Flow-Induced Noise Technical Group

Center for Acoustics and Vibration

Spring Workshop

May 9, 2011

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**
  - Turbulent boundary layer unsteady pressures
  - Fan noise reduction
  - Computational aeroacoustics
  - Marine renewable energy
Low-wavenumber turbulent boundary layer wall-pressure measurements from vibration data on smooth and rough cylinders in pipe flow

Neal Evans
Dr. Dean Capone
Dr. William Bonness
(1) A turbulent boundary layer generates eddies of varying scales throughout the boundary layer and the integrated effect of the resulting velocity fluctuations produces fluctuating pressures and fluctuating shear stress on the underlying structure.

(2) The pressures and shear-stress, correlated over some area, generate fluctuating forces which can excite the underlying structure producing undesirable vibration and noise.

(3) Most of the energy in a boundary layer is contained at convective wavenumbers which often do not couple well with structures. Low wavenumber energy (in water - low mach number) typically matches the wavelengths in structural vibration.

(4) Low wavenumber pressures have historically been difficult to measure and model correctly.
1. Measure acceleration response to flow

2. Measure accelerance response to a known input (standard modal analysis)

3. Infer required force to produce observations in step 1: TBL forcing function
Experimental Facility - ARL 48” WT

- Lower Leg
- Gate valve
- 6” PVC Pipe
- Cylindrical Test Section
- Reserve Tank beneath floor
- 45 ft ~ 90 pipe diameters

- Top of Test Section
- Ground Level
- 23 ft
- 12 ft
- Reserve Tank Floor

- Dimensions:
  - 12”
  - 24”
  - 12”
Instrumented test section

3 rings of 12 measurement accelerometers
2 hydrophones for point pressure spectrum measurement
8 reference accelerometers for noise reduction
Pitot-static probe for flow speed measurement
Surface roughness configurations

Surface roughness regimes for 6 m/s flow in water

Hydraulically smooth:

\[ k_s < \frac{5\nu}{\nu^*} < 30 \mu m \]

Fully rough:

\[ k_s > \frac{70\nu}{\nu^*} > 430 \mu m \]

Region between these limits = transitionally rough

\( \nu = \text{kinematic viscosity} \)

\( \nu^* = \text{friction velocity} \)
• Using this wavevector filtering method, TBL pressures can be extracted at lower wavenumbers than previously reported (figure from Bonness, et al. (2010))

• Data processing ongoing
Chassis Noise Reduction

S. D. Young, T. A. Brungart, J.E. Eaton and D.E. Capone
Penn State University, Applied Research Laboratory
Chassis Noise Reduction

Objective

The objective of this effort is to identify the treatment options that are available to reduce the sound power radiated by a chassis housing electronic components by approximately 14 dBA; sufficient to meet various industrial standards.

Approach

- Measure chassis radiated sound power
- Identify dominant transmission paths
- Examine feasibility of replacing axial flow fans with a smaller number of alternative fans, flow control treatments and mufflers
- Estimate reduction in sound power with smaller number of alternative fans, flow control treatments and mufflers
- Provide costs for developing and evaluating noise control treatments
Noise Control Methodology

• Radiated sound power is dominated by tube-axial fans

• Dominant noise transmission paths are through fan discharge and inlet
  - Multiple transmission paths
  - Little space available for absorptive treatments other than on cabinet
  - Absorptive treatments should be incorporated into new chassis and cabinet designs

• Greatest opportunity for noise reduction with smallest modifications to chassis and cabinet is to focus on the source (tube-axial fans)
  - Likely to also require transmission path (absorptive) treatments for reductions of the order of 14 dB

• Chassis is better suited for incorporation of centrifugal fans than axial flow fans

• Forward curved centrifugal fans were immediately available and served as demarcation point for final (backward curved) fan selection
  - Precise fan operating point required to minimize noise
Fan Noise

• Axial flow fan noise characterized by maximum level at mid-frequencies
  - Fall off in level toward higher and lower frequencies

• Centrifugal flow fan noise exhibits maximum levels at low frequencies
  - Continuous drop in level with increasing frequency

• Specific sound power levels lower for centrifugal fans than for axial flow fans
  - Lowest specific sound power levels at point of maximum efficiency
  - Backward curved centrifugal fans have lowest specific sound power levels
    > Lower than tube axial fans
    > Lower than forward curved centrifugal fans

