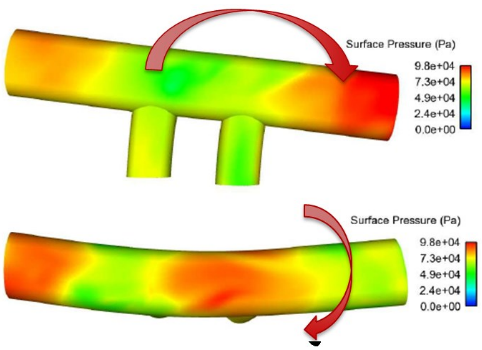
SAND2014-2680C



Cavity Flow Research at Sandia National Laboratories

Srinivasan Arunajatesan, Mathew F Barone, Steven J Beresh, Justin Wagner, Katya Casper

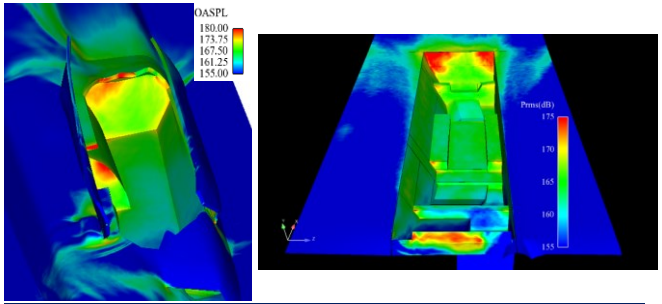
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

Outline

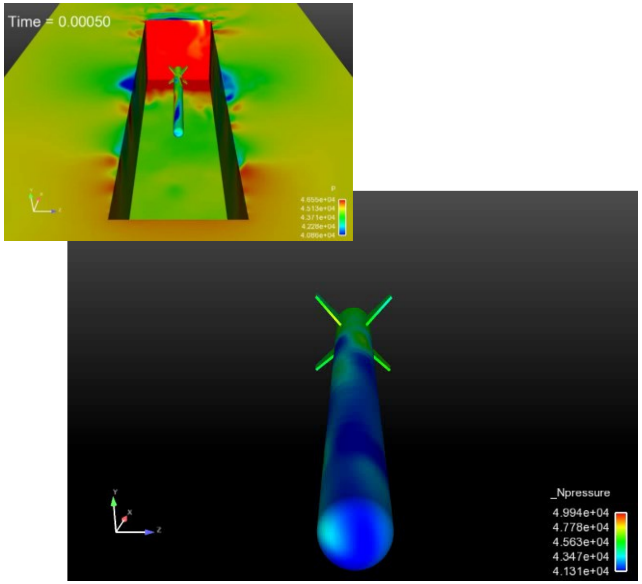
- Motivation
  - Why is Sandia Interested in Cavity Flows?
  - What are we interested in?
- Overall Approach
  - Combined Modeling-Simulation Approach
  - Modeling-Simulation Methodologies
  - Experimental Facilities and Techniques
- Examples
  - Modeling and Simulation Results
    - Where we are doing well, where we need some help.
  - Experiments
    - Measurements of Pressures, Flowfield and Store Response
- Future Work
  - Where we can contribute
  - Where we can learn from this group

Sandia's Interest in Captive Carriage Problems

- Stores in Weapons Bays Experience Intense Aero-Loading
  - Dynamic Loads can exceed 165 dB
- Tonal Content Can be Strong
  - Some evidence exists that even in complex bays at full tonal content is present
  - If these match structural modes, resultant response can be catastrophic.
  - The Physics of this FSI problem needs to be understood
- Our interest
  - Store and Component response in captive carriage
  - Acceleration experienced by store shell and components when subjected to this loading



Dynamic Pressure Load Levels in Complex Bays*



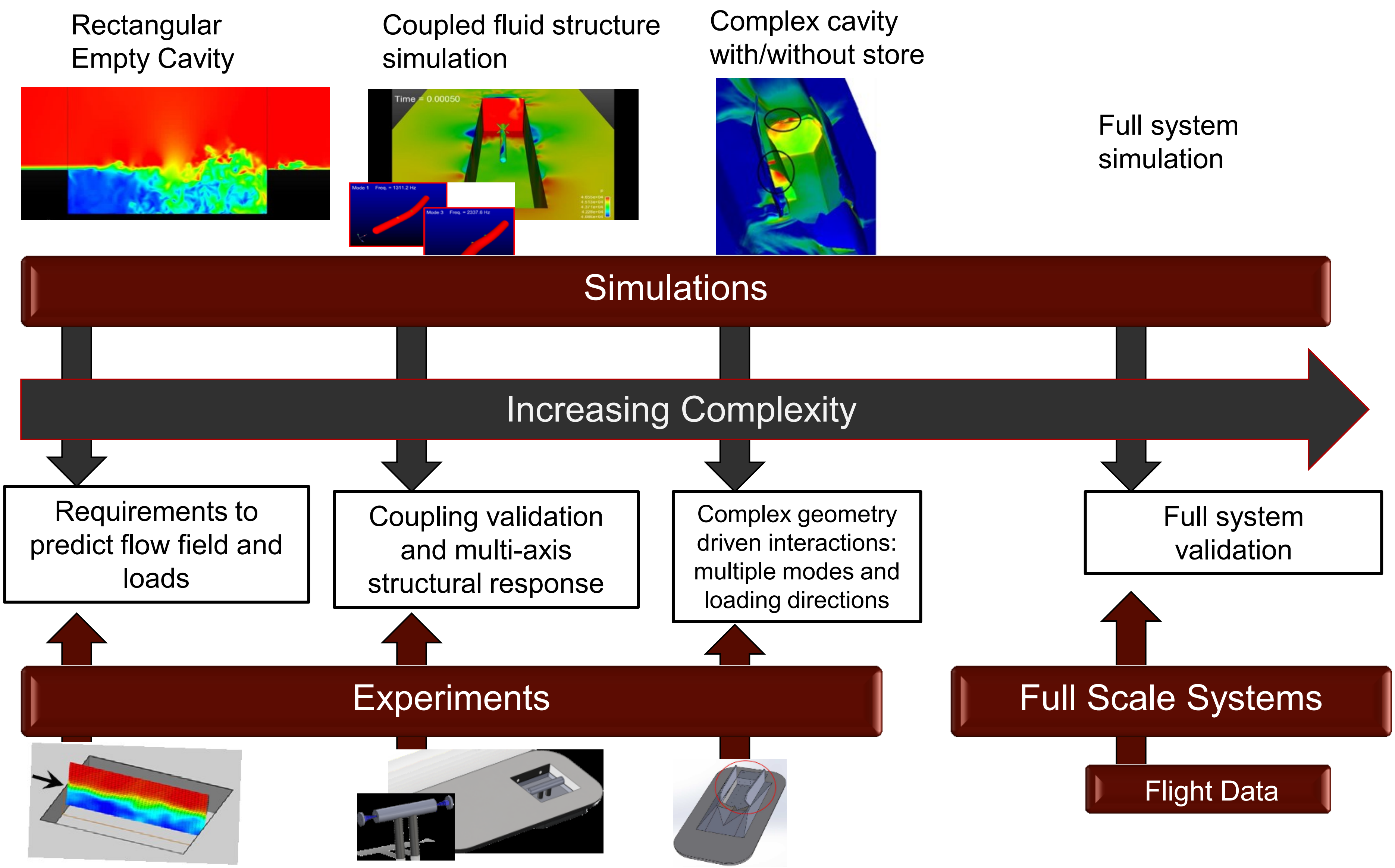
* Images from DOI 10.1109/HPCMP-UGC.2010.66 and DOI 10.1109/HPCMP-UGC.2009.14, respectively

Approach to Cavity Flow Research

- Combined Experimental and Modeling Activities
  - Unique Situation where both groups are part of the same department
    - Permits Strongly Collaborative Work
  - Experiments can measure exactly what is needed for CFD
    - For example, Accurate Boundary Conditions
  - Simulation Results can help Shed light on flow physics and further experiments necessary

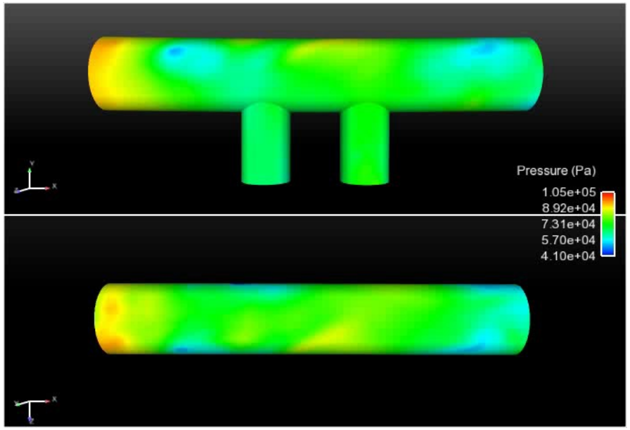
- This allows us to close the gap in testing using CFD/FSI effectively
  - Build confidence in our tools and methods
  - Understand the uncertainty in our predictions and the sources
  - Apply to full scale systems where testing is limited

Sandia's Validation Approach to M&S



Coupled Simulation Approach

- Fluid motion: simulated with an unsteady CFD model
- Structural motion: time domain CSD model
- Loose coupling between the fluid and structure
  - Pressure is transferred on wetted boundaries



- Coupling Is One-way
  - Small Store Deflections:
    - Generally Valid Under Captive Conditions
  - Structural Deflections Are Not Communicated To CFD Solver:
    - CFD Proceeds Assuming "Rigid" Structures
    - Deflections computed by CSD code are not used in CFD code
    - Results used to verify that this is true

S. Arunajatesan, M. Bhardwaj, W. C. Riley, and M. Ross. One-way coupled fluid structure simulations of stores in weapons bays. AIAA-2013-0665, 2013.

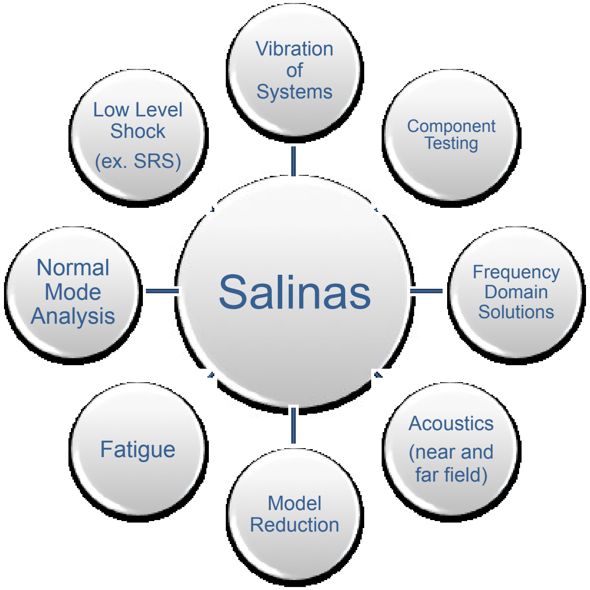
CFD Solver

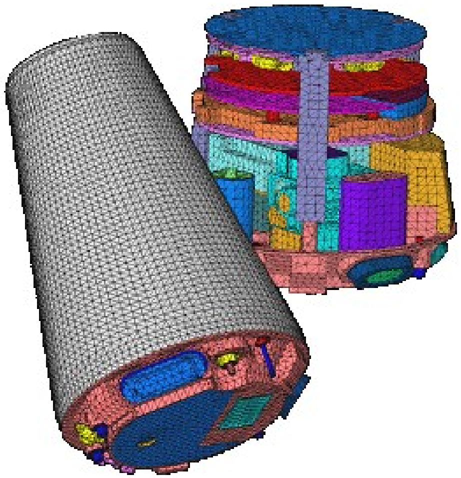
- **Pressure Loads Computed Using SIGMA CFD**
  - In-house Structured Multi-Block Solver Inherited from Georgia Tech's LESLIE 3D Code
- **Numerous Modifications for Sandia Applications**
  - Low-Dissipation fluxes using hybrid switched scheme
  - Implicit time integration
  - Sponge zone boundary conditions
  - Advanced turbulence model suite
- **Cavity Flow Simulations Carried out in Hybrid RANS-LES Mode**
  - Flow in the bay and the shear layer over the bay are well resolved (to the level of Large Eddy Simulations)
  - Flow Upstream and Downstream are modeled with RANS
  - Duprat *et al.* near wall model
- **Arunajatesan and Sinha Hybrid RANS/LES Model (2001)***
  - Unified one-equation k^{sgs} LES model and k-ε RANS model
  - Mesh dependence built into eddy viscosity calculation, LES solutions are obtained when resolution permits

*Arunajatesan, S. and Sinha, N., "Hybrid RANS-LES Modeling for Cavity Aeroacoustics Predictions," International Journal of Aeroacoustics, Vol. 2, No. 1, pp 65-91, 2003.

