CFD for Aeroacoustics

David P. Lockard

Meelan M. Choudhari, Mehdi R. Khorrami,
Veer N. Vatsa

Investigative Process: Source Identification

- Detailed study of the flowfield
  - Combined experimental / computational
  - Identify features in flowfield in which unsteadiness can develop
    - shear layers, vortices, separations
- Experimental measurement of source & noise details
  - Steady, unsteady surface pressure, hot-wire, PIV
  - Acoustic microphone arrays
    - Source location, spectra, directivity, amplitudes

Investigative Process: Source Identification

- Computational simulations of fluctuation-generating mechanisms
  - Computationally intensive prediction of source and resulting noise
  - Often gives a more detailed picture of the source than experiment alone

- Comparison / correlation
  - Understanding for noise reduction
  - Development of simplified models – based on flowfield features in common with actual configurations

Why Unsteady Simulations?

- Acoustic source is inherently unsteady
  - Fourth space-time covariance of the Lighthill stress tensor ~ $\rho\, u_i\, u_j - \tau_{ij} + (p - c_o^2\, \rho)\, \delta_{ij}$
    - Difficult to measure and model

- Steady RANS based noise prediction
  - Use the turbulence intensity and length scale as parameters in a model for the source
  - Efficient but highly dependent on modeling and calibration

- Unsteady simulations can be used to directly compute the noise source [for understanding and prediction] or to calibrate other methods

Activities

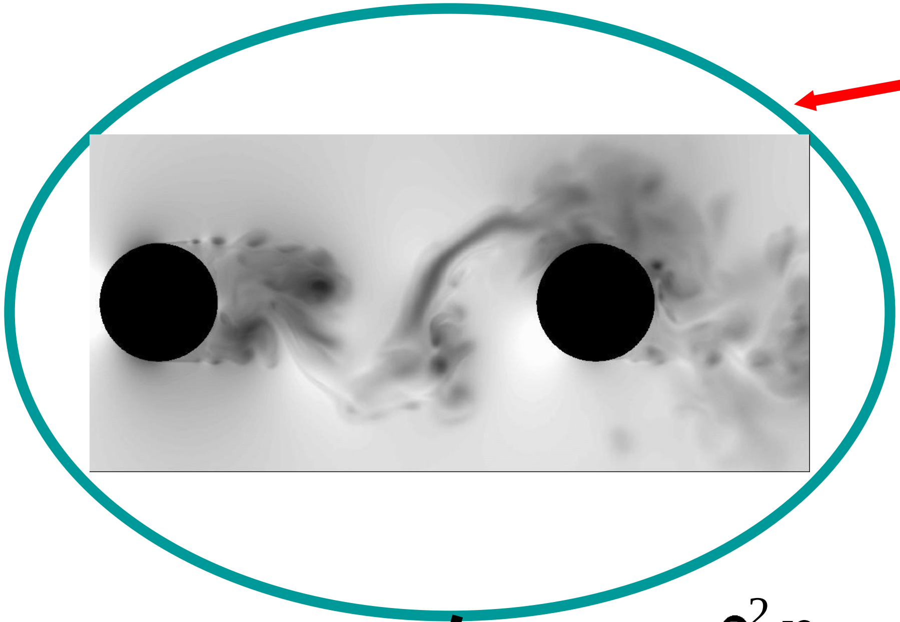
- Application of CFD tools to unsteady problems
  - Not involved with basic algorithmic development
  - Enhancements to collect data
    - Unsteady surface data
    - Time-averaged quantities
  - Evaluation of accuracy requirements
    - Time-step size & subiterations
    - Grid resolution
  - Testing of turbulence models
  - Validation studies
  - Analysis of configuration impacts on noise and performance

Activities

- Collaboration
  - NRA's
    - High-Fidelity Numerical Simulations in Airframe Aeroacoustics
      - Prof. Hussaini, Dr. Uzun of Florida State University
      - High-order LES on massively parallel computers
  - Space Act Agreements (SAA)
    - Gulfstream Partnership
    - Visiting researchers
      - ONERA
      - JAXA (awaiting final approval)
  - Sponsor workshops

How Do We Compute the Noise?

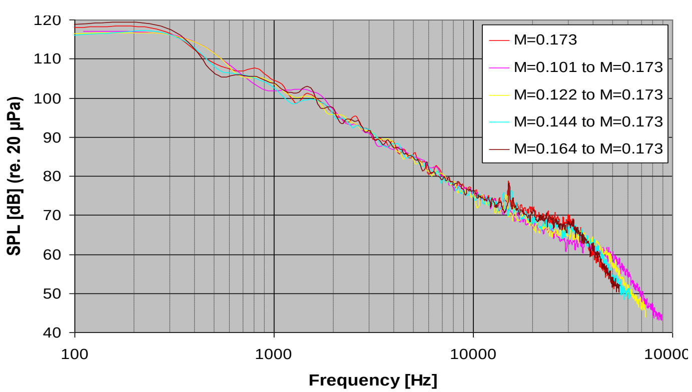
Unsteady Numerical Simulation



Accurately determine the unsteady noise source characteristics and account for near-field scattering.

$$\frac{\partial^2 p}{\partial t^2} - c_o^2 \frac{\partial^2 p}{\partial x_i \partial x_i} = \Box^2 p = S(x_i)$$

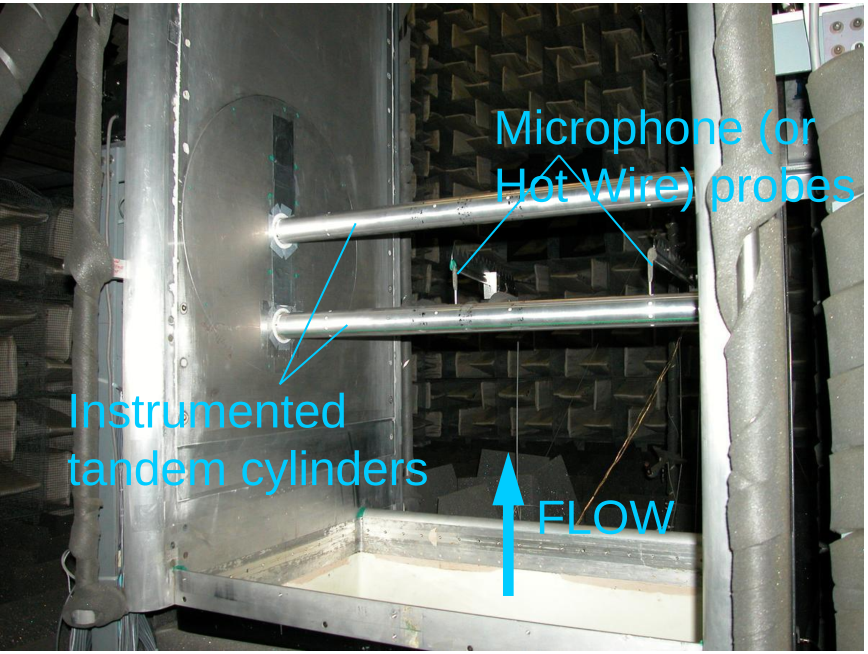
Experiment



Obtain the noise at far-field listener positions

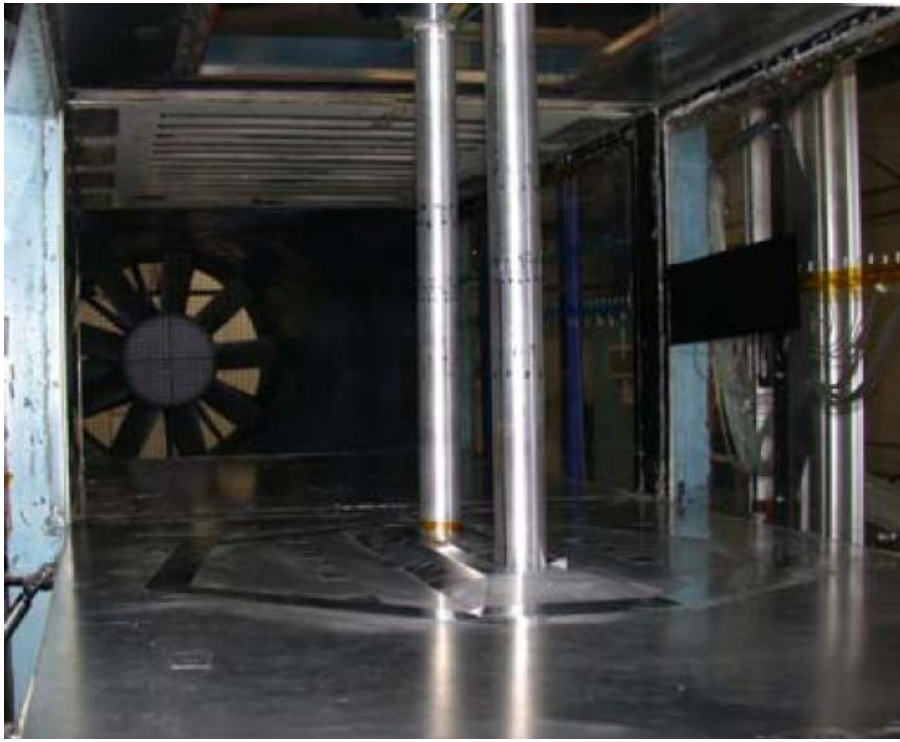
- **Physical insight**
- **Cause & effect relationships**
- **Detailed source description**

Tandem Cylinders



- BART + QFF measurements of tandem cylinders (prototype for landing gear interactions)
- Comparison with CFD+FWH computations

- Extensive aero comparisons
- Acoustics

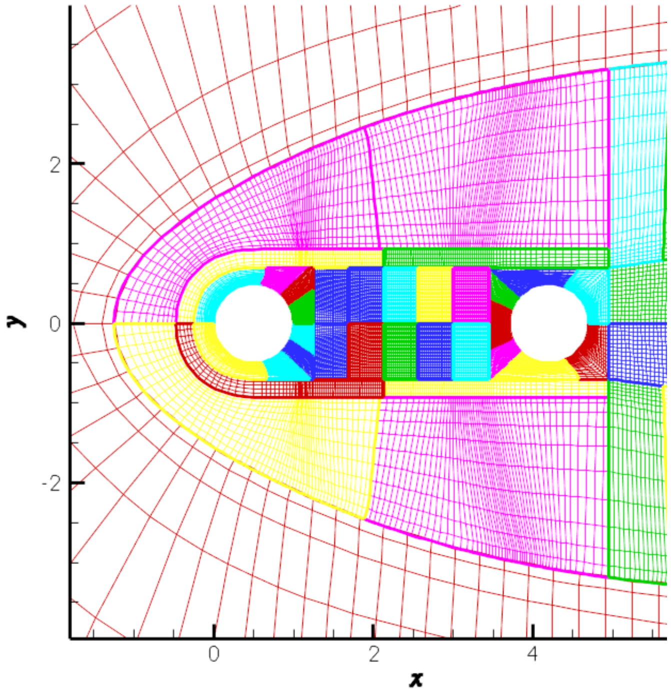


Computational Approach

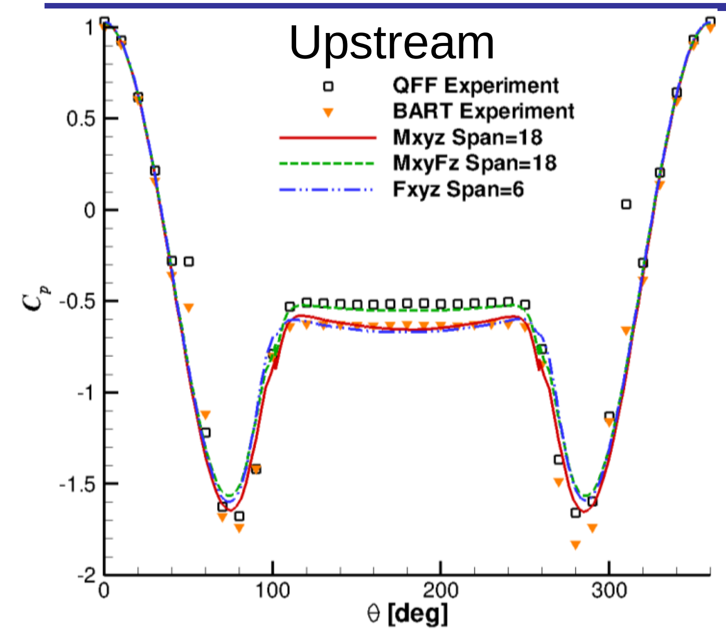
- Unsteady CFL3D Computations
  - 3D Navier-Stokes solver
  - Upwind, nominally 2nd order in space
  - 2nd order implicit time stepping (dual time)
  - Modified Menter's SST K-ω turbulence model
    - Production term turned off outside of boundary layers

