Flow-Induced Noise Technical Group

Center for Acoustics and Vibration

Spring Workshop

May 4, 2009

Presented by:
Dean E. Capone, Group Leader
Research Areas

- Supercavitation Hydroacoustics
- The Use of Dipole Configurations of Flow-Driven Resonators to Reduce Tonal Noise From Axial Fans
- Low Wavenumber TBL Wall-Pressure and Wall Shear Stress Measurements from Vibration Data on a Cylinder in Pipe Flow
- Turbulent Boundary Layer Shear Stress Transmitted through a Viscoelastic Layer
Supercavitation Hydroacoustics

Mr. Steve Young and Dr. Tim Brungart
Applied Research Laboratory
The Pennsylvania State University
Supercavitation: Enveloping an underwater body in a cavity of air to drastically reduce drag

ARL has a research task that seeks to identify and mitigate sources of supercavitation self and radiated noise through integration of experimental acoustic diagnostics and theoretical modeling
• Shown conclusively importance of cavitator and ventilation system as source of self noise
  - Cavitator self noise levels reduced up to 20 dB with advanced cavitator

• Need to better understand means by which cavity ventilation and interface disturbances result in self noise in order to further reduce it
  - Investigate integration of water tunnel and benchtop experimental measurements with theoretical modeling for predicting self-noise
Cavity Disturbances Resulting from Ventilation System Using Radial Gas Injection

Dramatic Disturbances

High Gas Injection Rate

Reduced Disturbances

Low Gas Injection Rate
Work to Date

• Developed expression for predicting self noise at cavitator relative to radiating gas jet forces impinging on cavity interface

• Performed benchtop measurements of unsteady jet pressures and jet forces

• Experimental results of jet impact force to be combined with transfer function approximation to determine self noise levels for single gas jet

The Use of Dipole Configurations of Flow-Driven Resonators to Reduce Tonal Noise From Axial Fans

Dr. (May 17, 2009) Lee Gorny, Dr. Gary Koopmann, and Dr. Dean Capone
The Pennsylvania State University
How Does This Work? -

Acoustic Cancellation Mechanism of Plane Wave Noise Reduction

Monopole Resonator

Monopole Resonator Source:
180 Deg Out of Phase with Downstream Noise

Increased Upstream Noise Level

Flow Direction

180 Deg Out of Phase with Fan

Reduced (US) Noise Level

Reduced (DS) Noise Level

Source Location (TE of Blades)

Upstream (US) Fan Noise
(Positive Dipole Lobe)

Downstream Fan Noise
(Negative Dipole Lobe)

Dipole Resonator

Dipole Resonator Source:
180 Deg Out of Phase with Fan

Reduced (US) Noise Level

Reduced (DS) Noise Level

Source Location (Stator Leading Edge)
Resulting Auto-spectra of Noise Radiated From Test Fan

With Simultaneous BPF Reduction

**a)**

**SPL dB (re 20 µPa)**

- Baseline 372 Hz BPF US Noise
- With Dipole Resonator

**Frequency (Hz)**

- BPF
- 2xBPF
- 3xBPF

**b)**

**SPL dB (re 20 µPa)**

- Baseline 372 Hz BPF DS Noise
- With Dipole Resonator

**Frequency (Hz)**

- BPF
- 2xBPF
- 3xBPF

**Upstream**

**Downstream**
FEM Model

- 1/16 Symmetry Model Posed to Model Ducted Propagations

- FEM Analysis – Discretized Wave Equation

- Geometry Specific – Necessary For Non-Uniformly Ducted Geometry
Low Wavenumber TBL Wall-Pressure and Wall Shear Stress Measurements from Vibration Data on a Cylinder in Pipe Flow

Mr. William Bonness, Dr. Dean Capone, and Dr. Steve Hambric
Applied Research Laboratory
The Pennsylvania State University

(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.
TBL Low Wavenumber Pressure Spectrum

Unresolved Issues
- General consensus that Corcos is too high at low wavenumbers
- Controversy over low wavenumber dependence (k² or “white”)
- Several proposed models have different low-K levels
- Limited low wavenumber pressure data and virtually no shear stress data

Advantages of Current Work
- Very quiet facility – no moving mechanical parts
- Measurements in water – high pressures (heavy fluid), low mach number flow extends low-wavenumber region
- Cylindrical shell provides coupling in all directions – ability to assess pressure and shear stress levels
For a flexible structure:

\[
\Phi_{FF}(\omega) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Phi_{pp}(k_1, k_3, \omega) S(k_1, k_3)^2 \, dk_1 \, dk_3
\]

- Integrated product of TBL wavenumber pressure spectrum and structural response represents force that excites the structure
- Flexible structure acts as a high wave-number filter rejecting energy in the convective wavenumber region
Experimental Facility - ARL 48” WT

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

Dimensions:
- Top of Test Section: 23 ft
- Ground Level: 12 ft
- Reserve Tank Floor: 23 ft
- 12" gate valve
- 24" gate valve
- 12" gate valve
Cylinder Response in All Directions

Analytical Shell Model

- Plot assumes shear stress in phi and z directions is the same as the normal pressure in the r direction

- Most cylinder modes are coupled in all directions:
  - 0,1 modes are predominately single direction (can isolate pressure and shear stress in each coordinate direction)
  - Higher order modes are combination of several directions

- Opportunity exists to quantify low-wavenumber shear stress in the streamwise and cross-flow directions as well as normal pressures
**Measured Low-Wavenumber TBL Pressure Levels**

**Present Study Data:**
- \( m = 1 \)
  - Sens Func lobes peak at \( k_1 \sim 0 \).
- \( m > 1 \)
  - Sens Func lobes peak at \( k_1 > 0 \).