Salinas Structural Dynamics Solver

- Part of the Sierra multi-physics simulation package
- Provides a **massively parallel** implementation of structural dynamics (linear and nonlinear) finite element analyses
- Current simulations performed in the time domain
- Linear FEA model with special joint elements





High-Performance Computing

- Both capability and capacity computing resources are used
- High-performance computing is *essential* for this effort

Cielo

- **1.3 Pflops***
- **142,000 cores**
- **LANL/SNL/LLNL resource (NNSA)**

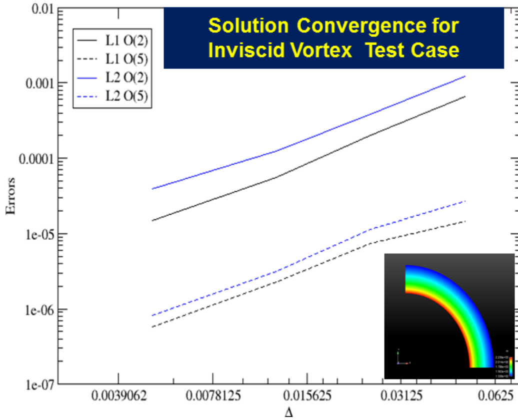
Sequoia

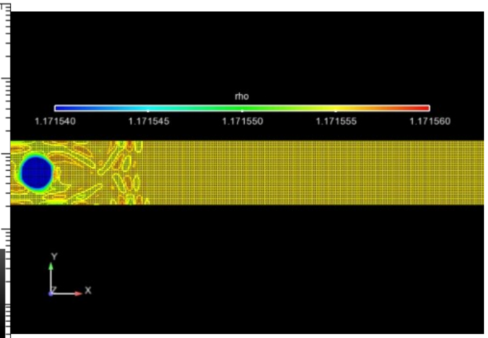
- **20 Pflops**
- **1.5 million cores**
- **LANL/SNL/LLNL resource (NNSA)**

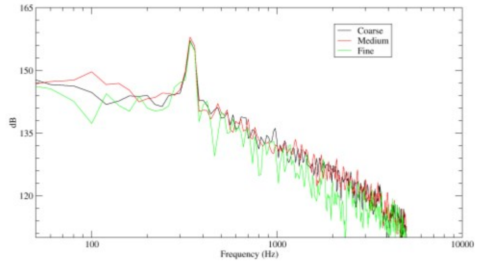
Verification Studies

- Solution Verification to quantify Accuracy of Solver
  - Unit Level Tests to gain confidence in solver accuracy
- Mesh Refinement studies on Cavity Flows
  - Helps identify Meshing requirements for schemes used
  - Confidence in numerics and modeling
    - Both consistency and accuracy are important
  - Both CFD Predictions and Structural Response Predictions are examined.

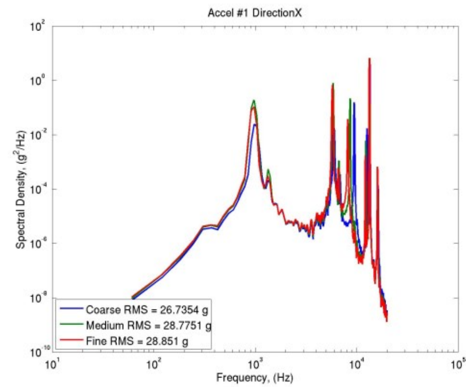
Solution Convergence for Inviscid Vortex Test Case







Bay with Store Mesh Refinement Study: Spectra on a model store - 18m,36m,72m meshes.

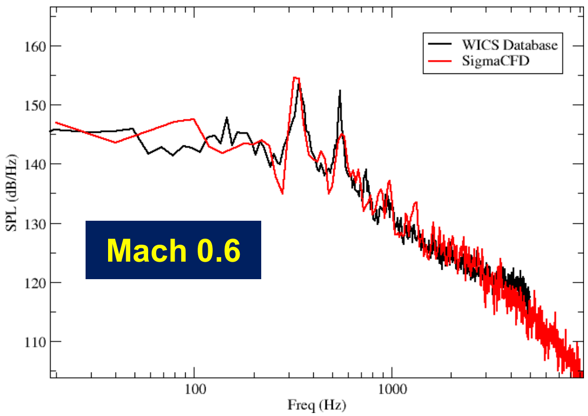


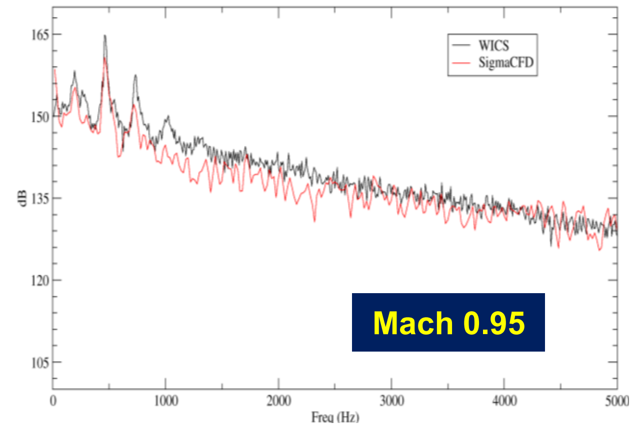
Bay with Store Mesh Refinement Study: Structural Response Spectra on a model store.

Validation of Unsteady Pressure Loads

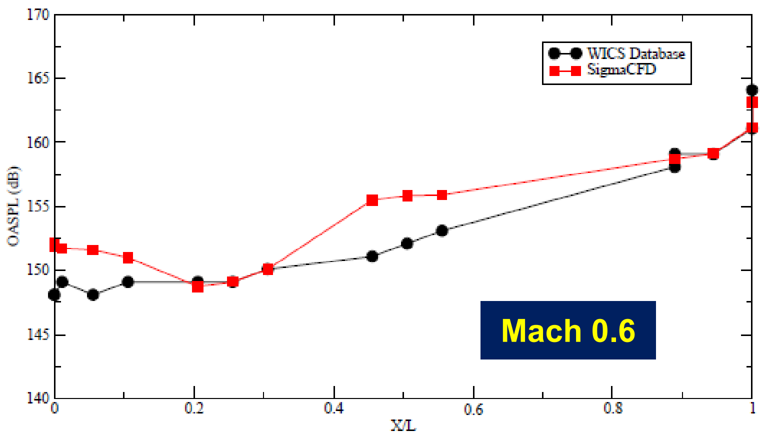
- Overall Approach
  - Use as diverse a source of datasets as possible
- WICS
  - Mach 0.6, 0.95
  - L/D=4.5, Re = 3 million.
  - Only wall pressure PSDs are available.
- Experiments By Murray and Ukeiley – AIAA-2006-2428.
  - L/D=6 Cavity Spanning 2” Tunnel Test Section
  - Wall Pressure and PIV Data available.
- Experiments in Sandia’s TWT
  - LxDxW=5x5x1, Mach 1.5
  - Wall Pressure, PIV and Store Response data available

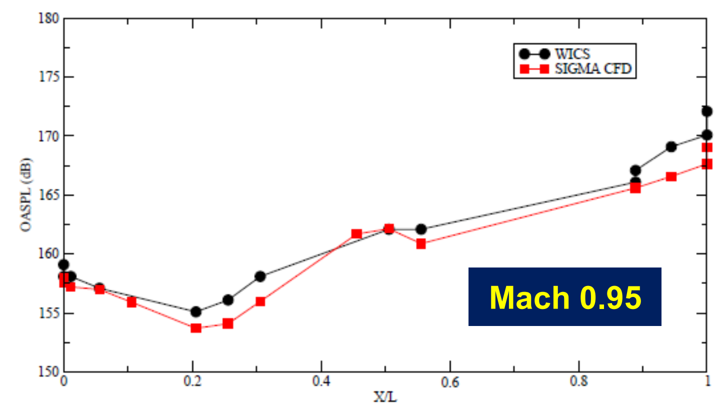
WICS Dataset: Comparison of Pressure Fields





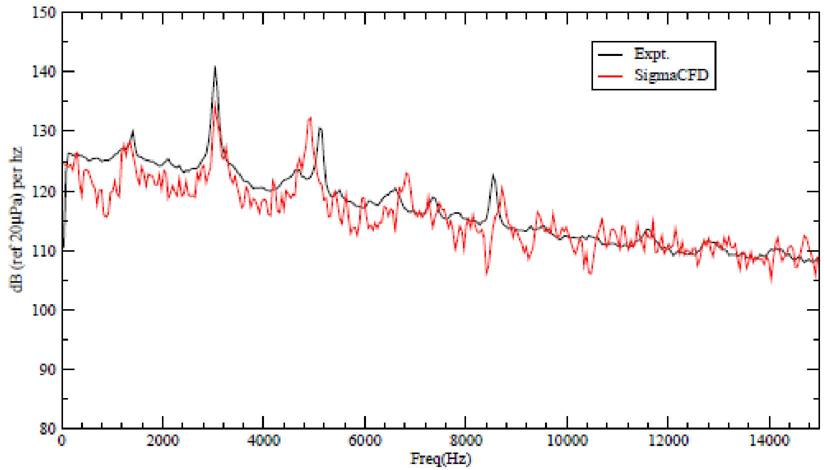
Comparison of Aft Wall Pressure Spectra for WICS Cases



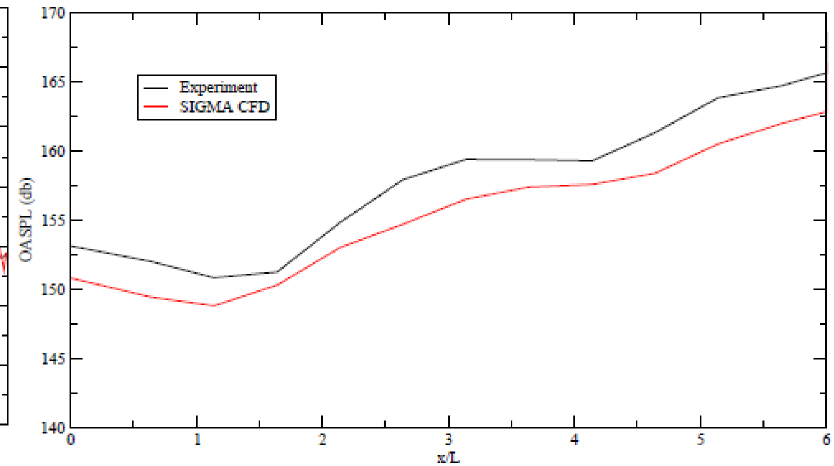


Comparison of OASPL for WICS Cases

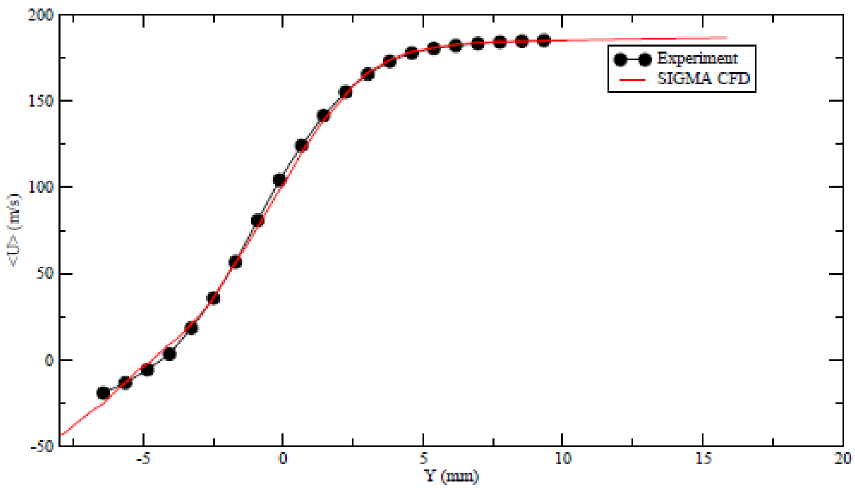
NCPA Dataset: Comparison of Pressures and Flowfield