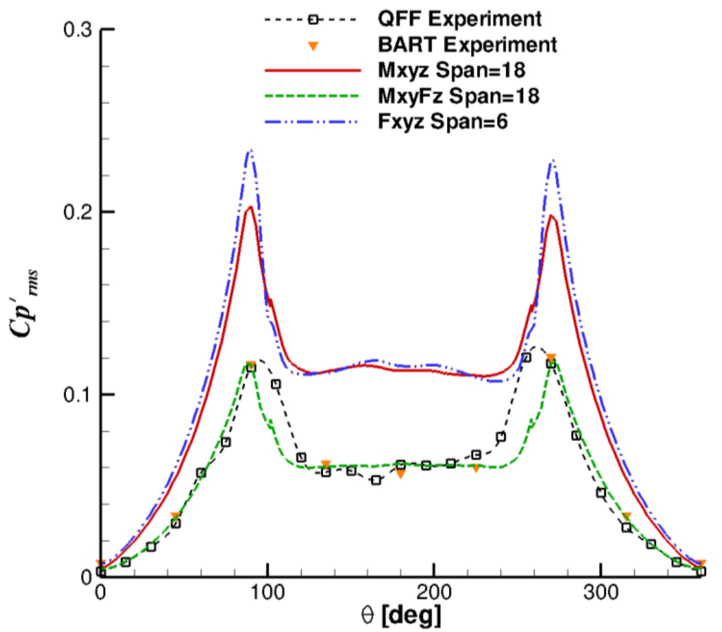
- Block Structured Grids
  - Spans of 3, 6, 18
  - Grid refinement
    - 5M – 80M grid points

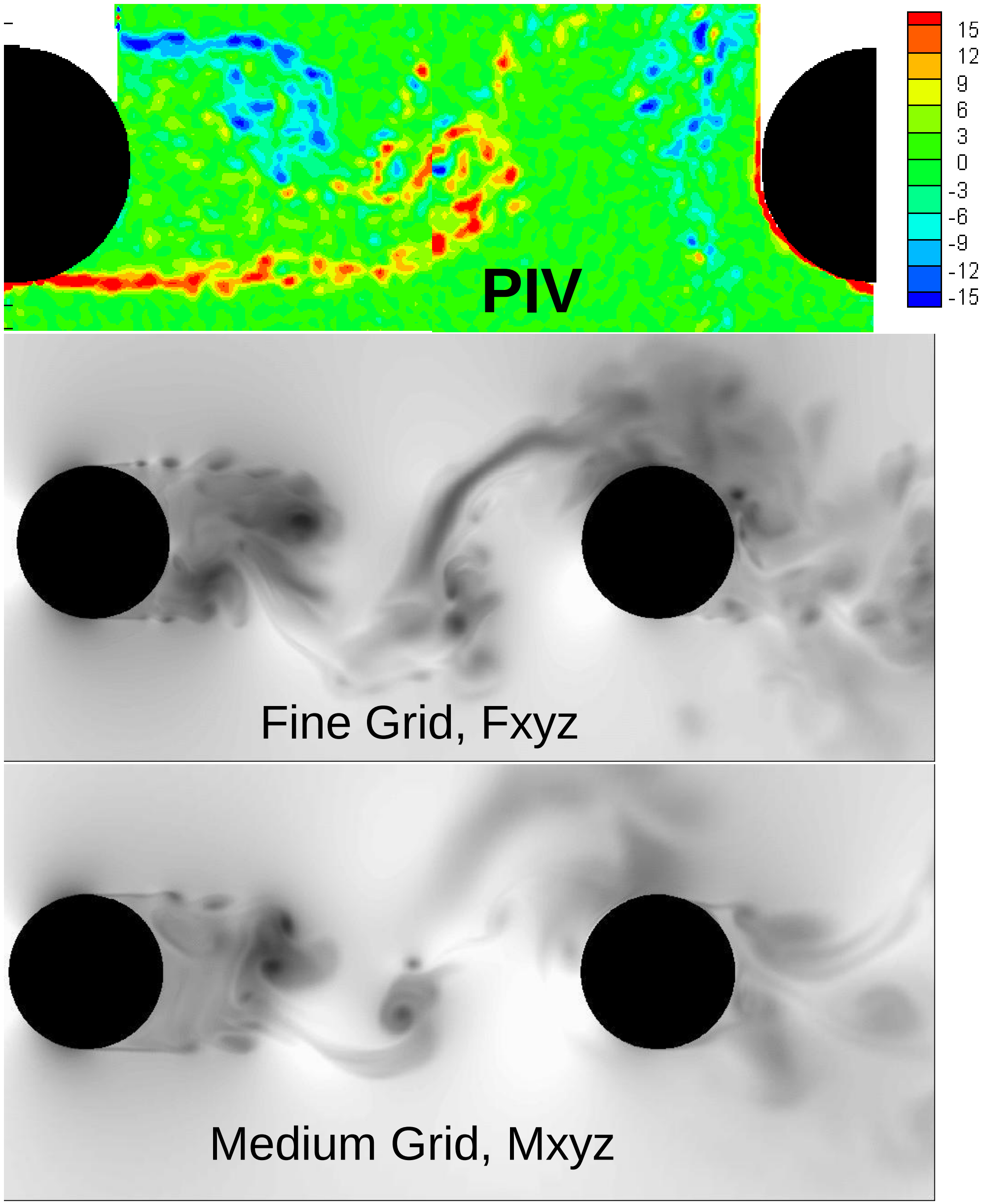
- Operating Conditions
  - Re=166E3
    - Fully turbulent simulations
    - Transition strip used in experiments
  - M=0.166



