Flow-Induced Noise Technical Group

Center for Acoustics and Vibration

Spring Workshop

April 30, 2014

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.

• Topical Research Area Presentations
  - Dr. Ken Brentner: PSU-WOPWOP noise prediction code
  - Dr. Robert Campbell: Fluid Structure Interaction (FSI) Research, including A Wind Turbine Project
Ongoing Projects

- **Project Topic: Fluid-Structure Interaction (FSI) of a Flexible Strut with Strong Turbulent Upstream Vortices**
  - **Student:** Abe H. Lee (Ph.D in Acoustics)
  - **Advisors:** Dr. S.A. Hambric, Dr. R.L. Cambpell

- **Project Topic: Modelling and Measurement of Turbulent Boundary Layer Unsteady Shear Stress in Elastomer Layers**
  - **Student:** Cory Smith (Ph.D in Acoustics)
  - **Advisors:** Dr. D. E. Capone and T. A. Brungart

- **Project name: High Cycle Fatigue Simulations and Measurements**
  - **Sponsor:** Pratt & Whitney
  - **PI(s):** Philip Morris
  - **Students/degree levels:** Michael Lurie, PhD

- **Project name: Adjoint Design for Low Noise**
  - **Sponsor:** Office of Naval Research
  - **PI(s):** Philip Morris
  - **Students/degree levels:** Nidhi Sikarwar, PhD
• Ongoing projects
  – Project name: Simulation of Jet Noise Reduction Devices
    • Sponsor: Office of Naval Research
    • PI(s): Philip Morris
    • Students/degree levels: Matthew Kapusta, MS
  – Project name: Rotorcraft Broadband Noise Predictions
    • Sponsor: Bell Helicopter Textron Inc.
    • PI(s): Kenneth Brentner, Philip Morris
    • Students/degree levels: Abhishek Jain, MS
  – Project name: Nonlinear Sound propagation from Distributed Sources
    • Sponsor: Un-sponsored
    • PI(s): Philip Morris
    • Students/degree levels: Donald Hyatt, MS
An Overview of PSU-WOPWOP:
A General Purpose Ffowcs Williams – Hawkings Solver

Kenneth S. Brentner
Department of Aerospace Engineering

CAV Workshop – April 30, 2014
Historical Background – Ffowcs Williams – Hawkings Equation

J. E. Ffowcs Williams and D. L. Hawkings (1969)

- Laid the framework for treating sound field of a surface moving at high speed
- Surfaces are replaced by discontinuities in the flow-field
- Generalized conservation equations valid everywhere in space
- The FW-H equation is the most general form of Lighthill's acoustic analogy
Key Concepts: Ffowcs Williams–Hawkings Equation

- Rearrangement of Navier-Stokes equations into an inhomogeneous wave equation

\[ \Box^2 p'(\vec{x}, t) = \frac{\partial}{\partial t} \left[ Q \delta(f) \right] - \frac{\partial}{\partial x_i} \left[ F_i \delta(f) \right] + \frac{\bar{\partial}^2}{\partial x_i \partial x_j} \left[ T_{ij} H(f) \right] \]

\( f = 0 \) describes the integration surface

Thickness
displacement of fluid generates sound

Loading
accelerating force distribution generates sound (includes BVI noise)

Quadrupole
All volume sources, non-linear effects nonuniform sound speed
**Rotor Noise Theory**

- Aeroacoustics is governed by the conservation equations of fluid dynamics
  - Navier-Stokes equations
  - wave equation
- Three main computational approaches:
  - acoustic analogy
    - treats real flow effects by fictitious sources; exact in principle
    - Ffowcs Williams–Hawkings equation (1969) appropriate when solid bodies are present (Lighthill analogy)
  - Kirchhoff approach
    - based upon wave equation
    - actual sources replaced by their influence on a surface
  - direct computation (CFD and CAA)
    - high spatial and temporal accuracy needed
Comparison with Other Approaches

- **Acoustic analogy:**
  - FW-H equation (surface & volume integrals required)
  
  \[ \Box^2 p'(\vec{x}, t) = \frac{\partial}{\partial t} [Q \delta(f)] - \frac{\partial}{\partial x_i} [F_i \delta(f)] + \frac{\partial^2}{\partial x_i \partial x_j} [T_{ij} H(f)] \]
  - practical approximation (only surface integrals)
  
  \[ \Box^2 p'(\vec{x}, t) = \frac{\partial}{\partial t} [Q \delta(f)] - \frac{\partial}{\partial x_i} [F_i \delta(f)] \]

