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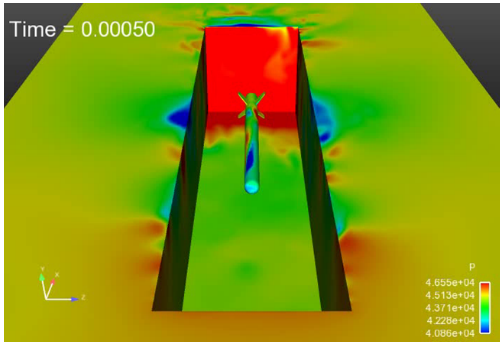

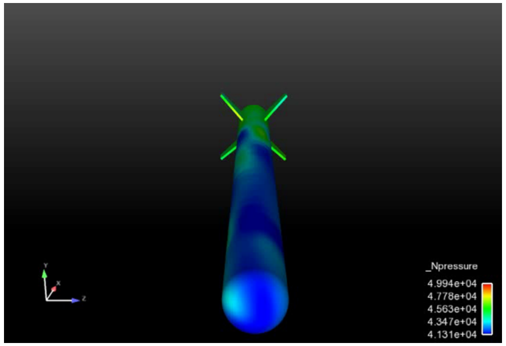

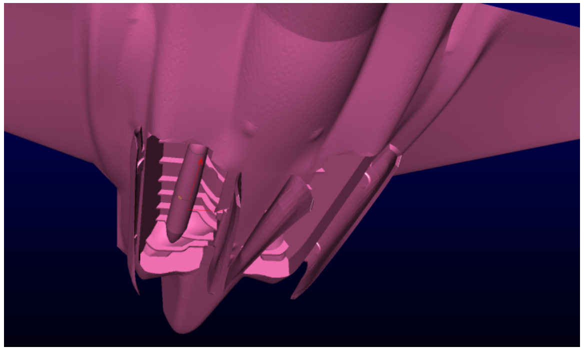

ESRF External Review

Computational Aerodynamic Loading Prediction for Captive Carriage

Micah Howard, Srinivasan Arunajatesan, Matt Barone, Travis Fisher

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

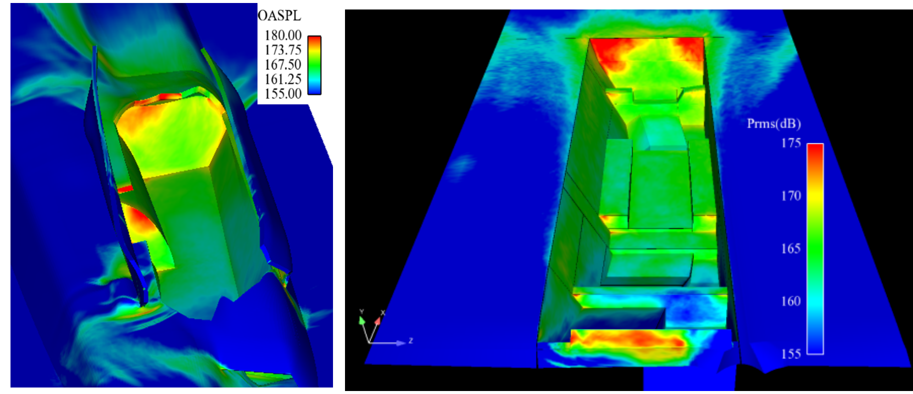
- Background
- Current work for captive carriage problems
  - Computation of unsteady pressure loads
  - Sigma CFD Code: methods and models
  - Application to model problem
- Numerics and algorithms research and development
  - Low-dissipation flux schemes
  - Higher-order discretizations – structured and unstructured
  - Turbulence modeling
- Uncertainty Quantification
  - Approaches for aleatoric uncertainty using ROMs
- Summary

Background

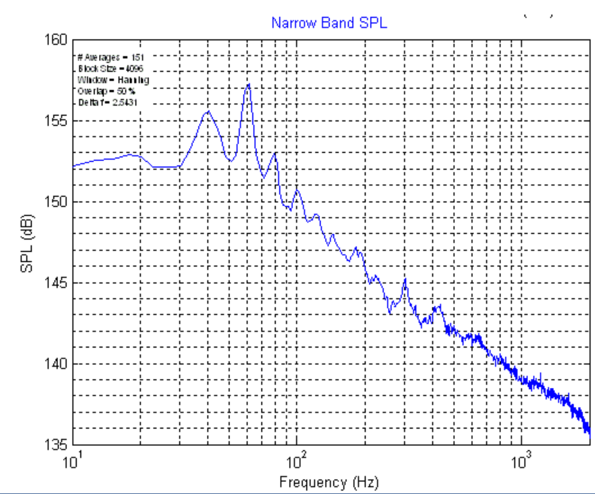
- Problem of interest: store in the weapons bay of an aircraft
- Sandia's interest is the store itself
  - Store and component response in Captive Carriage
    - Environment must be well understood
    - Acceleration/vibration experienced when subjected to this environment
    - Components must survive and perform as designed
- Prior work on stores in weapons bays
  - Focused on the release event
    - Store trajectories and unsteady effects on the trajectories
  - Very little work on component response and accelerations

Background

- Stores in Weapons Bays Experience Intense Aero-Loading
  - Dynamic loads can exceed 165dB
- Tonal Content Can be Strong
  - Considerable evidence exists that tonal content is present in complex bays at full scale
  - Narrow band behavior – concentration at distinct frequencies can get very high
  - If these frequencies match structural modes, it can have sever consequences
  - Effects need to be understood for the harsh environment of the F-35



Dynamic Pressure Load Levels in Complex Bays*

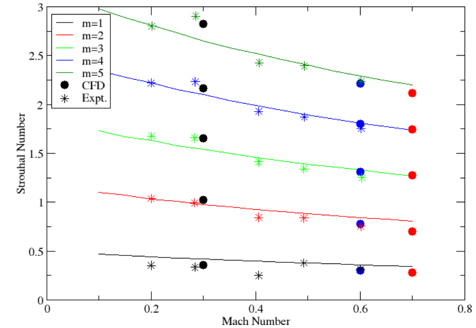


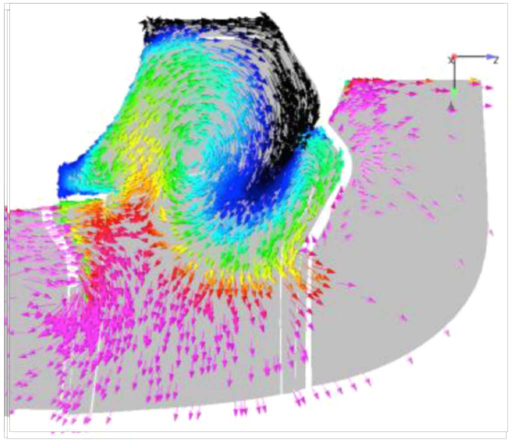
Narrow Band Spectra in Full Scale Configuration

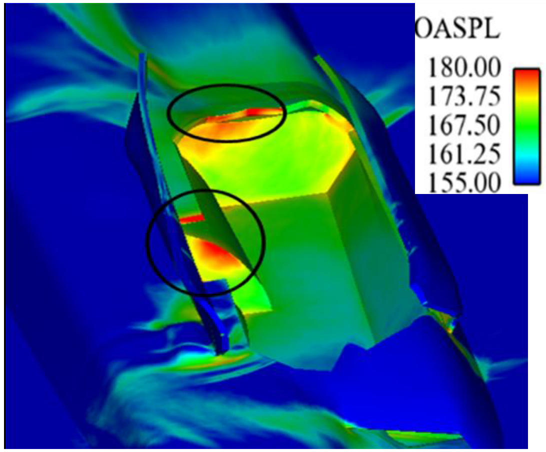
* Images from DOI 10.1109/HPCMP-UGC.2010.66 and DOI 10.1109/HPCMP-UGC.2009.14, respectively

Background

- Physics of weapons bays reasonably understood using cavity flow as a model problem
  - Rossiter's Formula & More Complex Models (Kerschen et al. etc) also exist
    - Simple formulas can only predict possible frequencies
    - Cannot predict what modes will occur under what circumstances
    - Cannot predict amplitude and spatial variations in loading
- To truly capture the physics we need high fidelity CFD
  - Highly non-linear flow field with strong fluid-acoustic coupling
  - Generates strong pressure fluctuations on the bay and store surfaces
  - Important to capture these non-linear interactions to accurately model the bay environment







Flow field and bay surface pressure loads visualizations from recent CFD simulations of the JSF bay (AIAA-2011-2774)

