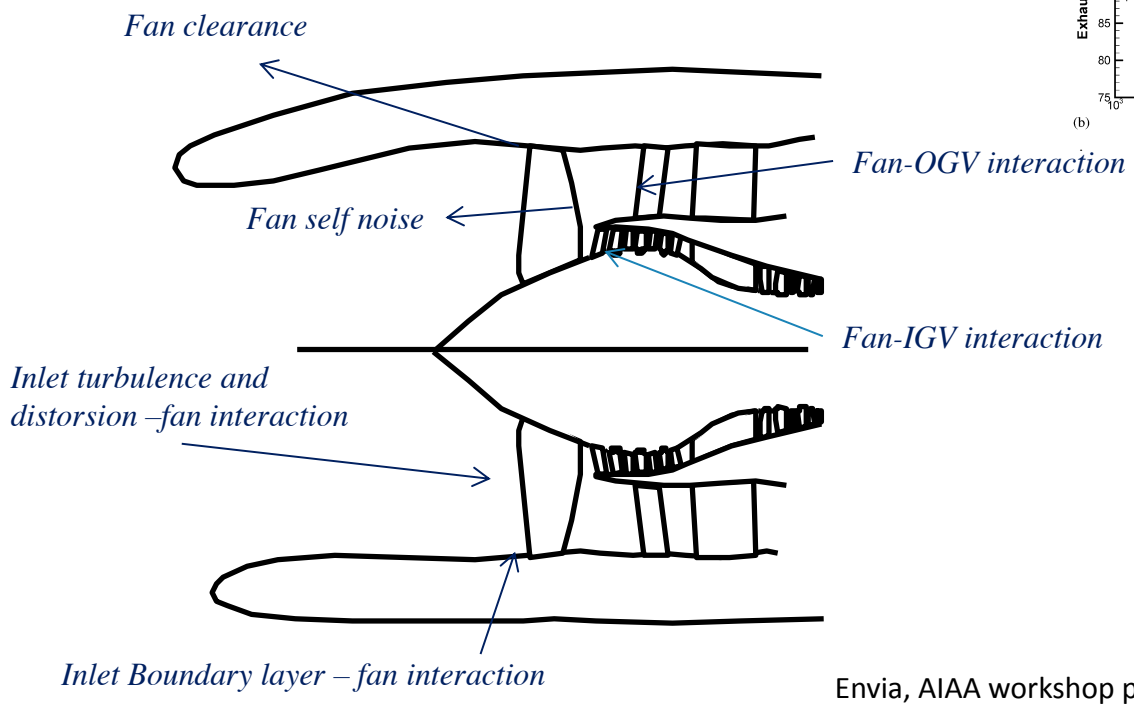


***Frequency** depends on number of blades and rate of rotation*
***Propagation** depends on number of blades and vanes, the frequency, the axial flow speed, the shape of the annulus, etc.*

Engine designers have this pretty well modeled
Use blade counts and duct liners to control

Fan-stage broadband noise, primer





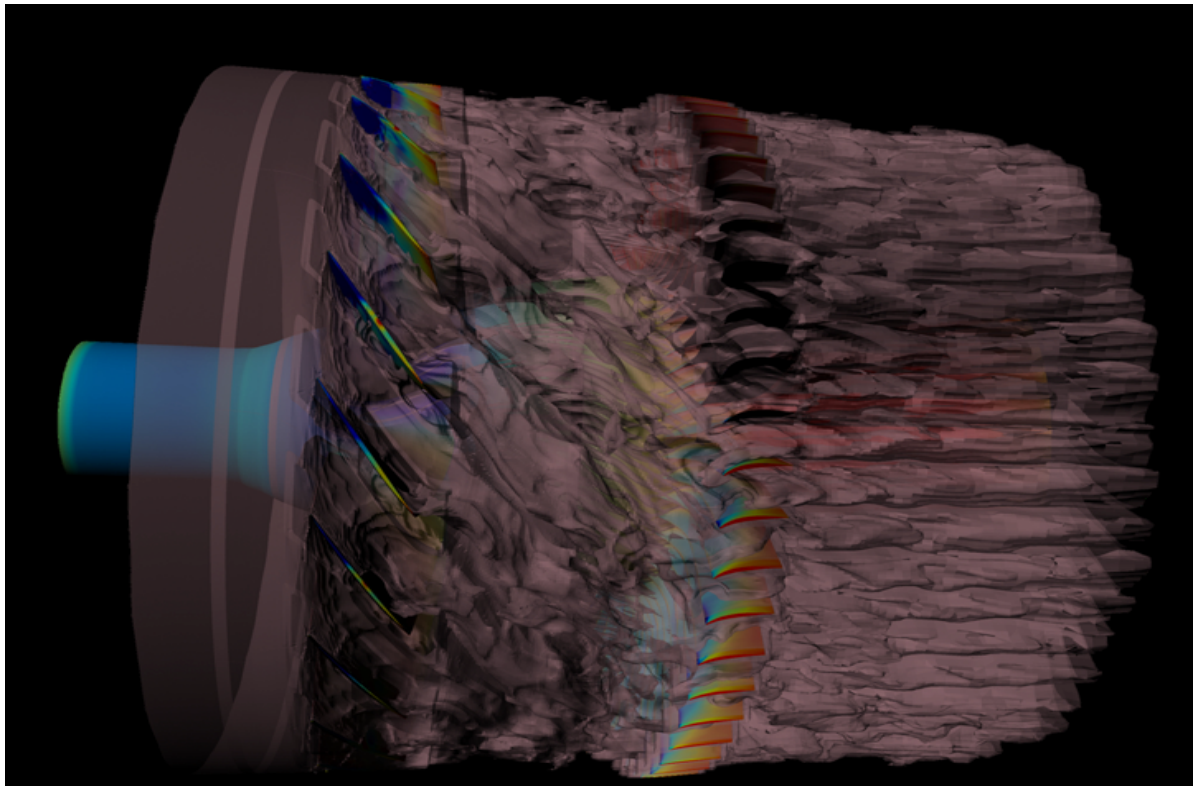
Envia, AIAA workshop presentation, 2014

Rotor-FEGV interaction noise considered dominant source (especially at exhaust plane)

Can CFD be used?

Full RANS CFD of rotor stator interaction (even if modeled as one-on-one) takes several months to start up and then weeks to obtain enough data to perform the statistics. May not even capture turbulence statistics correctly.

Some think only LES might be able to do the job



This is where my research comes in…

Motivation

- *Create a computational tool for predictions of fan-stage noise that can be used in design*
    - *Focus on interaction noise problem and exhaust noise*
    - *Must be a low-order model*

Outline

- *Describe two essential building blocks*
- *Give overview of how the pieces fit together to develop the model*
- *Describe two experiments used for validation*
- *Show some broadband noise predictions from the method*
- *Wrap up*

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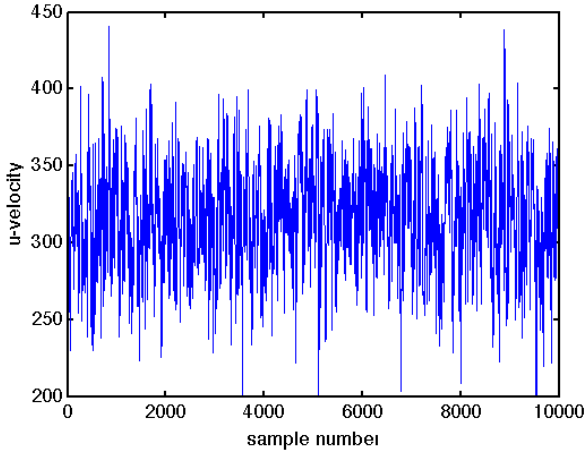
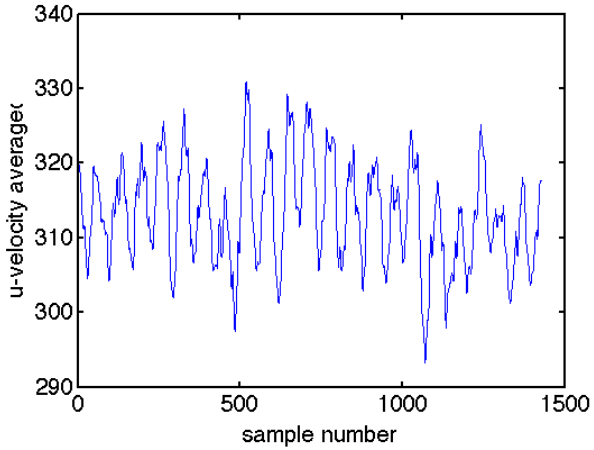
1st building block --- inflow

Physically, you have turbulence coming into the FEGV and interacting with it

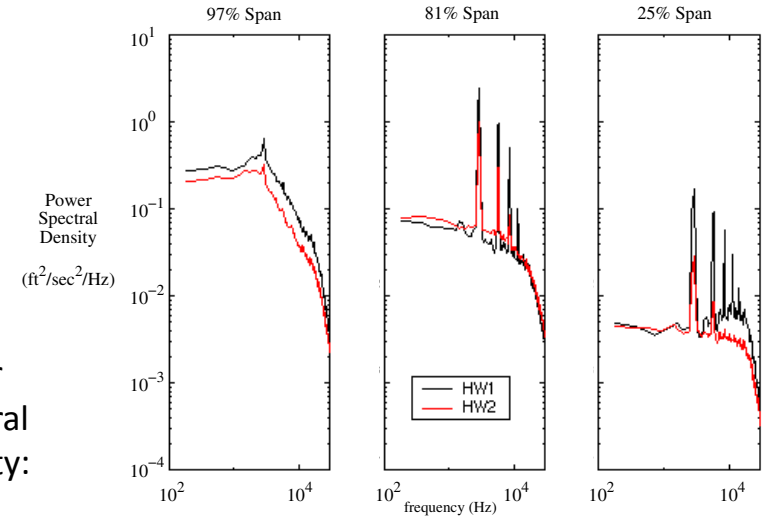
Data from hot-wire probe upstream of vane



Data averaged over 129 wheel rotations

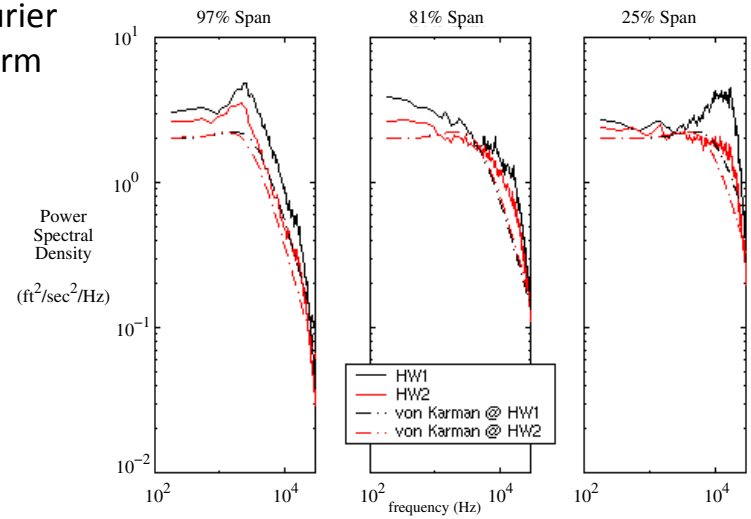


Power Spectral Density: think square of the Fourier Transform



Full signal

Figure 26. PSDs computed from upwash velocities measured in the rotor wake with the rotor operating at 61.7% speed (7808 RPMC).