• Critical to operate backward curved centrifugal fans at point of maximum efficiency to minimize noise
Comparison of Fan Sound Power Spectra

- Fans at identical operating conditions (37% PWM)
  - Upper fan units only
  - Matched flow rates measured at inlet

- FC centrifugal fans reduce mid freq. levels but increase low freq. levels
  - FC centrifugal fan lower frequency levels higher than expected
  - Achieved 2 to 3 dBA reduction in sound power
  - Lower freq. levels are dominated by flow separation noise

- Backward curved centrifugal fans will further reduce noise
The Path Forward – Reduce the Source Level

- Test backward curved centrifugal fan configs.
  - Radiated sound power levels
  - Flow uniformity
  - Test fans with existing motors
  - Work with manufacturer to integrate custom motor(s) to accommodate higher speed operation
> On configuration/fans selected

- 4 x 175 mm
  - 13 dB Down*
  - No Chassis Mod.

- 2 x 280 mm
  - 16 dB Down*
  - Chassis Mod.

- 1 x 355 mm
  - 21 dB Down*
  - Chassis Mod.

* Relative to Levels with Tubeaxial Fans at 37% PWM
Project Title: Dual-Stream Jet Noise Prediction Using Hybrid LES Approach

Adviser: Prof. Philip J. Morris
Research Assistant: Ms. Swati Saxena
Sponsor: Pratt & Whitney

Project Goals: Noise prediction of high subsonic commercial aircraft dual-stream jet engines.
General Approach:
- An LES flow solver is written for the flow calculation of dual-stream jet nozzles. Main features of the solver:
  - Parallel 3D multi-block structured grid
  - High order spatial discretization and explicit time marching
  - Non-matching interface for different grid resolution in adjacent blocks
  - Immersed boundary method for finer geometric changes
  - No artificial excitation: finite nozzle lip thickness to trigger instability
  - Artificial dissipation
  -Characteristic and radiation boundary conditions
- Hybrid LES (DES) approach is used for the turbulence modeling coupled with Ffowcs Williams-Hawkings acoustic analogy for noise prediction.
- Pressure field on structured grid surface used for the noise calculation.
Case 1: 2D Dual-stream jet flow

- Converging nozzles
- $M_{\text{exit}} = 0.5$
- 9 blocks
- 1.7 million grid points
- 30 processors
Case 1: 2D Dual-stream jet flow

Pressure Contours
Case 2: 3D Single-Stream jet flow

Nozzle Geometry
- $M_{\text{exit}} = 0.5$
- 14 blocks
- 3.5 million grid points
- 60 processors

Pressure Contours
Case 2: 3D Single-Stream jet flow

Mach Contours along the jet exit

Pressure Contours

Noise spectrum obtained after averaging 3 data sets of 1024 points each. Data sampled after 70000 physical time steps.

$St_{\text{max}} = 1.7$, $r/D = 100$, $\theta = 135^\circ$ from jet inlet

Very preliminary
Project Title: Trailing-Edge Noise Prediction Using the Nonlinear Disturbance Equations

Advisers: Prof. Philip J. Morris & Prof. Kenneth S. Brentner

Research Assistant: Ms. Monica Christiansen

Sponsor: Sandia National Laboratories

Project Goals: To accurately and efficiently calculate the turbulent flow field near the trailing edge of a wind turbine blade and calculate the associated noise.
General Approach

• Solve a modified version of the Navier-Stokes equations called the Nonlinear Disturbance Equations (NLDE)
  – The instantaneous flow variable is decomposed into an estimated mean and fluctuation
  – The mean is obtained from a RANS solver
  – The time accurate solution is found using the NLDE solver

• Enables the solution to be restricted to a region of interest

• Noise radiation calculated with a Ffowcs Williams – Hawkings solver
Acoustic Data Surface

Flow variables are saved to the acoustic data surface at a specified NLDE time step.