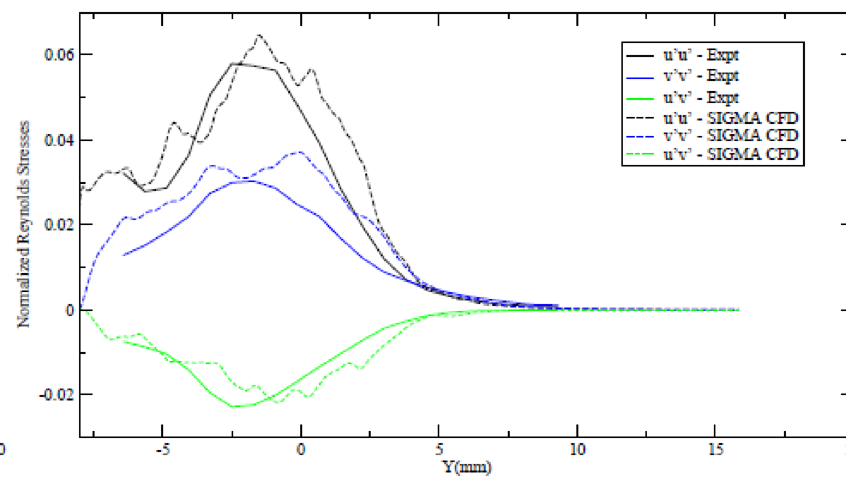
Wall Pressure Spectrum at Mid-Point of Aft Wall



OASPL along Cavity FLoor



Mean Velocity Profile at x/L=0.5



Turbulent Stress Profiles at x/L=0.5

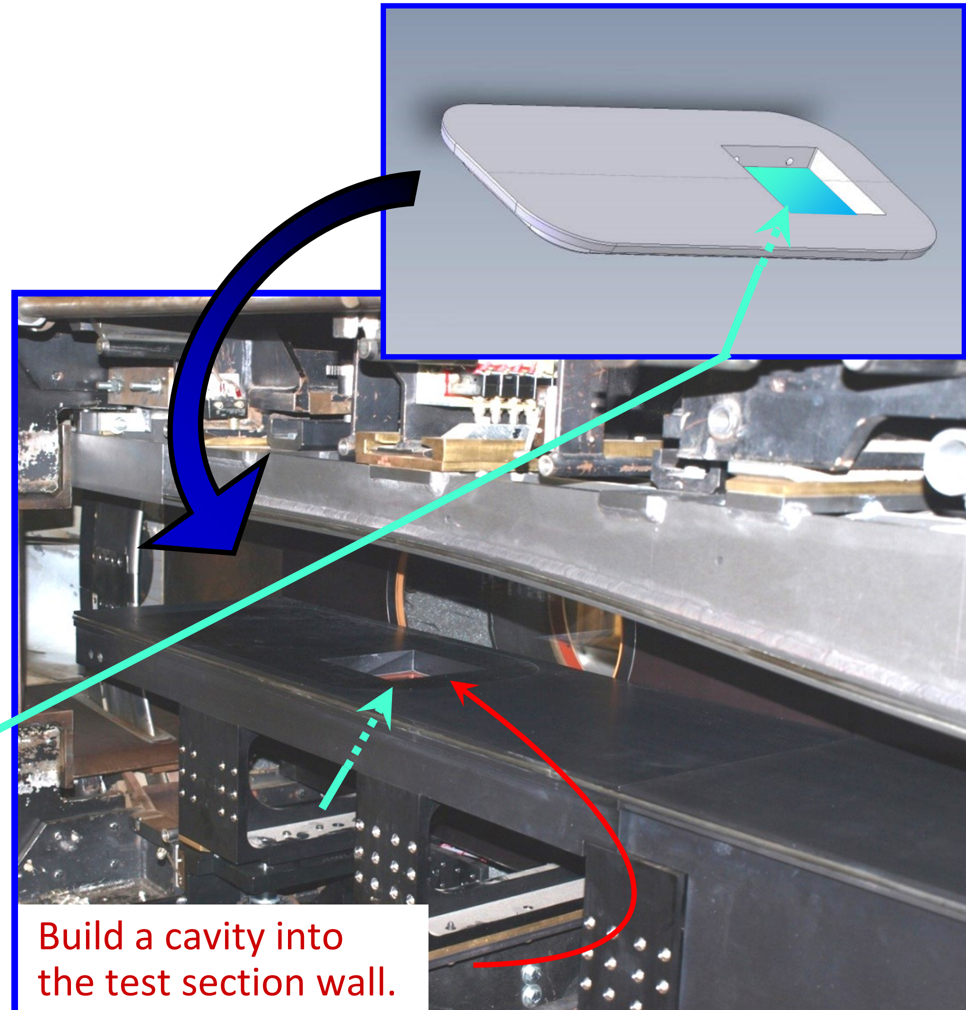
Measurements of Unsteady Pressure Loads

Our 3-D cavity is a rectangular cutout

- **Provides baseline for FSI tests**
- Mounted in either the floor or ceiling of nozzle.
- Length *L* of 127 mm
- Variable depth ***L / D:* of 5 and 3.33**
- Three variables widths for aspect ratios ***L / W* of: 1, 1.7, and 5**

Flow Conditions in the TWT

- Extensive data for Mach 0.5-2.5 for a variety of geometries

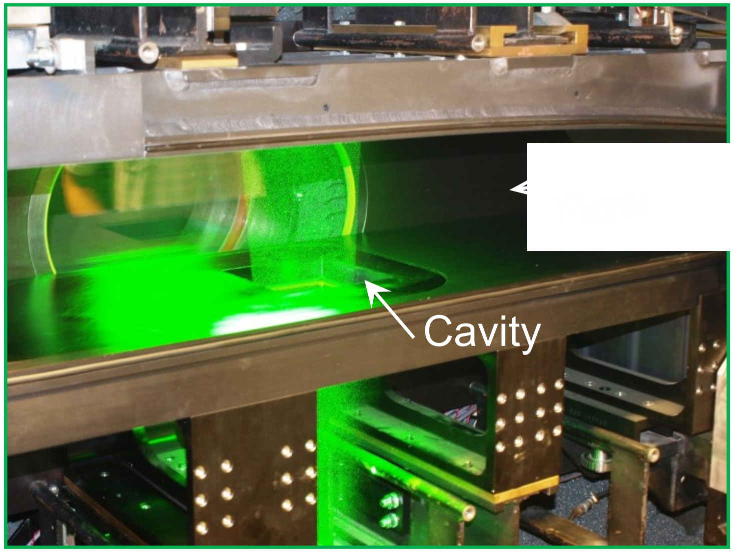


The cavity bottom is glass for laser access.

Pressurized plenum makes finding optical access for cavity flows challenging.

PIV: Supersonic setup

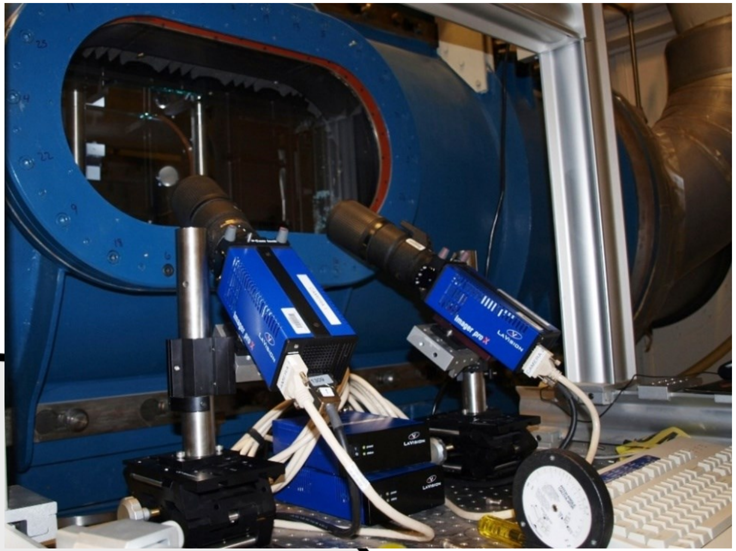
Streamwise Parallel Sheet

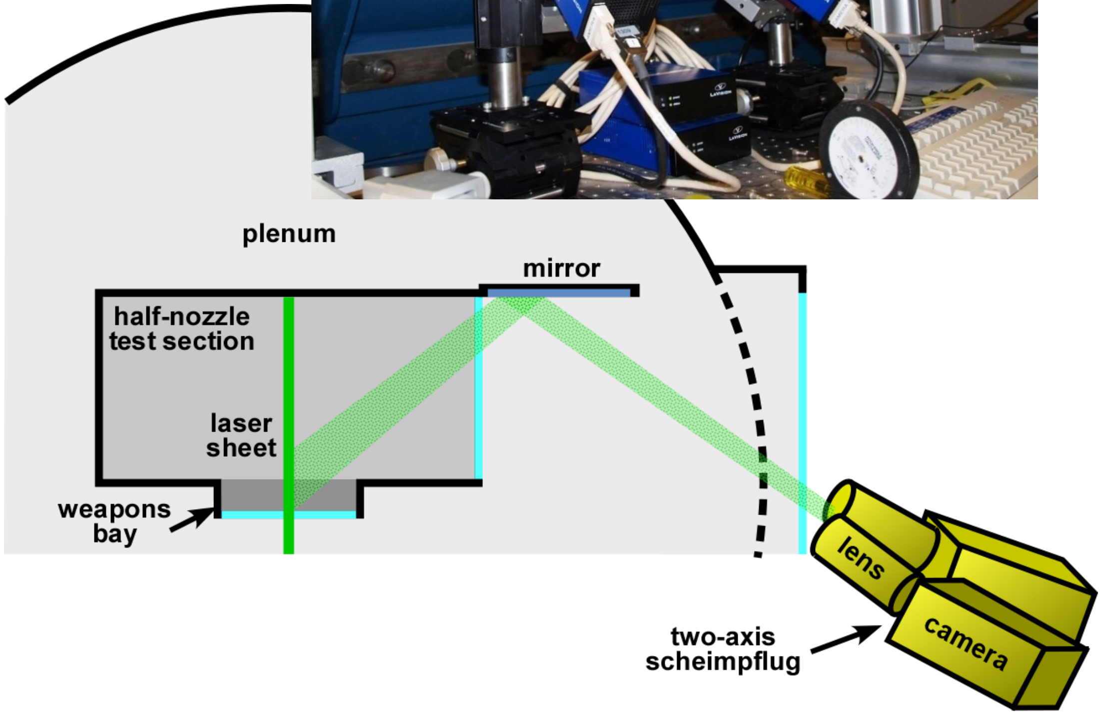


- Solid test section floor occludes view below cavity lip
- Stereo view of aft-end only

Peer into cavity by angling cameras and using a mirror to maximize viewable depth