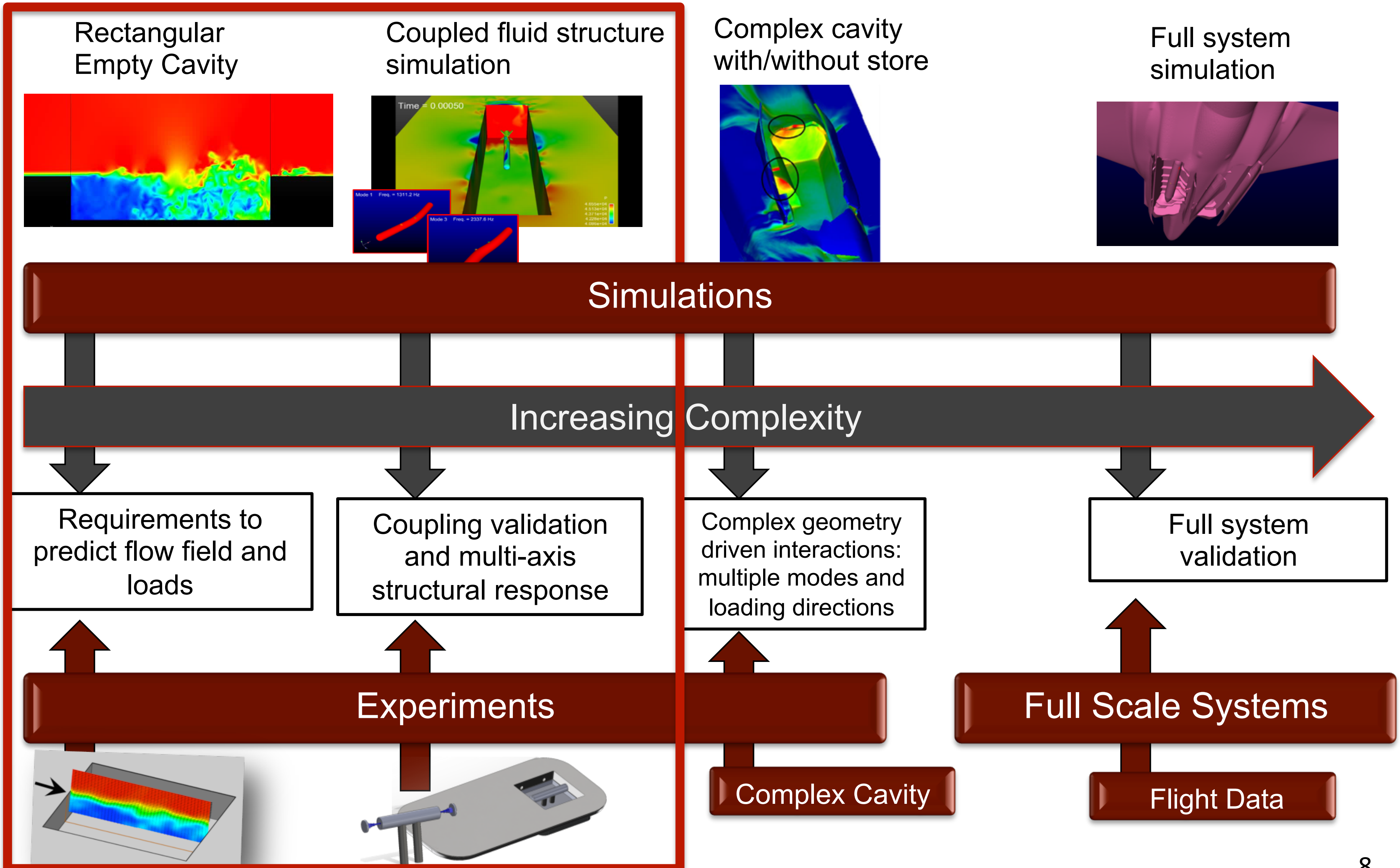
Background

- Some characteristics of Captive Carriage environment
  - Small deflections
    - Store is held captive, motion is small and restricted
  - Large accelerations
    - Affects survivability of the store's internal components
  - For simulations
    - Important to capture the distributed loading on the store
    - Accurate load transfer to the store structural dynamics model
- One-way coupling can work effectively
  - Small store motion does not significantly affect flow field
  - Complications and computational cost mesh motion not necessary

Objectives

- Develop a Coupled FSI Modeling Capability for Captive Carriage Applications
  - Need accurate predictions of store response to aerodynamic loading in weapons bays
- Requirements
  - Accurate Computations of
    - Unsteady Pressure Loads – Complex geometries
    - Structural Response – Mounts and nonlinearity of them
  - Consistent and Convergent Behavior
    - Force Transfer Consistency
    - Mesh and time step convergence – DES, long run times
  - Validation
    - Need Detailed Measurements
      - Surface Pressures, Flow field and Store Vibration response

Captive Carry Mod-Sim Progression



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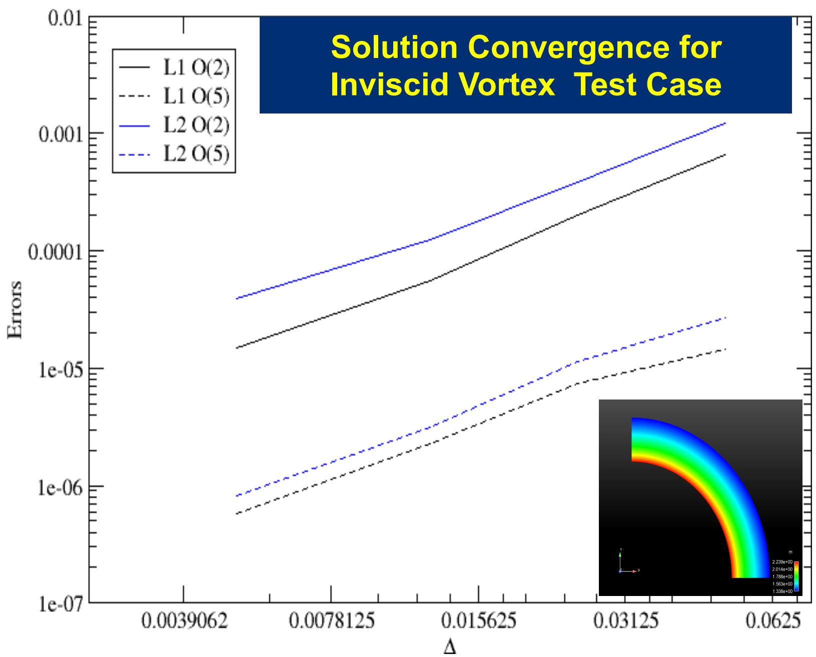
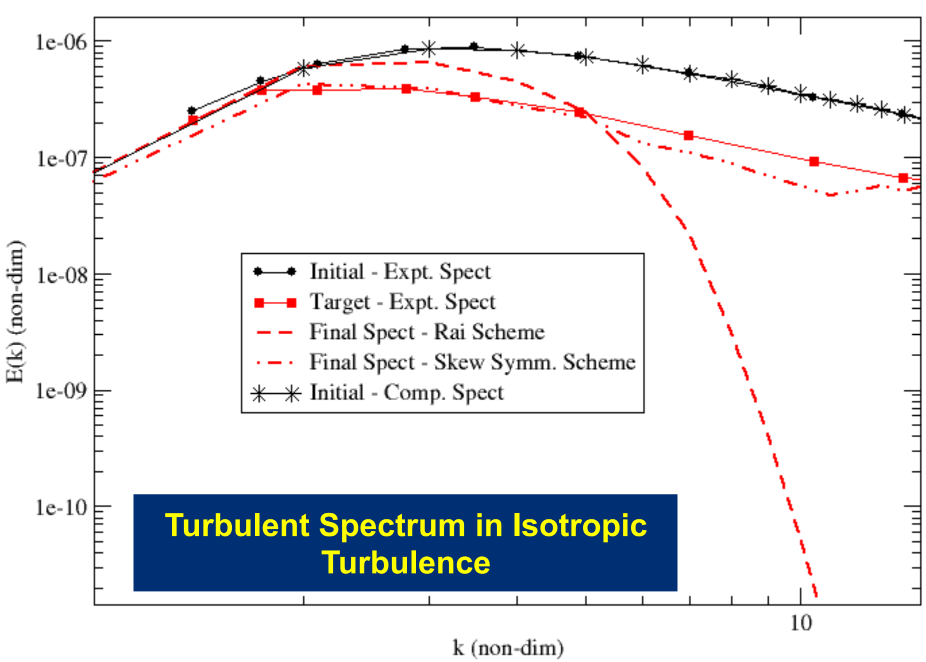
Computation of Unsteady Pressure Loads

- 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
  - Lower Dissipation Fluxes with reduced errors
  - Implicit Time integration
  - Advanced Turbulence Models – Hybrid RANS-LES (SST-DES and K^{sgs})





K^{sgs} Hybrid RANS-LES Model

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- Known : Turbulence at every point in flow satisfies a spectrum
  - Parameterized by energy containing wave number k_e
  - K^{sgs}= integral from smallest η scale to Δ
    - **Solved iteratively to obtain k_e**
  - Once all length scales are known
    - Compute eddy-viscosity to support only unresolved scales.

