Flow-Induced Noise Technical Group

Center for Acoustics and Vibration

Spring Workshop

May 4, 2010

Presented by:
Dean E. Capone, Group Leader
• The mission of the Flow-Induced Noise Group of the Center for Acoustics and Vibration is the understanding and control of acoustic noise and structural vibration induced by fluid flow.

• Research Areas
  – Supersonic Jet Noise
  – Turbulent boundary layer unsteady pressures
  – Flow-induced vibrations
    • Piping vibration
  – Helicopter rotor noise
  – Cavitation noise
  – Fan noise
  – Blade rate noise
  – Turbulence ingestion noise
Recently Completed Projects

• Effects of Flow on Hydrofoil Vibrations and Hydrodynamic Performance (MS Acoustics, Marc Reese, Steve Hambric – advisor)
  – NACA 66 Aluminum hydrofoil mounted in 12” Water Tunnel
  – Tested at variable angles of attack and flow rates
  – Measured
    • Hydrodynamic damping
    • Flow tone lock-in (1st and 2nd blade modes interacting with trailing edge vortices)
    • Effects of foil vibration on tip vortex cavitation
  – Measurements complete, expected MS completion – August 2010
Recently Completed Projects

- Low Wavenumber Turbulent Boundary Layer (TBL) Wall-Pressure and Wall Shear Stress Measurements from Vibration Data on a Cylinder in Pipe Flow (Ph.D. William Bonness Summer 2009, Dean Capone, Advisor)
  - Measured pipe vibration levels due to turbulent water flow inside the pipe
  - Used measured vibration levels and cylinder modal analysis to establish low wavenumber unsteady pressure and unsteady shear stress levels of the TBL
Supersonic Jet Noise

Dr. Dennis McLaughlin and Dr. Phil Morris
Aerospace Engineering Department
The Pennsylvania State University
Aeroacoustic Research on Turbojet Exhaust Jet Models

Dennis K. McLaughlin
and
Philip J. Morris

Department of Aerospace Engineering
Penn State University

Presented at CAV Workshop
May, 2010
Outline

Background, Research goals and objectives

Laboratory experiments
- Facilities, Instrumentation and technical approach
- Acoustics & Optical Deflectometer Benchmarking
  - (M. Doty, B. Petitjean)
- Scaling Experiments (C.W. Kuo)
- Optical Deflectometry experiments (J. Veltin, B. Day)
  - Turbulence properties for aeroacoustic modeling
- Turbulence – Acoustic correlations (J. Veltin, B. Day)

Modeling and Computations – comparison to experiments
- (S. Miller, S. Saxena and Yongle Du)

Conclusions and Future work
Background
**F 22** – the newest fighter aircraft in the US military

Take-off conditions of exhaust nozzle are (approximately):
- Exhaust Aspect Ratio = 1.75 : 1
- $M_j = 1.5$, $TTR = 4$

The new **Joint Strike Fighter engine**; the hot exhaust is glowing and the shock cell pattern is readily visible.
Research Goals and Objectives

Current focus is on modeling of military (fighter) aircraft exhaust jet noise

Current / Recent Projects:

Strategic Environmental Research and Development Program (SERDP)
- a project involving Penn State, NASA, GE, Wyle & the Air Force.

NASA NRA – development of a unified jet noise model including a new broad band shock associated noise (BBSAN) model – w / Boeing.

NASA NRA – multi-sensor aeroacoustic experiments including turbulence – acoustic correlations – w / UC Irving

ATA Air Force SBIR – acoustic holography development

SERDP Program - Testing at all Scales


Moderate Scale Tests - NASA

F404-400 Static Engine Test

Note forward flight simulation

Small Scale Tests
Penn State
Penn State Jet Noise Laboratory

Jet Nozzle

Forward Flight Nozzle

rotating microphone array
Forward Flight Capability

Developed with PSU College of Engineering funds over the last 2 years.

One use has been on *Effects of Empennage on Noise Directivity*
Jet Nozzles

- Nozzle diameters up to 1”
- Interchangeable nozzles with variety of shapes
- Nozzles can be fabricated by rapid prototyping
Instrumentation
Pitot probe measurements of the mean flow properties:
- In cold or heat simulated jets, subsonic and supersonic, with and without shocks
- Validated against CFD results and other experimental data

Comparison between the experimental (dots) and numerical (lines) $M_f$ of a $M_d = 1.0$, $M_j = 1.5$ jet. (Each set of data is separated by $x/D = 0.20$ starting at $x/D = 0.0$ at the left and stopping at $x/D = 2.0$ on the right.)
Pitot probe results
Measurements in rectangular jets

Pitot probe measurements made along both axis of rectangular jets

- Fully expanded jet: \( M_d = 1.5, M_j = 1.5 \)
- Over-expanded jet: \( M_d = 1.5, M_j = 1.3 \)
- Under-expanded jet: \( M_d = 1.5, M_j = 1.7 \)

\[ \frac{P_p}{P_0} \]

Sample Pitot pressure measurements for \( M_d = 1.5 \), \( M_j = 1.7 \)

⇒ Nice visualization of the shock pattern
⇒ Minor axis seems to switch with the major axis
A Schlieren based system with pinholes and photodetectors (PMTs) at different positions in the 2 image planes
Jet Noise Components are:

Mixing Noise
- Large scale: well understood for supersonic $M_c$, strong directivity
- Small scale: generation process not fully understood, cone of silence