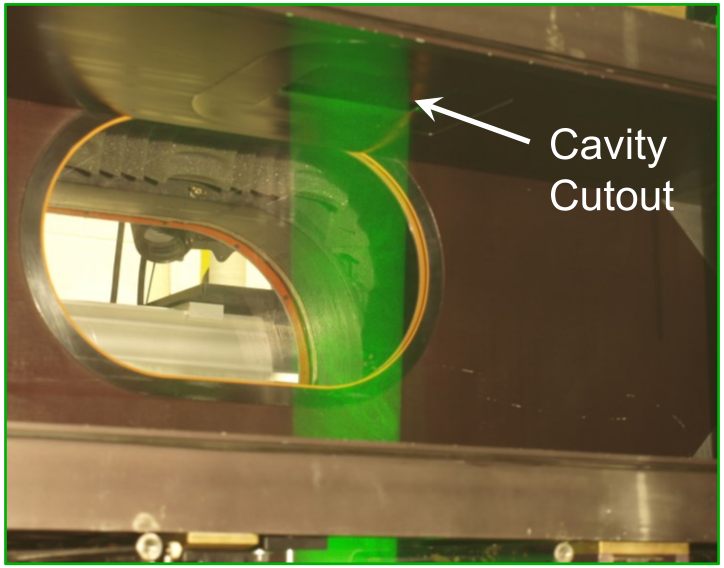
Stereo (3-component) Setup



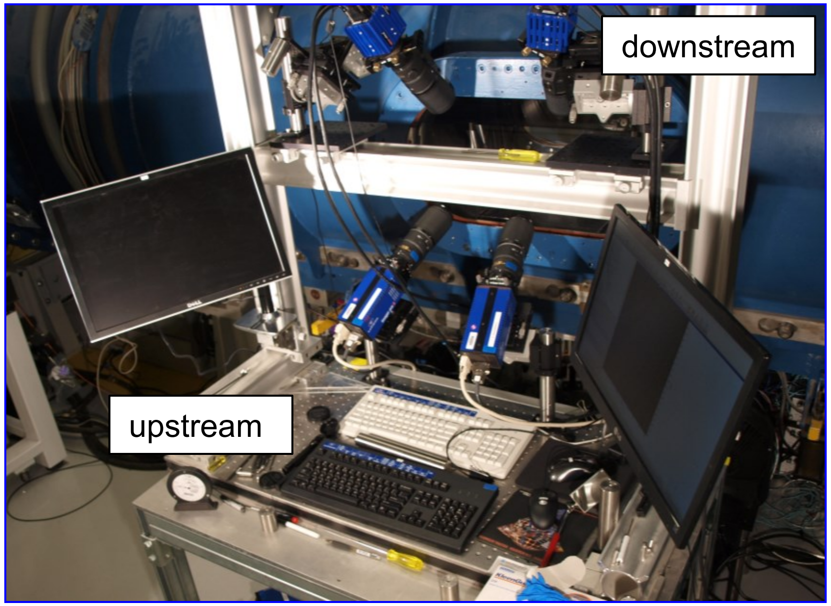


PIV: Transonic setup

Streamwise Parallel Sheet



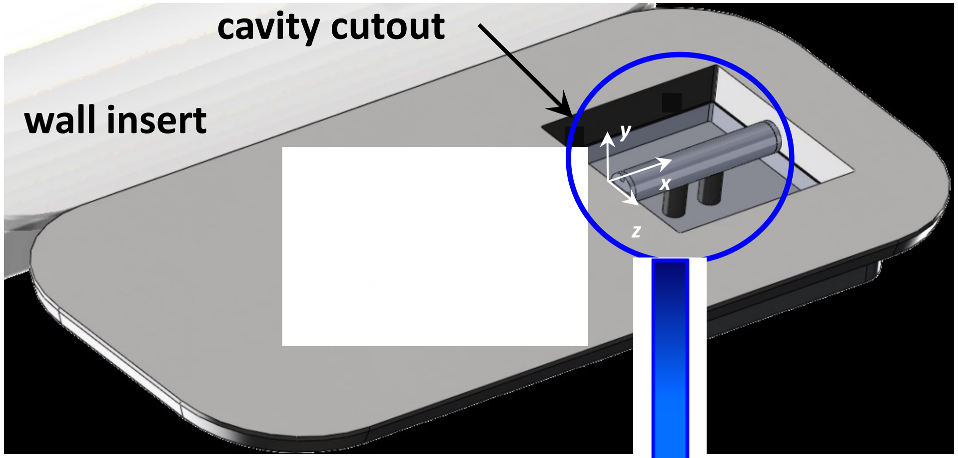
Dual Stereo PIV Setup

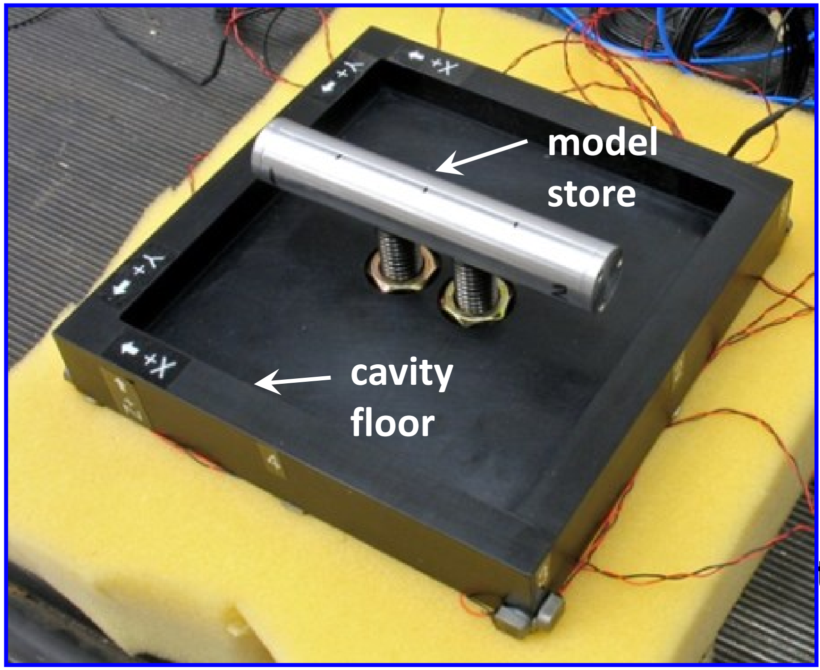


- Cavity now mounted in ceiling of TWT
- Two stereo views for the entire cavity length & to maximize spatial resolution
  - Upstream cameras angled to peer into cavity
  - Downstream cameras see cavity with a mirror to allow a greater view depth

Provides efficient means to acquire data without sacrificing resolution

FSI experimental setup

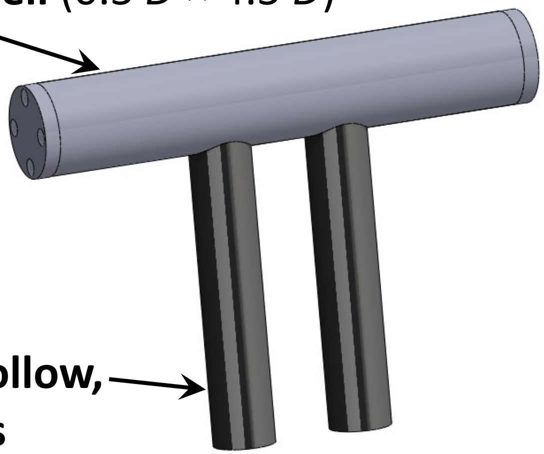




Pa

th

Simplified Model Store

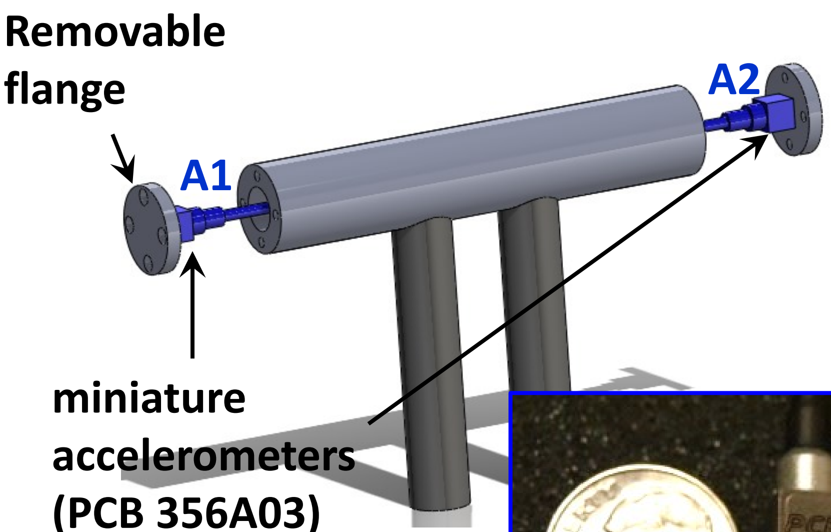


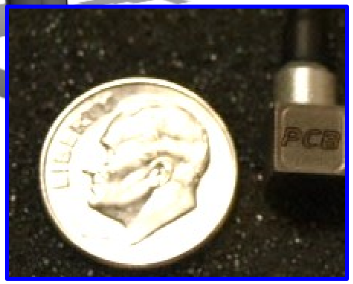
Two main objectives for this simplified geometry:

1) **Development of vibrational diagnostics including miniature accelerometers and laser Doppler Vibrometry (LDV)**
2) **Discovery of the key physical parameters for future experiments**

FSI vibration diagnostics

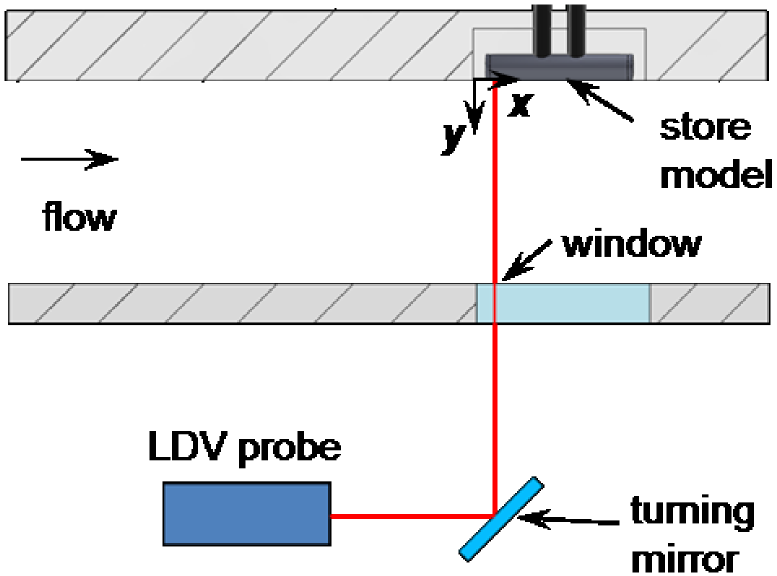
Triaxial Accelerometers





Provides comparison of upstream and downstream accelerations along all three axes

Laser Doppler Vibrometry (LDV)



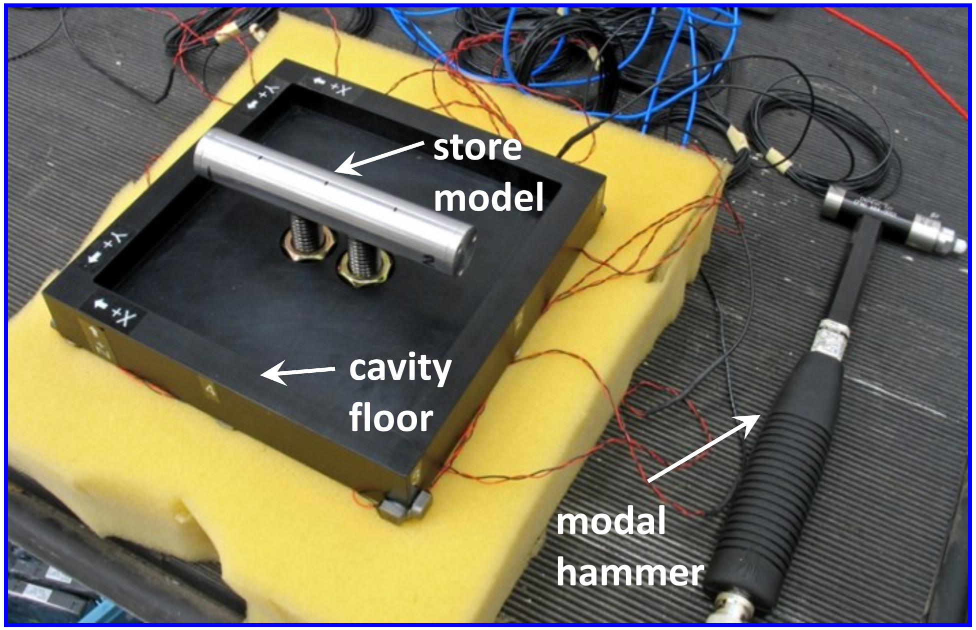
- Polytec (PSV 400) single-component, scanning LDV system
- Doppler shift provides the surface velocity of the store

Provides measurements at many locations along the store, but for one axis

Modal hammer tests

Interpretation of the vibration data requires knowledge of the store's natural frequencies.

