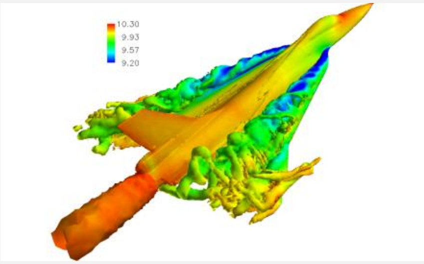
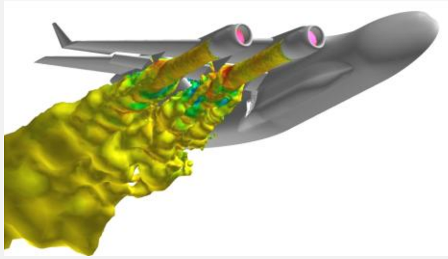




Engineering Resilient Systems Through the Use of Kestrel a High Fidelity Aircraft Simulation Tool and Compact Efficient Reduced Order Models of the Aircraft Static and Dynamic Loads

DOD HPC MODERNIZATION PROGRAM

Dr Scott A. Morton, **Kestrel Principal Software Developer**

17-19 July 2012

Motivation

- **Virtually every new aircraft program encounters unexpected aerodynamic or structural integrity problems**
  - Unpredicted complex aerodynamic issues such as vortex/shock/boundary layer interactions have resulted in
    - issues such as tail buffet, abrupt wing stall, limit cycle oscillations
    - greatly reduced performance and/or increased structural weight
  - Control surface sizes have been modified on almost every fighter in the modern era
    - Increased or even decreased empennage after flight demonstrations
  - Modifications after “bending metal” are at the costliest stage in the program and can even kill an aircraft program due to cost and schedule
- **Engineering Resilient Systems Requires a More Global View of the System – Unpredicted issues can come from**
  - Off design conditions
    - A few design points analyzed heavily and in between points interpolated
    - Static aerodynamics analyzed but transient behavior ignored
  - Multi-disciplinary issues
    - Aerodynamics of rigid bodies dominates analysis with little aero-structural, aero-kinematic/kinetic, or aero-propulsion analysis performed

Motivation

- **Why are these off-design and multi-disciplinary issues unchecked?**
  - Conceptual/Preliminary Design is the driver of life-cycle cost but has the lowest fidelity information available
  - Empirical methods are fast and successful for on-design conditions but
    - force designs to remain within knowledge space (conventional)
    - miss nonlinear aerodynamic issues
  - Low-order aerodynamic tools are fast but
    - require very highly experienced designers to overcome modeling deficiencies
    - miss nonlinear aerodynamic issues
  - Loads models are primarily built from a wind tunnel campaign and modified by "fix-ups" over time for configuration changes
    - Expensive tunnel testing can be delayed significantly from concept to ensure applicability of the data to the detailed design phase
    - Rarely do a complete re-run for aerodynamic shape changes
    - Can miss nonlinear aerodynamic issues due to model scale/shape difference from flight configuration