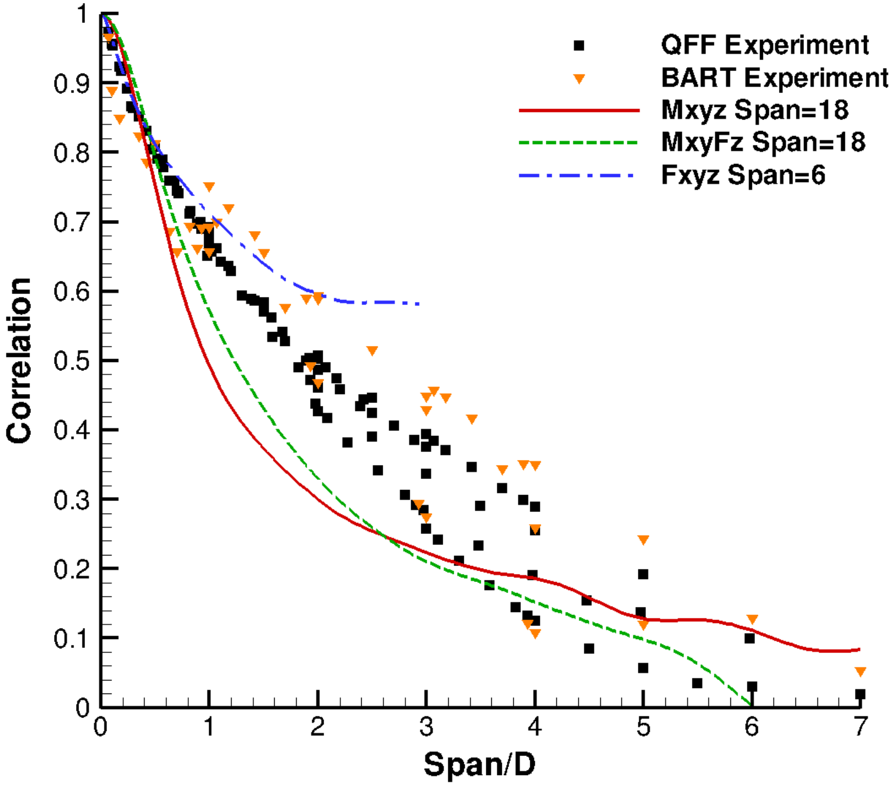
Tandem Cylinders





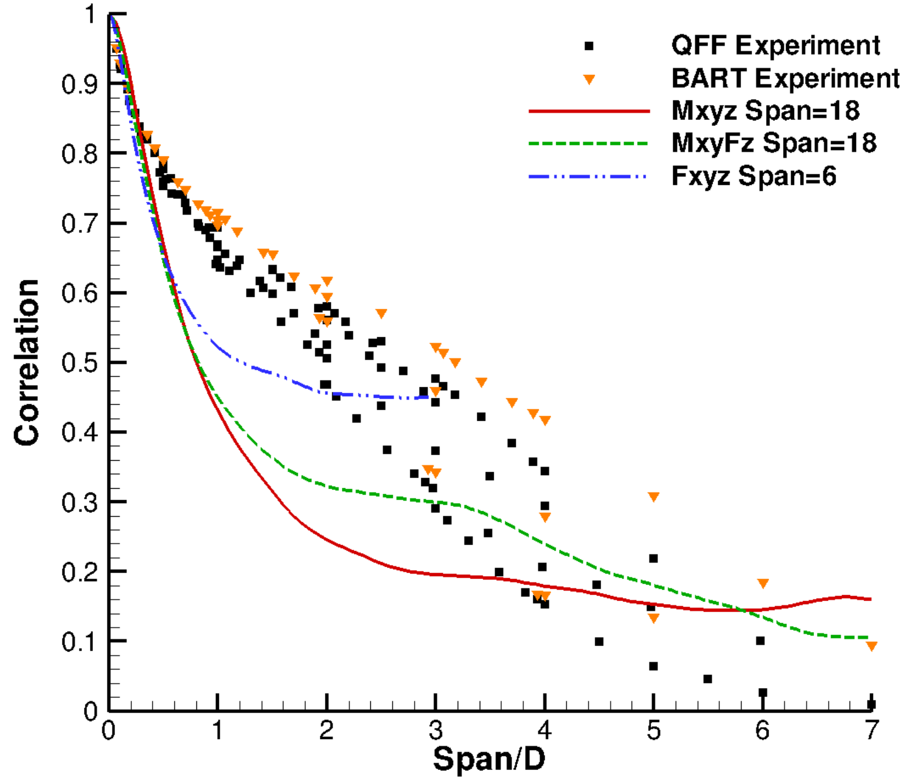


Spanwise Correlation



Upstream

135 deg

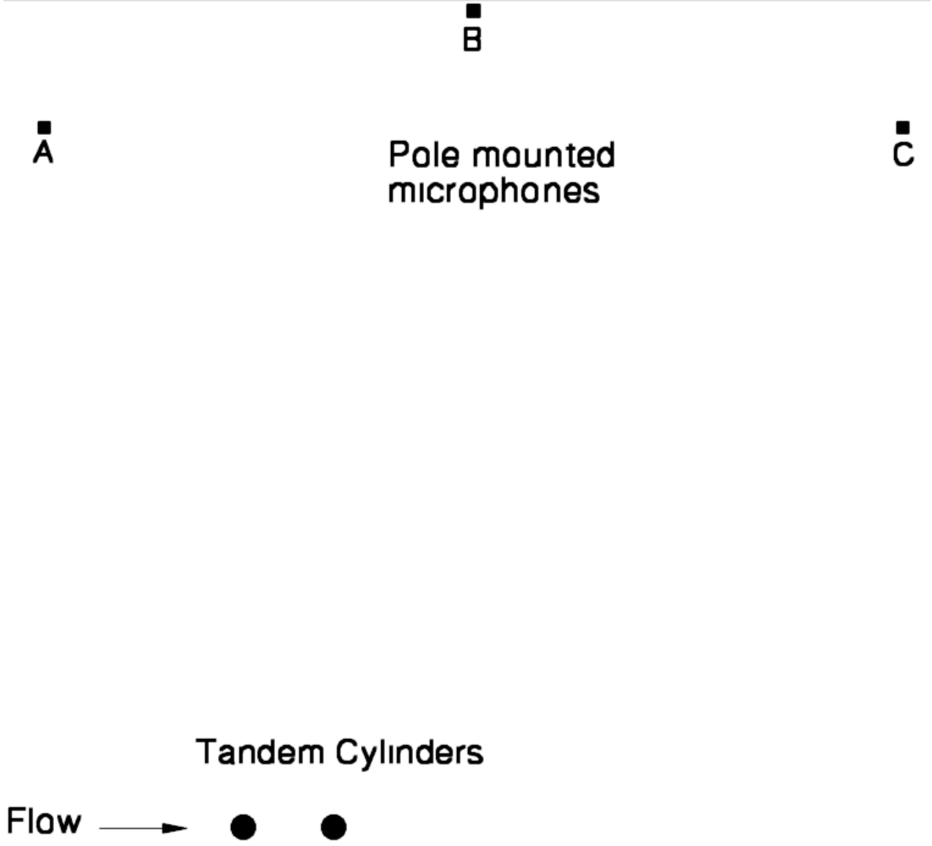


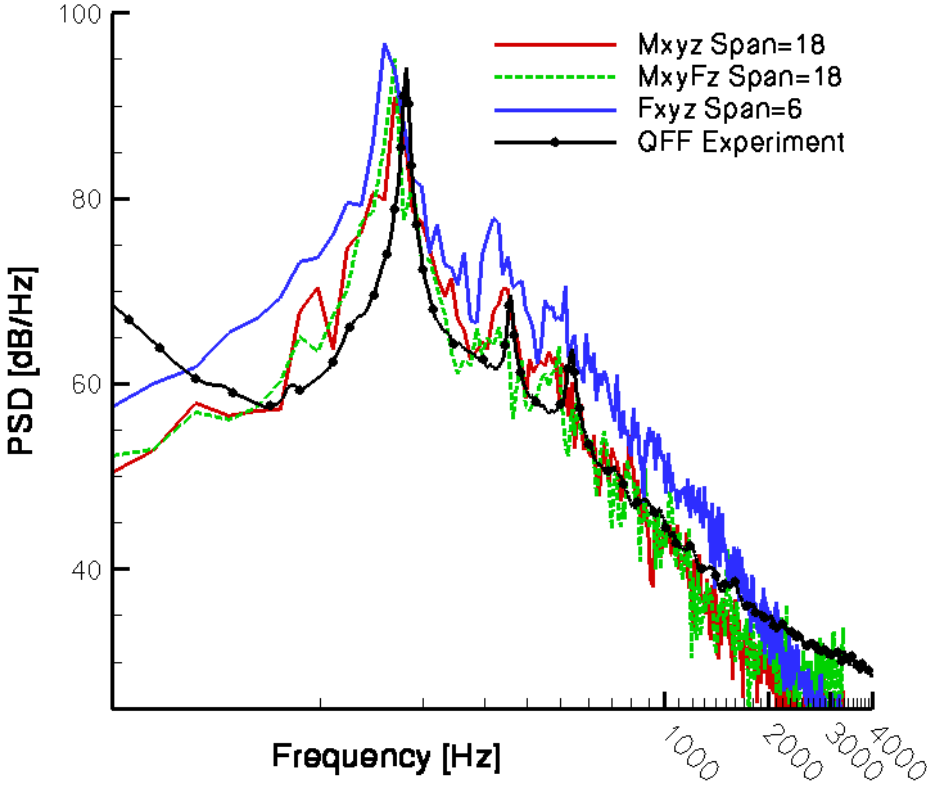
Downstream

- Similar correlation on upstream and downstream cylinders
- Only span=18 calculations capture the complete decay

Computational Approach

- Ffowcs Williams – Hawkings Noise calculations
  - Integral technique derived from the Navier-Stokes equations

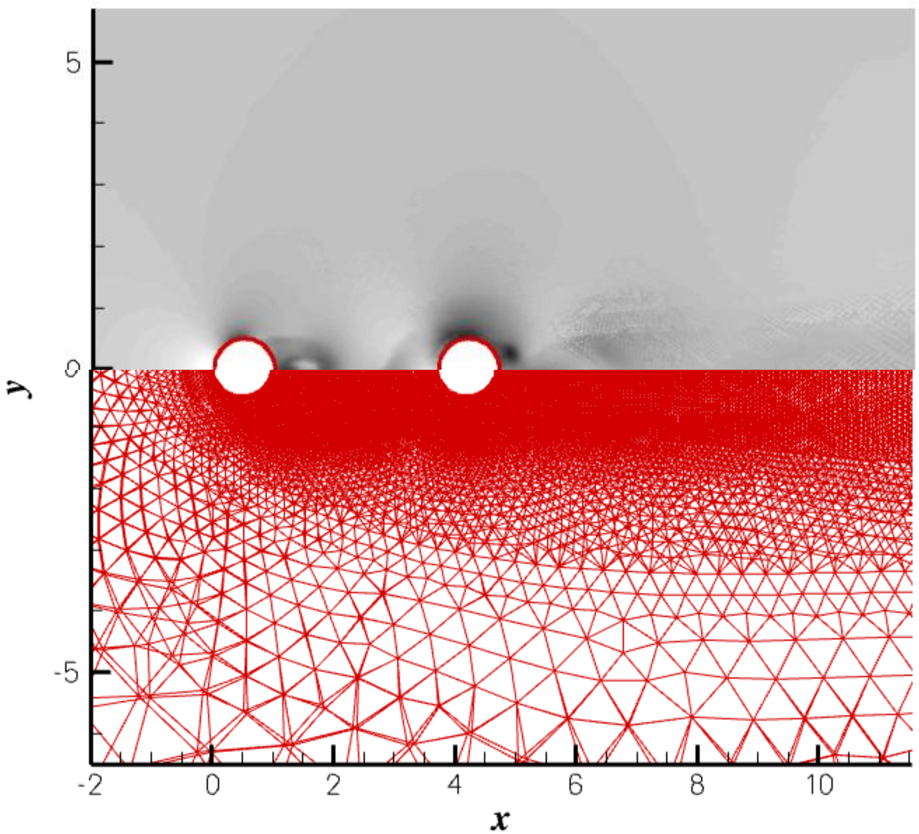




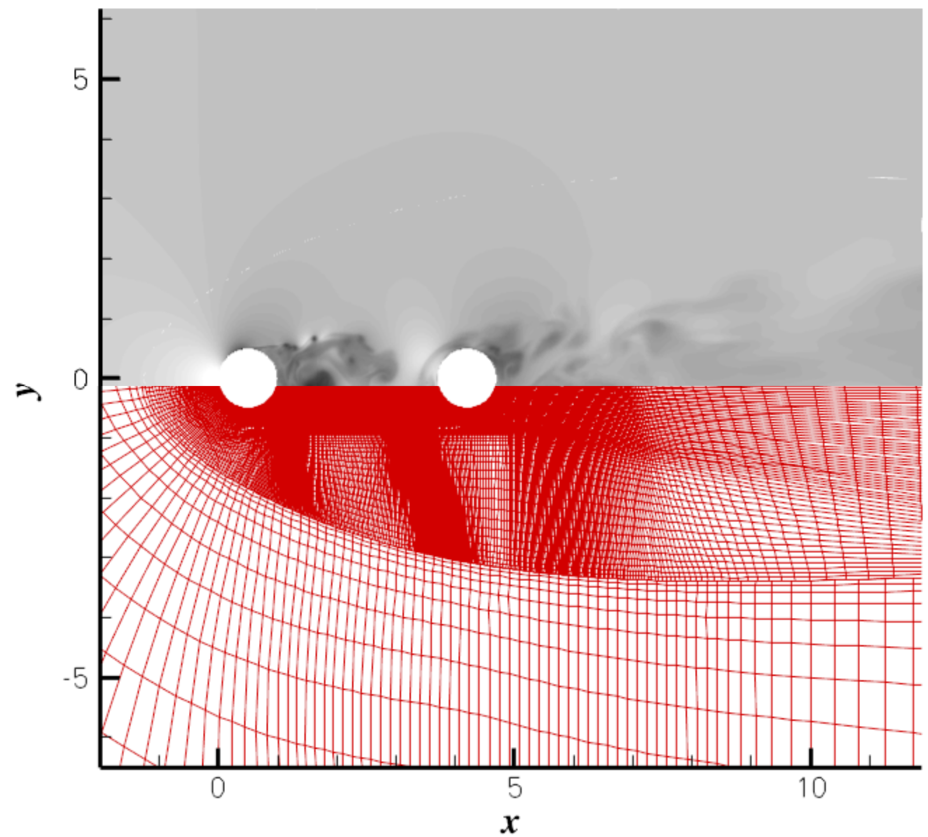
Spectra at A

Tandem Cylinders

- Evaluating different numerical approaches using cylinder test cases
  - Hybrid RANS/LES turbulence models