Shock associated noise
- **Broadband Shock Associated Noise (BBSAN)**
  - interaction between turbulent structures and shocks
  - peak increases with pressure and temperature ratios of jet
  - peak frequency changing with polar angle
- **Screech**
  - predictable frequency
  - does not typically occur in real aircraft jets
Experimental Results

Acoustics and

Optical Deflectometry
Acoustic Data Comparison Between PSU and NASA GE Nozzle Design

GE Md1.5D0.676, Cold Jet, Scaled R/D = 100, PR = 4, M* = 1.56

- SPL per unit Strouhal Number (dB/0.15\(I\rho_a^2\))
- Red line: NASA, \(f_c = 3,469\) Hz
- Blue line: PSU, \(f_c = 25,321\) Hz

The graphs show the comparison of acoustic data between PSU and NASA for the GE nozzle design at different Strouhal Numbers and angles. The data indicates a peak at \(20\) dB and 110 dB, with slight variations at different angles and Strouhal Numbers.
Noise Reduction Concepts: Chevron Nozzle

GE Md 1.5 nozzle operated at Mj 1.223, Cold

\[ Md = 1.5 \quad Mj = 1.64 \]

Short chevron

Long chevron

\[ TTR = 1 \]

\[ TTR = 3 \]
Turbulence Spectra results compared with other instruments

- UCI OD - Mj = 1.75
- Panda & Seasholtz (2002) - Rayleigh Scattering - Mj = 1.8
- PJM - Mj = 0.25

Supersonic Round Jets
- LDA ---
- Rayleigh Sc. ---
- Hot Film probe ---
- Opt. Def. ---
- PIV NASA GRC to come
Convection velocity as a function of frequency

From the phase of the OD cross spectra, the convection velocity is calculated as:

\[ U_c(f) = 2\pi f \left( \frac{d \Phi_S}{d x_1} \right) (f) \]

\[ M_j = 1.5 \text{ & } 1.65 \]

\[ M_c = 1 \]

⇒ Convection velocity varies with frequency and with jet condition
Experiments in Cooperative Project with ATA Engineering, Inc.

- Provided support in experimental design
- Assistance with experiments in PSU jet noise facility in data interpretation:
- General assistance in Jet noise source characterization

Near field microphone array on rotating traverse

Model scale set-up for proof of concept experiments.

Full size system is being assembled for aircraft engine exhaust tests.
Acoustic Holography with ATA Engineering. Inc

Close up of computer controlled rotation stage for microphone boom

There are two additional stationary far-field arrays
Recent Supersonic Flow and Noise Simulations
Jet Noise Simulations
GE Nozzle

$M_j = 1.56$, $TTR = 3.02$

$\theta = 60^\circ$

Comparisons to Computations by P.J. Morris & Yongle Du
Rectangular Jet  BBSAN Spectra

\[ M_d = 1.5 \quad M_j = 1.7 \quad TTR = 1.0 \]

Comparisons to Computations by Steve Miller & P.J.Morris
Conclusions

The program of acoustic measurements at small and moderate scale has been very productive.

The turbulence (and mean flow) properties measured with Optical Deflectometry (& Pitot rake) have provided important modeling data for BBSAN modeling.

Correlations between Optical Deflectometry & acoustic array have provided new data that may lead to improved understanding and modeling.
Future Work

In the development of the fundamental source modeling, optimization of the parameters of the flow field models is underway to improve the accuracy of the far field acoustic predictions.

We are currently examining several noise reduction concepts including nozzle shaping, chevrons, rectangular and beveled nozzles, and have a new idea that holds considerable promise.

- Rapid prototyping is an important aspect of such studies.

We have been cautious of the fact that noise reduction concepts that work well in static conditions often underperform in forward flight.

So….. Stay tuned.
The End

Thanks for your attention
Extra Slides
Turbulent structures in the jet shear layer may travel supersonically relative to the ambient sound speed.

This generates a strong directional noise radiation – Mach wave radiation, that can be seen on this Schlieren image.
Shown is one-time frame of a dynamic noise exposure model. This has recently been updated to:

- Incorporate more extensive and more accurate data on exhaust jet source noise—plus nonlinear propagation effects.

This noise annoyance is greatest at Naval aviation bases with simulated carrier landing practice.
GE Design Baseline Nozzle

Area ratio – $M_d = 1.5$

Experiments at NASA

$D_{exit} = 4.84 \text{ in}$

Experiments at PSU

$D_{exit} = 0.676 \text{ in.}$

12 sided – end view
4 to 6 Microphone Array

Array of four B&K 1/8 microphones; bandwidth to 120 kHz
Nonlinear Propagation
Effect at Different Scales

- the same physics -

\[ Md = Mj = 1.5 \]
\[ TTR = 2.2 \]

NASA  R / D 140
Dnoz 4.8”

PSU  R / D 280
Dnoz 0.5”

PSU data show nonlinear “turn-up” in spectral level at lower Strouhal No. because recorded at greater R / D

File: CAV Seminar Apr 2010.pptx
Synthesized Spectra from $R/D$ 35

Far field spectra synthesized from closer microphone array

$Md = Mj = 1.5$

$TTR = 2.2$

$\theta = 50^\circ$
Note strong variation of acoustic field with azimuthal position. In direction below “long lip”, more than 5 dB of OASPL noise reduction is observed.