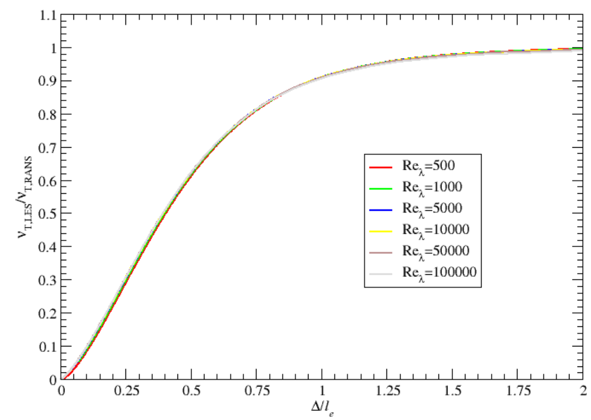
$$\hat{E}(\hat{k}) = C_e \hat{k}_e^{-5/3}\left(\frac{\hat{k}}{\hat{k}_e}\right)^4\left[1+\left(\frac{\hat{k}}{\hat{k}_e}\right)^2\right]^{-17/6}\exp\left(-\frac{3}{2}a\hat{k}^{4/3}\right)$$

$$\varepsilon = \int_0^1 \hat{D}(\hat{k}) = \int_0^1 2\hat{k}^2\hat{E}(\hat{k})d\hat{k};$$

$$\eta = \left(\upsilon^3/\varepsilon\right)^{1/4}; k^{sgs} = \int_{k\Delta}^{\infty} E(k)\,dk; \quad \varepsilon^{sgs} = \int_{k\Delta}^{\infty} D(k)\,dk$$

$$\nu_{T,LES} = f_\mu C_\mu \frac{k^{sgs2}}{\varepsilon^{sgs}}; \mathrm{Re}_\lambda = \left(\frac{20}{3}\right)^{1/2}\frac{k^{RANS}}{\sqrt{\upsilon\varepsilon}} = \int_0^1 \hat{E}(\hat{k})d\hat{k}$$

- Steps
  - Given ε, compute η $\quad \eta = \left(\upsilon^3/\varepsilon\right)^{1/4}$
  - Iteratively Solve for k_e $\quad k^{sgs} = \int_{k\Delta}^{\infty} E(k)\,dk$
  - Compute ε^{sgs} $\quad \varepsilon^{sgs} = \int_{k\Delta}^{\infty} D(k)\,dk$
  - Compute υ_T^{LES} $\quad \nu_{T,LES} = f_\mu C_\mu \frac{k^{sgs2}}{\varepsilon^{sgs}}$
- Observation
  - Iterative solution in step 2 can be very expensive and ill behaved
  - Eddy-viscosity Ratio (LES to RANS) collapses for different Re_λ!!!
  - Can be used to Simplify Model!!!



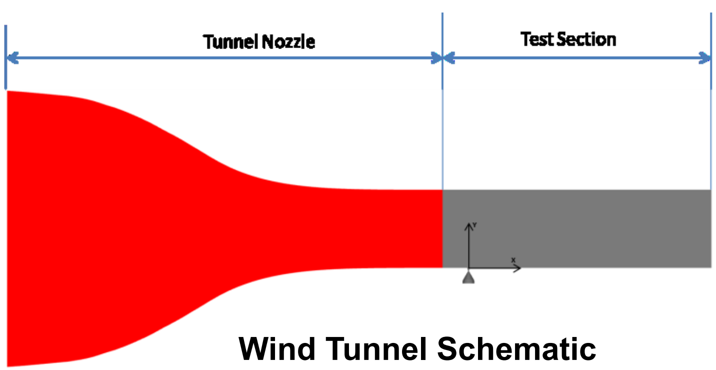
Eddy Viscosity Ratio as a function of Mesh to Turbulent Length scale ratio

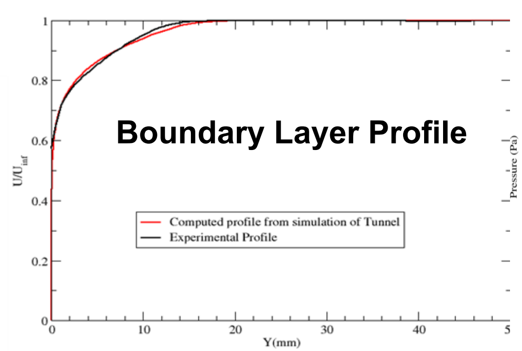
Computation of Unsteady Pressure Loads

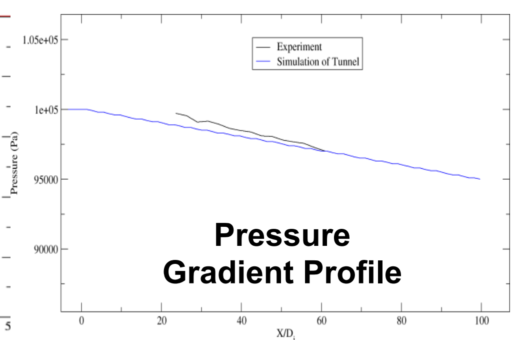
- Validations
  - Against AEDC's Weapons Internal Carriage and Separation (WICS) cavity flow database
    - Large dataset covering wide range of parameters
    - Only wall pressure PSD data available, no flow field data
    - L/D=4.5, δ/D ~ 1.0/8.0
  - Against data collected here at Sandia's Tri-sonic Wind Tunnel (TWT)
    - Wide range of Mach numbers and geometric configurations
    - Wall pressure data
    - Flow field PIV data
    - Store response data
    - L/D = 5.0, δ/D ~ 1.0/2.0- 1.0/3.0
    - Accurate boundary conditions available from detailed measurements.

Computation of Unsteady Pressure Loads

- Computational setup
  - Care taken to ensure the “correct” boundary conditions are imposed
  - “Precursor” empty wind tunnel calculation is done
    1. Entire TWT tunnel from downstream of settling chamber is modeled in a separate calculation
       - Downstream pressure boundary condition is adjusted to match the boundary layer profile and pressure gradient measured in the experiments
    2. Solution at the station corresponding to the boundary of the domain is extracted and used to provide inflow conditions to DES simulation



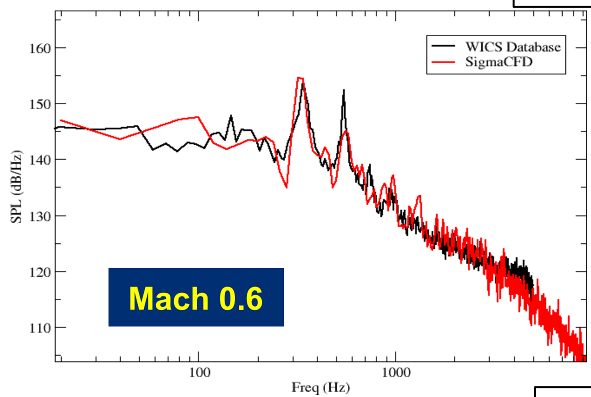


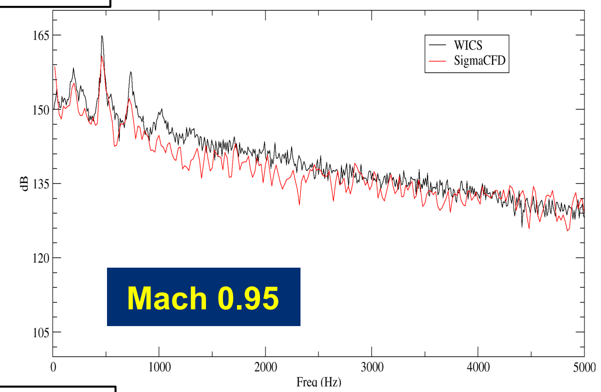


Computation of Unsteady Pressure Loads

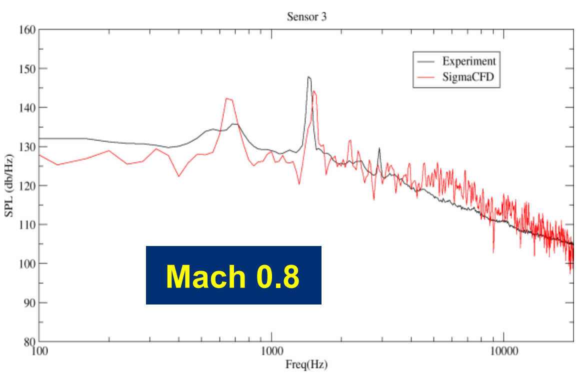
- Validated across a wide range of Mach numbers
  - Looking to see that we get the location and amplitude of the fluctuations
  - This represents the strength and location of the shear layer