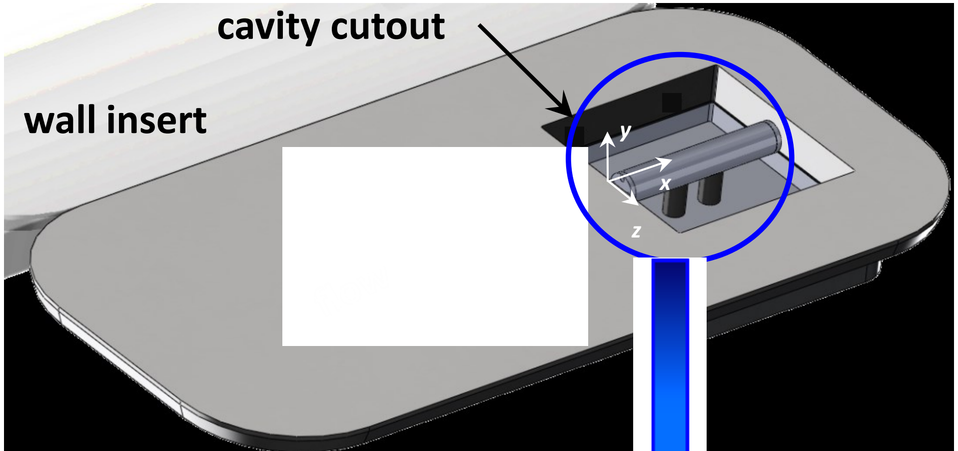
Modal Hammer Test

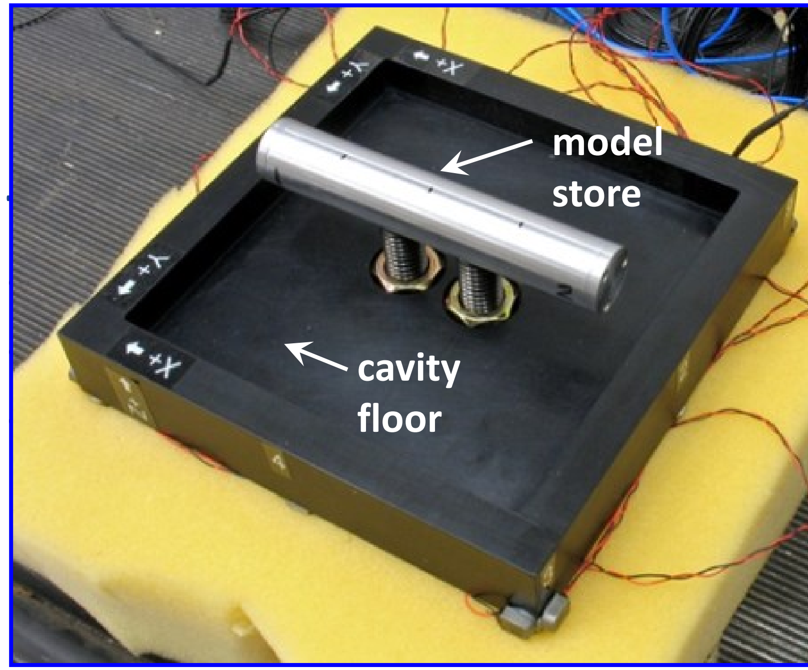


- Model store excited with an impact hammer for frequencies up to 10 kHz
- Force transducer on the hammer tip to measure force input

Natural frequencies for all three axes were obtained

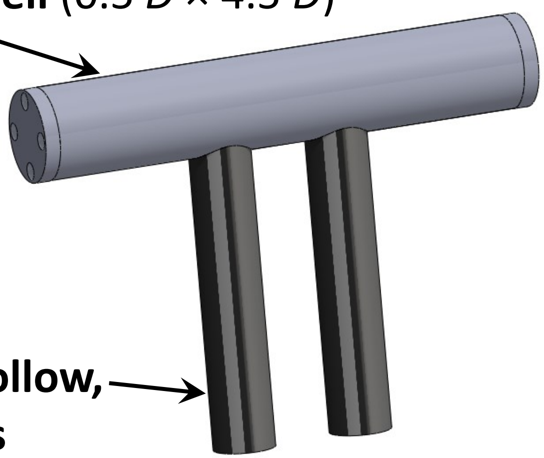
FSI experimental setup - TWT





Simplified Model Store

cylindrical shell (0.5 *D* × 4.5 *D*)



12.7-mm threaded, hollow, support rods

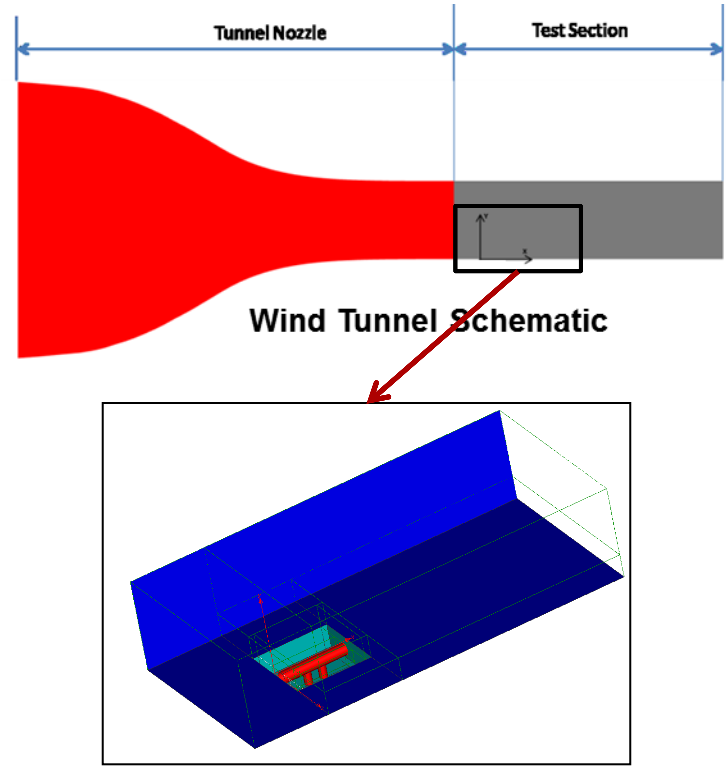
Cavity

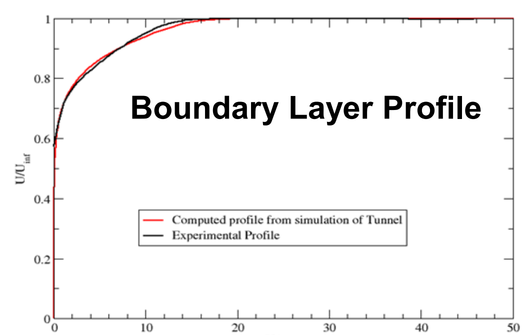
- *D* = 38 mm (δ ≈ 0.4 D)
- *L* / *D* = 3.33, *L* / *W* = 1

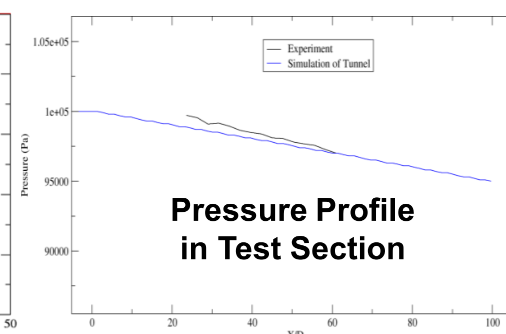
J. Wagner, S. Beresh, J. Henfling, R. Spillers, and J. Blecke. Simultaneous vibration and acoustic measurements of a store in a compressible open cavity flow. AIAA-2013-0228, 2013.

Computation of Unsteady Pressure Loads

- Care is taken to ensure that the “Correct” boundary conditions are being imposed
  - Wind tunnel walls included (side walls modeled with slip b.c.)
  - Non-reflecting sponge b.c. applied at inflow and outflow of subsonic simulations
- Entire TWT tunnel from downstream of settling chamber is modeled in a “Precursor”calculation
  - Downstream pressure boundary condition is adjusted to match the boundary layer profile and pressure gradient measured in the experiments
  - Solution from this at the station corresponding to boundary of DES domain is extracted and used to provide boundary conditions to DES simulation
- Mesh Sizes
  - Empty Cavity: 86M grid cells
  - Cavity With Store: 100M grid cells

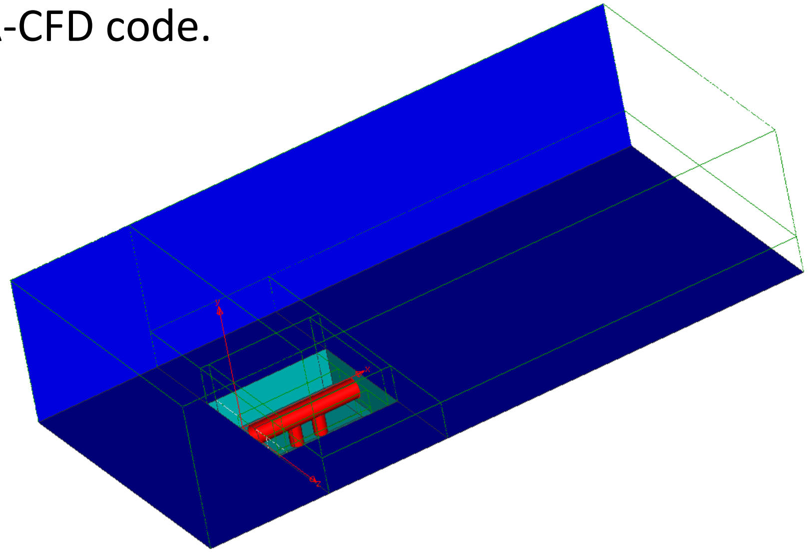






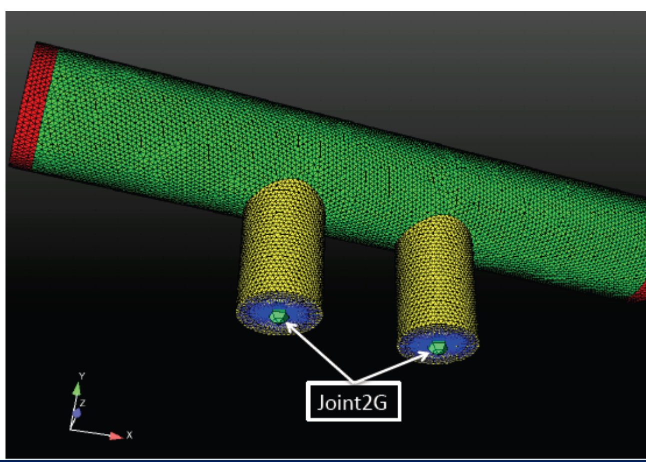
CFD Model

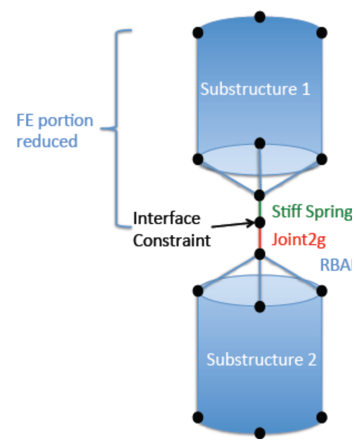
- Wind tunnel walls included (side walls modeled with slip b.c.)
- Non-reflecting sponge b.c. applied at inflow and outflow of subsonic simulations
- Mesh for supersonic cavity-with-store configuration
  - Test section height = 6 inches
  - 86M grid cells
- Mesh for subsonic cavity-with-store configuration
  - Test section height = 12 inches
  - 100M grid cells
- Mesh resolution and time step chosen based on previous empty cavity verification studies with the SIGMA-CFD code.