- **Kirchhoff:**
  - physical sources represented by mathematical sources on surface (only surface integrals)
  
  \[ \Box^2 p'(\vec{x}, t) = \frac{\partial}{\partial t} [Q' \delta(\vec{f})] - \frac{\partial}{\partial x_i} [F'_i \delta(\vec{f})] \]
  - Common use inappropriate for most rotor noise prediction

- **Direct computation:**
  - limited to relatively near field (full domain discretized)
  - provides input to other approaches
PSU-WOPWOP

- Numerical solution to Farassat’s Formulation 1A of the FW-H equation
  - Requires geometric and loading or flow data as input
  - Arbitrary source and observer motion can be specified – including deformable surfaces
  - Many sources can be specified at one time (e.g., multiple rotors)
  - Observer parallel
- Accepts Variety of Input Data Types
  - Compact patch (Line)
  - Regular surfaces
  - Permeable acoustic data surfaces (ADS)

Used in varied applications
- Rotorcraft noise
  - Discrete frequency and broadband
  - Maneuver
  - Civil noise certification
  - Near real-time
- Permeable Surface applications
  - Wind turbine noise
  - Open rotor noise (commercial aircraft)
  - Jet noise
  - Landing gear and airframe noise
- Acoustic scattering
  - PSU-WOPWOP can compute the acoustic pressure gradient
Rotor Noise Prediction during a Complex Maneuver

- Very complicated source motion
  - Aircraft motion is complex
  - Each blade is moving in an independent, aperiodic trajectory
- Significant blade-vortex interaction during aggressive right turn

Supersonic Jet Noise and a Synthetic Phased Array

- Highly detailed CFD prediction provided input data for PSU-WOPWOP (ITAC and PSU)
- PSU-WOPWOP predicted the noise on two virtual arrays
- Acoustic array data used with advanced phased array processing (OptiNav)

Wind Turbine Noise Prediction

- Unsteady Navier-Stokes computation (OVERFLOW) of wind turbine flow field
- PSU-WOPWOP noise prediction

Acoustic Scattering for a Notional Quad Tiltrotor

- PSU-WOPWOP computes acoustic pressure gradient
- NASA FAST scattering code predicts scattered field

Sound Pressure Level 10 m below the front rotor plane (6 times rotor BPF : 91.6639 Hz, L=-0.5)
Questions?
Fluid-Structure Interaction (FSI) Efforts at the Penn State Applied Research Laboratory

Presented by:
Robert Campbell
Noise Control and Hydroacoustics Division
Applied Research Laboratory
The Pennsylvania State University

Presented at:
CAV Workshop
30 April 2014
Fluid-Structure Interaction

Fluid Phase Fraction

Fluid Force on Structure

No Fluid Slip/Flux at Surface

Structure Motion

Fluid Motion
• FSI Modeling Overview
  – ARL Partitioned FSI Solver

• Overset Grid Technology and FSI Simulations

• Application Examples
  – Unsteady Hydrofoil (in Cylinder Wake)
  – 3D Flag Benchmark
  – Wind Turbine

• Student Projects
**Fluid–structure interaction (FSI):**
Fully-coupled motion of a deformable solid and a surrounding and/or contained fluid

**Two approaches to FSI modeling**

- **Monolithic**
  - Governing equations for both the fluid and solid cast in terms of the same primitive variables (velocity and pressure)
  - Single discretization scheme applied to entire domain

- **Partitioned**
  - Fluid and solid domains modeled separately
  - Separate discretizations of each domain
  - Stress and displacement communication across the domain interface
• FSI solver based on a partitioned approach with body-fitted meshes:
  – Independent flow and structural solvers that communicate at the fluid/solid interface
• OpenFOAM for the flow solver
• Custom FEANL structure class for the structural solver
• fsiInterface class to interface the solvers
• Subiterations each time step to ensure fluid and structure interaction is converged
• Under-relaxed structural displacements to improve convergence
• Variable under-relaxation coefficient ($\omega$) determined using Aitken’s method

\[ u_i = \omega \hat{u}_i - (1 - \omega) u_{i-1} \]