Periodic part removed

Figure 27. Comparison of experimental and von Karman model PSDs. Experimental PSDs were computed from same time traces used in Fig 26., but after removing periodic component of the signal.

We need a useful model of the turbulent inflow

Hot wire data is not going to be available
LDV data may be available (averaged, not time accurate)
CFD calcs just give statistics – like turbulent kinetic energy and dissipation

Simplifications

homogeneous (same throughout space, definitely not true, wake flow)
isotropic (same in all directions $u_1u_1 = u_2u_2 = u_3u_3$*)*

$$Q_{2,2}(\mathbf{x},t,r) = \overline{(u_2)_A(u_2)_B} = \overline{u_{2_A}(\xi,t')u_{2_B}(\xi+\mathbf{x},t'+t)}$$

Correlation tensor defined by correlations

$$Q_{2,2}(\mathbf{x},t,r) = \frac{1}{(2\pi)^3}\iiint E_{2,2}(\mathbf{k},\omega,r)e^{i\mathbf{k}\cdot\mathbf{x}}d\mathbf{k}\; e^{-i\omega t}\,d\omega$$

3-D energy spectrum defined by correlation tensor

turbulence convected by the meanflow (relates space and time through velocity)

(x,t) → *x + U t* *k_1 and ω related through U*

$$E_{2,2}(\mathbf{k},\omega) = (2\pi)^3\frac{2u'^2}{\pi^2}\frac{L_s^5(k_1^2+k_3^2)}{(1+(kL_s)^2)^3}$$

Liepmann model for energy spectrum

Example of spectrum from experimental turbulence intensity and length scale

Experimentally based spectrum

$$E_{2,2}(\mathbf{k},\omega) = (2\pi)^3 \frac{2u'^2}{\pi^2} \frac{L_s^5(k_1^2+k_3^2)}{(1+(kL_s)^2)^3}$$

Related 1D form ($\Lambda = L_s$)

$$\frac{8u'^2\Lambda}{\pi}\frac{(k\Lambda)^4}{(1+(k\Lambda)^2)^3}$$

mid-gap

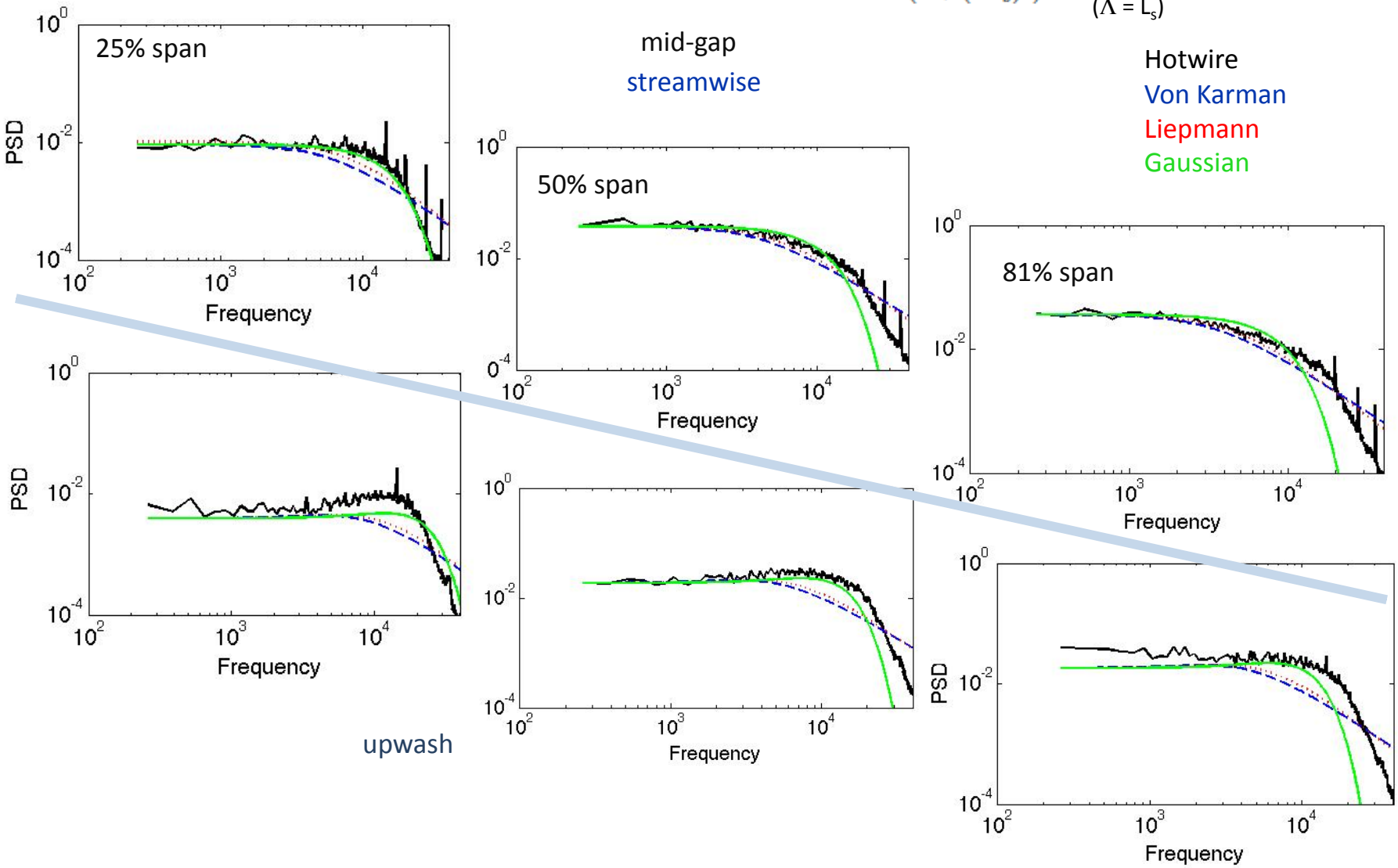
streamwise

Hotwire

Von Karman

Liepmann

Gaussian



upwash

2nd building block --- interaction model

Really high level overview of unsteady aerodynamics

Early unsteady aerodynamics – focus was flutter

used Linearized Euler Eqs. as basis

considered response of flat-plate airfoil in unsteady setting

"airfoil" moving : heaving and/or pitching (Wagner, Theodorsen)

considered response of stationary flat-plate airfoil to flow disturbance

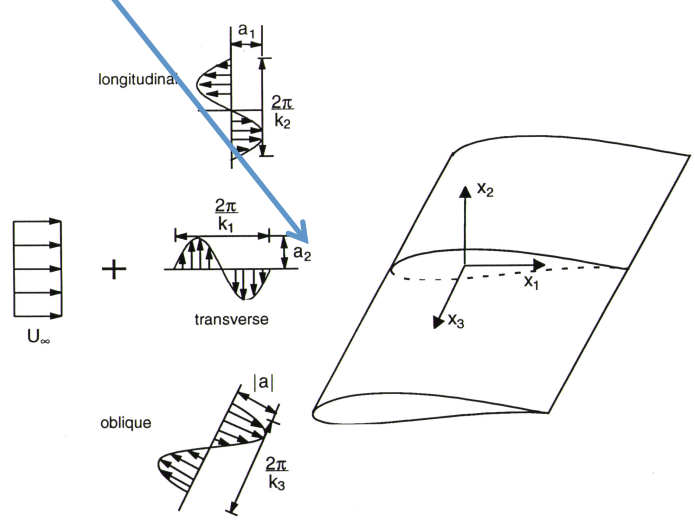
"airfoil" with unsteady inflow (gust) (Kussner, von Karman, Sears, Possio)

We have 2nd type of problem

$$Q_{2,2}(\mathbf{x},t,r) = \frac{1}{(2\pi)^3}\iiiint E_{2,2}(\mathbf{k},\omega,r)e^{i\mathbf{k}\cdot\mathbf{x}}d\mathbf{k}\ \ e^{-i\omega t}\,d\omega$$