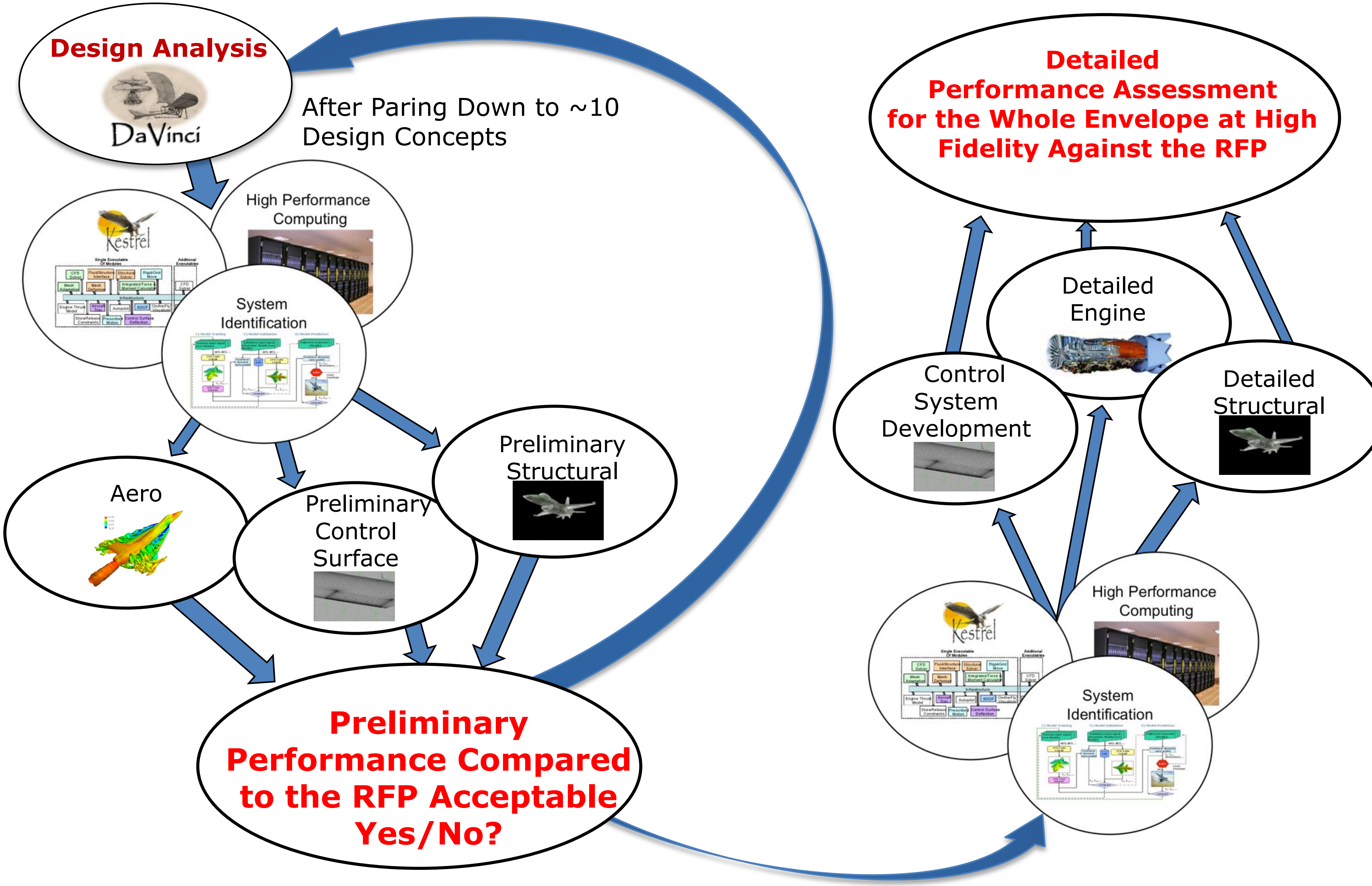
Motivation

- **To engineer a more resilient system and capture these issues earlier we need high fidelity multi-dimensional tools to be used earlier**
- **CFD has not been fully incorporated into early conceptual design process due to**
  - Cost of a single point calculation
    - May take days on hundreds or even thousands of processors
  - Number of single points necessary to fill a database for the flight envelope
    - Can number in the millions of points
    - Do nothing to predict dynamic effects
    - May miss aerodynamic issues between points
  - Lack of confidence in whole envelope accuracy (e.g. high alpha, dynamics)
  - Simulation traditionally did not incorporate critical systems such as control surfaces, flight control systems, structural models, propulsion effects
  - CFD has been used like wind tunnel tests rather than flight tests
- **We need a new analysis process compatible with the design process that uses the high fidelity tools in a different way**