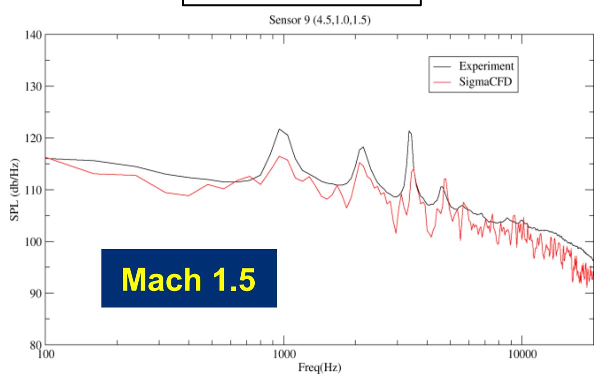
WICS Cavity

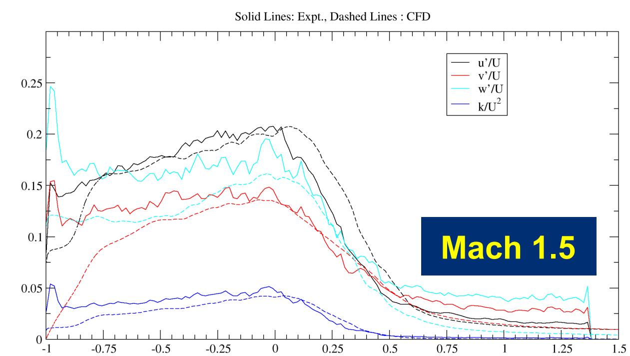




TWT Cavity





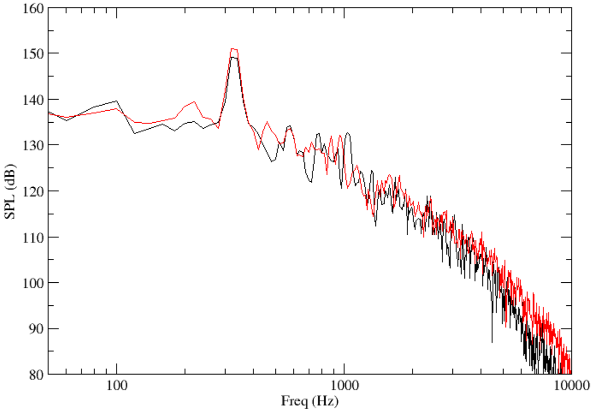


Turbulent flowfield stats vs. PIV data

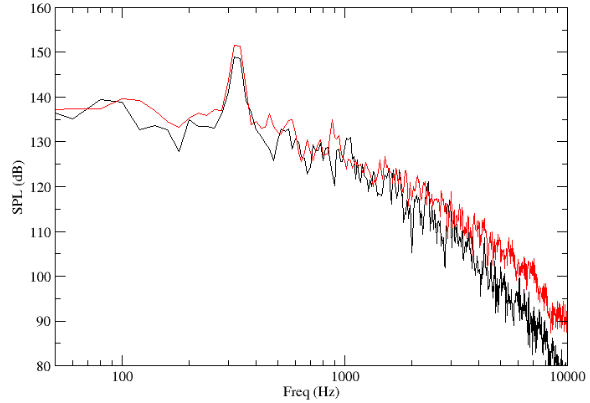
Computation of Unsteady Pressure Loads

- Mesh refinement: key step to ensure reliable predictions
  - Looking to see that we consistent statistics out of the hybrid RANS-LES model as we refine the mesh

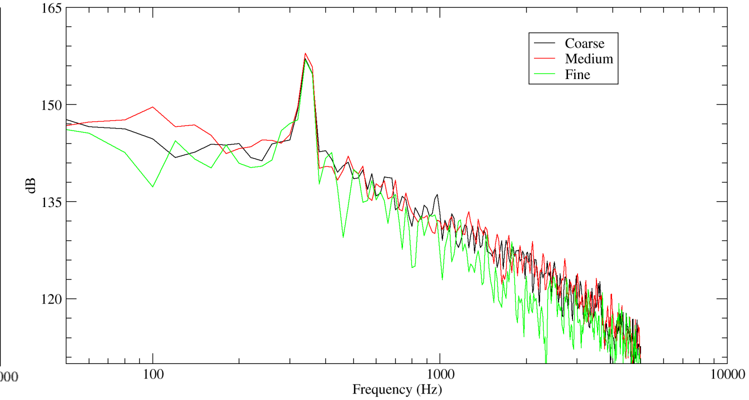
WICS Cavity – Floor



WICS Cavity – Aft Wall



WICS Cavity w/ Store – Store Wall

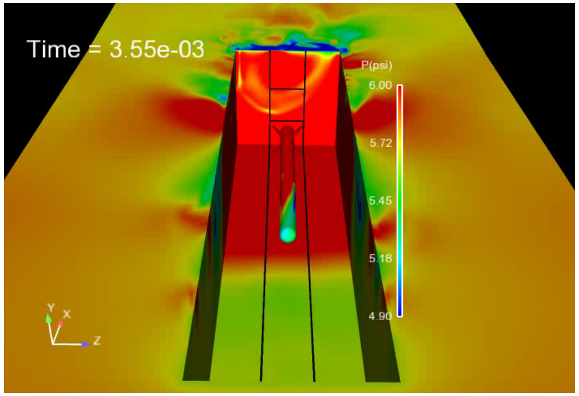


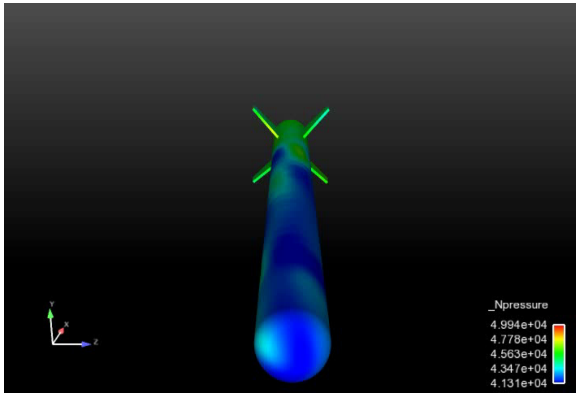
PSD computed on 2 meshes: 8m cells & 20m cells

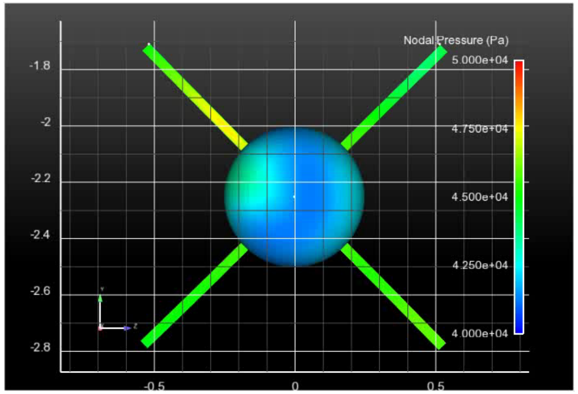
PSD computed on 3 meshes: 18m, 36m & 72m cells

Application to Model Problem

- After this validation step we have some confidence we can predict the pressure load and distribution accurately
- Next step in our Mod-Sim progression: finned store in a cavity
  - ~26m Elements for CFD Mesh
  - ~64K Elements for CSD Mesh
  - Mach 0.6, Re=$3x10^6$





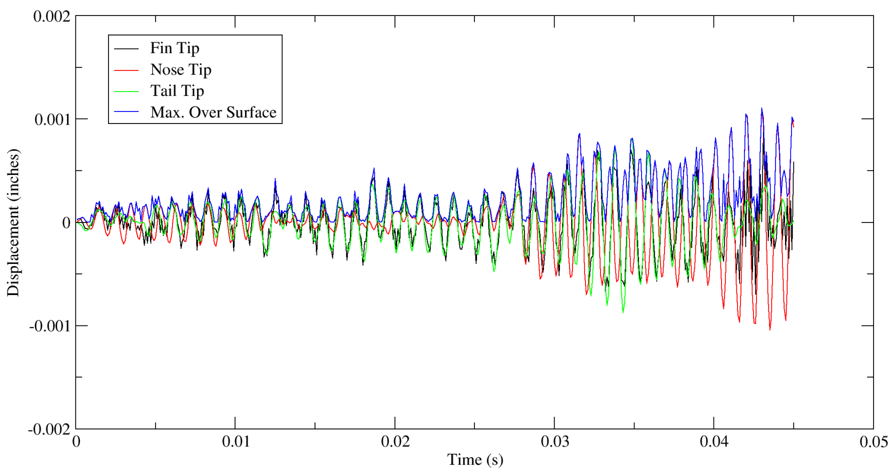


Animations showing pressure field and store deflection

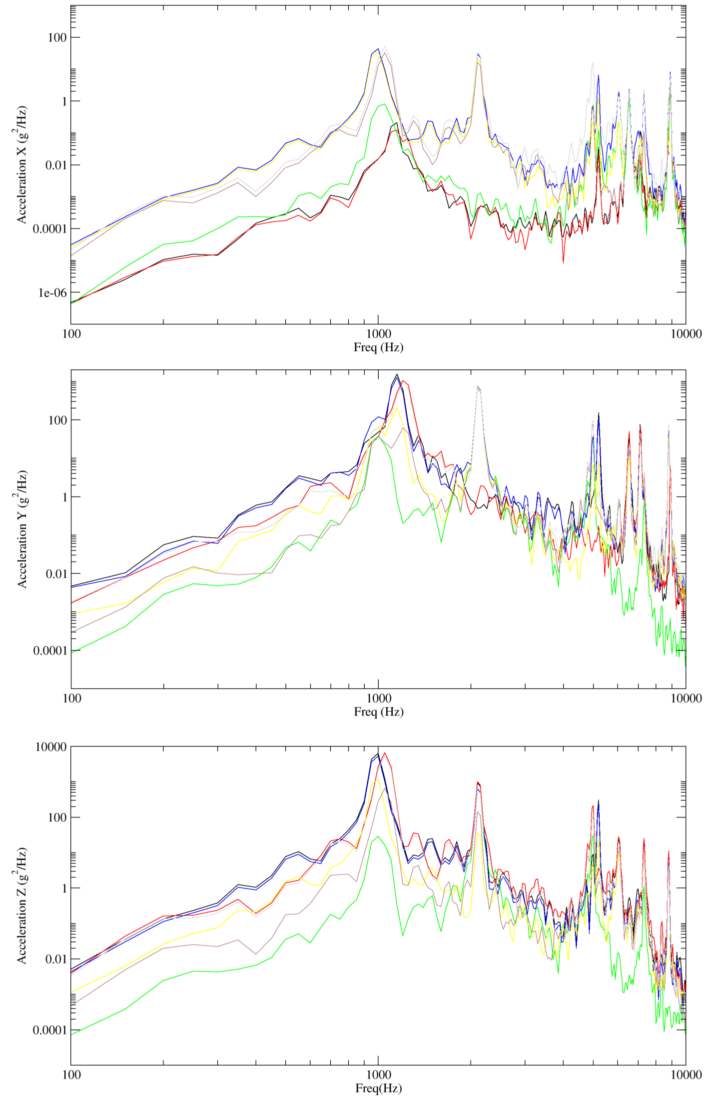
Store deflections have been amplified 100x.