Each component looks like an individual gust-type disturbance

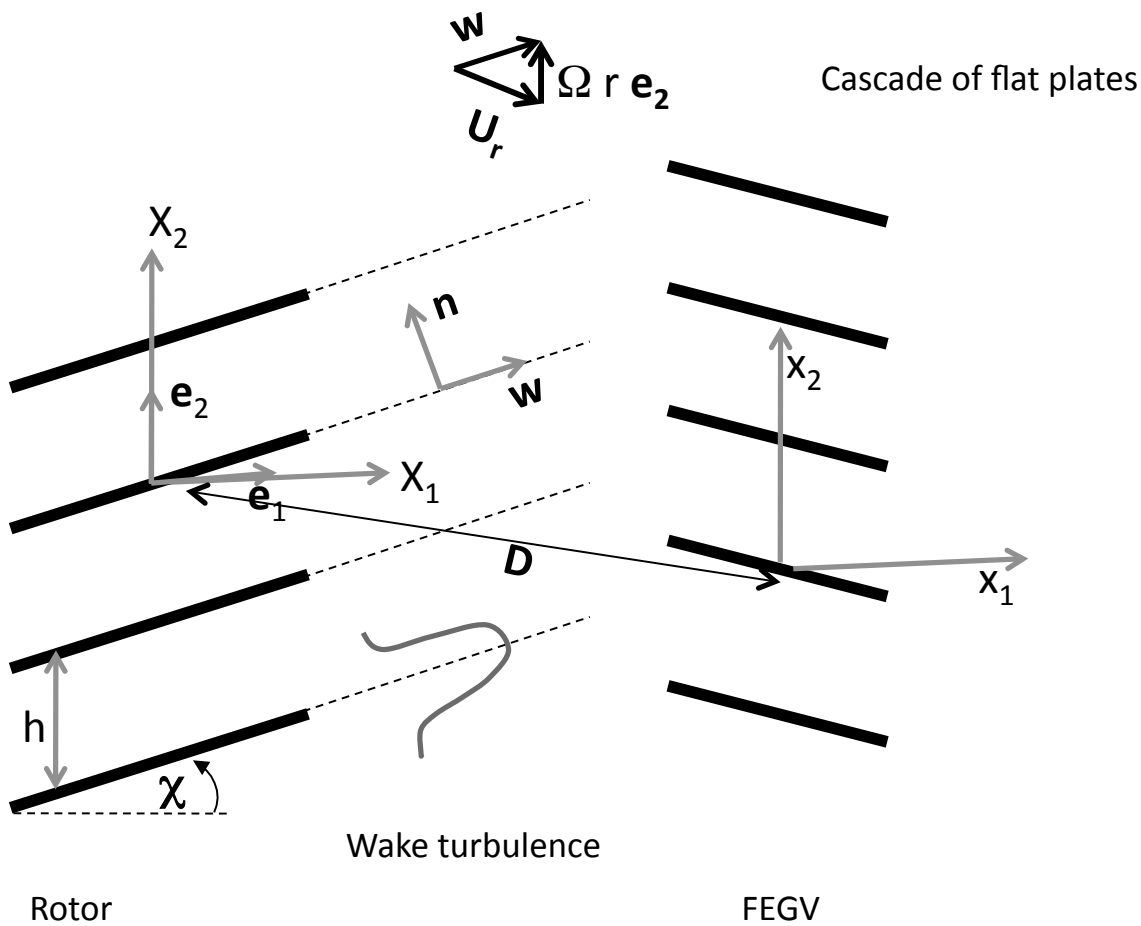
$$E_{2,2}e^{i(k_1x_1-\omega t)+ik_2x_2+ik_3x_3}$$



Later, real airfoil shapes were considered and the associated field acoustics (Atassi and others)

Also similar methods for determining the response of a cascade of "airfoils" were derived

Think about the fan-stage
Slice it at a given radial position and unwrap it



Use strip theory to build up unsteady pressure on entire vane

Outline

- *Describe two essential building blocks*
- *Give overview of how the pieces fit together to develop the model*
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- *Wrap up*

Method

Inflow wake turbulence

Based on experimental or CFD data, 3D spectrum model

$$\langle \Delta\tilde{p}_j(r_1, z_1, \omega)\, \Delta\tilde{p}_l^*(r_2, z_2, \nu) \rangle = \frac{(\rho_o U_r)^2}{(2\pi)^6} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \mathfrak{F}\left(r_1,\, z_1,\, \vec{k},\, k_3,\, \omega\right) \mathfrak{F}^*\left(r_2,\, z_2,\, \vec{K},\, k_3,\, \nu\right)$$
$$e^{ij\vec{k}\cdot\vec{H}_1} e^{-il\vec{K}\cdot\vec{H}_2} \langle \tilde{w}\tilde{w}^* \rangle \, d^2\vec{K}\, dK_3\, d^2\vec{k}\, dk_3$$

Cascade response to oblique gust

Aerodynamic core : 2-D, *flat-plate* cascade response to *3D gust* + strip theory

Vane unsteady pressure spectrum

$$\langle \tilde{p}_{mn}(\omega)\tilde{p}_{mn}^*(\nu) \rangle = \frac{1}{4\Gamma^2 k_{mn}(\omega) k_{mn}^*(\nu)} \int_{r_H}^{r_T}\int_{r_H}^{r_T}\int_{-b}^{b}\int_{-b}^{b} \mathcal{R}(r_1,\, \omega)\mathcal{R}(r_2,\, \nu) e^{i\mu(r_1,\omega)z_1} e^{-i\mu(r_2,\nu)z_2}$$
$$\left\{ \sum_{j=0}^{V-1} e^{i2\pi\frac{mj}{V}} \sum_{l=0}^{V-1} e^{-i2\pi\frac{ml}{V}} \langle \Delta\tilde{p}_j(r_1, z_1, \omega)\, \Delta\tilde{p}_l^*(r_2, z_2, \nu) \rangle \right\} dz_2\, dz_1\, dr_1\, dr_2$$

Acoustic pressure and velocity spectrum in duct

Acoustic pressure: Green's function for *annular duct (avoid singular values $k_{mn} \rightarrow 0$)*

Power spectrum at duct exit

Outline

- *Describe two essential building blocks*
- *Give overview of how the pieces fit together to develop the model*
- *Describe two experiments used for validation*
- *Show some broadband noise predictions from the method*
- *Wrap up*

Source Diagnostic Test (SDT)

9 x 15 Foot Wind Tunnel (NASA Glenn)

22-inch diameter turbofan model

Configuration

- 22 blade rotor
- 54 vane stator – baseline
- 26 vane stator – low count
- 26 vane stator – swept

Design Parameters

- Maximum RPM: 12,656
- Maximum tip speed: 1,215 ft/s
- Maximum fan weight flow: 100.5 lbm/s

Experiments

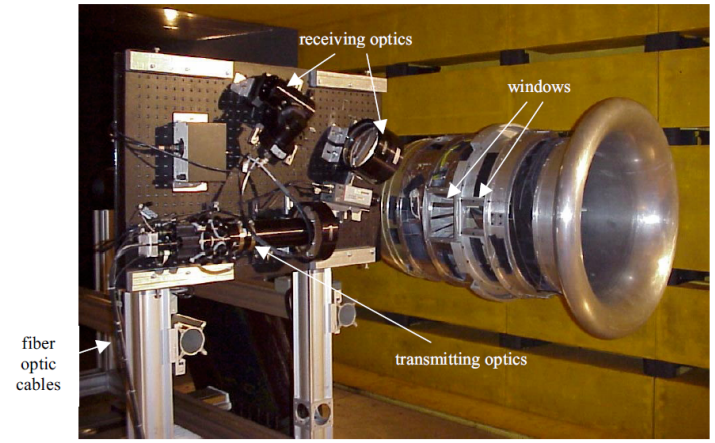
Experimental wake data

Laser Doppler Velocimetry (LDV)

- Optical, 2-component (axial, tangential) system
- Steady measurements not restricted by rotor speed

Hot-wire Anemometer

- 4-wire (5 micron diameter tungsten) anemometer
- 3-component system
- Unsteady measurements restricted by rotor speed



LDV System

Experimental acoustic data

Sideline Traversing Microphone System

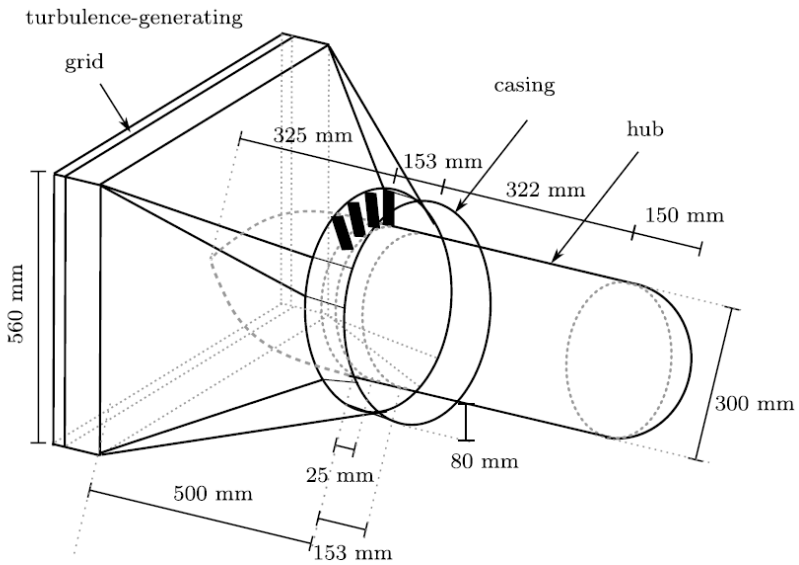
- Translating microphone probe + 3 aft fixed microphones
- Provides total PWL only – includes extraneous modes

FC2 benchmark

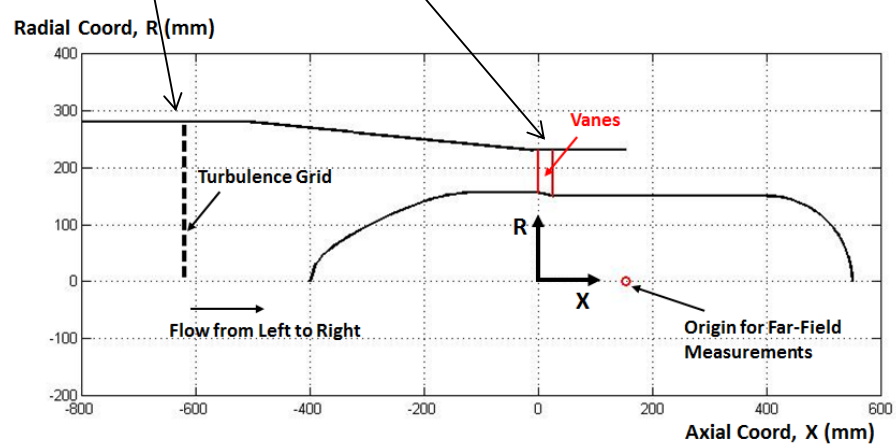
Subsonic open-jet facility at Ecole Centrale de Lyon