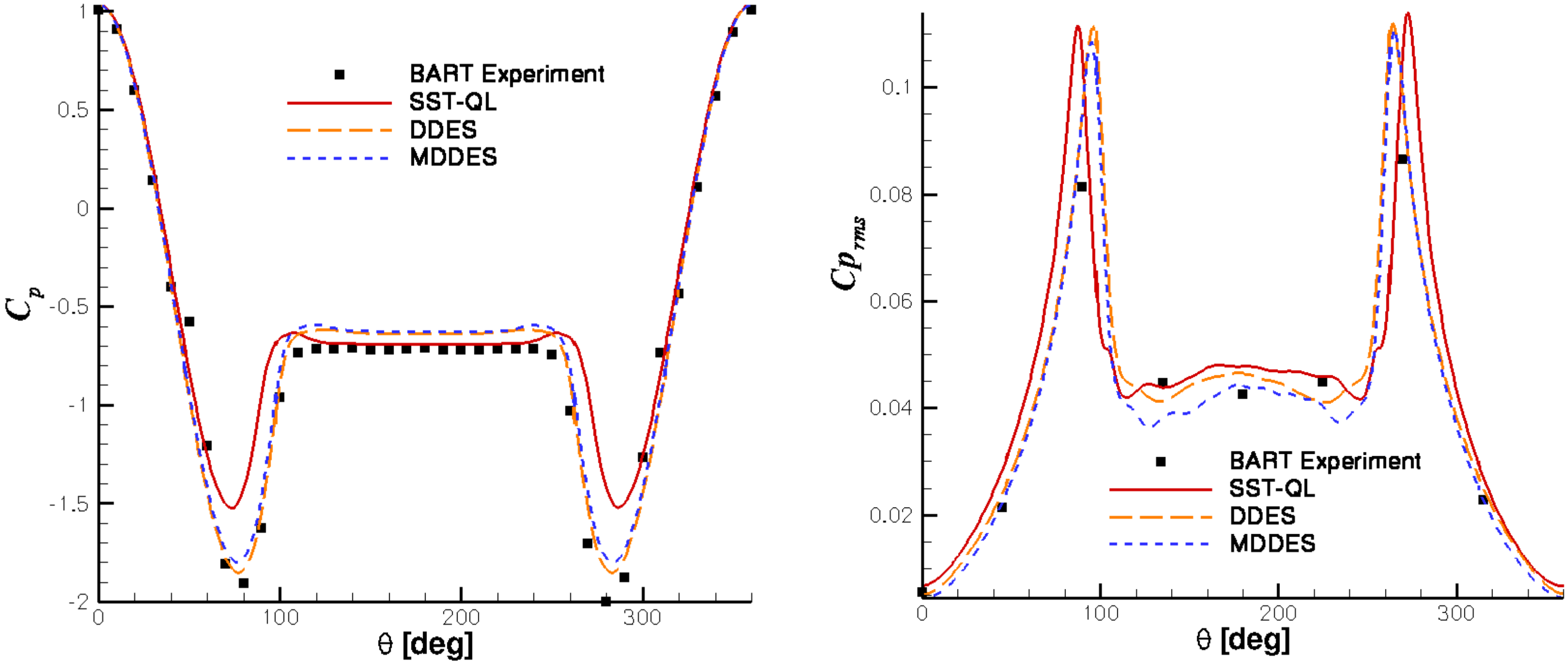


Unstructured Grid



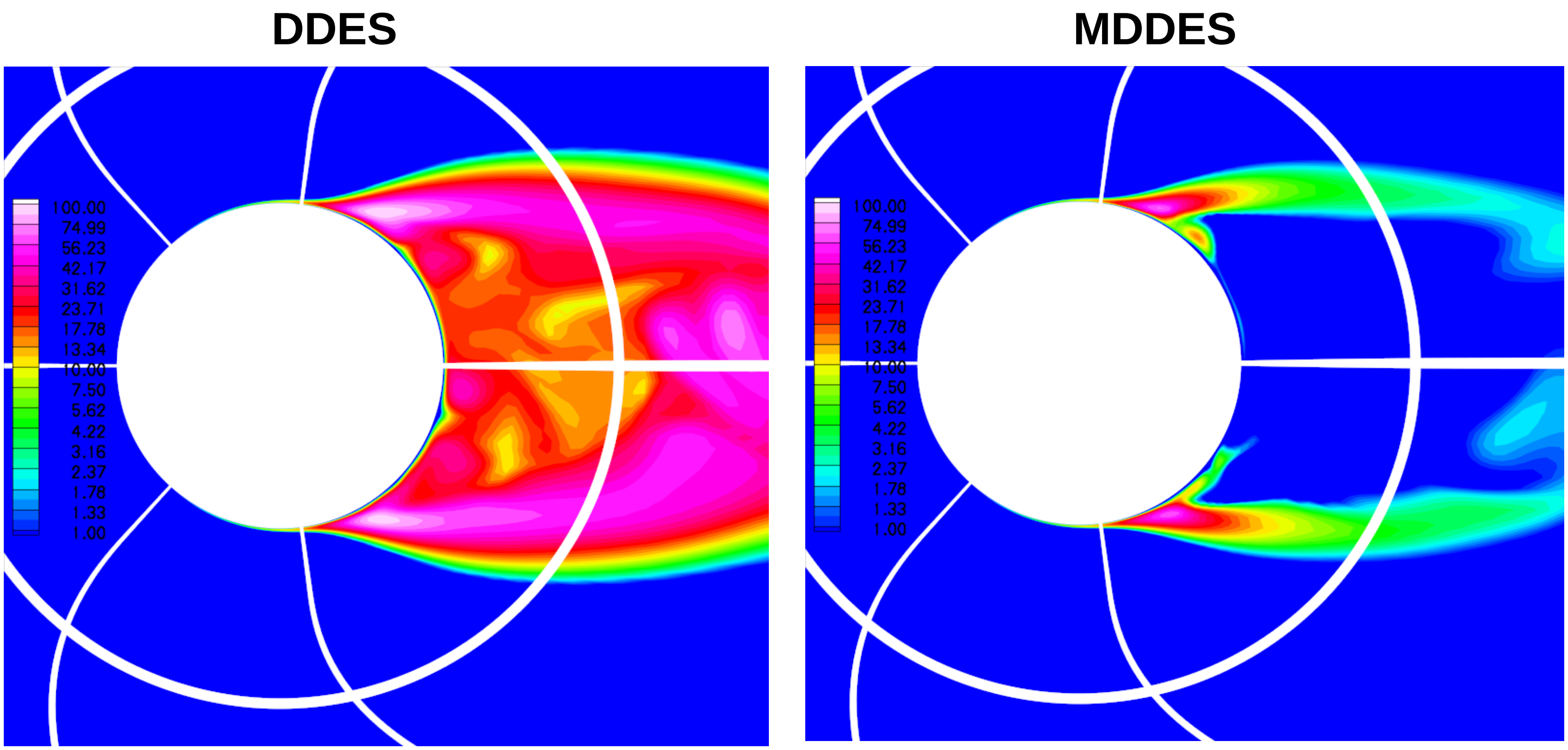
Structured Grid

Single Cylinder Results



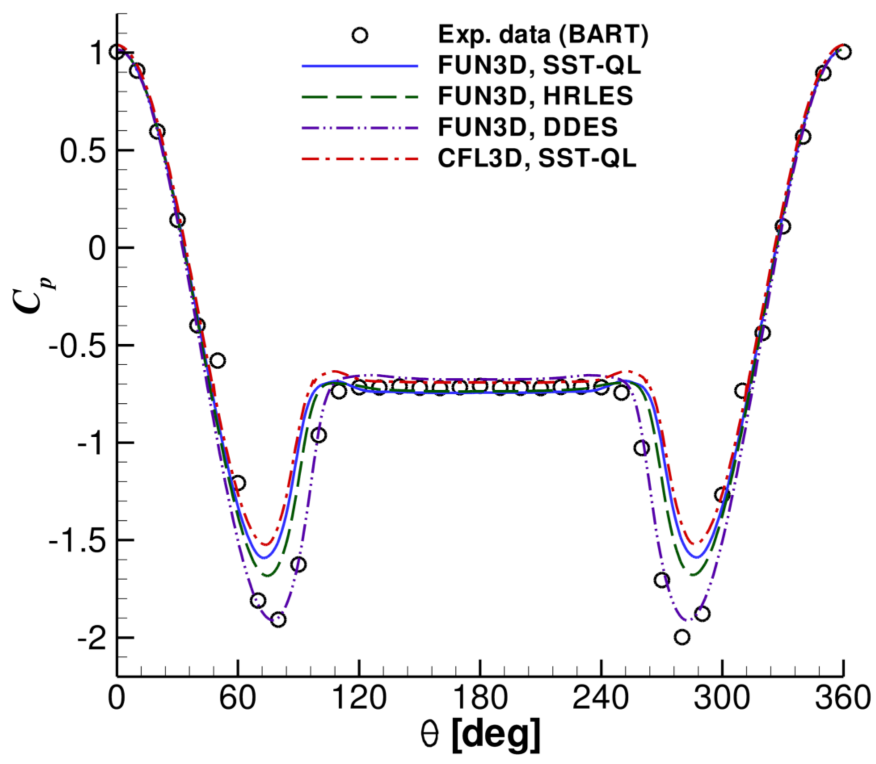
• Modified DDES (MDDES) also changes the production term using the f_d function

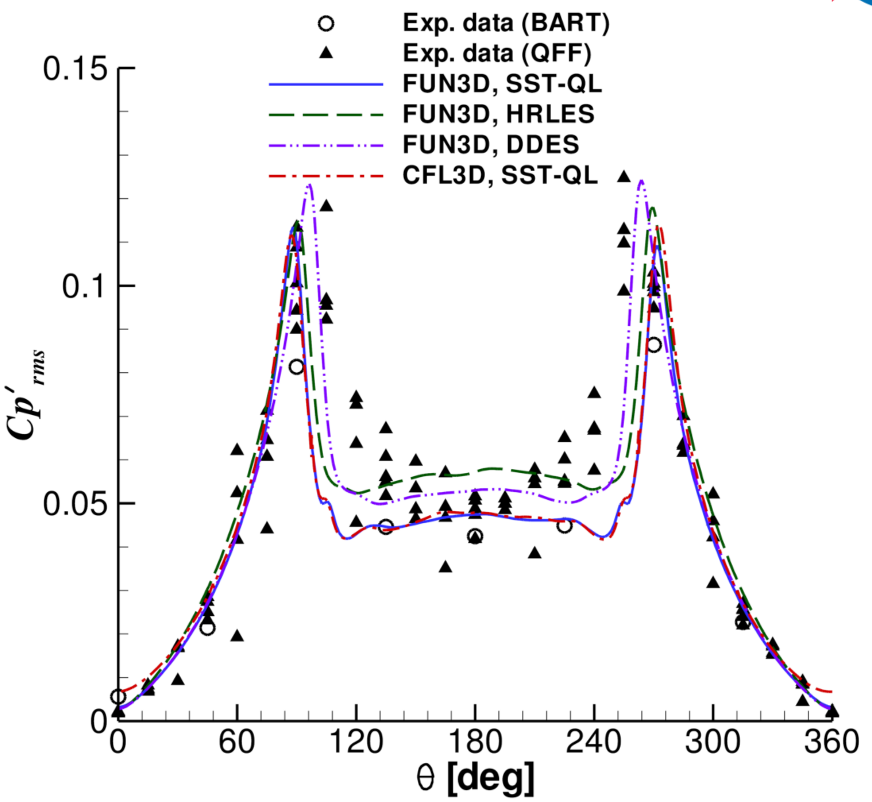
Single Cylinder Eddy Viscosity Results



- MDDES maintains near wall behavior but decreases eddy viscosity that propagates into the field
  - Have not observed significant differences in measured quantities in any problem tested