Fixed-Point Iteration

\[ \left| \hat{u}_{F/S,i} - \hat{u}_{F/S,i-1} \right| < \epsilon \]
• An overset mesh assembly is comprised of a set of overlapping grids
• Interpolation is performed across the overlapping boundaries in order to create a continuous domain
• Overset grids enable the meshing of complex geometries
  – Component grids can be built independently
  – Components can be easily modified, added, or removed
Overset Mesh Advantages: Translating Body

Continuous Re-Meshing
Overset Mesh Advantages: Translating Body

Continuous Re-Meshing  Morphing Mesh
Overset Mesh Advantages:
Translating Body

Continuous Re-Meshing  Morphing Mesh  Overset Mesh
Overset Mesh Motion

Traditional Mesh Motion:
- Structural Displacements
- Apply as BC to Full Mesh Displacement

Overset Mesh Motion:
- Structural Displacements
- Apply as BC to Full Mesh Displacement
- Linear Solver for Mesh Displacement
- Move Mesh
- UpdateDCI (Suggar++)

Subset Overset Mesh Motion:
- Structural Displacements
- Apply as BC only to Overset Interface Mesh Displacement
- Linear Solver only for Overset Interface Mesh Displacement
- Move only the Overset Mesh
- UpdateDCI (Suggar++)

Significant savings in mesh motion calculations

Three-dimensional Flag Benchmark

- Three dimensional “Turek” experiment mounted in 12” Tunnel
- Goal is to publish 3D turbulent validation data for FSI simulations

Images provided by Cooper Elsworth/Grant Dowell
• Tip displacement is measured from the center of the flag trailing edge in the y-direction

• $Y = 0$ is determined by the mean of the location values
Objective

- Perform validation and verification of the overset FSI solver
- Simulate Grant’s 3D experiment
DOE Program: Cyber Wind Facility

- Highly resolved 4-D cyber data
- Coupled atmospheric turbulence-blade loadings-shaft torque data
- Coupled wave structure – platform motion – turbine loadings data
- Experiment design, test-bed, turbine design, controls concepts and testing
- Advanced correlations for ALM and other design tools using look-up tables

* Platform-Wave Hydrodynamics and 6-DOF Motions (Hybrid URANS/LES + VOF)
* Blade and Tower Elastic Deformation (FEM, Modal model + FSI)
* Blade Aerodynamics, Space-Time Loadings (Hybrid URANS/LES)
* Wake Turbulence Blade-Wake-Atmosphere (Actuator Vortex Body Embedding within LES)
* Wake-Turbine Interactions (Wind Plant)

Cyber Wind Facility
- Sensors, controllers, diagnostics
SOE-Sponsored “Cyber Wind Facility”

Moderately Convective Boundary Layer: Turbulence Structure Size similar to Rotor Diameter

Turbulence inflow at the “microscale”

Unsteady flow simulation over turbine blades
The Penn State Cyber Wind Facility Team

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Industry Partner: GE GR
Cyber Wind Facility: Single Rotating Blade in Atmosphere

Plane 10m in front of blade

U* X

Time = 0.0s

Pressure Torque per unit span (kN)

Torque (kNm)

Time = 0.0 s

u' = -2.5 m/s
Initial Spacing of 5.2 μm (on a 63 m blade!)

Parked Rotor Simulation with Uniform 10 m/s Inflow
• Abe Lee: Propeller Crashback
• Cooper Elsworth: Partitioned FSI Mesh Convergence Metrics
• Javier Motta-Mena: Wind Turbines with ABL Turbulence
• Kenneth Aycock: Blood Vessel and IVC Filter FSI
• Jason Sheldon: Flow-induced Loads by Unsteady Wake
• Erica Lieberknecht: FSI Monolithic Solver Development
• Grant Dowell: FSI 3D Flag Benchmark Experiment
• Nick LaBarbera: Towed Array Dynamics
• Jason Halwick: FSI for Cavitation Erosion
• Byron Gaskin: Cancer Cell Migration
• Michael McPhail: Human Voice Production
• We are/have organized FSI mini-symposia on FSI:
  – “Fluid-Structure Interaction Algorithms and Applications,” 10th World Congress on Computational Mechanics, Sao Paulo, Brazil, July 8-13, 2012