Grid turbulence interaction with annular cascade

Hot wire measurements and field microphones



2 Turbulence Grids T1 (~3%), T2 (~6%)
2 Cascades C1 (V=49), C2 (V=98)
Giving four test cases
T1C1, T2C1, T1C2, T2C2

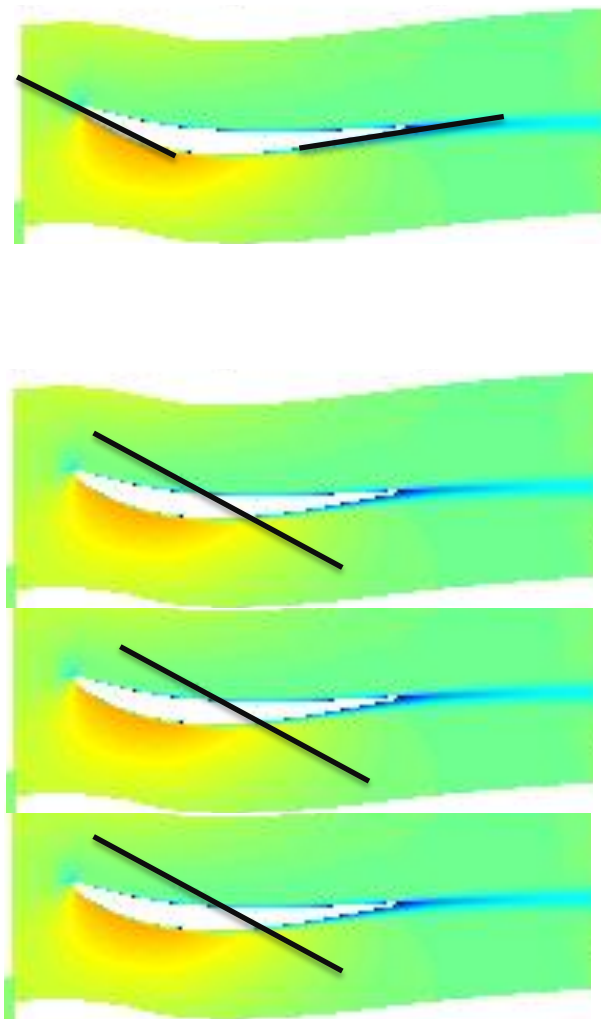


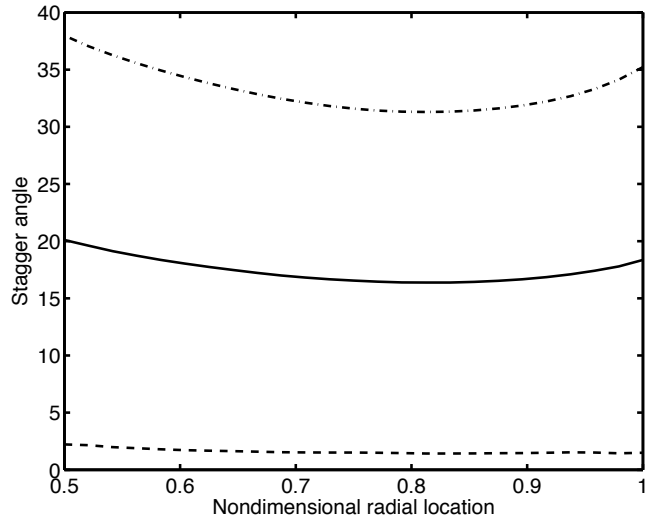
Coupland, AIAA workshop presentation, 2014

Outline

- *Describe two essential building blocks*
- *Give overview of how the pieces fit together to develop the model*
- *Describe two experiments used for validation*
- *Show some broadband noise predictions from the method, describe caveats*
- *Wrap up*

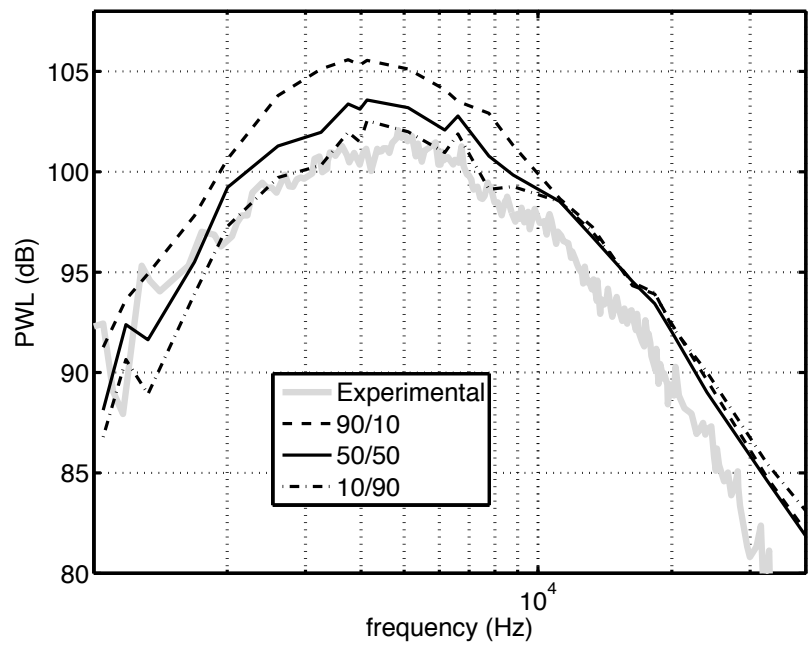
Must select a stagger angle – flat plate model



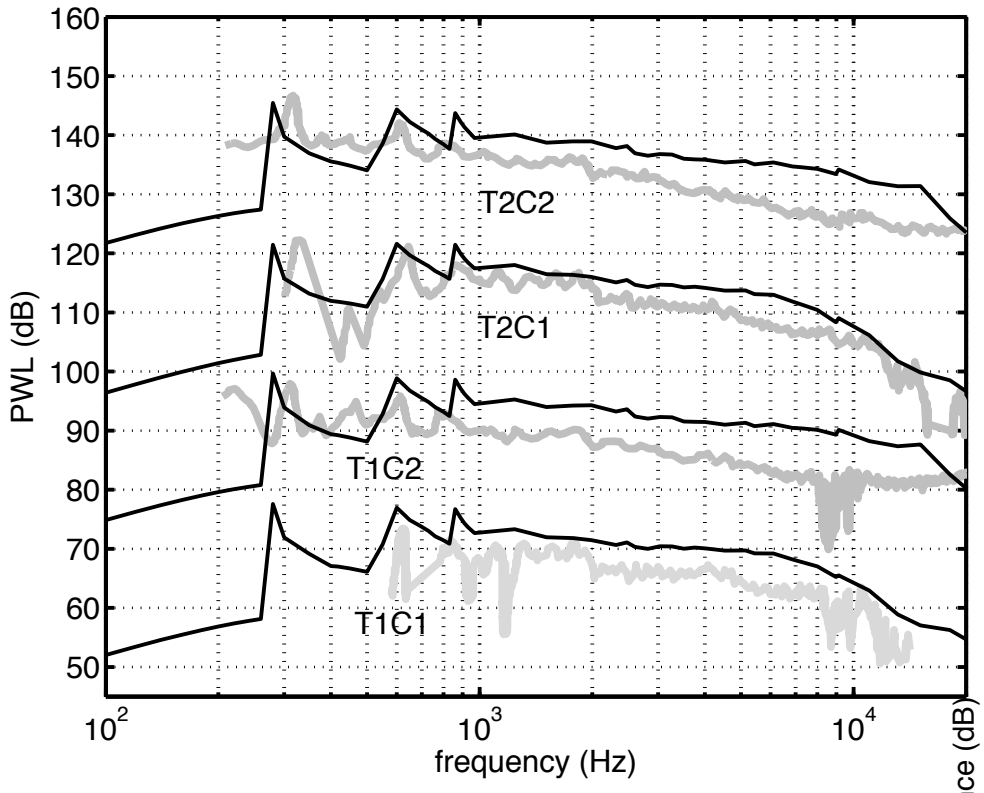


It makes a difference!
No clear winner

Use mid value for now



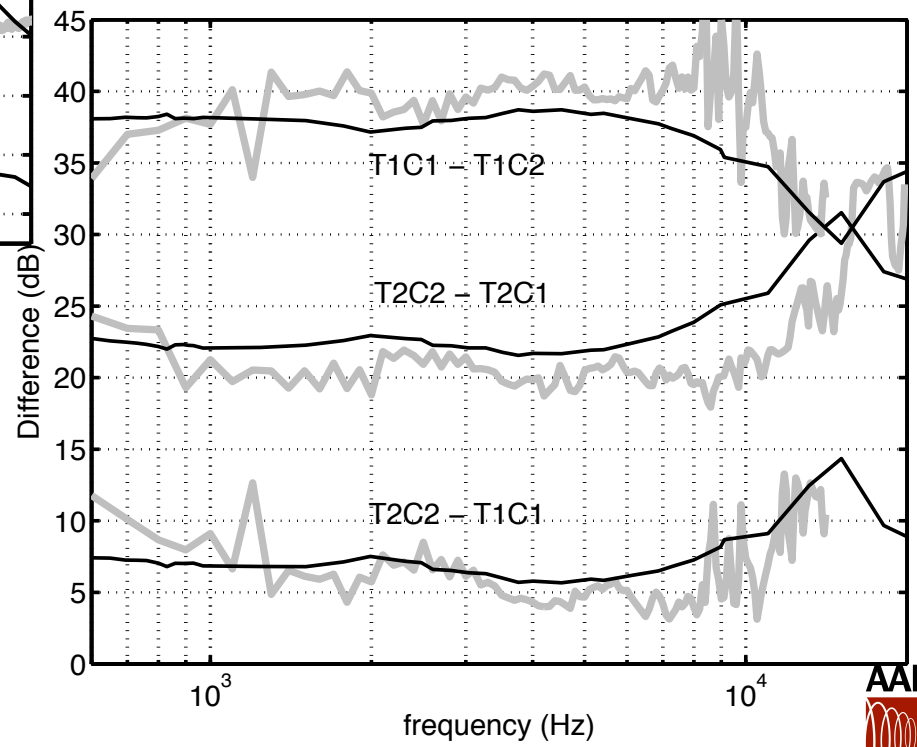
FC2 predictions – based on experimental input