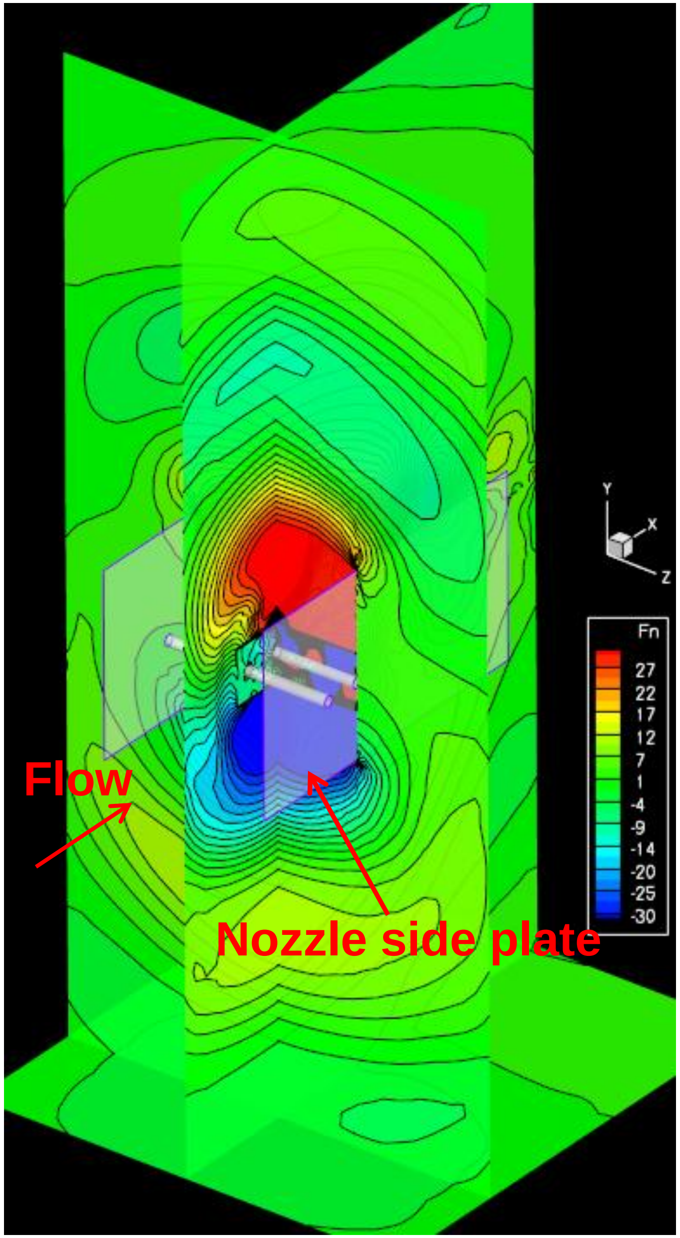
Single Cylinder Results





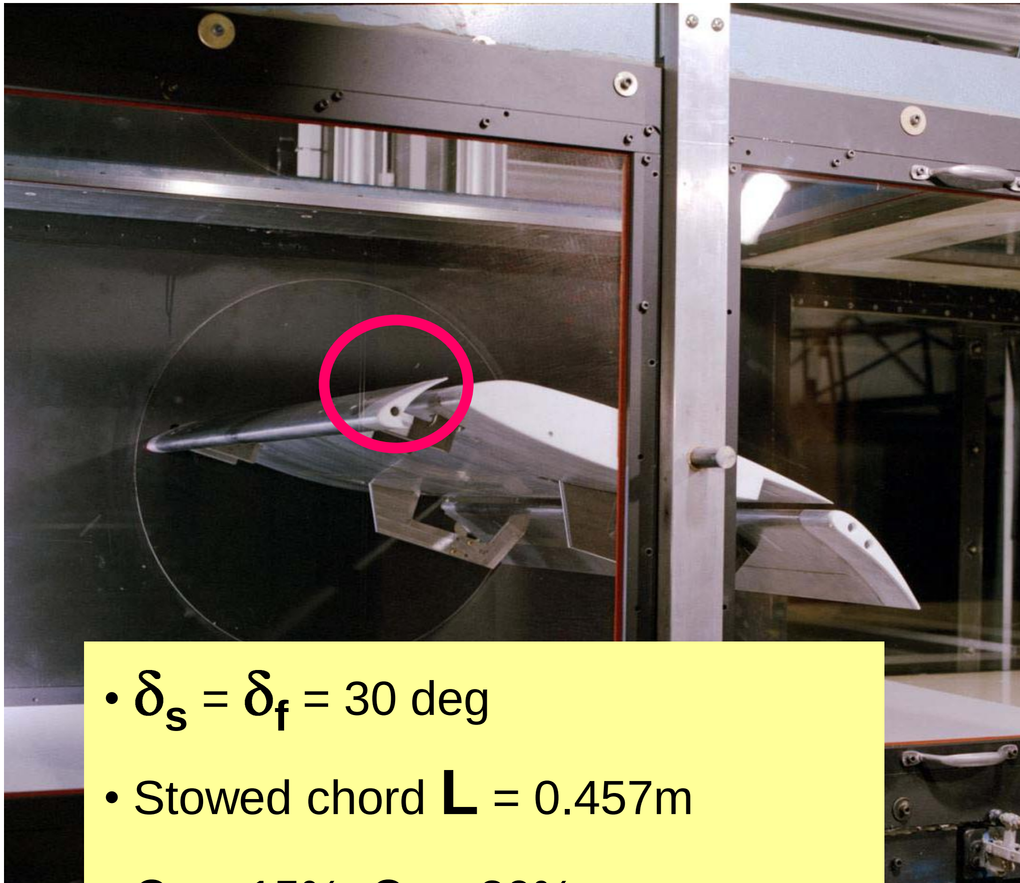
- Good agreement between CFL3D (structured) and FUN3D (unstructured)
  - Used same grid in both codes
- Most turbulence models produce early separation
  - High Re flows difficult to simulate

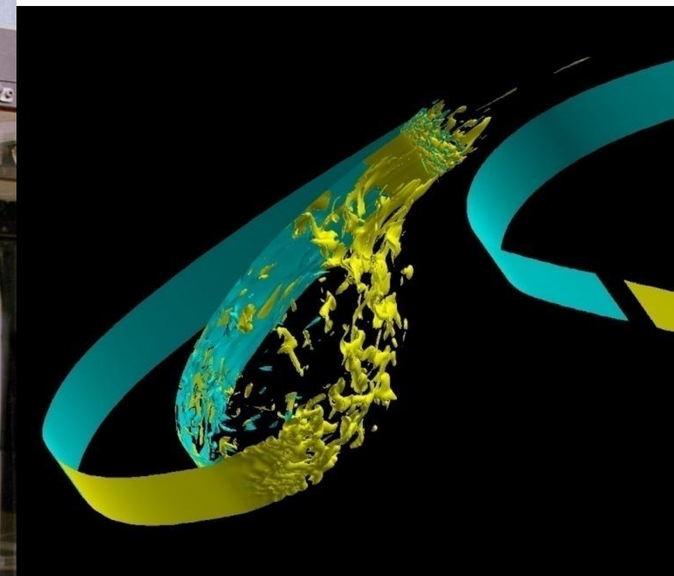
Installation Effects: Scattering Simulations



- Collaborative effort to quantify installation effects on acoustic experimental data
  – Space Act Agreement (SAA) between NASA and ONERA
- ONERA's high-order, overset grid CAA code used to compute acoustic propagation
  – Source imposed from near-field CFD simulation
  – Compare free-field results with case including scattering from nozzle side plates and collector

30P30N BART Configuration



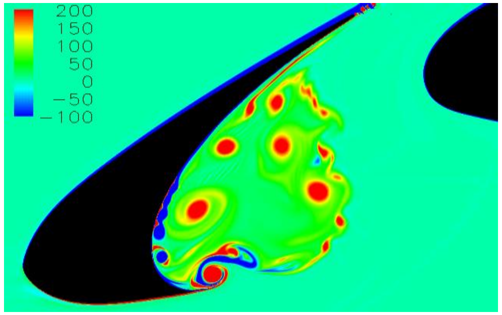


- $\delta_s = \delta_f$ = 30 deg
- Stowed chord **L** = 0.457m
- $\mathbf{c_s}$ = 15%; $\mathbf{c_f}$ = 30%
- $\mathbf{Re_L}$ = 1.7 M

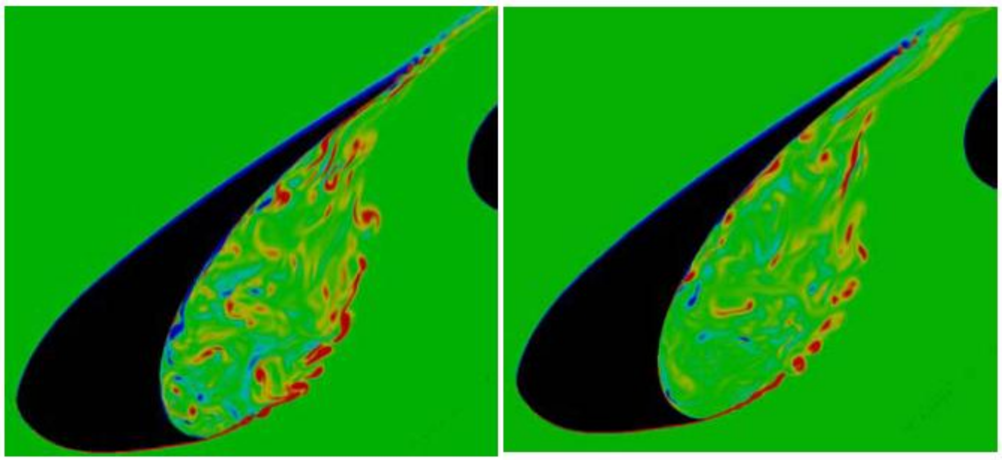
Investigating a span = 2.24 $\mathbf{C_s}$ using 186 million grid points

