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
Types of noise from fan stage

Tonal

Broadband

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

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
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
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

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

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 \( u_1 u_1 = u_2 u_2 = u_3 u_3 \))

\[
Q_{2,2}(x, t, r) = \langle u_2 \rangle_A \langle u_2 \rangle_B = u_2 \langle \xi, t' \rangle u_2 \langle \xi + x, t' + t \rangle
\]

\[
Q_{2,2}(x, t, r) = \frac{1}{(2\pi)^3} \iiint E_{2,2}(k, \Theta) e^{ik \cdot x} d\omega
\]

Correlation tensor defined by correlations
3-D energy spectrum defined by correlation tensor

turbulence convected by the meanflow (relates space and time through velocity)
\((x,t) \rightarrow x + Ut\)
\(k_1 \) and \( \omega \) related through \( U \)

\[
E_{2,2}(k, \Theta) = (2\pi)^3 \frac{2u^2}{\pi^2} \frac{L_s^5(k_1^2 + k_3^2)}{1 + (kL_s)^2} \]

Liepmann model for energy spectrum
Example of spectrum from experimental turbulence intensity and length scale

\[ E_{2,2}(k, \omega) = (2\pi)^3 \frac{2u'^2}{\pi^2} \frac{I_s^5(k^2_1 + k^2_3)}{(1 + (kL_s)^2)^3} \]

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

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

Experimentally based spectrum

- 25% span
- Mid-gap streamwise
- 50% span
- 81% span
- Upwash

Hotwire
- Von Karman
- Liepmann
- Gaussian
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 2\textsuperscript{nd} type of problem

\[ Q_{2,2}(x, t, r) = \frac{1}{(2\pi)^3} \iiint E_{2,2}(k, \phi, r) e^{ik\cdot x} dk e^{-i\omega t} d\omega \]

Each component looks like an individual gust-type disturbance

\[ E_{2,2} e^{i(k_1 x_1 - \omega t) + ik_2 x_2 + ik_3 x_3} \]

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*

• *Describe two experiments used for validation*

• *Show some broadband noise predictions from the method*

• *Wrap up*
**Method**

Inflow wake turbulence

\[
\langle \Delta \tilde{p}_j(r_1, z_1, \omega) \Delta \tilde{p}_i^*(r_2, z_2, \nu) \rangle = \frac{(\rho_0 U_r)^2}{(2\pi)^6} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \tilde{f}(r_1, z_1, \tilde{k}, k_3, \omega) \tilde{f}^*(r_2, z_2, \tilde{K}, k_3, \nu) \]

\[e^{ijk \cdot \hat{H} \cdot e^{-i\tilde{K} \cdot \hat{H}^2}} \langle \tilde{w} \tilde{w}^* \rangle d^2 \tilde{K} dK_3 d^2 \tilde{k} dk_3\]

Vane unsteady pressure spectrum

\[
\langle \tilde{p}_{mn}(\omega)\tilde{p}_{mn}^*(\nu) \rangle = \frac{1}{4\pi^2 k_{mn}(\omega)k_{mn}^*(\nu)} \int_{r_H}^{r_T} \int_{r_H}^{r_T} \int_{-b}^{b} \int_{-b}^{b} R(r_1, \omega)R(r_2, \nu)e^{i\mu(r_1, \omega)z_1}e^{-i\mu(r_2, \nu)z_2} d\tilde{z}_2 d\tilde{z}_1 dr_1 dr_2
\]

\[
\left\{ \sum_{j=0}^{V-1} e^{i2\pi \frac{m_j}{V}} \sum_{l=0}^{V-1} e^{-i2\pi \frac{m_l}{V}} \langle \Delta \tilde{p}_j(r_1, z_1, \omega) \Delta \tilde{p}_i^*(r_2, z_2, \nu) \rangle \right\}
\]

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

Acoustic pressure and velocity spectrum in duct

Acoustic pressure: Green’s function for annular duct (avoid singular values \(k_{mn} \to 0\))

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)

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

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?

- 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*

<table>
<thead>
<tr>
<th>Code</th>
<th>Grid config.</th>
<th>Grid density* ( x, \theta, r )</th>
<th>Tip clearance</th>
<th>Turb. Model</th>
<th>Rotor config.</th>
<th>Vane config.</th>
<th>Comp. type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>O-H</td>
<td>95x64x36</td>
<td>y</td>
<td>k-( \omega )</td>
<td>hot</td>
<td>baseline</td>
<td>loosely coupled</td>
</tr>
<tr>
<td>2</td>
<td>C-H</td>
<td>86x89x81</td>
<td>y</td>
<td>k-( \omega )</td>
<td>hot</td>
<td>baseline</td>
<td>loosely coupled</td>
</tr>
<tr>
<td>3</td>
<td>H</td>
<td>11x51x51</td>
<td>n</td>
<td>k-( \varepsilon )</td>
<td>approach</td>
<td>baseline</td>
<td>average passage</td>
</tr>
<tr>
<td>4</td>
<td>O-H</td>
<td>51x33x57</td>
<td>y/n</td>
<td>k-( \omega )</td>
<td>hot</td>
<td>none</td>
<td>rotor alone</td>
</tr>
</tbody>
</table>

*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

Baseline:
- 
- 54 vanes

Low count:
- 
- 26 vanes

Turbulence intensity

Length scale (streamwise)

CFD2
- Baseline, hot geometry
- Largest tip gap
- Background turb. level really low

CFD4
- Rotor alone
- Hot geometry
- No tip gap at high speed

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

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

Cutback-Approach

Take-off – Cutback

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) ($\phi, \psi$)-space.
Thick, perfectly aligned flow (t.e. stagger)

Cambered, flow aligned with chord

Cambered, flow aligned with chord, stagger simulated

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

Same unsteady response
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