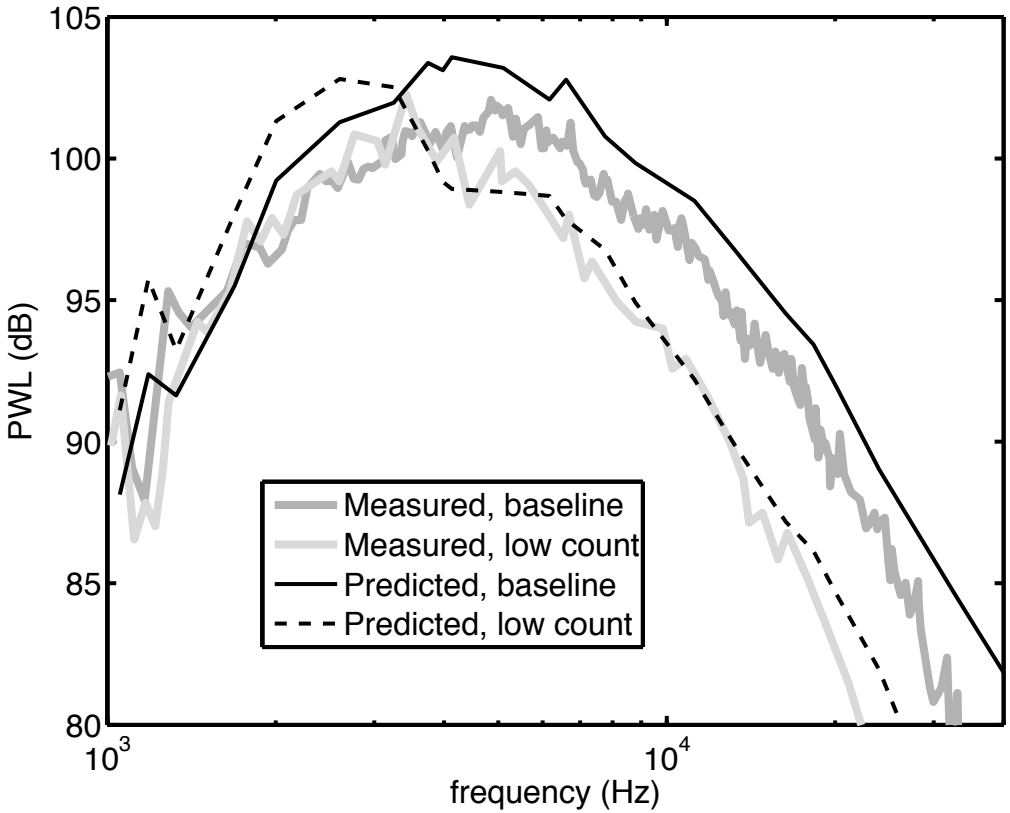
Trends are captured reasonable well

C2 – C1 : too large of difference , dependence on number of vanes not perfectly modeled

Some singular frequencies had to be included



SDT prediction (based on hot-wire)



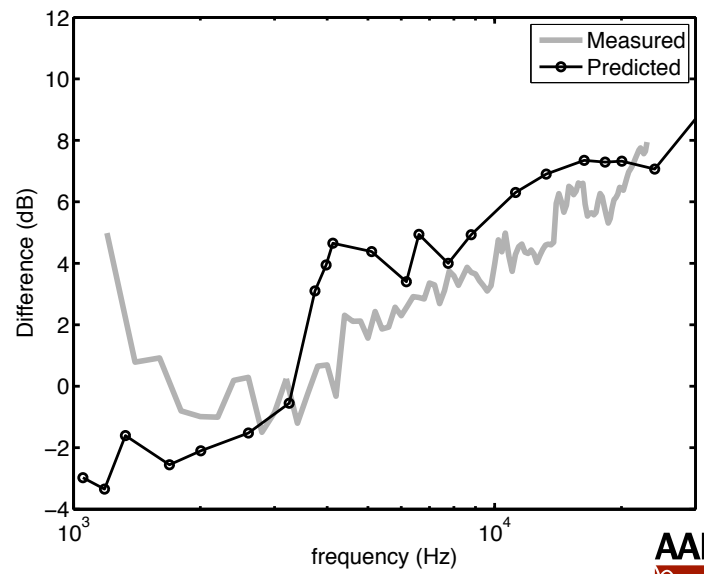
Approach speed

Low-count prediction better
Used mid-stagger for both

Spectral shape very good

Low frequency bump in low-count

Trend is captured

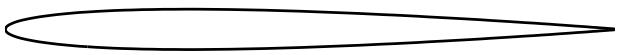


Summary and conclusions

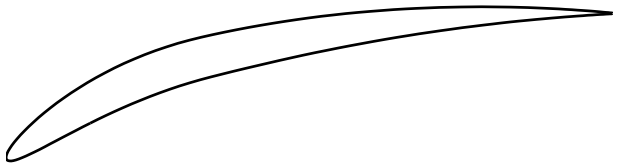
- *The possibility exists for predicting broadband noise trends from a fan stage using a low-order method*
- *Parameter selection necessary due to simplified model (stagger) does not affect trend prediction*
- *Fully computational prediction suffers from reliance on turbulence length scale modeled with CFD*
- *Difference due to selected background turbulence intensity does not affect trends but does affect individual predictions*
- *Low-count configuration is better predicted : potential effect*
- *These are the best predictions shown in the literature for the broadband workshop case and for the SDT*

Future directions

- *Can more realistic vane geometry be modeled?*



Thickness



Thickness and camber : flow turning

- *Can "soft" vanes be modeled? Need to add impedance of surface to model.*

Thanks

- *NASA Glenn – Ed Envia, Gary Podboy, etc.*
- *GE, P&W, NASA Glenn : CFD files*
- *AARC for funding*
- *My collaborators Doug Sondak and Victor Yakhot*
- *Graduate students on this project Jeremy Maunus and Andy Wixom*

Questions

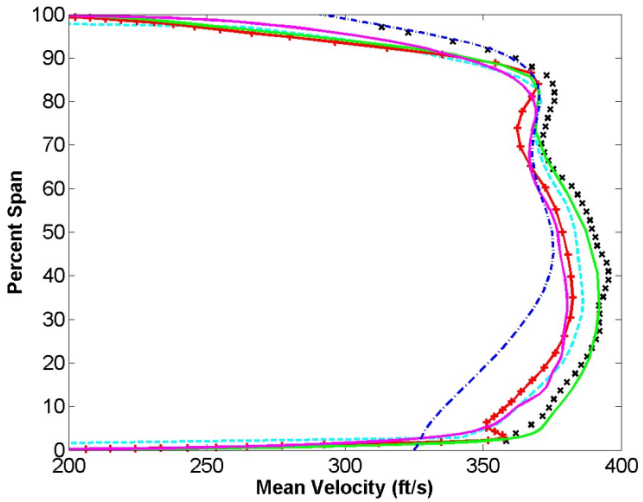
What if input based on CFD

4 simulations of the SDT rig obtained

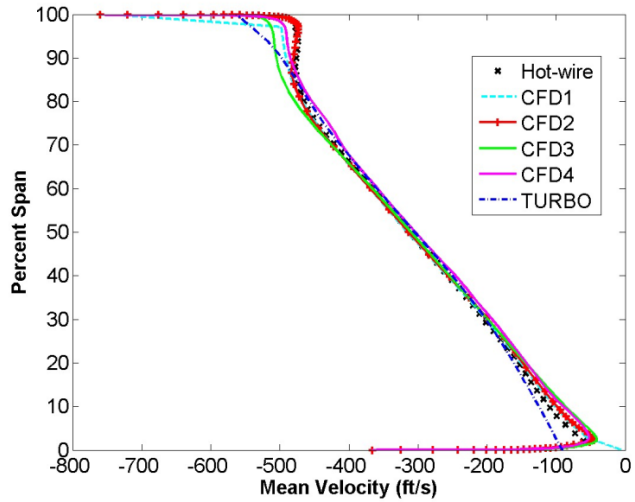
Code	Grid config.	Grid density* x,θ,r	Tip clearance	Turb. Model	Rotor config.	Vane config.	Comp. type
1	O-H	95x64x36	y	k-ω	hot	baseline	loosely coupled
2	C-H	86x89x81	y	k-ω	hot	baseline	loosely coupled
3	H	11x51x51	n	k-ε	approach	baseline	average passage
4	O-H	51x33x57	y/n	k-ω	hot	none	rotor alone

*between two measurement locations in gap

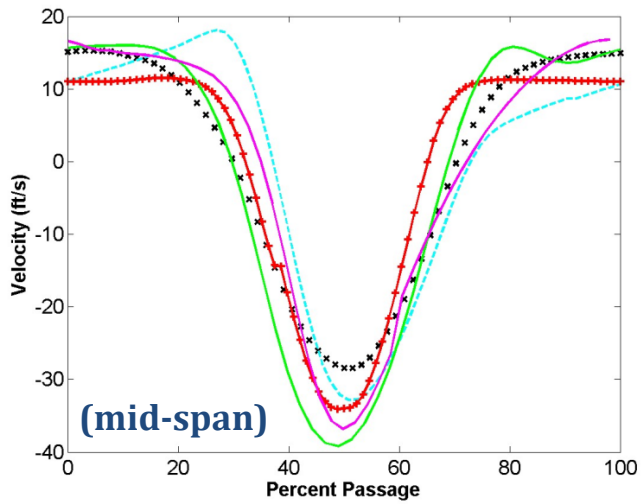
CFD wake accuracy: SDT (Approach)