Acoustic data surface
2D circular cylinder vortex shedding case:

Flow variables:
- \( U_\infty = 68.65 \text{ m/s} \)
- \( P = 101.3 \text{ kPa} \)
- \( \rho = 1.2 \text{ kg/m}^3 \)
- \( D = 0.02 \text{ m} \)
- \( Re_D \sim 90,000 \)

Sampling frequency:
- \( f = 44 \text{ kHz} \)

Expected vortex shedding frequency:
- \( f \sim 700 \text{ Hz} \)
Computational Parameters

- Grid size 301x128 (x7 for 2D cases)
- 640,000 iterations
- Physical time \( \sim 0.073 \) s
- Run time \( \sim 25.0 \) hrs
- Run on 64 cores

Radiation boundary condition

No slip wall condition
RANS and NLDE Flow Solutions

RANS mean flow solution (WIND-US flow solver)

NLDE instantaneous flow

*Velocity magnitude contours are in m/s
Sound Pressure Level Results

Project Title: Numerical Simulation of Supersonic Jet Noise

Adviser: Prof. Philip J. Morris

Research Assistant: Mr. Yongle Du

Sponsor: Strategic Environmental Research and Development Program and US Navy

Project Goals: Simulate the flow and noise from high performance military jet engines.
Simulation Strategy

• Hybrid method: CFD + acoustic analogy

Jet flow simulation (CHOPA):
  • URANS + modified DES (low dissipation)
  • 4th-order DRP
  • Dual-time stepping
    • Multigrid
    • IRS
  • Parallel computation using MPI
  • Boundary conditions:
    • Radiation
    • Optimized block interface conditions

Jet noise prediction (PSJFWH):
  • FWH formulation
  • Modified version proposed by Spalart et al.
  • Integrated with the jet flow simulation code
Military-Style Baseline and Chevron Nozzles

Baseline

Chevron (4/12 are shown)

Operating conditions. (Md=1.5)

<table>
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<th>NPR</th>
<th>TTR</th>
<th>M_j</th>
<th>T_j/T_∞</th>
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Computational Mesh
Noise Predictions

![Graphs showing SPL per unit St (dB, ref 20μPa²) vs. St, fDj/Uj for different angles (θ) from 30° to 120°. The graphs compare experimental data with predictions at NASA and PSU baseline.]
Unsteady Jet Flow and Noise Radiation

- $M_j=1.47$, $TTR=3$ (chevron nozzle jet)
Noise Source Identification

- Beamforming method: noise source locations

Baseline

Chevron

Mj=1.56
Marine Renewable Energy Technologies

Funded Research Programs

Applied Research Lab / Penn State Univ.

Dr. Arnie Fontaine
• PSU/ARL has unique technical capabilities to support the development of underwater power generation systems
  – Experimental Facilities
    • Water tunnels with up to 4-foot diameter test section
    • Pump loops
    • Water tanks
    • At-sea testing experience
  – Turbomachinery Design
    • Blade design
    • Hydrodynamic analysis
    • CFD
  – Hydroacoustics
  – Erosion and deposition testing
  – Advanced coatings
  – Trade space design exploration
  – Embedded diagnostics for condition based maintenance
Sandia National Lab
Hydrokinetic Turbine Design Project

- Performance – efficiency and loading
- Acoustic Performance Prediction and Testing
- Cavitation
- Materials and structural modeling
- Device testing
- Environmental / Sediment Transport Testing

Small Scale Device Testing

- DoE Funded 50kW motor/generator
  - 25 to 2200 rpm
CURRENT PROGRAMS
DOE / NATIONAL LABS

DoE Test Center for
Marine Hydrokinetic Turbine Evaluation

- Leverage Navy Developed Facilities and Expertise
- Recognized Center for:
  - Small Scale Testing & Computational Mechanics
  - Acoustics & Cavitation
  - Marine Composites and Marine system design
- Sandia National Lab partnership for small scale device testing

DoE Reference Turbine Program

- Turbine Design
- Power Take - Off
- Cavitation
- Materials
- Device testing
- National Lab Support

DoE Marine Renewable Energy Education Program

- Graduate Student Support – ARL and CoE
- Computational Modeling in Conventional Hydro Power
**Dehlsen / Ecomerit**

**Ocean Current Turbine Design**

- Turbine Design
- Performance – efficiency and loading
- Cavitation and Noise
- Materials and structural modeling
- Power Take Off
- Computational Modeling
- Environmental Impact and Resource Assessment

**Ocean Renewable Power Company ORPC**

- Noise and vibration
- Computational modeling
- Cavitation
- Environmental impact
- Acoustic Field data review

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Turbine Generator Unit

[www.oceanrenewablepower.com/home.htm](http://www.oceanrenewablepower.com/home.htm)