### Equation

\[
10 \log_{10} \left( \frac{\Phi_{pp}(k_1, k_3, \omega)}{\phi_{pp}(\omega) k_c^{-2}} \right)
\]

- \( \Phi_{pp}(k_1, k_3, \omega) = H_0 \rho^2 u_t^4 U_c^2 \omega^{-3} e^{-2.2(\omega u_t/\tau)} \)

### Notations
- \( k_3 \neq 0 \)
- \( k_1/k_c \)
- \( k_0/k_c \)
- \( H_0 = 10^{-4.1} \)
- \( H_0 = 10^{-3.75} \)
- Acoustic Domain
Turbulent Boundary Layer Shear Stress Transmitted through a Viscoelastic Layer

Dr. Dean Capone and Mr. William Bonness
Applied Research Laboratory
The Pennsylvania State University

Background

- Underwater vehicle applications
  - Unsteady pressure transducers are mounted on a steel backing plate and covered with an elastomer layer
    - Detection of acoustic waves

- Turbulent boundary layer (TBL) flow over the vehicle induces unsteady pressures and unsteady shear stress on the surface of the elastomer
  - Unsteady pressure contribution to sensor self noise has been investigated extensively

- What is the impact of the unsteady shear stress on the sensor self-noise?
Unsteady pressure model proposed by Chase¹

\[ P(k_x, k_y, \omega) = \frac{\rho^2 u_3^3}{[K_+^2 + (b\delta)^{-2}]^{5/2}} \left\{ c_2 \left( \frac{|K_c|}{K} \right)^2 + c_3 \left( \frac{K}{|K_c|} \right)^2 \right\} \]

\[ + 1 - c_2 - c_3 ]C_1K^2 \left[ \frac{K_+^2 + (b\delta)^{-2}}{K^2 + (b\delta)^{-2}} \right] + C_M \left( \frac{K}{|K_c|} \right)^2 k_x^2 \}

where \( P(k_x, k_y, \omega) \) is the two-dimensional wavevector frequency spectrum of the turbulent wall pressures

Unsteady shear stress model proposed by Chase²

\[ S(\omega) = \rho^2 u_3^3 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} S^+(k_{x+}, k_{y+}, \omega_+) \, dk_{x+} \, dk_{y+} \]

where

\[ S^+(k_{x+}, k_{y+}, \omega_+) = B_0 \omega_+^{-3/2} (1 + m\omega_+)^{-n} \sum_{\pm} \left( \frac{K_{*+\pm}^2}{\omega_+} \right)^{-r+3/2} \]

and

\[ K_{*+\pm}^2 = (\omega_+ - k_{x+} / \epsilon)^2 h^2 + k_{x+}^2 + \left( k_{z+} \pm \xi_0 \omega_+^{1/2} \right)^2 + \alpha_0 \omega_+ + (\beta \delta)^{-2} \]


The one-sided auto-spectral density function of pressure is calculated using

$$\Phi_{pp}(\omega) = 2 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P(k_x, k_y, \omega) |H(k_x, k_y, \omega)|^2 \, dk_x \, dk_y$$

Using the in-plane wavenumber transducer response function of \( Ko^1 \)

$$|H(k_x, k_y)|^2 = \left[ \frac{2J_1\left(\left(\frac{k_x^2 + k_y^2}{1/2}R\right)^{1/2}\right)}{\left(\left(\frac{k_x^2 + k_y^2}{1/2}R\right)\right)} \right]^2$$

\( J_1 \)-Bessel function of first kind of order one

\( R \)-radius of the measurement sensor

Using the formulations for unsteady pressure and shear the computed results are compared to measured data from Keith and Bennett\(^3\).

Results for pressure and shear compare favorably to the models.

The transfer of the unsteady pressure and shear is computed based upon the work of Ko\textsuperscript{4}. The unsteady pressure at the surface of the plate due to the unsteady pressure and shear on top of the elastomer is denoted by $\tau_{zz}$

where

$$T_{pors}(k_x, k_y, \omega) = \frac{\tau_{zz}(k_x, k_y, \omega)^2}{\Phi_{pp} \text{ or } \Phi_{ss}}$$

and the final pressures seen by a sensor at the surface of the plate is given by

$$\Phi_{TBL}(\omega) = 2 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} P(k_x, k_y, \omega) H(k_x, k_y, \omega)^2 T_p(k_x, k_y, \omega) dk_x dk_y$$

$$+ 2 \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} S(k_x, k_y, \omega) H(k_x, k_y, \omega)^2 T_s(k_x, k_y, \omega) dk_x dk_y$$

\textbf{References}

Frequency Dependent Unsteady Pressure and Shear Transfer Functions

Frequency dependent transfer function for a flow speed of 15 m/s

Elastomer Thickness
7.62 cm

Elastomer Thickness
2.54 cm
Unsteady Pressure and Shear at the sensor face for elastomer thickness of 7.62 cm

Flow speed 15 m/s

Flow Speed 5 m/s