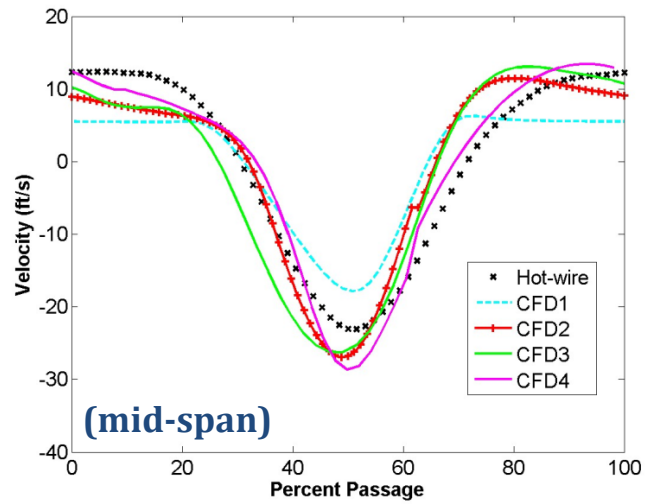
Passage-averaged axial velocity



Passage-averaged circumferential velocity

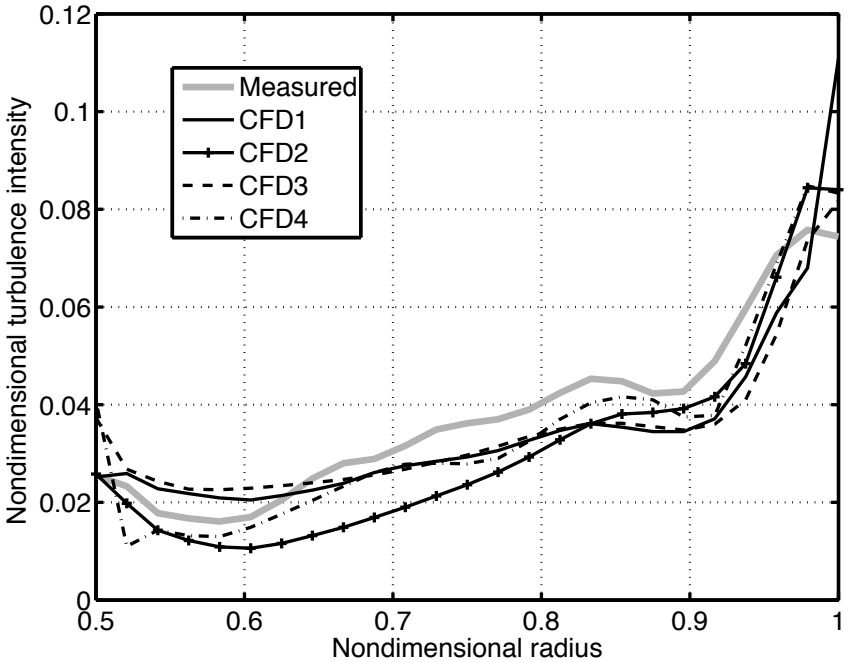


Streamwise velocity

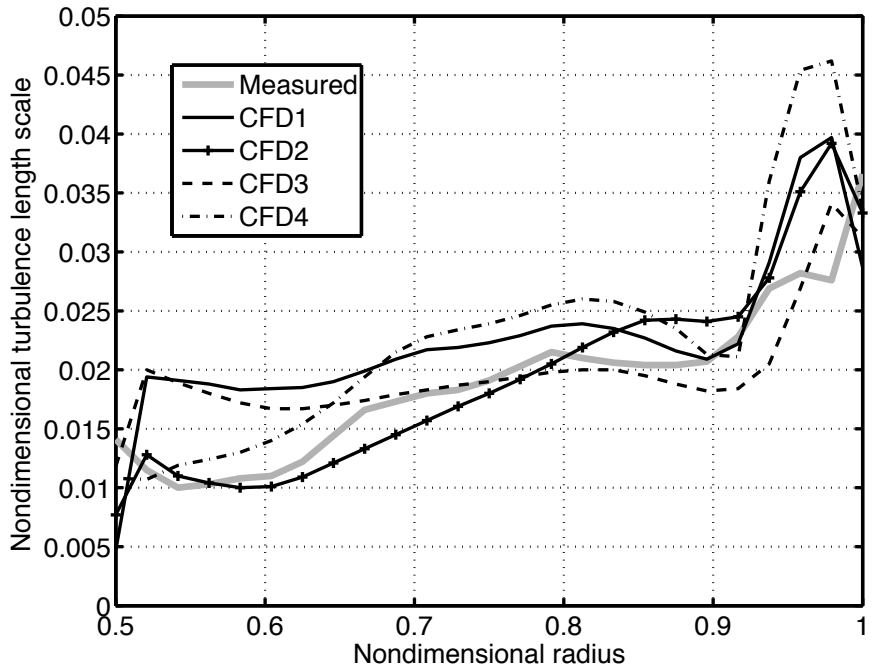


Upwash velocity

CFD wake accuracy: SDT (Approach)



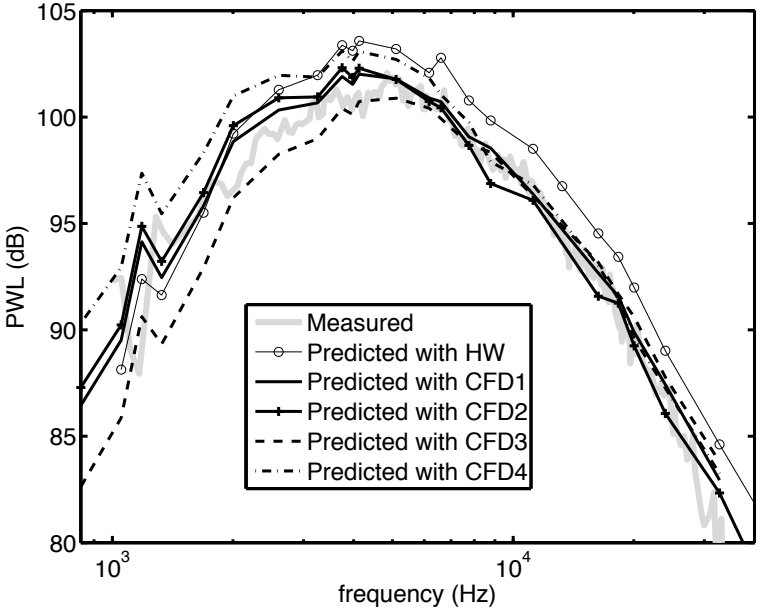
Turbulence intensity



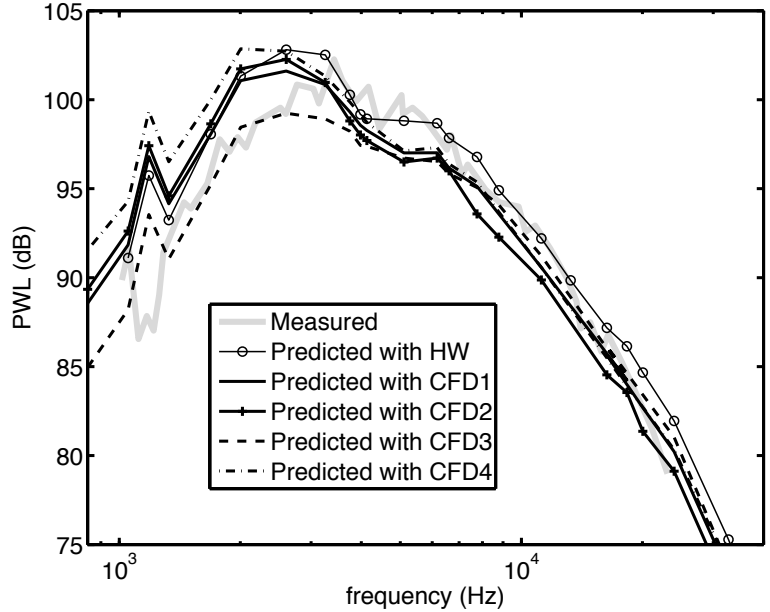
Length scale (streamwise)

SDT approach case

Exhaust sound power level prediction: approach



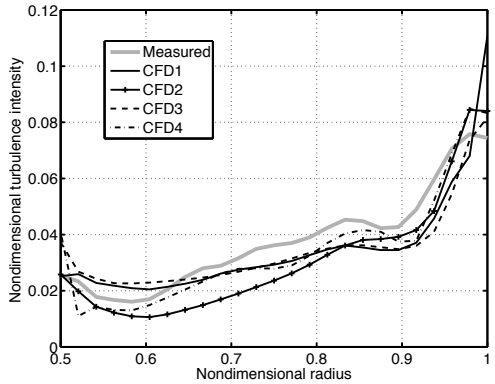
Baseline: 54 vanes

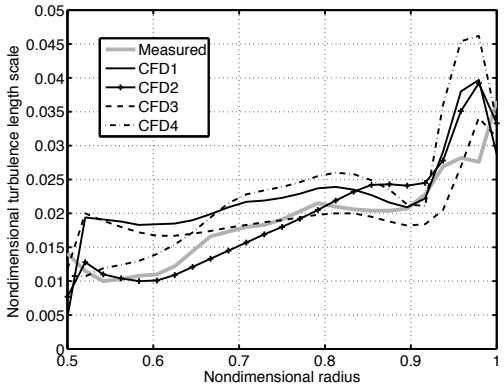


Low count: 26 vanes

SDT approach case

- **HW based prediction higher:**
  - **potential effect maybe**
- **Largest variations come from largest length scale differences**