Motivation

- **Proposed revolutionary improvement to the Conceptual/Preliminary Design process to improve resiliency**
  - Continue using low-order/empirical methods to reduce number of configurations from order 10,000 to order 10
    - Current methods work well to explore the design space for on-design conditions
    - Result should be an outer mold line (OML) shape for order 10 configurations
  - Use CSE to determine the aerodynamics of the entire envelope
    - Starting with OML quickly build surface and volume meshes (1-2 days)
    - Develop a center of gravity (CG) loads model that incorporates higher order effects (e.g. turbulence, separation, shock/vortex/boundary layer interactions) that can be exercised in milliseconds on a laptop for any point in the envelope and practical maneuver (2-3 days)
    - Develop a surface loads model that can be exercised in milliseconds on a workstation for any point in the envelope and maneuver (same 2-3 days)
    - Explore the CG and surface loads model looking for problem areas and structural design requirements to eliminate late defect discovery
      - Develop database search algorithms looking for strange behavior
    - Optimize configuration for both on- and off-design conditions to make the design more resilient: re-run 2-3 day simulations to regenerate models
  - Use high fidelity CG and surface loads models to size control surfaces, create preliminary structural design, assess mission performance, and create early man-in-the-loop simulator. **All from an OML…**

Vision for CSE Use in Conceptual/Preliminary Design



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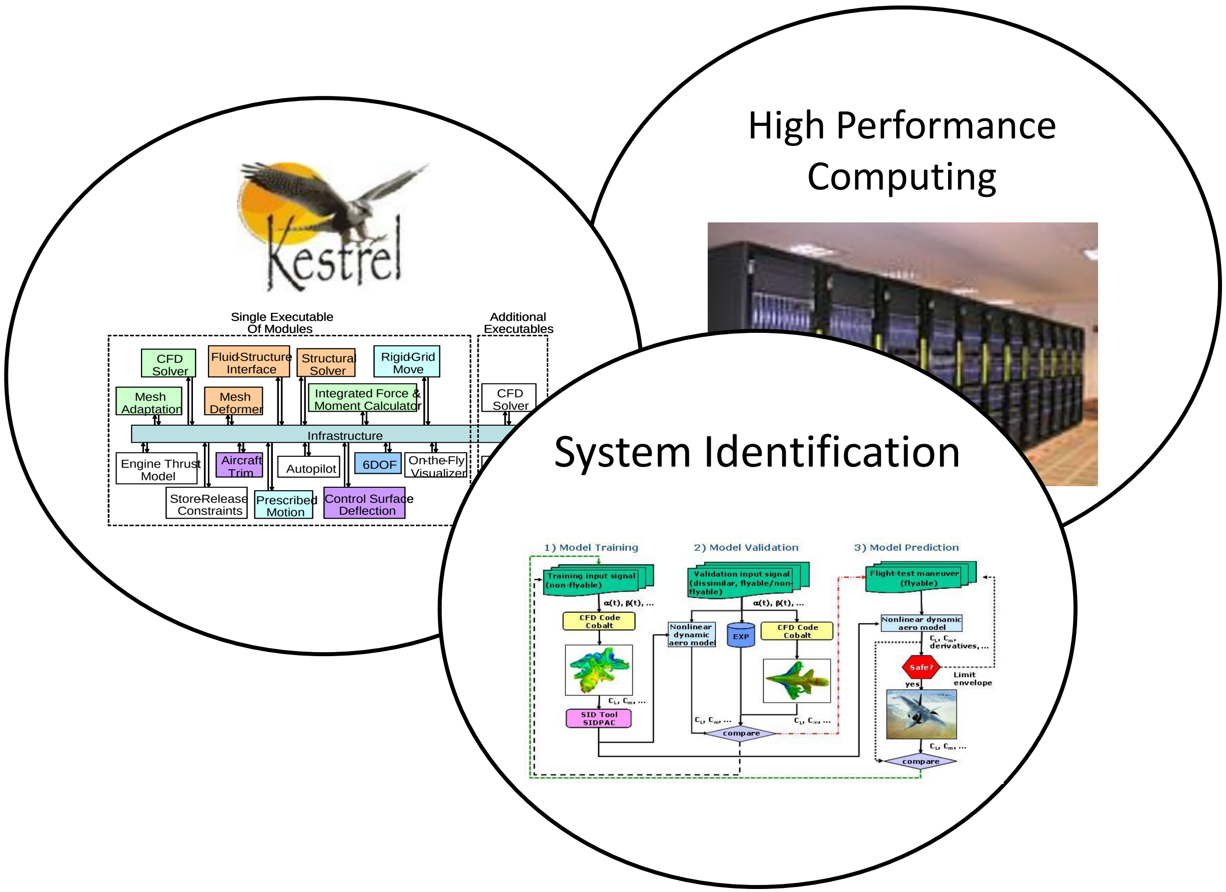
Game Changing Combination