Application to Model Problem

- Store Deflections
  - Max deflections are less than 1st cell thickness in CFD mesh
  - Accelerations are very large
    - Spanwise deflections and accelerations are largest



Store Deflections at Different Locations



Store Accelerations at Different Locations

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Numerics and Algorithms R&D

- Focus on fundamental numerics and algorithms work
  - Investigation and selections of low-dissipation flux schemes
    - Appropriate for transonic turbulent flows
  - Development of higher-order accurate discretizations
    - Unstructured grids
    - Structured grids
    - Hybrid Structured-Unstructured
  - Turbulence modeling
    - Pursuing an accurate hybrid RANS-LES capability for this class of flows
      - Full LES is the ultimate goal
    - Wall modeling for LES

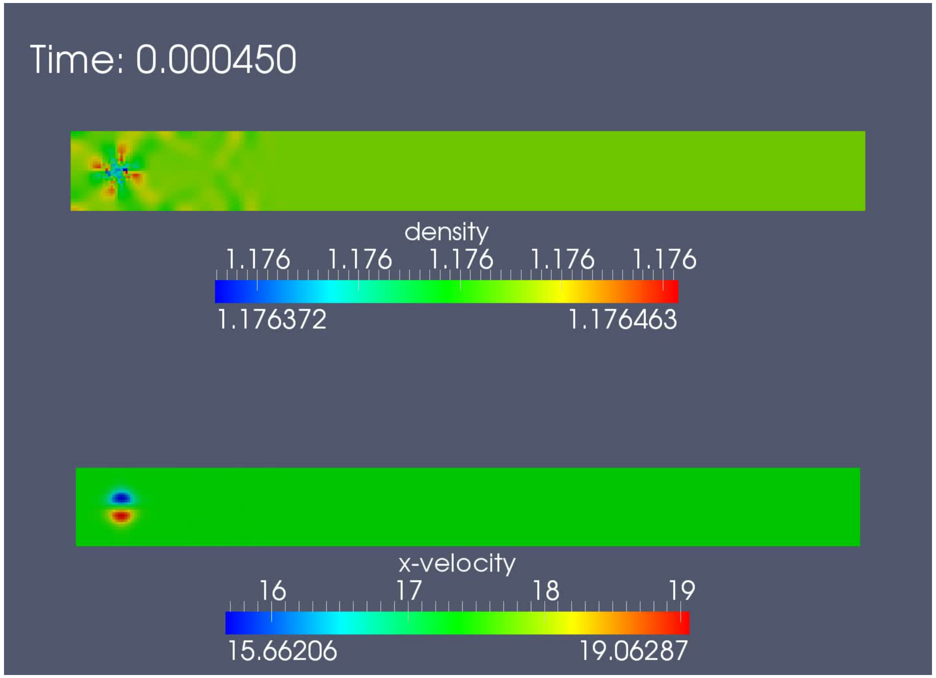
Model Problems for Flux Scheme Eval

- Test cases from 1st Workshop on Higher-Order CFD Methods used to evaluate flux scheme (and discretization method) performance

Inviscid vortex transport

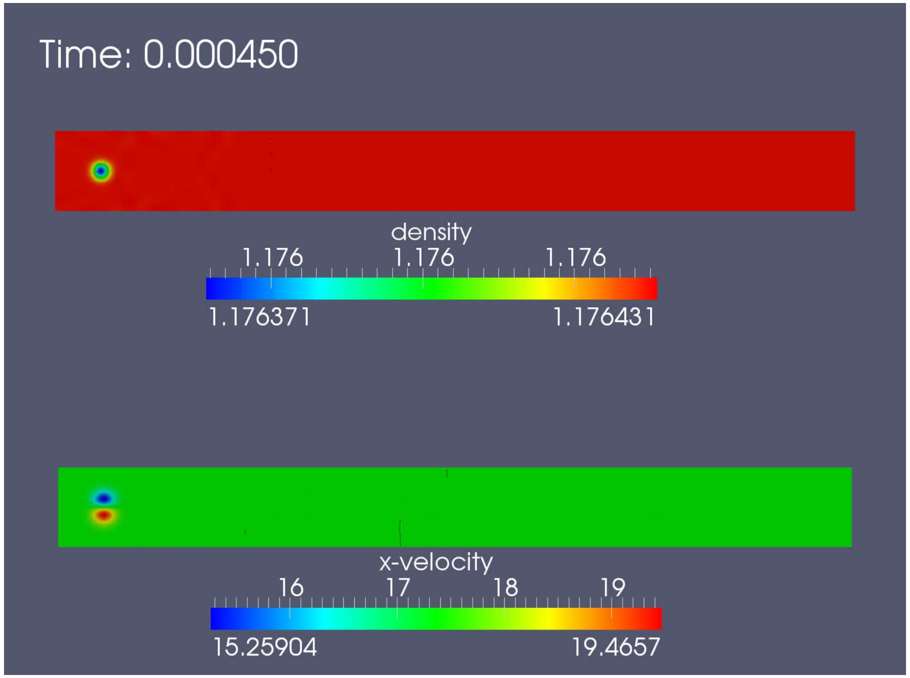
Accurate transport of vortices at all speeds is important for hybrid RANS-LES and LES simulations

Standard Roe Flux Scheme



Vortex is immediately dissipated

Kinetic Energy Consistent Flux Scheme



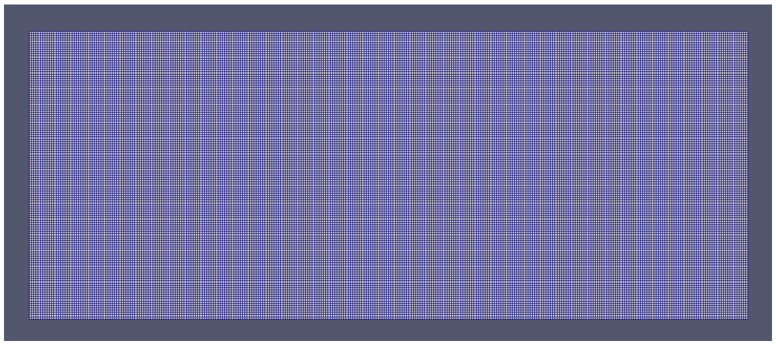
Vortex holds its structure and strength

Model Problems for Flux Scheme Eval

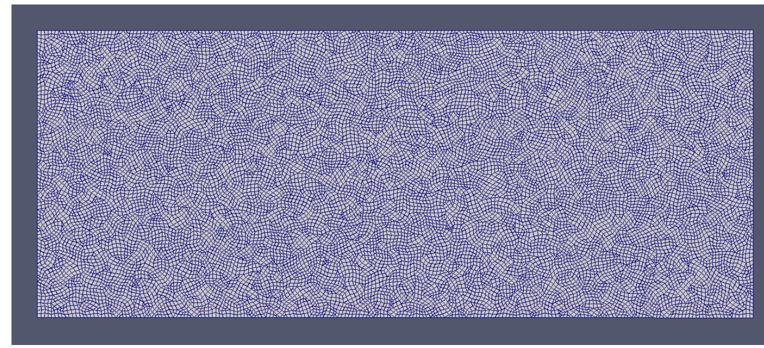
Inviscid vortex transport

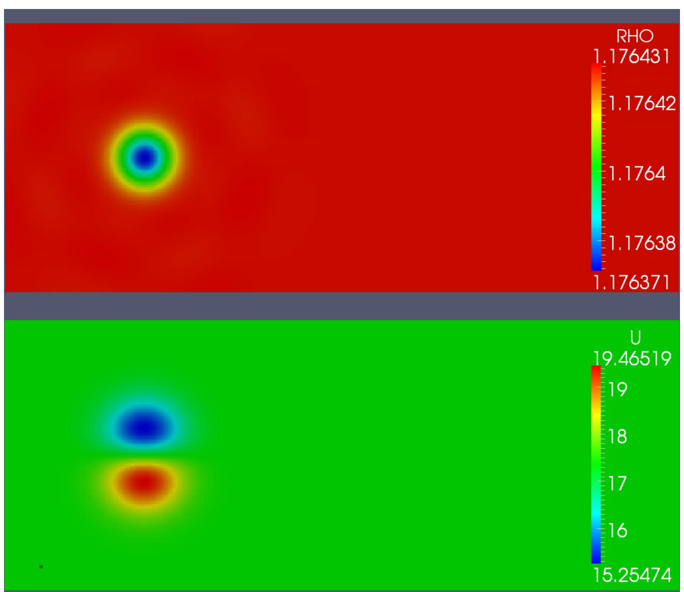
Accurate transport of vortices at all speeds is important for hybrid RANS-LES and LES simulations