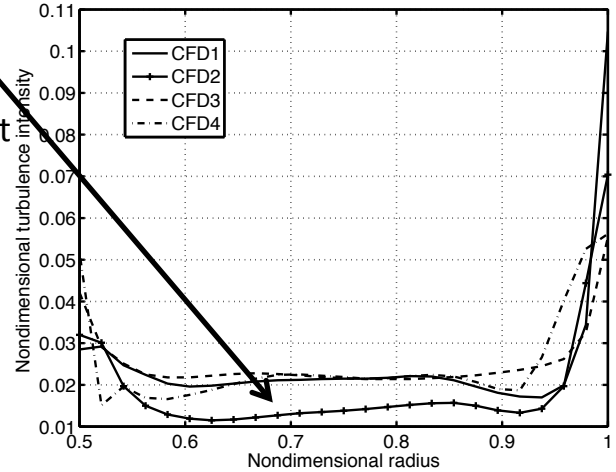
Exhaust sound power level prediction: takeoff

CFD2

Baseline, hot geometry

Largest tip gap

Background turb. level really low



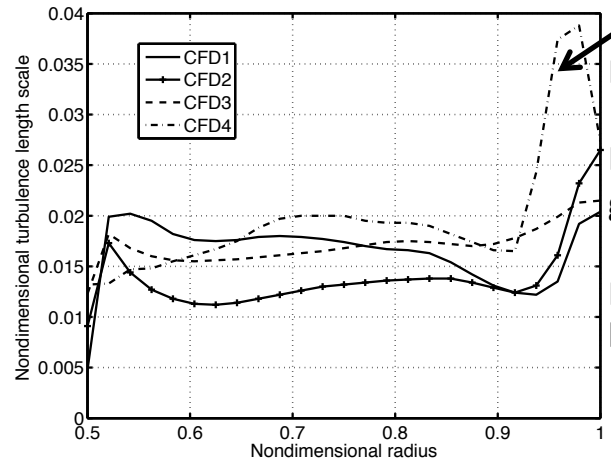
Turbulence intensity

CFD4

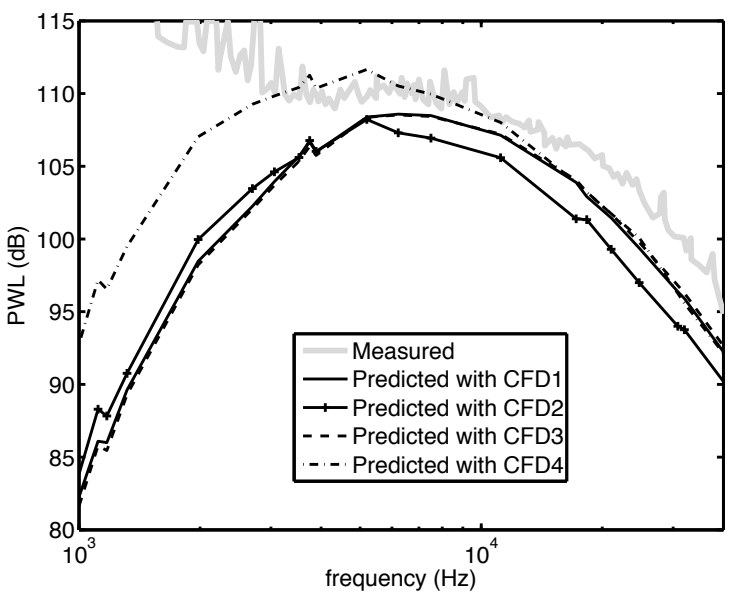
Rotor alone

Hot geometry

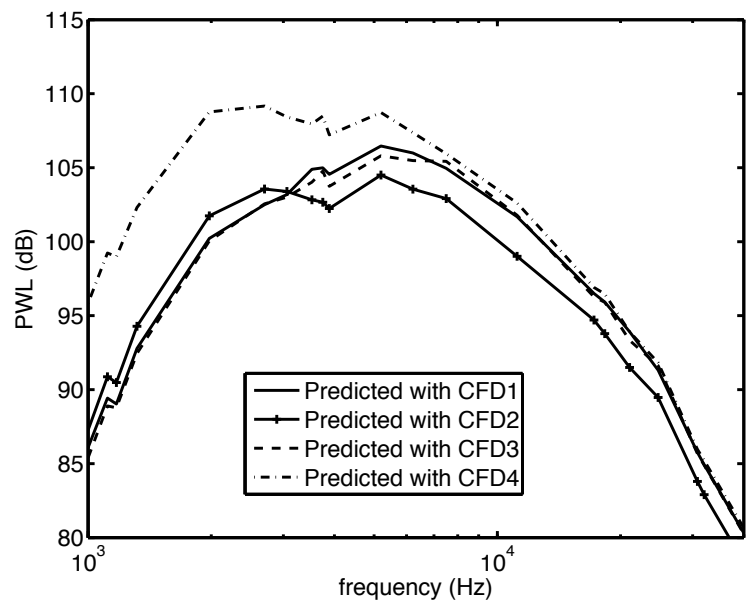
No tip gap at high speed



Length scale (streamwise)



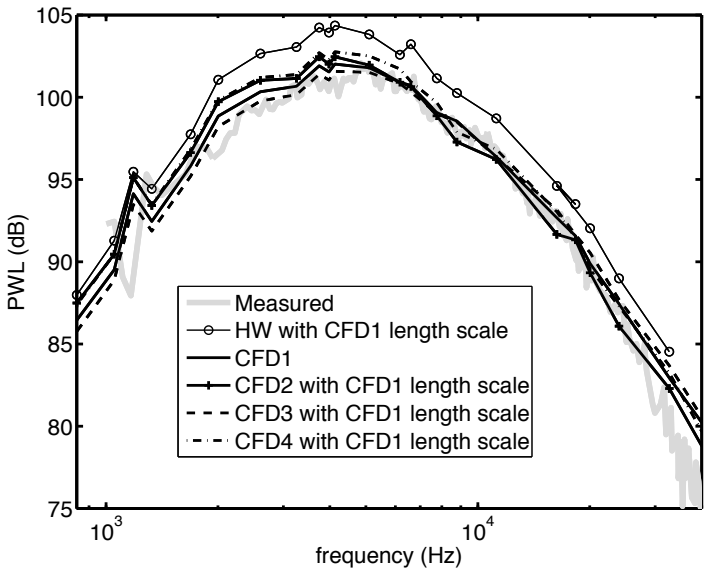
Baseline: 54 vanes



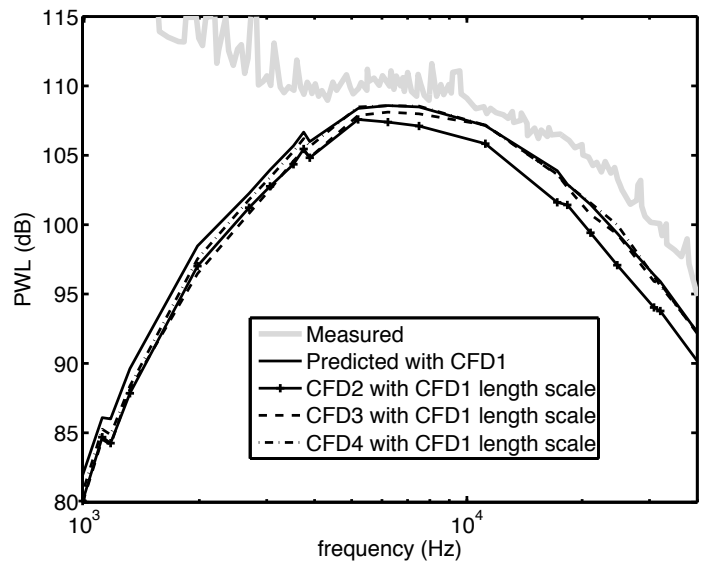
Low count: 26 vanes

Exhaust sound power level prediction
Use CFD1 length scale

Baseline: 54 vanes



Approach

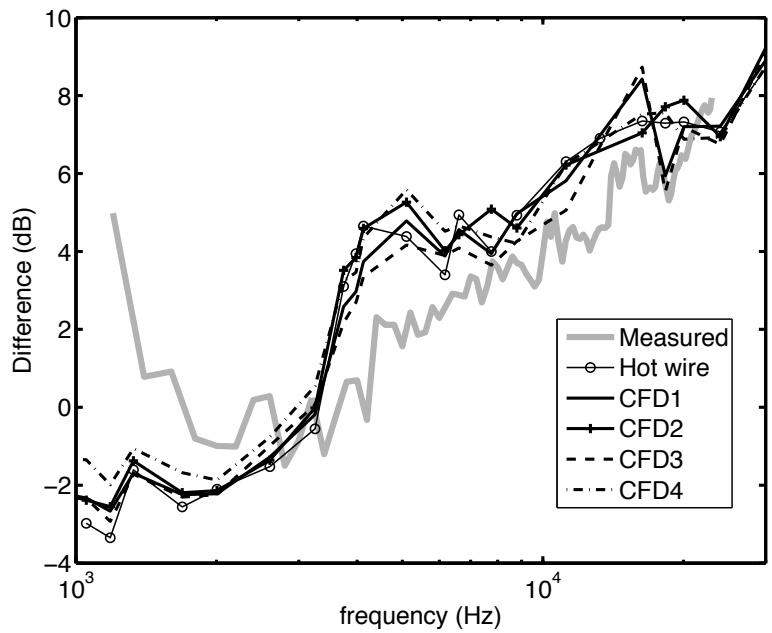


Takeoff

Collapses predictions, except for hw based

Exhaust sound power level prediction Trends

Number of vanes (shape of vanes also)