High Fidelity CSE Code

- System level high fidelity solver including aerodynamics, structural dynamics, flight mechanics, and propulsion
- Efficient on large processor count (single simulation in hours, full envelope in days)

High Performance Computing

- Large computational resources (order 10^4 to 10^5 cores)
- Current US DoD buys are for several machines at approximately 100,000 cores

Compact Model Building

- Approach that can convert days of high fidelity CSE to compact, efficient model for use on laptop/workstation
- Approach that can allow higher and higher fidelity simulation (add control surfaces, aero-elasticity, propulsion, etc.)

Compact Model Approach (CG Loads)

- **Simulate closed-loop, full-scale a/c at edge-of-the-envelope conditions with a single, complex and efficient maneuver (possibly non-flyable) per flight condition**
- **Generate nonlinear, dynamic reduced-order aerodynamic models**

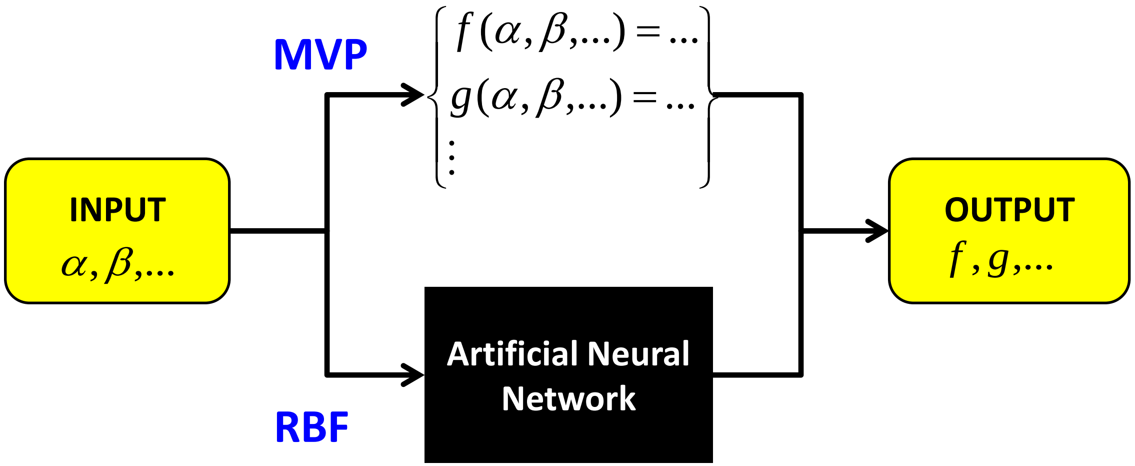
$$C_L(\alpha,\beta,p,q,r) = C_1 + C_2\alpha + C_3 q + C_4 p^2 + C_5 \alpha q^2 + C_6 \beta p q +$$
$$C_7 \beta p + C_8 \alpha^2 q + C_9 r + C_{10} \alpha \beta^2 + C_{11} \alpha^3 + C_{12} p r +$$
$$C_{13} \beta^2 p + C_{14} \beta^2 q + C_{15} p + C_{16} \beta^2$$

- **Use model for S&C analysis, flight simulation, control system design, etc.**
  - **New approach much more efficient than traditional "brute force" static solutions filling a database and then computing derivatives numerically**
  - **Allows Engineers flexibility to handle any new configuration and independence from contractors**