Store Structural Dynamics Model

- Store Material
  - Aluminum Casing
  - Accelerometer, steel connector and Copper wires modeled to match mass accurately
- Model Verification
  - Mesh resolution studies on modal analysis – first 3 modes converged to within 2% and next 3 modes to within 5%
- Model Calibration
  - Comparisons against measured fixed base modes
  - Joint2G element used to model the fixed base to match nut/washer combination at the base
- Model Validation
  - SD model validated against acceleration measurements from a shaker table test

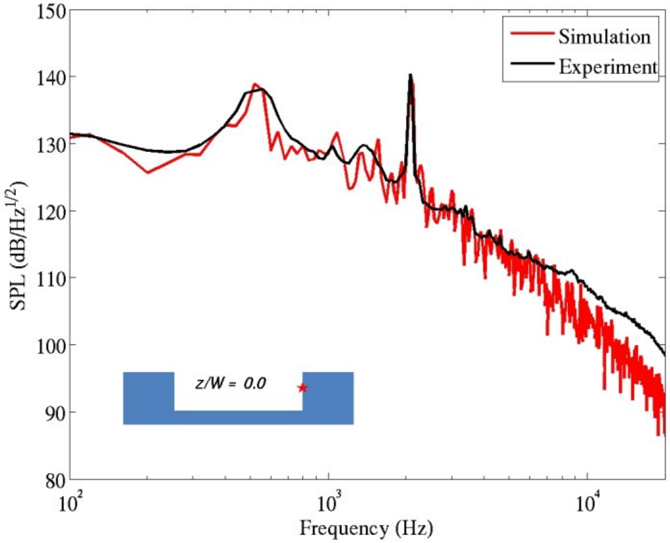




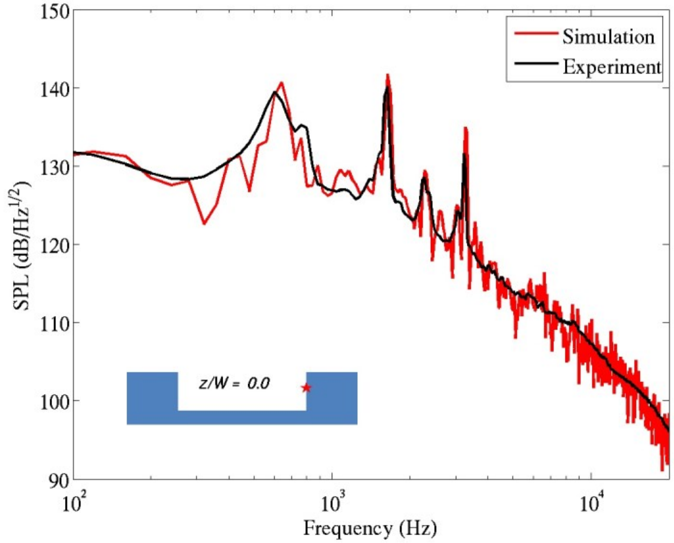
Model Fixed base model using Joint2G element

Computation of Unsteady Pressure Loads: TWT

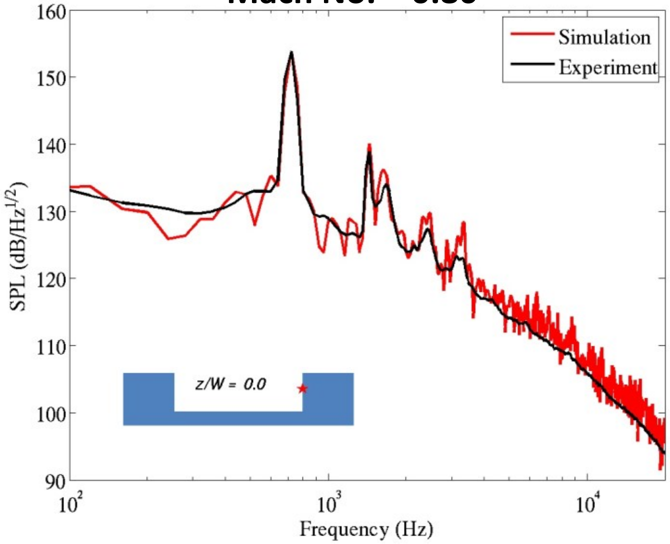
Mach No. = 0.60



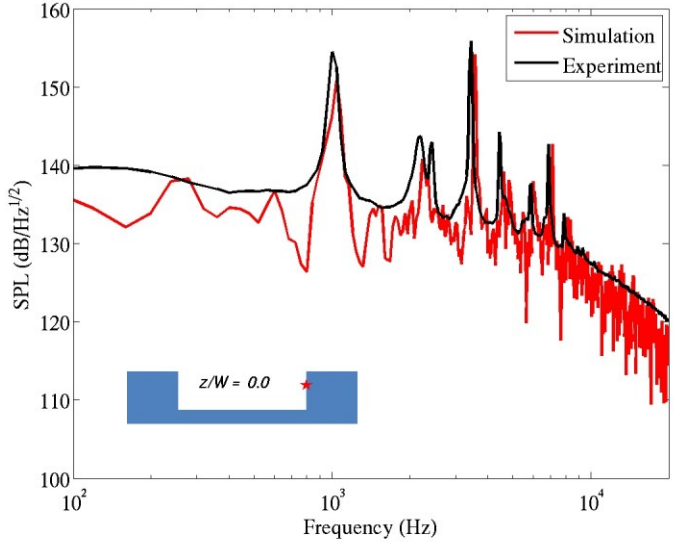
Mach No. = 0.71



Mach No. = 0.80

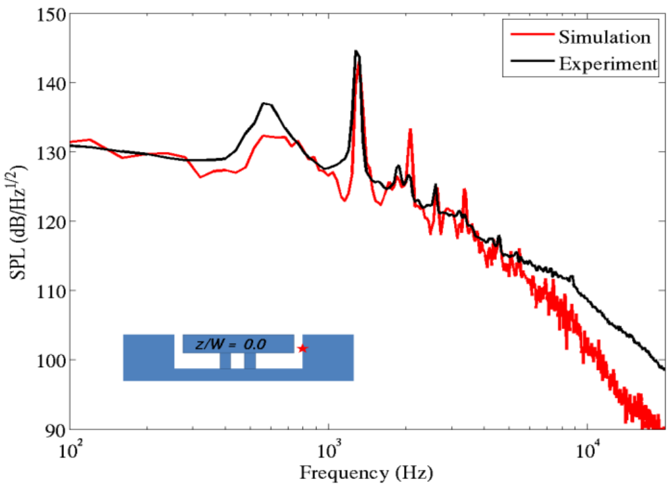


Mach No. = 1.47

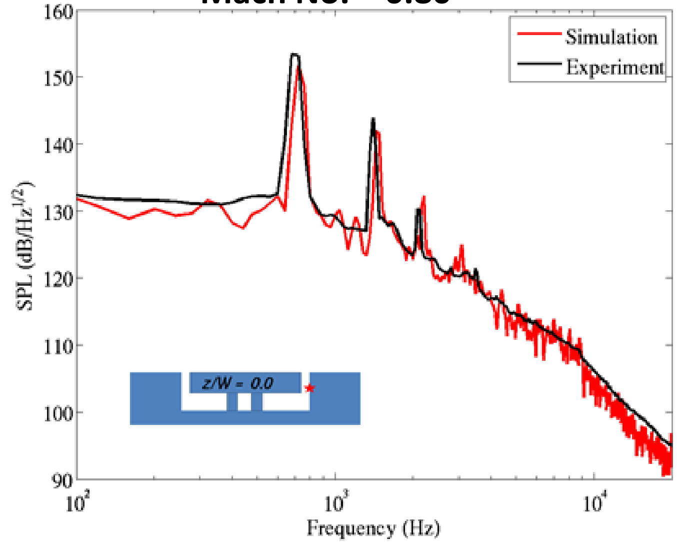


Empty Cavity : Cavity With Store

Mach No. = 0.60



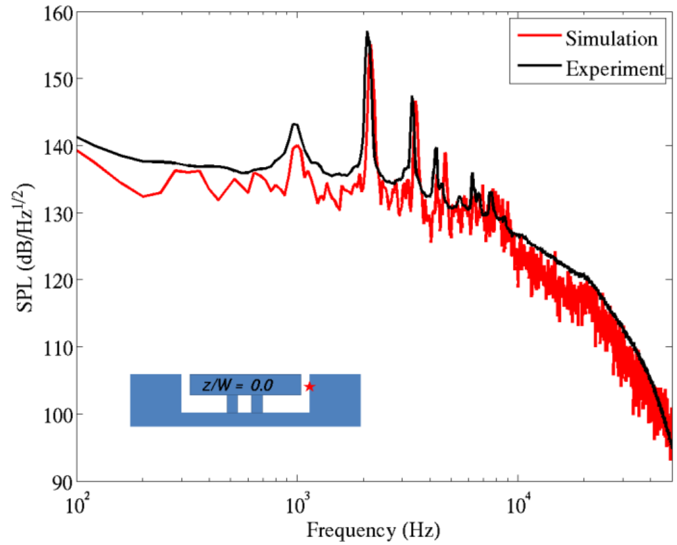
Mach No. = 0.80



x/L	y/D	z/W	Predicted OASPL (dB)	Measured OASPL (dB)	Difference (dB)
0.00	−0.42	0.40	171.0	171.1	-0.1
0.00	−0.42	0.20	171.7	170.1	1.6
0.00	−0.42	0.08	172.2	171.8	0.4
0.00	−0.42	0.00	172.1	170.8	1.3
1.00	−0.33	0.00	178.7	179.3	-0.6
1.00	−0.33	0.08	179.5	178.9	0.6
1.00	−0.33	0.20	178.0	180.4	-2.4
1.00	−0.33	0.40	181.6	180.4	1.2