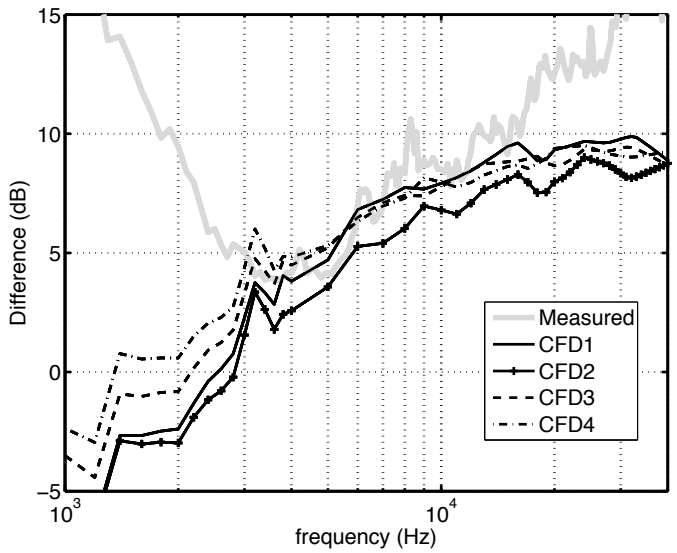


Baseline - lowcount

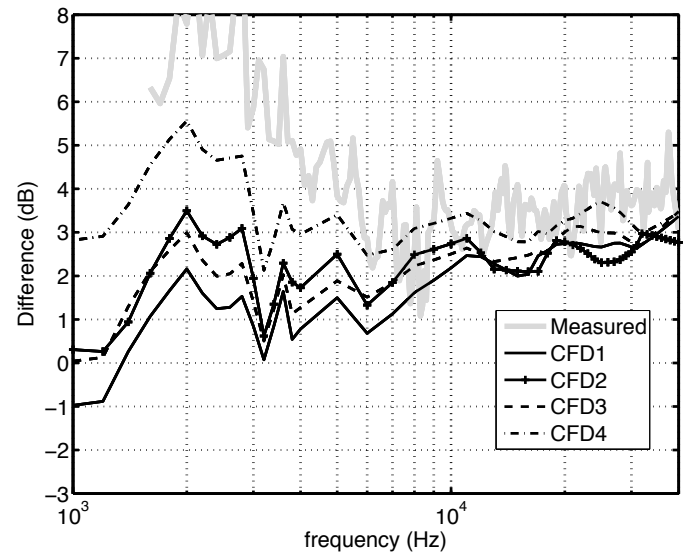
- Completely consistent
- Slightly high

Exhaust sound power level prediction
Trends

Baseline: 54 vanes

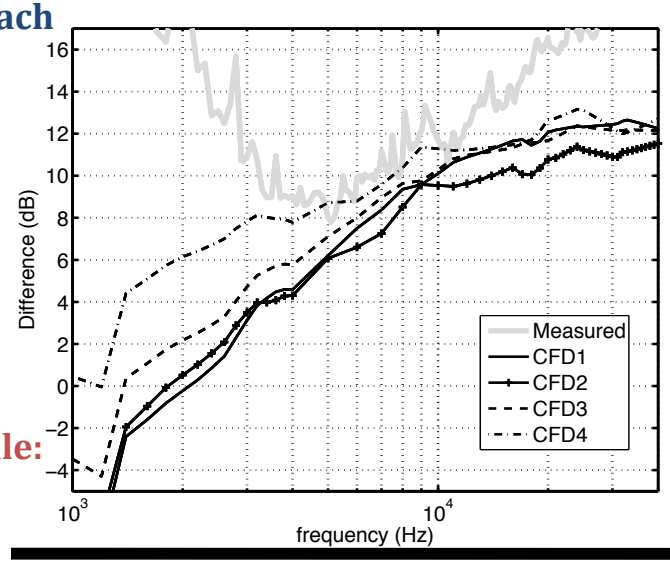


Cutback-Approach



Take-off – Cutback

- **Trend with frequency : good**
- **Trend with rotor speed :**
  - **CFD2 less variation than expected**
  - **CFD4 gives closest, but driven by large tip length scale: physical?**



Takeoff - approach

Mean loading effects

End goal: use asymptotic method of Peake et al. for cascade gust response
extend method to calculate the unsteady surface pressure

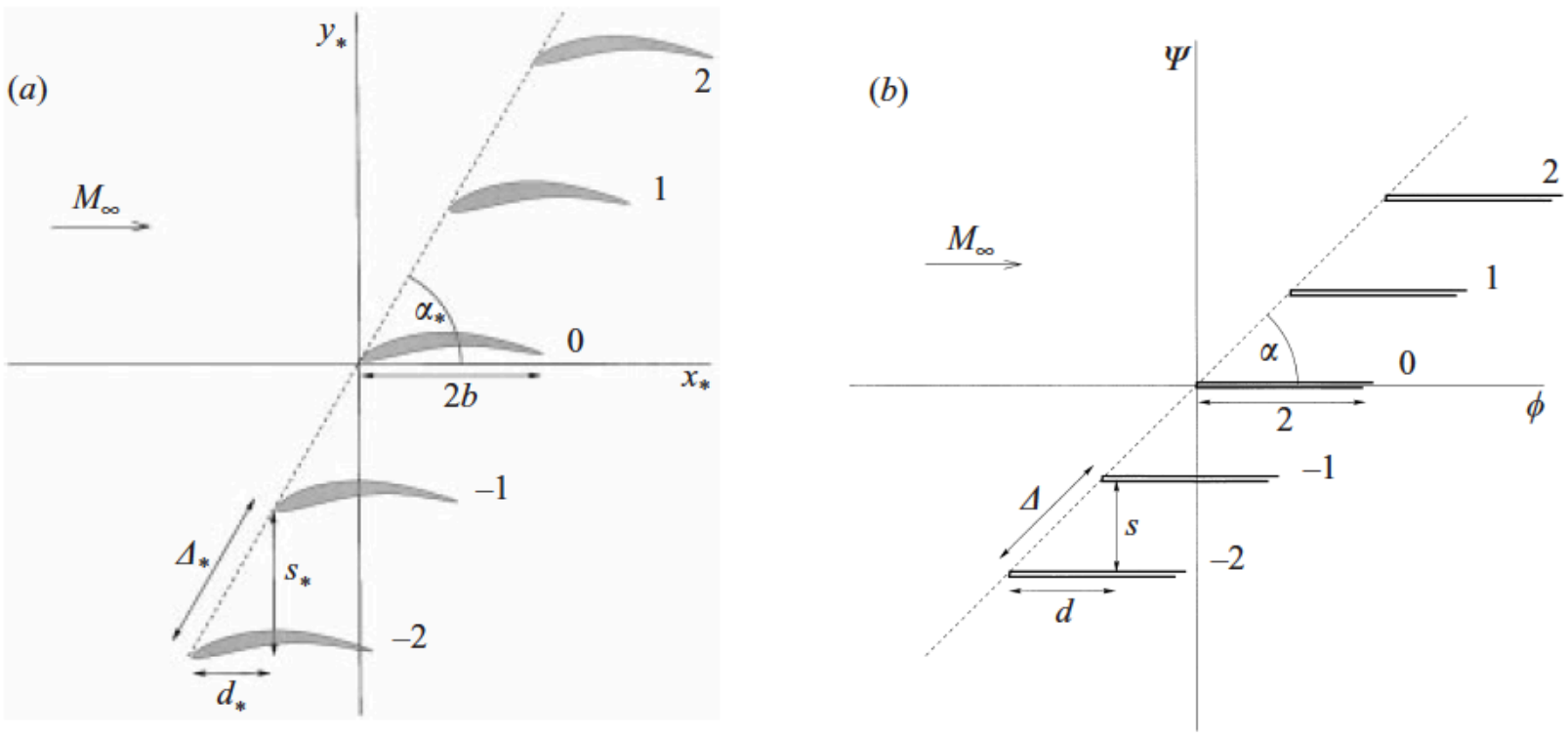
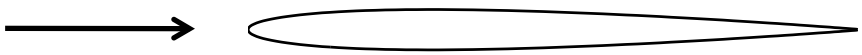


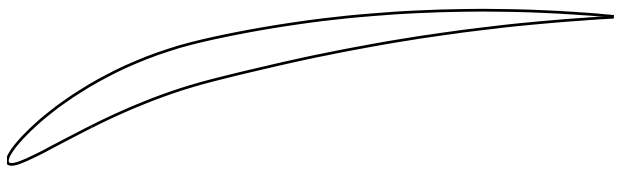
FIGURE 2. The staggered cascade in (*a*) physical space, and (*b*) (ϕ, ψ)-space.



Thick, perfectly aligned flow (t.e. stagger)

Cambered, flow aligned with chord

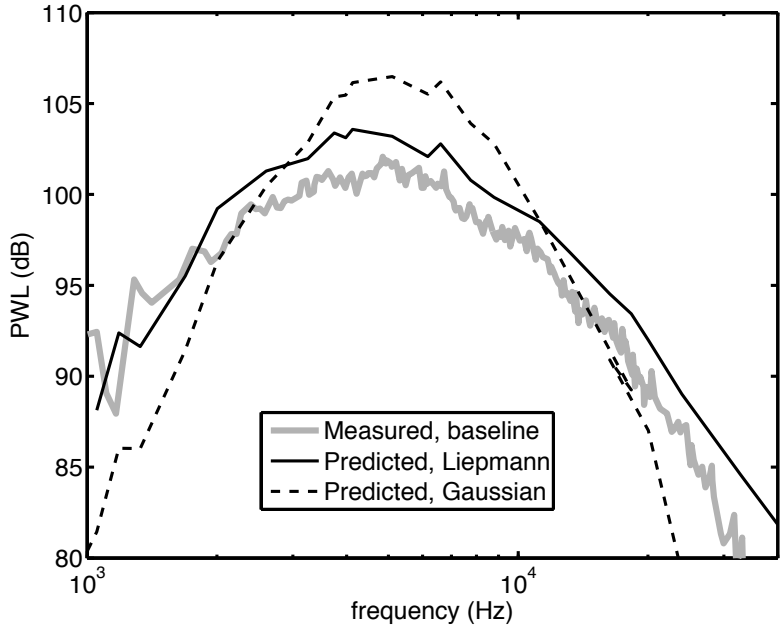
Same unsteady response



Cambered, flow aligned with chord,
stagger simulated

7% thick
9% camber
13° stagger
30° aoa - approach

Effect of inflow modeling assumptions



Different turbulence spectra

Liepmann matched turbulence the best and gives good spectral shape for acoustics

Turbulence length scale is Achilles heel

Both streamwise and radial length scales are in the model

Doubling radial lengthscale doubles pressure (3 dB)

Doubling streamwise tilts the spectrum