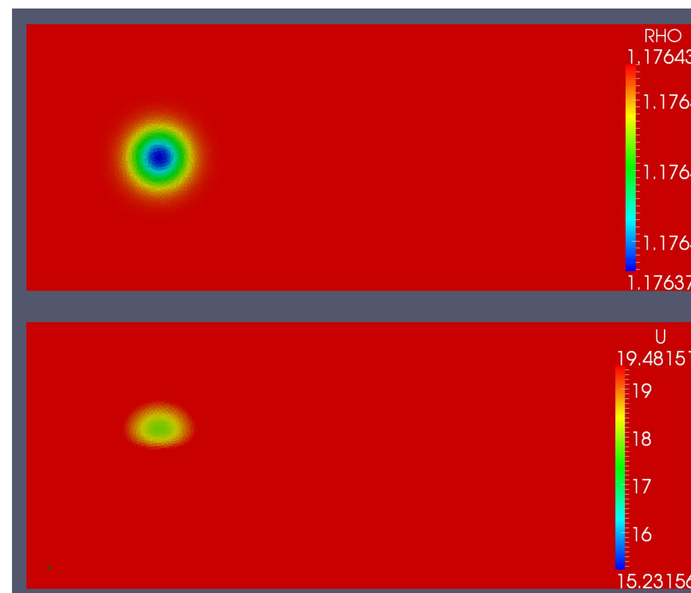
Unstructured (but structured) Hex Grid



Unstructured (but paved) Hex Grid







Model Problems for Flux Scheme Eval

- Main lessons learned:
  - Choice of flux scheme is very important
  - High grid resolution is often required -> driver for higher-order
  - Grid quality and structure is very important

- This has driven several decisions:
  - Selection of a low-dissipation flux scheme appropriate for these flows
  - Investigation of higher-order unstructured methods
    - Goal is accurate solutions on "reasonable" meshes in terms of size & quality
  - Investigation of higher-order structured methods
    - Goal is accurate and fast solutions on structured grids
  - Development of a hybrid structured-unstructured solver

High Order Unstructured Collocation

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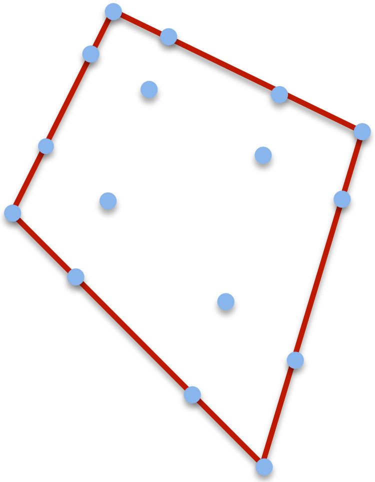
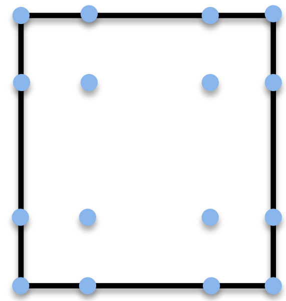
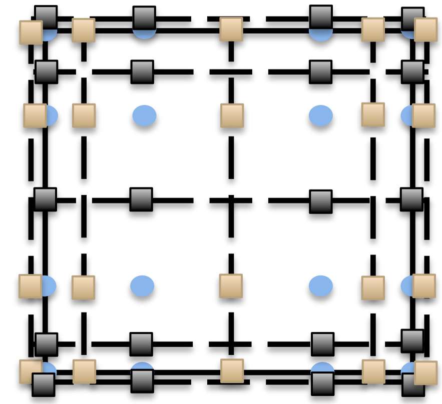


Unstructured Element



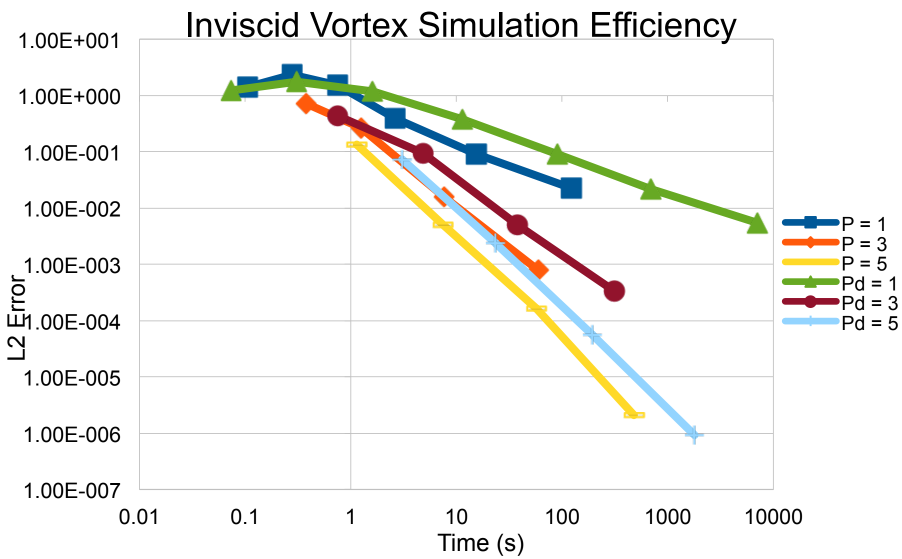
Standard Element

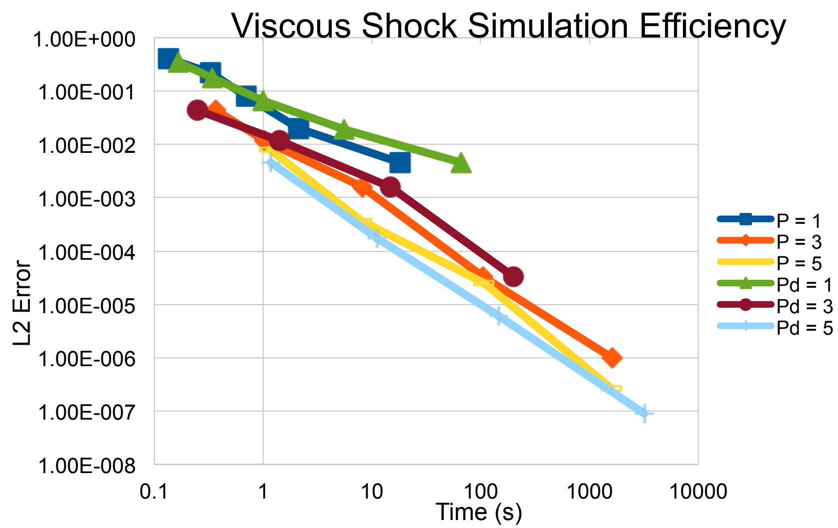


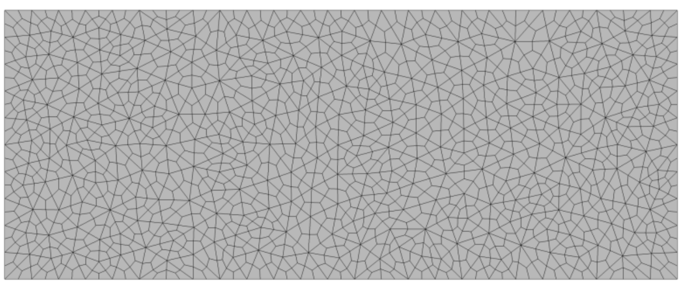
Flux-based Formulation

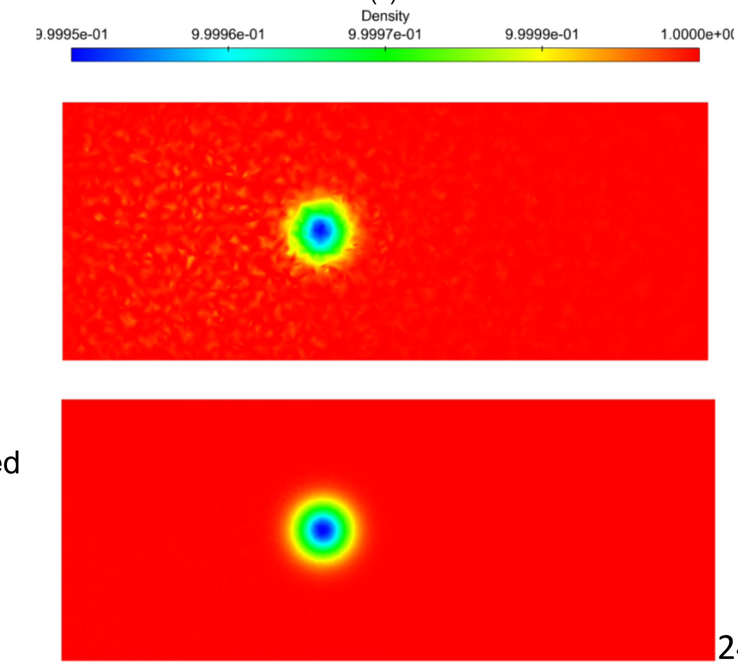
- Continuous and Discontinuous Formulation
- Efficient parallelism
- Accurate on unstructured topologies
- Very efficient resolution of vortical structures
- Able to capture shocks
- Provably Entropy (nonlinear) Stable