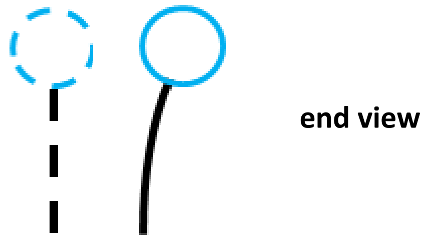
OASPL Comparisons to Measurements

Mach No. = 1.47

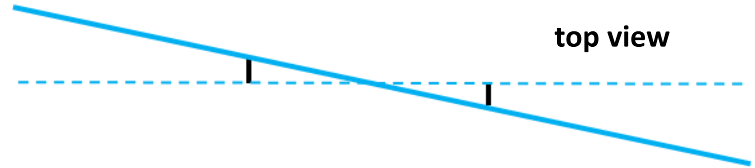


Measured Store Modes

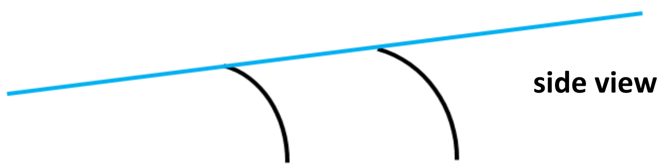
Side-to-side rocking, 1505 Hz



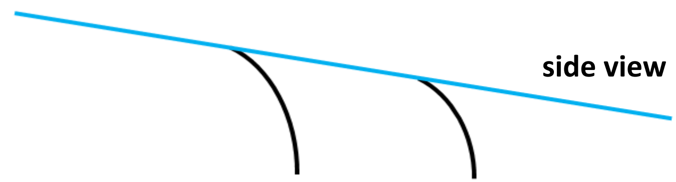
Yawing, 1645 Hz



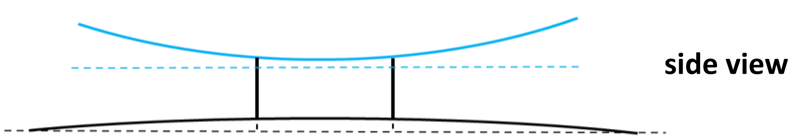
1st rocking fore-aft, 2223 Hz



2nd rocking fore-aft, 4243 Hz



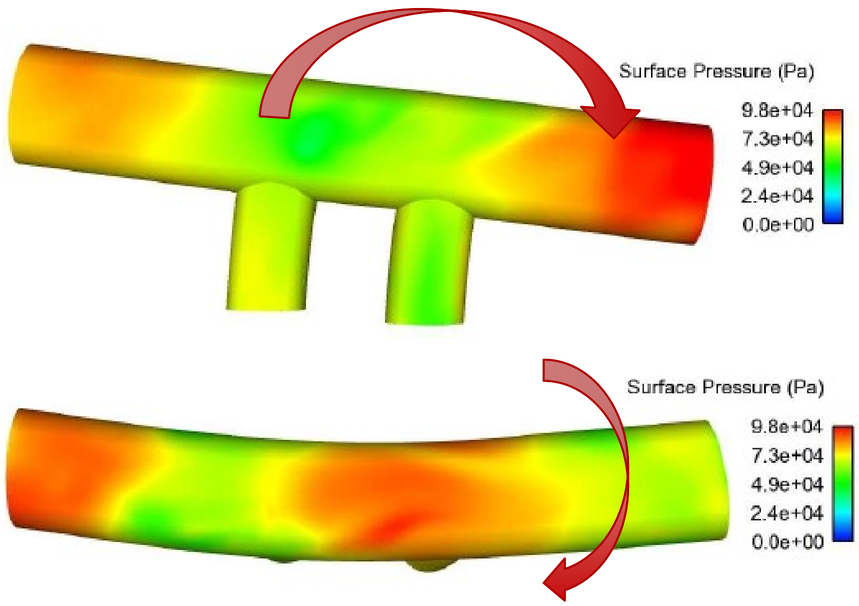
1st vertical bending, 5158 Hz

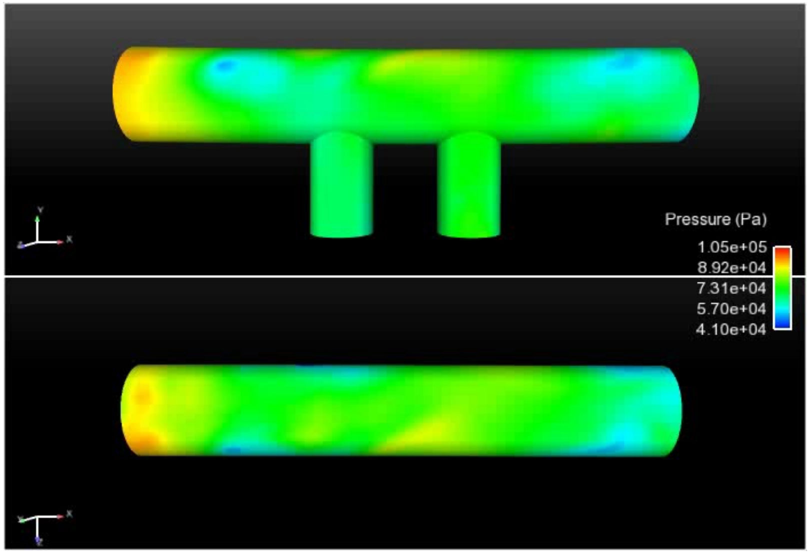


1st horizontal bending, 6638 Hz

FSI Simulations of Store in Cavity – Mach 1.47

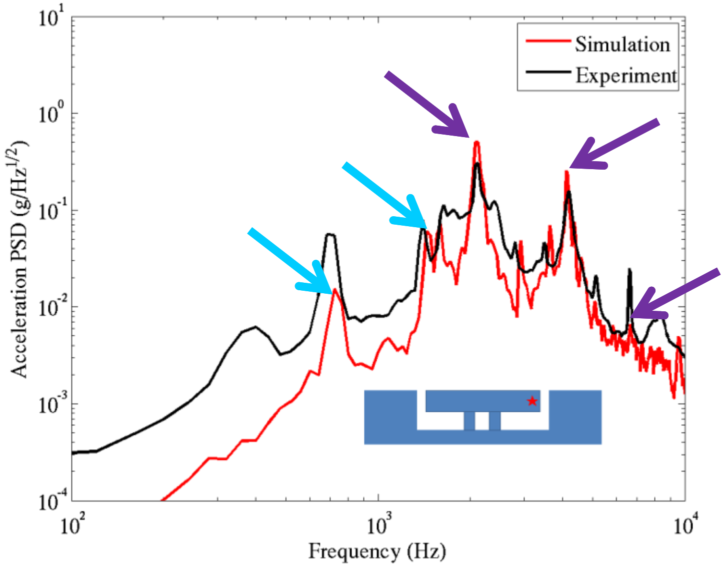
- Store Motion
  - Dominated by a fore-aft rocking motion at 2098Hz.
  - Spanwise bending mode at 6640 Hz is other clearly observable mode