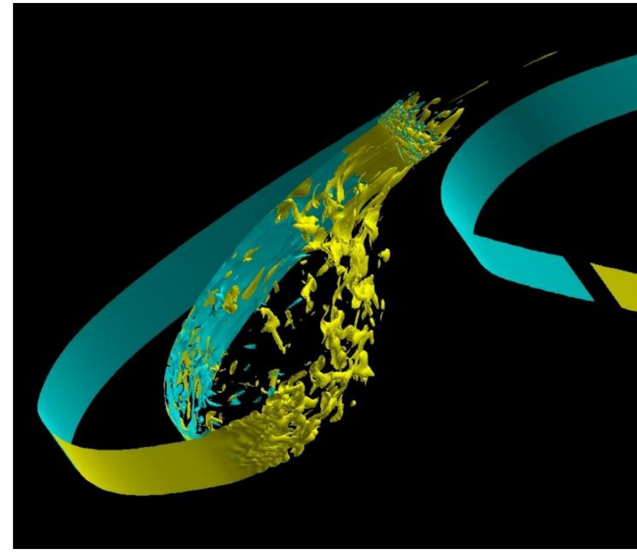
30P30N High-Lift in BART

Near-field validation for Instantaneous vorticity-field

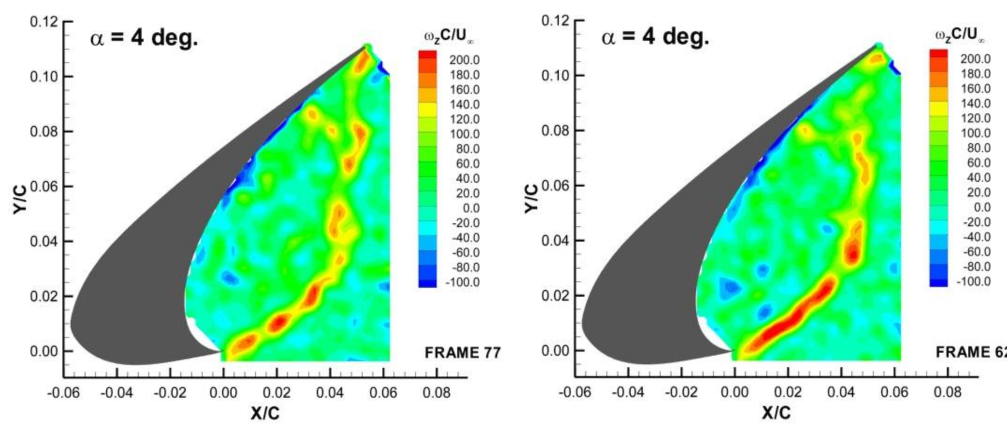


2D, in-tunnel CFD





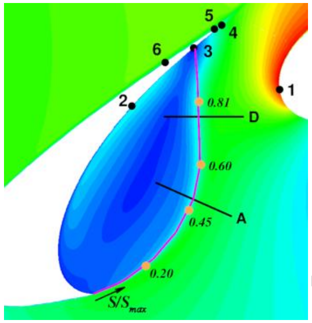
3D CFD

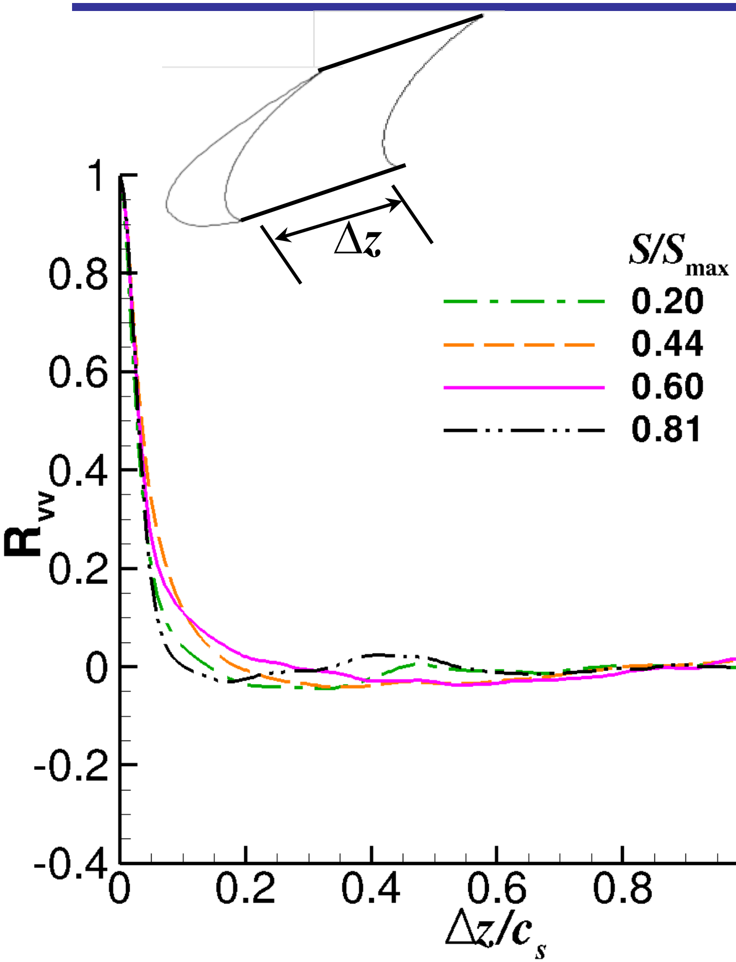


PIV

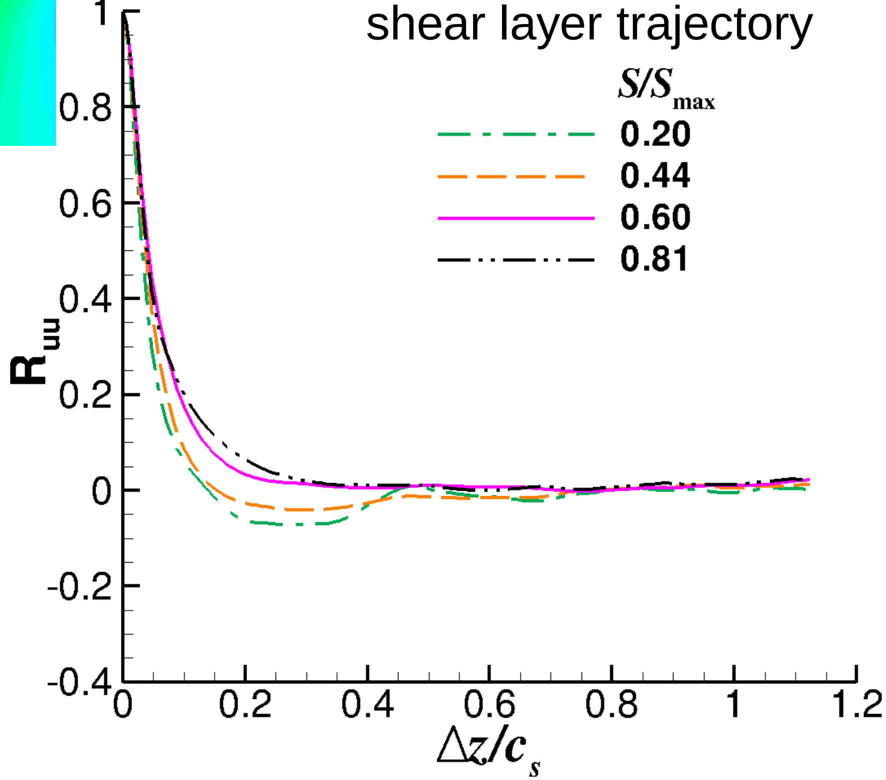
Jenkins '04

Spanwise Velocity Correlation





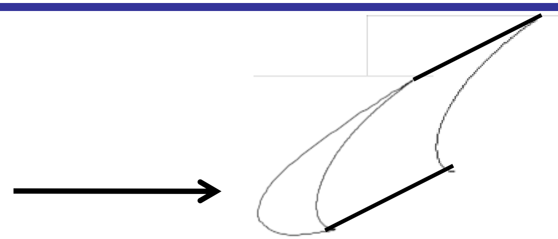
Correlation of v



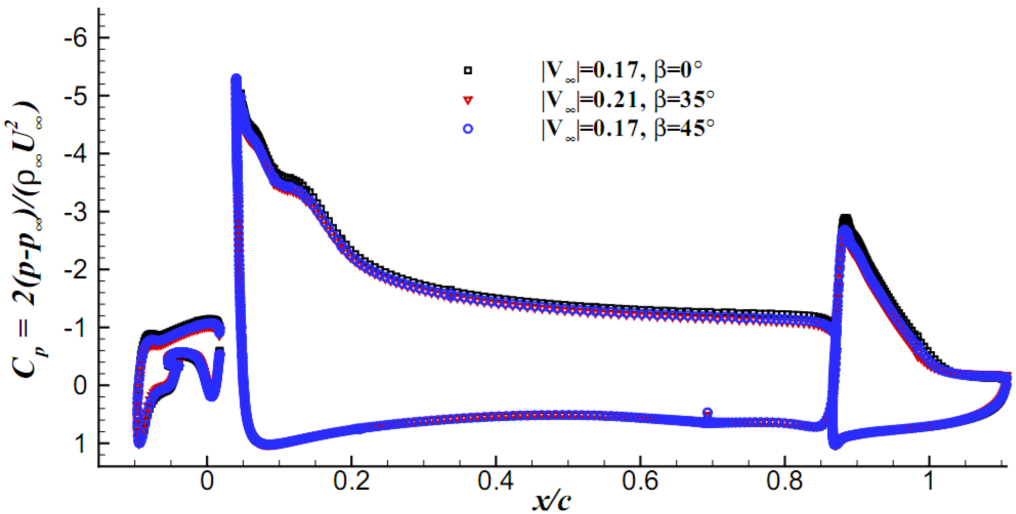
Correlation of u

- Appear to need a span of 2 x 0.4 = 0.8 c_s

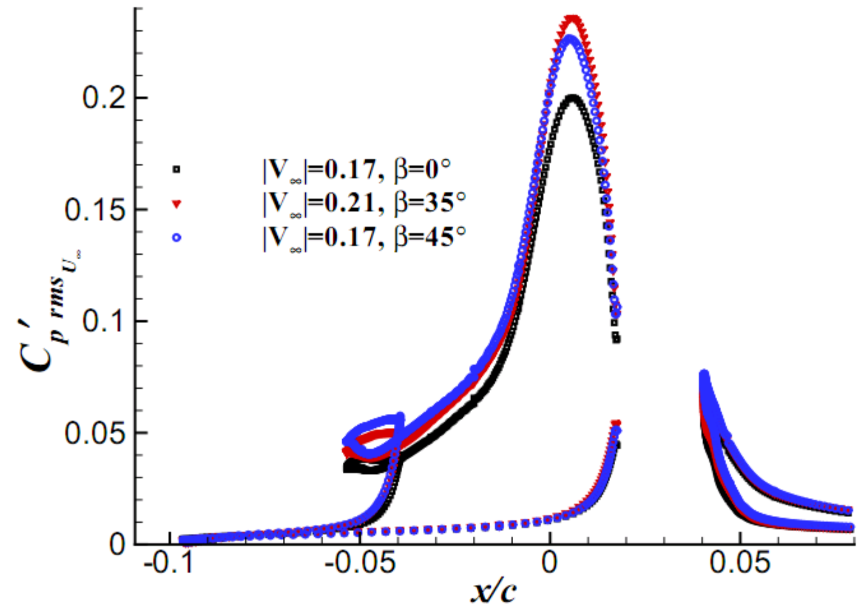
Investigating the Effect of Sweep



β = sweep angle



Time-averaged Surface Pressure

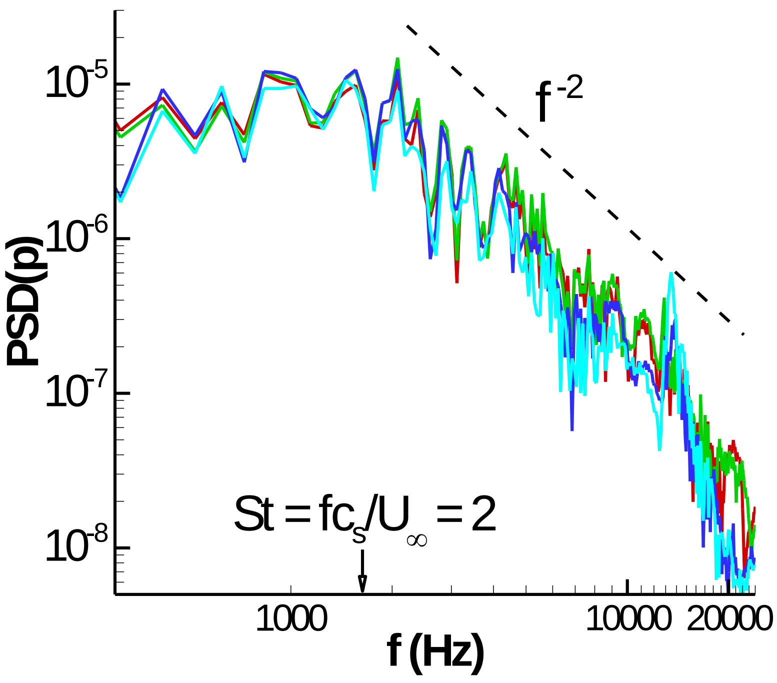


RMS Surface Pressure

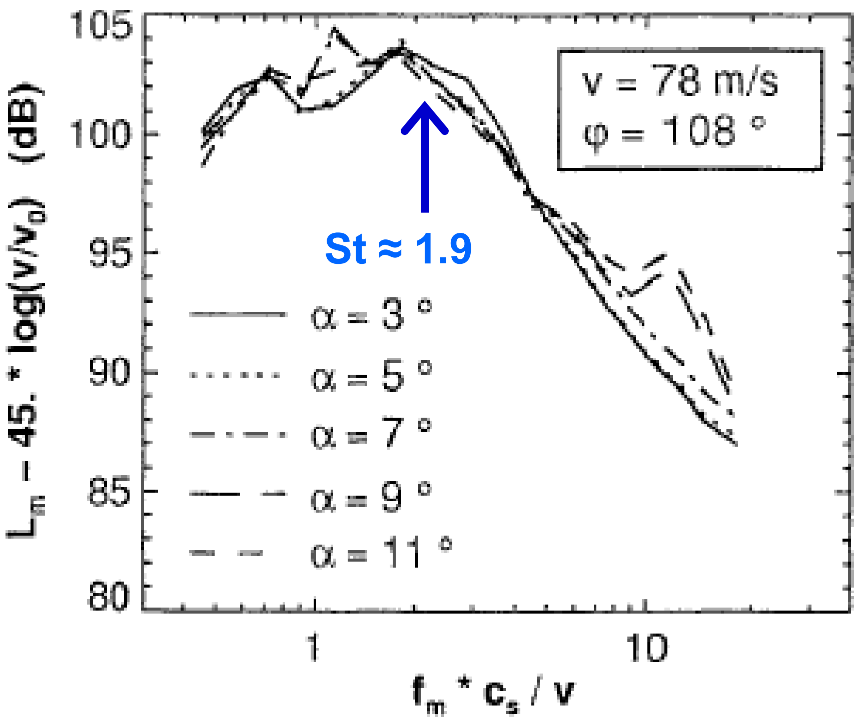
- C_p collapses with velocity normal to leading edge
- Different behavior of rms of C_p