High Order Unstructured Collocation









CVFEM
P = 2
100x40

Unstructured
Collocation
P = 3
50x20

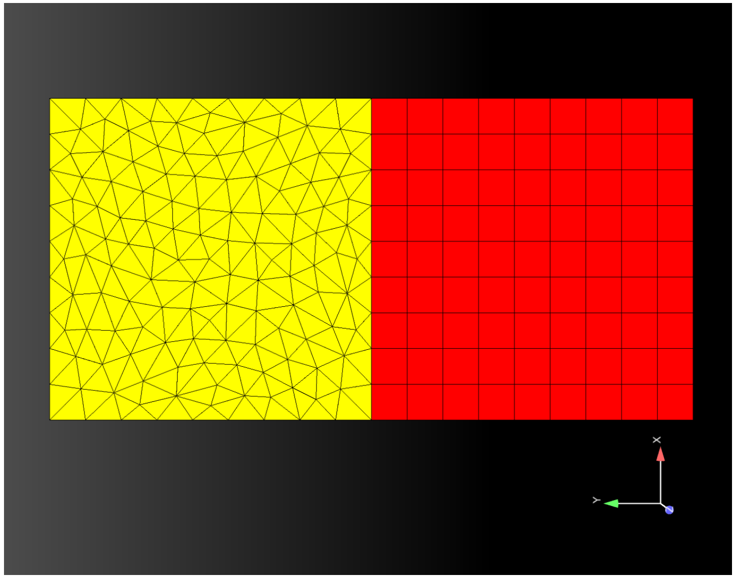
High Quality Solutions
on Unstructured Topologies

Higher-Order Structured Grid Methods

- Development currently ongoing
- Take advantage of:
  - Inherent grid structure (and quality) driven by geometry
  - The fact that "good" grids are often needed regardless of numerical scheme
  - Many of our grid construction tools utilize structured grid techniques
- Pro: Straightforward to achieve higher-order stencils
- Con: Complex geometry leads to significant time investment in grid generation

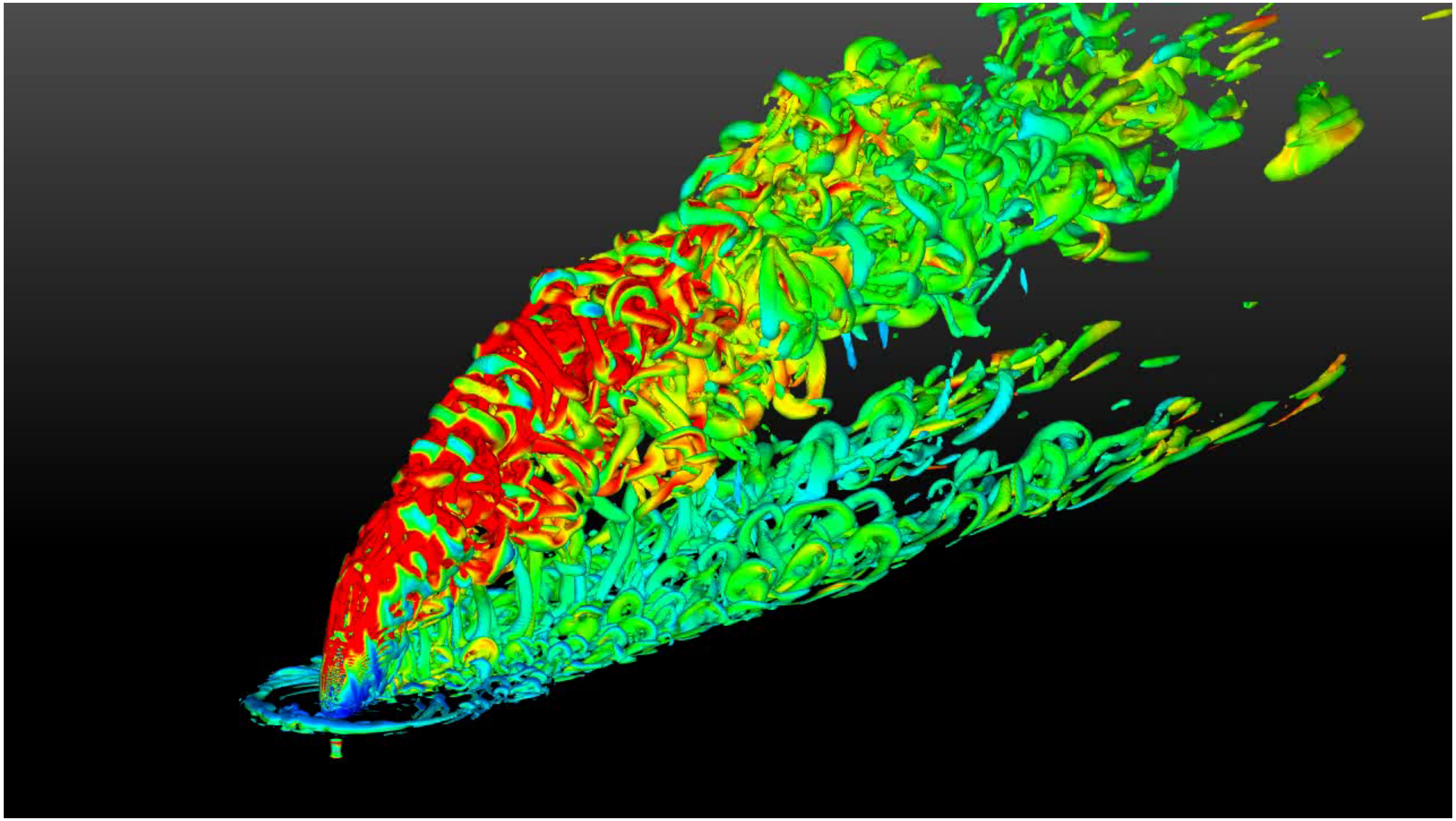
Higher-Order Accurate Discretizations

- Hybrid structured-unstructured grid methods
  - Use structured grids where solution quality is most important and geometry dictates (wall normal direction)
  - Use unstructured grid where solution quality is less important and geometric complexity is high
  - Several interesting challenges in realizing such a solver



Turbulence Modeling

- Hybrid RANS-LES capabilities being developed in Sigma CFD



Turbulence Modeling

- Wall model development for hybrid RANS-LES & LES
  - Even with RANS in the near wall regions, time steps can be restrictive
    - Compressible extension to original incompressible form derived
    - Developed to relieve mesh resolution requirements
    - Sign of pressure gradient and shear stress -> application to separated flows

Incompressible Model

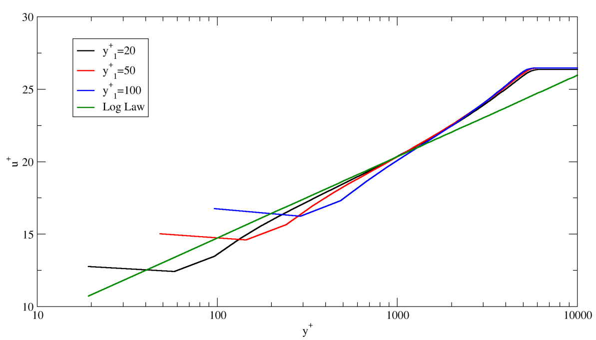
$$\left(1+\frac{\nu_t}{\nu}\right)\frac{\partial u}{\partial y} = sign\left(\frac{\partial p}{\partial x}\right)(1-\alpha)^{3/2}y + sign(\tau_w)\alpha$$

$$\frac{\nu_t}{\nu} = \kappa y\left(\alpha + y(1-\alpha)^{3/2}\right)^{\beta}\left(1-\exp\left(\frac{y}{1+A\alpha^3}\right)\right)^2$$

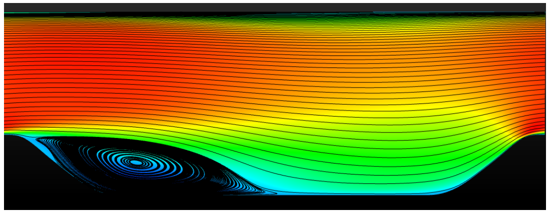
Compressible Model

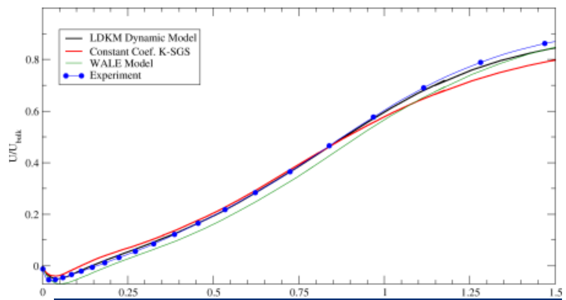
$$\left.\frac{u}{u_\infty}\right|_{eff} = \frac{Q}{2a^2}\tanh\left(\frac{Q}{2}\left(\frac{u_{LES\_inc}}{u_\infty}\right)\right) + \frac{b}{2a^2}$$

$$b = \frac{T_{aw}}{T_w} - 1;\; a^2 = \frac{1}{2}(\gamma-1)M_\infty^2;\; Q = \sqrt{b^2+4a^2}$$



Flat Plate Boundary Layers can be accurately simulated using large wall spacings





LES of separated flows using A wall-layer model

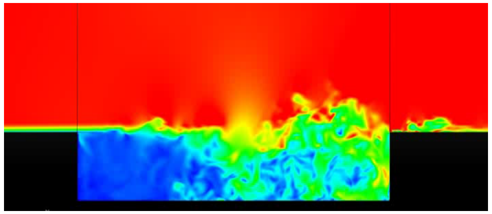
Outline

- Background
- Current work for captive carriage problems
  - Computation of unsteady pressure loads
  - Sigma CFD Code: methods and models
  - Application to model problem
- Numerics and algorithms research and development
  - Low-dissipation flux schemes
  - Higher-order discretizations – structured and unstructured
  - Turbulence modeling
- Uncertainty Quantification
  - Approaches for aleatoric uncertainty using ROMs
- Summary