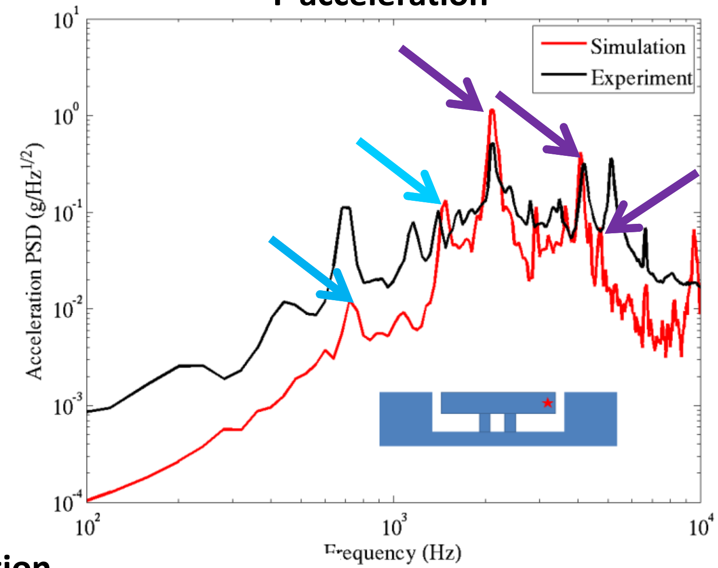


Structural Response : M = 0.80

X-acceleration



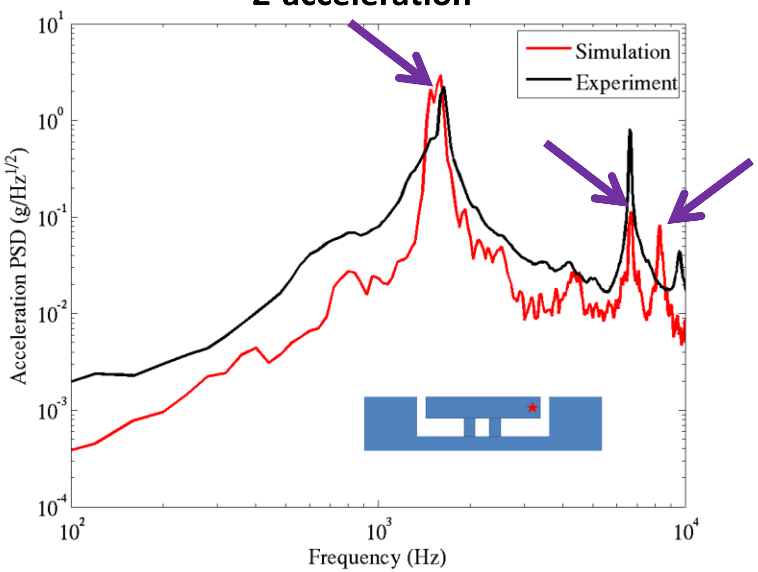
Y-acceleration



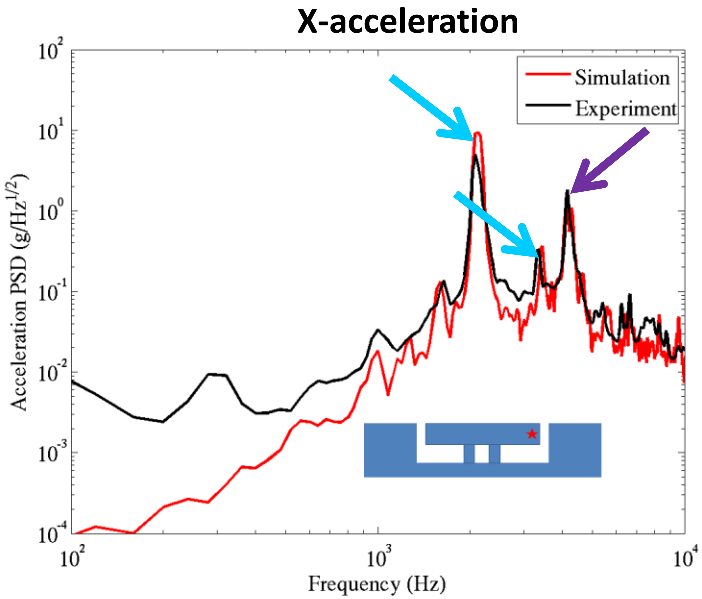
Forced Response

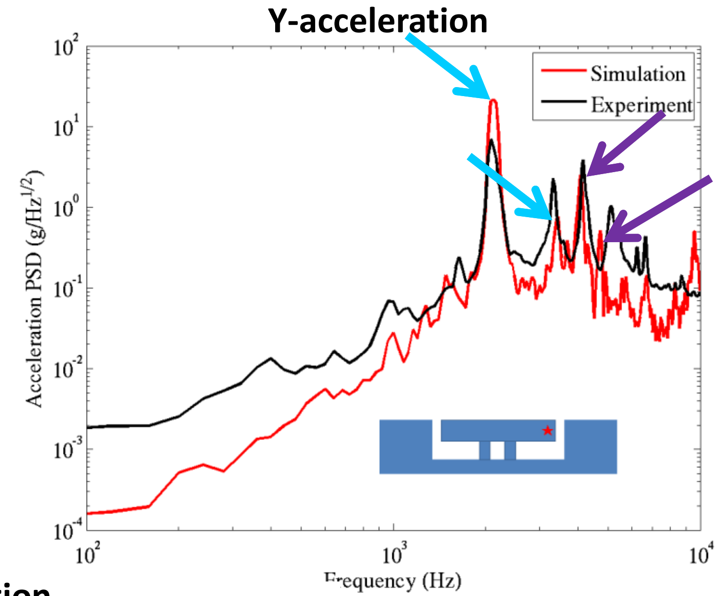
Modal Response

Z-acceleration



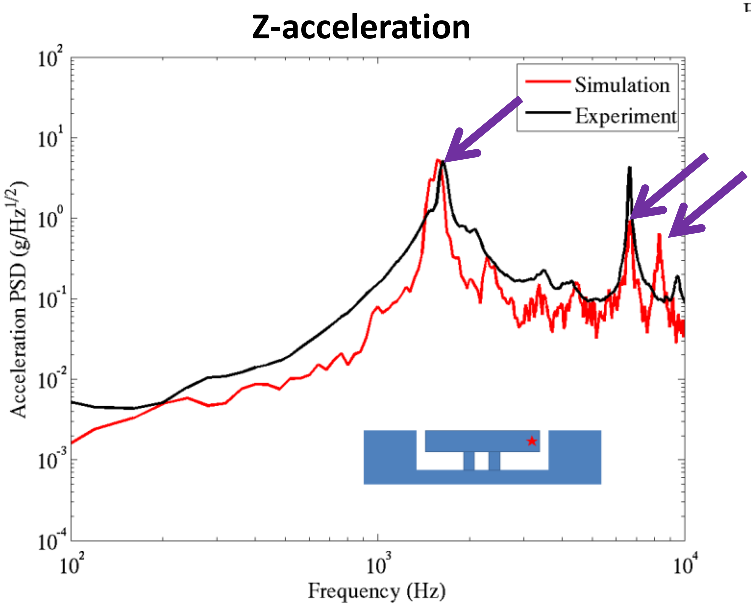
Structural Response : M = 1.47





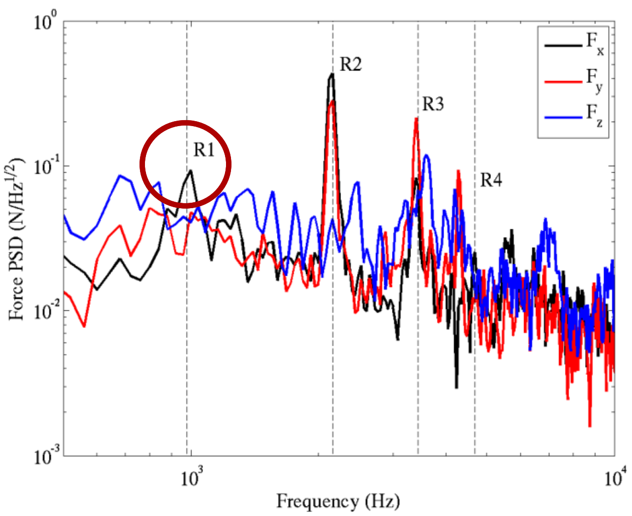
Forced Response

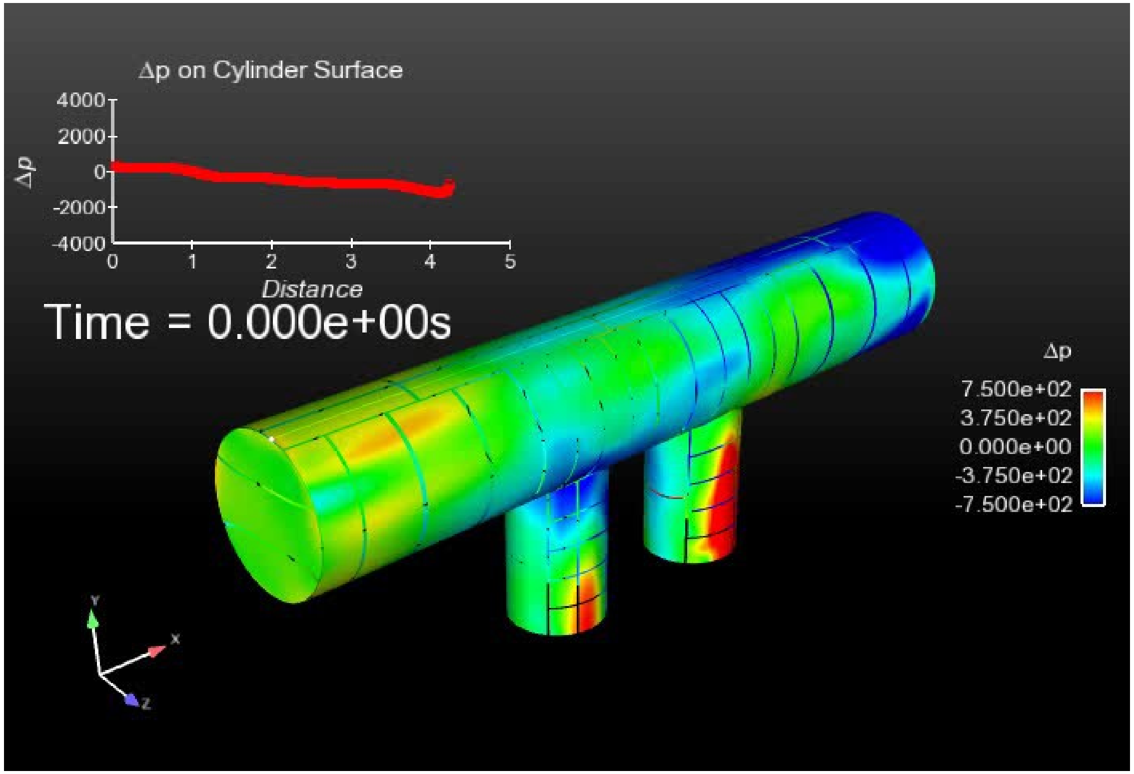
Modal Response



Band-Pass Filtered Pressure Fields

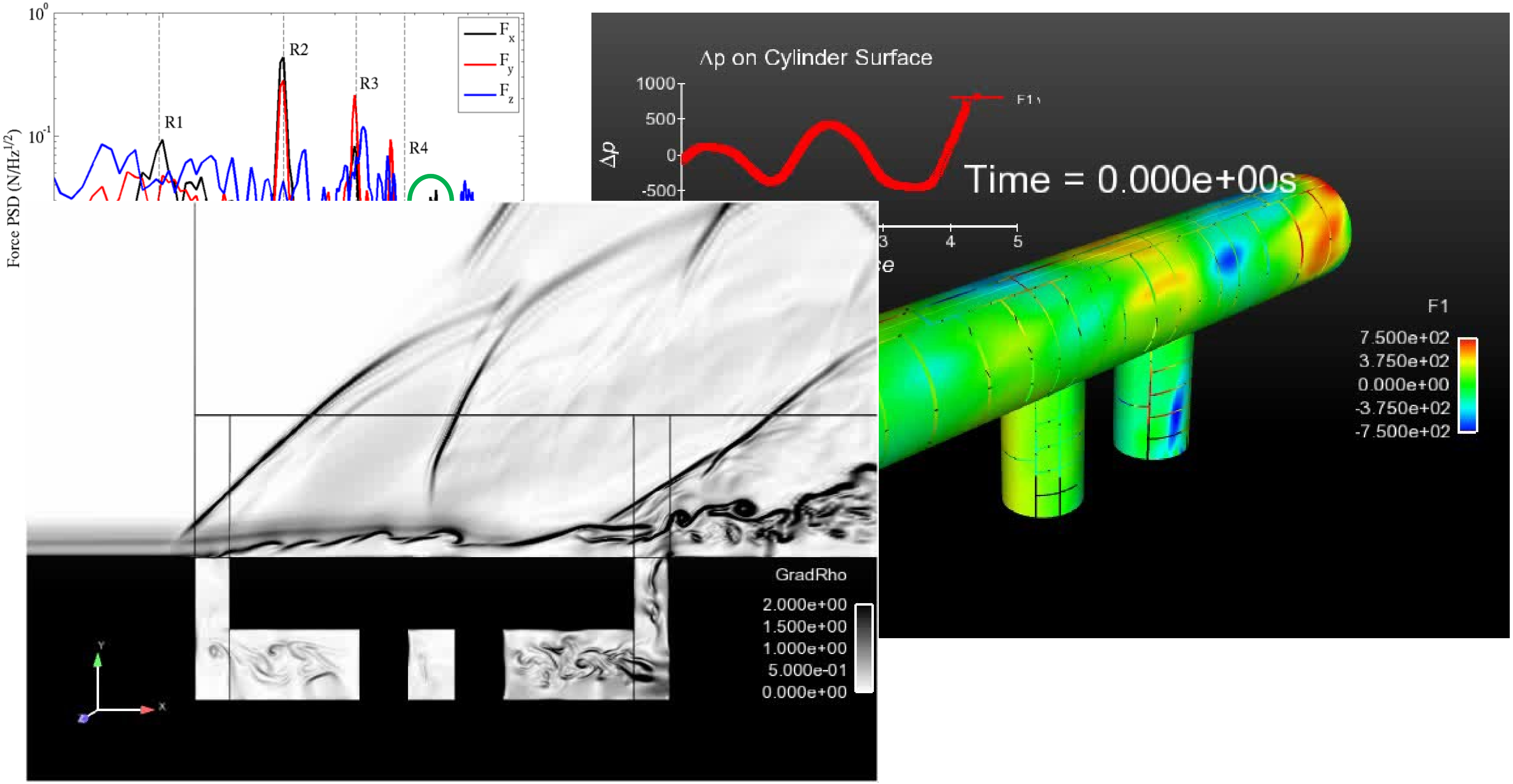
M=1.47, 1000 Hz, 1^{st} Rossiter Mode



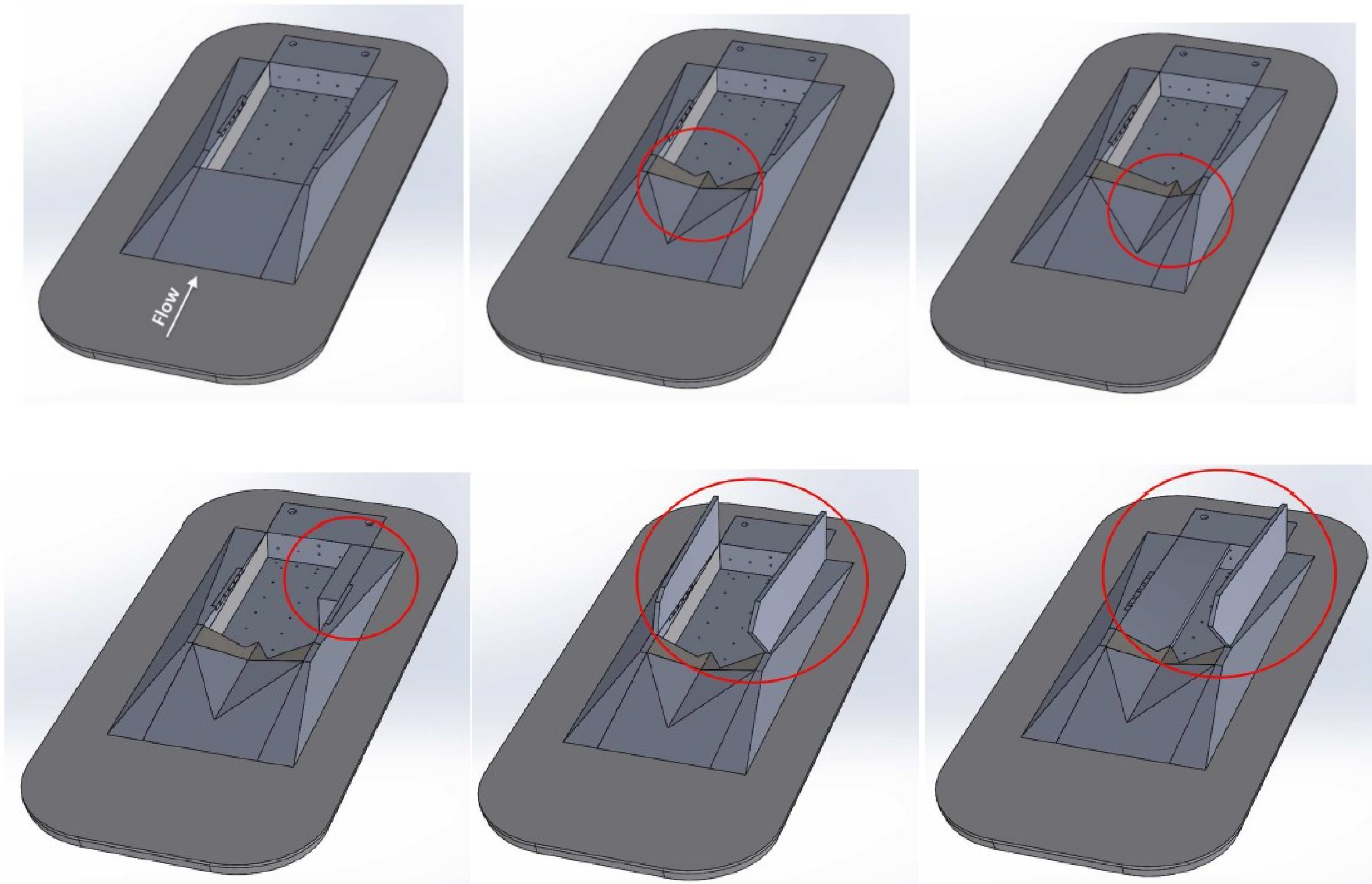


Band-Pass Filtered Pressure Fields

M=1.47, 5580 Hz, possibly 5th Rossiter Mode



Complex Cavity Study



Current and Future Work

- Refinement of model store structural dynamics model
- Need to include UQ for ES 3.0 – some relevant uncertainties:
  - Flight conditions
  - Structural dynamics model parameters
  - Weapon unit-to-unit variability
  - Turbulence model form
- Model reduction techniques
  - Less costly models derived from high-fidelity simulations
  - Useful for long-time integrations, UQ studies
- Two-way fluid-structure coupling
  - Implementation for SIGMA/Salinas currently underway
- Unstructured Grid CFD
  - Sierra gas dynamics code (“Conchas”), testing is in progress

Summary and Conclusions

- High-fidelity coupled fluid/structure simulations are being used to establish captive carriage environmental specifications for the B61-LEP
- Validation studies are being used to establish accuracy of the simulation approach
  - Results to date show “good” predictive capability
  - Refinements to the models should further improve results
  - A plan for a thorough hierarchical validation is in place