Acoustic Spectrum

CFD



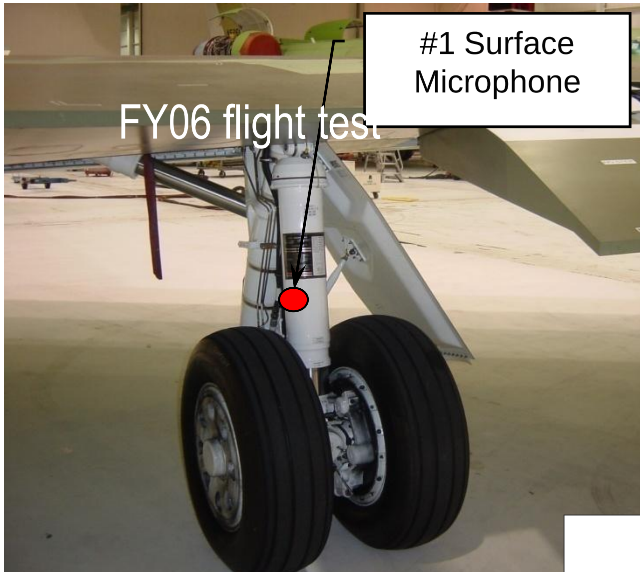
Dobrzynski+Pott-Pollenske (2001)

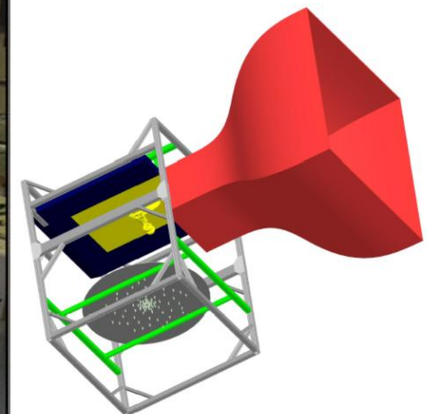


- Acoustic spectrum similar to p' spectrum near reattachment
- St ≡ fc_s/U = 2−3 => f ≈ 155−233 Hz for L = 5m (M=0.17)
- f^{-2} like roll-off similar to model (Guo), data (Mendoza+Brooks), and observations for other shear flows (Lilley)

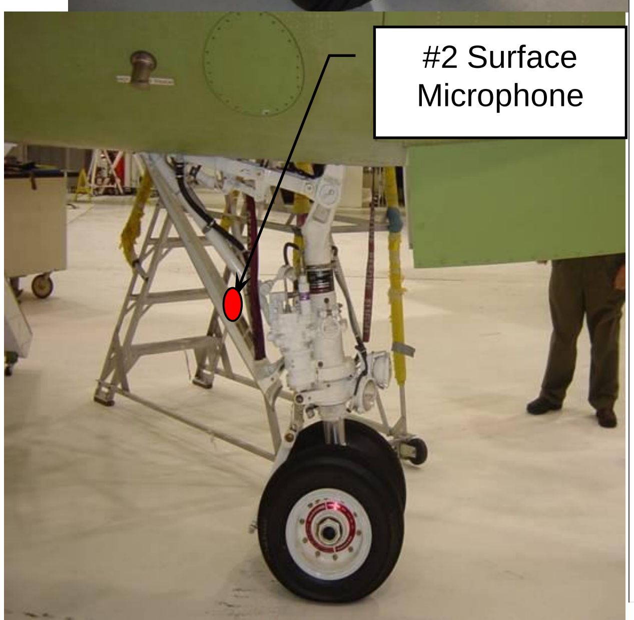
NASA-Gulfstream Partnership: Nose Landing Gear

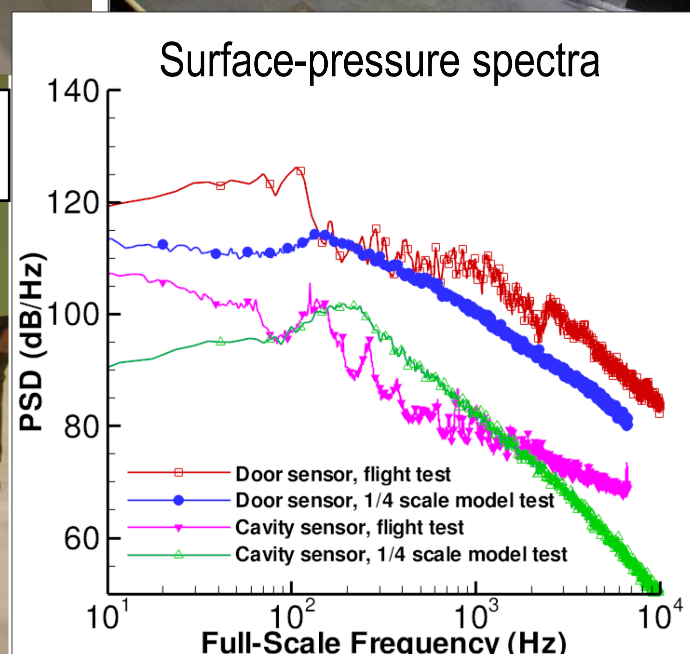
Comparison between model-scale and full-scale surface pressure fluctuations





Acoustic Testing at UFL
Gulfstream funded

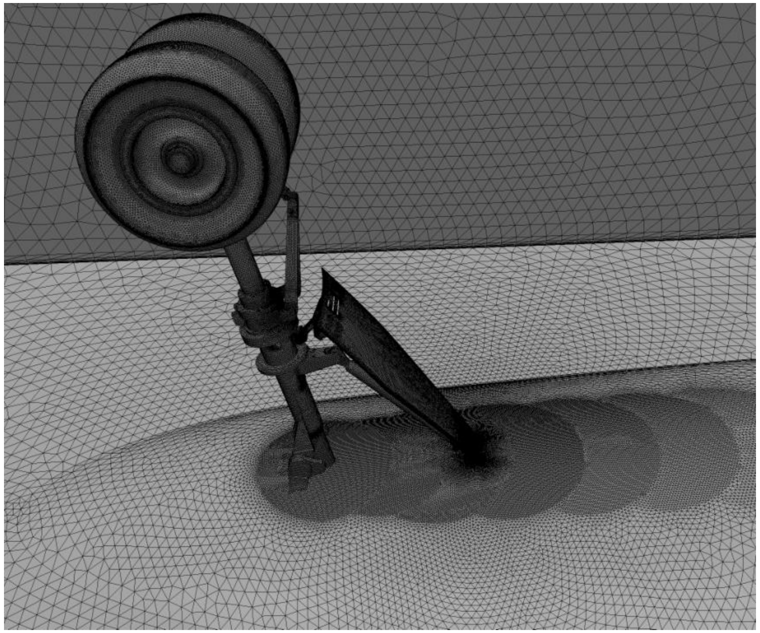


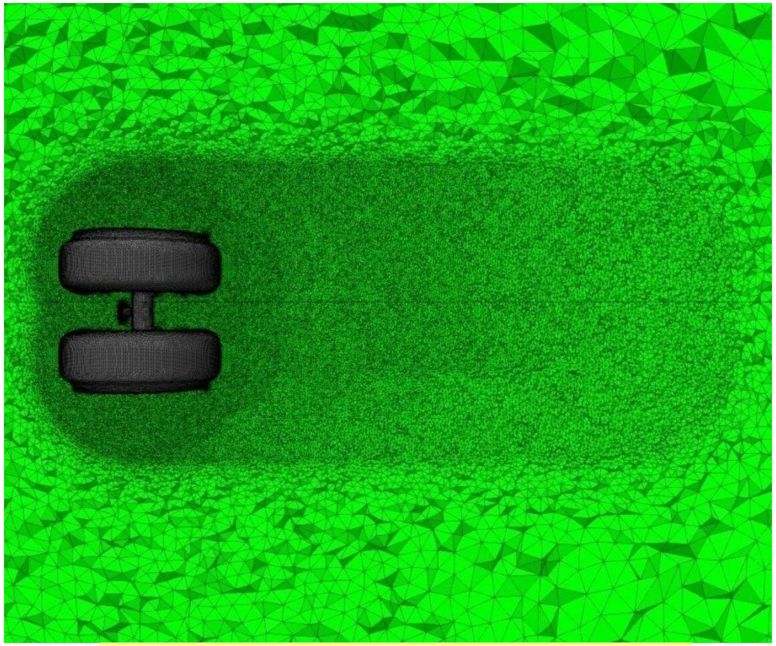


- SAA between NASA and Gulfstream
- Extensive experimental dataset from tunnel tests
- Connection to flight

Nose Landing Gear

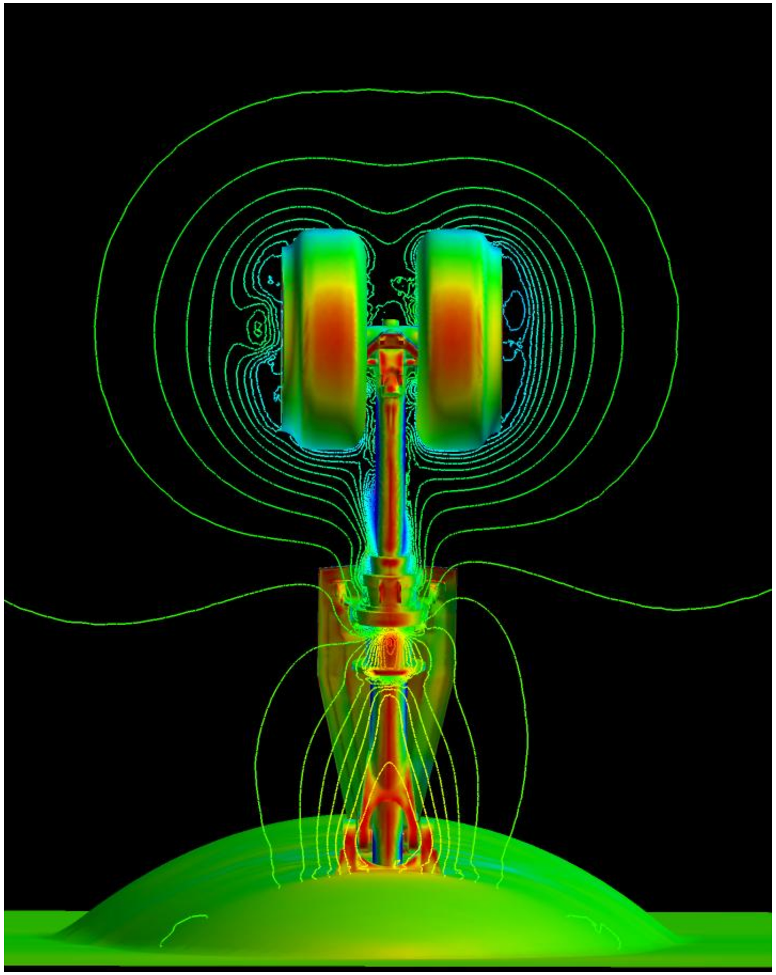
- Concurrent aeroacoustic simulations:
  - FUN3D unsteady simulations of partially dressed gear, no cavity
  - Generation of highly resolved grids
    - Tetrahedral and mixed-element grids
    - Required enhancements to the grid generation process
    - Consistent family of grids generated