Uncertainty Quantification (UQ)

- Important uncertainties in captive carry aerodynamic predictions
  - LES subgrid turbulence model errors
  - Aleatoric uncertainties in the flight environment - free stream conditions, inflow boundary layer thickness, etc.
- Physics of the captive carry problem demands a LES or Hybrid RANS/LES approach
  - Unsteady, separated turbulent shear flow
- We need UQ approaches compatible with LES
  - Each LES simulation takes days to weeks to compute
  - At best, only tens of simulation results will be available
  - Probabilistic UQ methods typically require many more samples
- **Current research focus** :

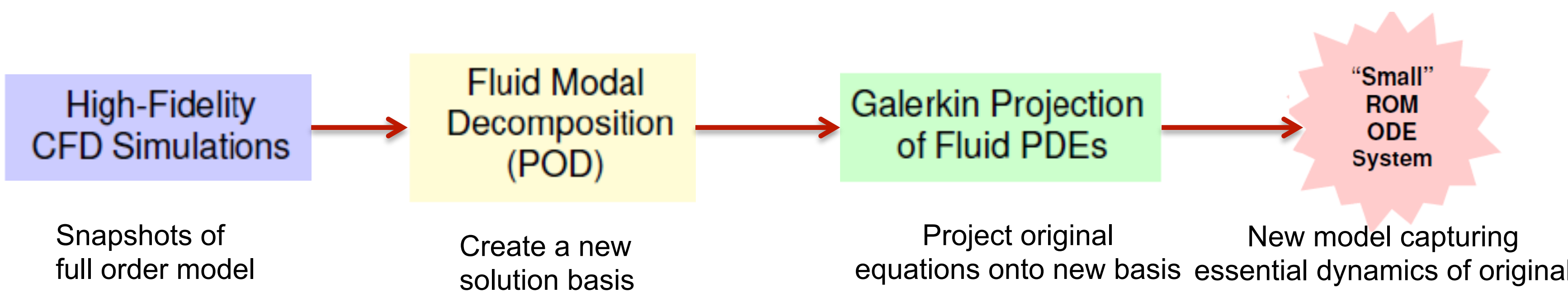
Reduced order models as physics-based surrogates for LES



Reduced Order Models (ROM)

- Goal
  - Develop physics-based reduced order models
  - Limited number of LES simulations
  - Efficient UQ studies requiring many (>= O(100)) function evaluations
- Approach
  - Leverage existing ROM research in other groups at Sandia
  - Apply and adapt new ROM techniques to captive carry problems

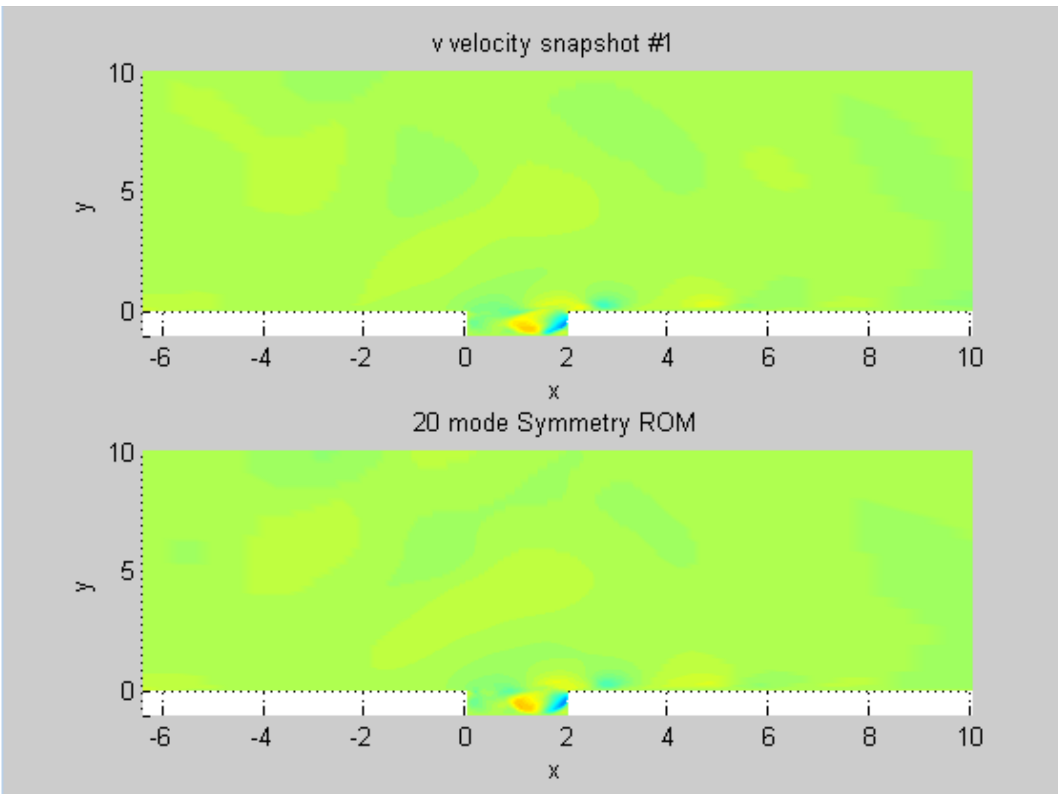
Example of a Projection-Based ROM Technique



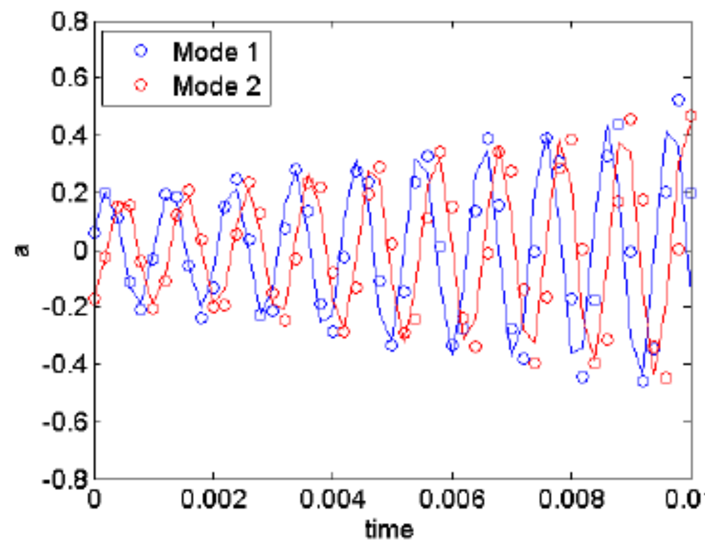
Application to a Driven Cavity Flow Problem

- Mach=0.6, Re=1898
- Forcing applied to Y-Momentum

$$F_v(\mathbf{x}, t) = \frac{1}{2}\cos(2000\pi t)$$

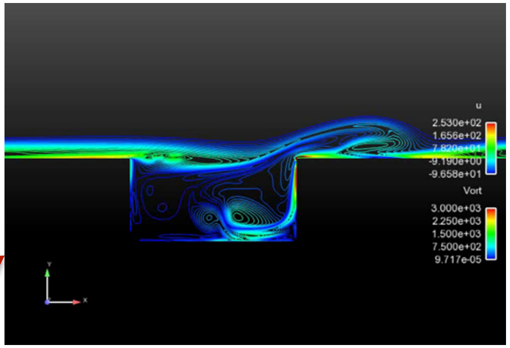


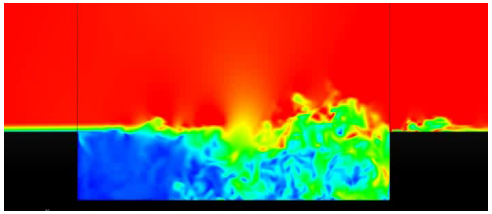
POD Mode amplitudes
Symbols: full order model
Lines: ROM



Model Reduction Research

- ROMs can be used as "surrogates"
  - To explore aleatoric uncertainty
  - To extend simulated time window
- Using "Linearized" ROMs
  - Using the proper projection method, the ROMs are provably stable
  - Works well for 2D, low Reynolds number flows
  - What about High Reynolds number, turbulent flows?
- Current Research Areas
  - Can we control the ROMs? Use "control" techniques to keep ROMs stable at practical Re (with Irina Kalashnikova – SNL Center 1400)
  - Nonlinear model reduction techniques (with Kevin Carlberg – SNL-CA)





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Summary

- Current work in computational aero loading predictions of stores in weapons bays
  - FSI framework has been developed
  - Currently restricted to one-way loosely coupled applications
  - Verification tests and demonstration carried out on a model problem
    - Consistent Force Transfers
    - Mesh and Time step Refinements
- Numerics and algorithms research and development
  - Providing capabilities suitable for LES for this class of flows
  - Development of low-dissipation flux schemes & higher-order discretization methods
- Uncertainty Quantification through ROMs
  - Used as physics-based surrogates for aleatoric uncertainty quantification
  - Control techniques and nonlinear reduction approaches shows promise