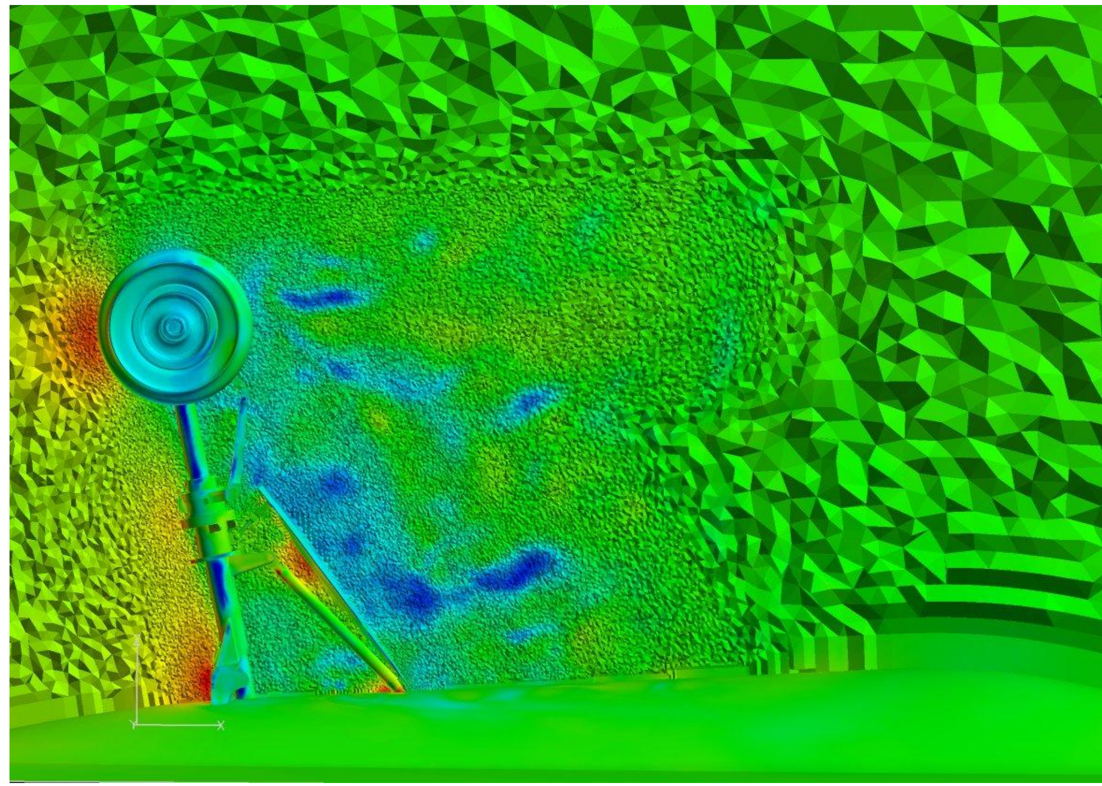


Critical to resolve gear wake

Nose Landing-Gear Configuration



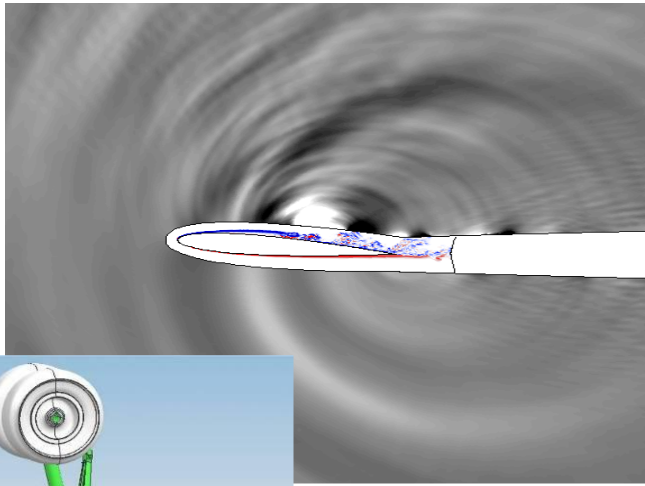
Instantaneous pressure from FUN3D simulation

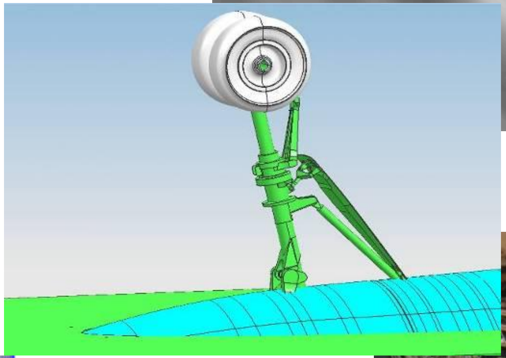


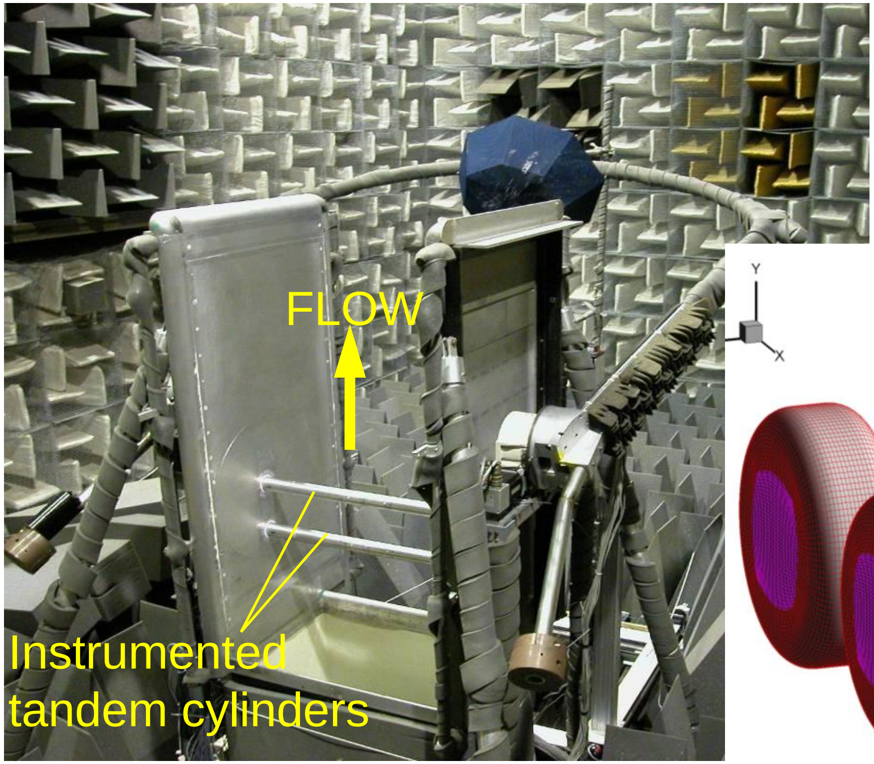
- Family of 3 meshes – 9, 25, 71 million nodes
    - Manually refined 48 million node mesh
- Two turbulence models

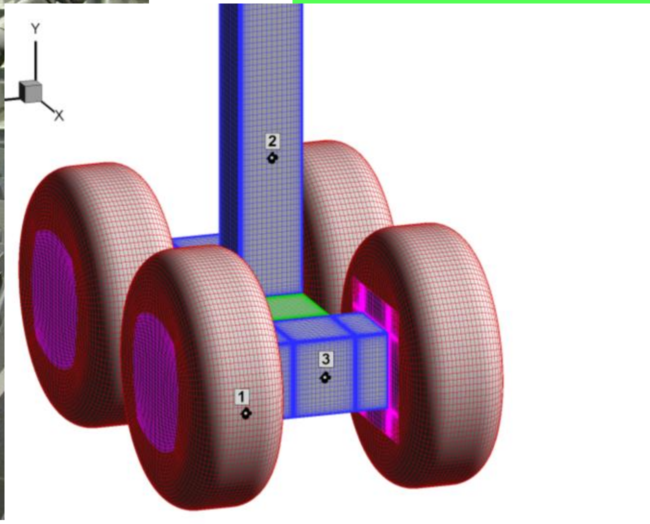
Benchmark problems for Airframe Noise Computations I (BANC-I)

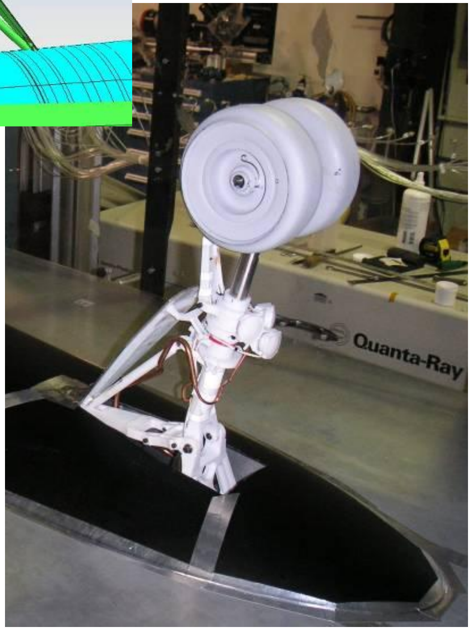
- 2010 workshop following AIAA/CEAS Aeroacoustics conference in Stockholm
  - Tandem cylinders (NASA dataset)
  - Trailing-edge scattering (Multiple datasets)
  - Nose landing gear (NASA dataset)
  - Main landing gear (Boeing dataset)











BANC Workshops

- Computational AeroAcoustics (CAA) community developed a set of verification and validation cases from a series of 4 CAA Workshops
- A new series of workshops (BANC) is being organized in coordination with the AIAA Aeroacoustics and Fluid Dynamics Technical Committees
  - Complex configurations for which no exact solutions are available
    - 2 of the 4 problems use NASA datasets
  - Holistic datasets from unsteady aero to acoustics, with a thorough quantification of the individual stages or links
    - Also valuable for the unsteady CFD community
  - Collective efforts (computations AND experiments) for common configurations
    - Develop validation cases for airframe noise applications
  - Iterative process refining computations and experimental data

BANC Summary

- Collective effort to develop validation cases for complex airframe noise configurations
  - Develop confidence and identify problems more rapidly
  - Leverage different expertise / distribute the expenses
  - → Formation of AIAA Discussion Group on Benchmark Experiments and Computations for Airframe Noise (https://info.aiaa.org/tac/ASG/FDTC/DG/BECAN.aspx)
- Several BANC workshops envisioned
  - BANC I: June 10-11, 2010
    - 55+ Notices of Intent (NoI) to participate in workshop
      - 12 countries represented (US, UK, France, Germany, Belgium, Sweden, Netherlands, Italy, Japan, Brazil, Australia), 5 airframers, 6 government agencies, 5 software vendors, 3 research consortia, 18+ universities
  - Other datasets for following workshop (besides continued consideration of BANC-I configurations) currently under consideration and/or development

Summary

- Unsteady simulations are enhancing our understanding of acoustic sources
  - Computations are expensive
  - Errors can be large and are unknown without experimental data

- Using a collaborative, community oriented approach
  - Collecting high-quality experimental data
  - Assessing different models and numerical techniques