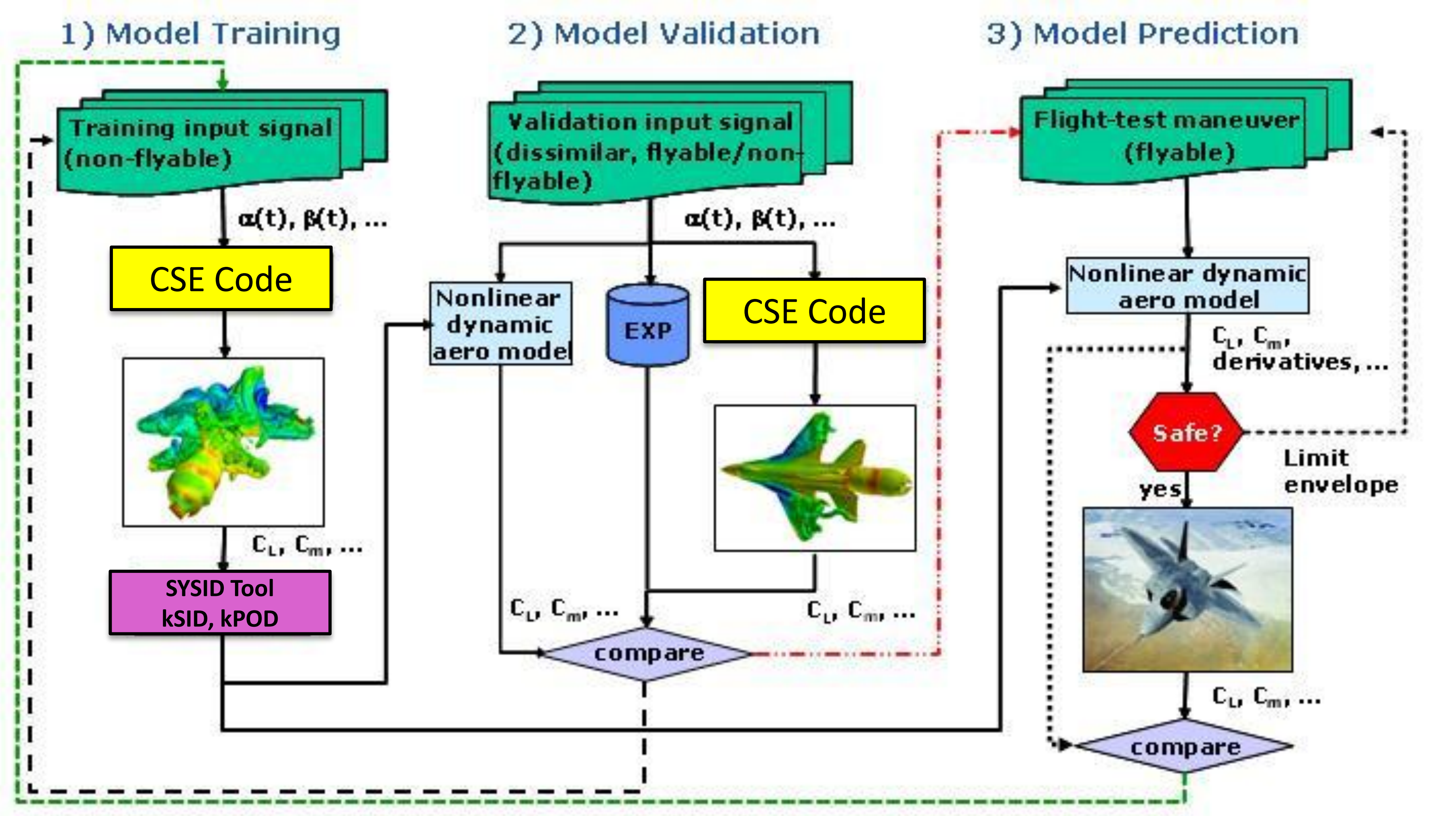
Compact Model Approach (cont.)

Aircraft System Identification (SID)

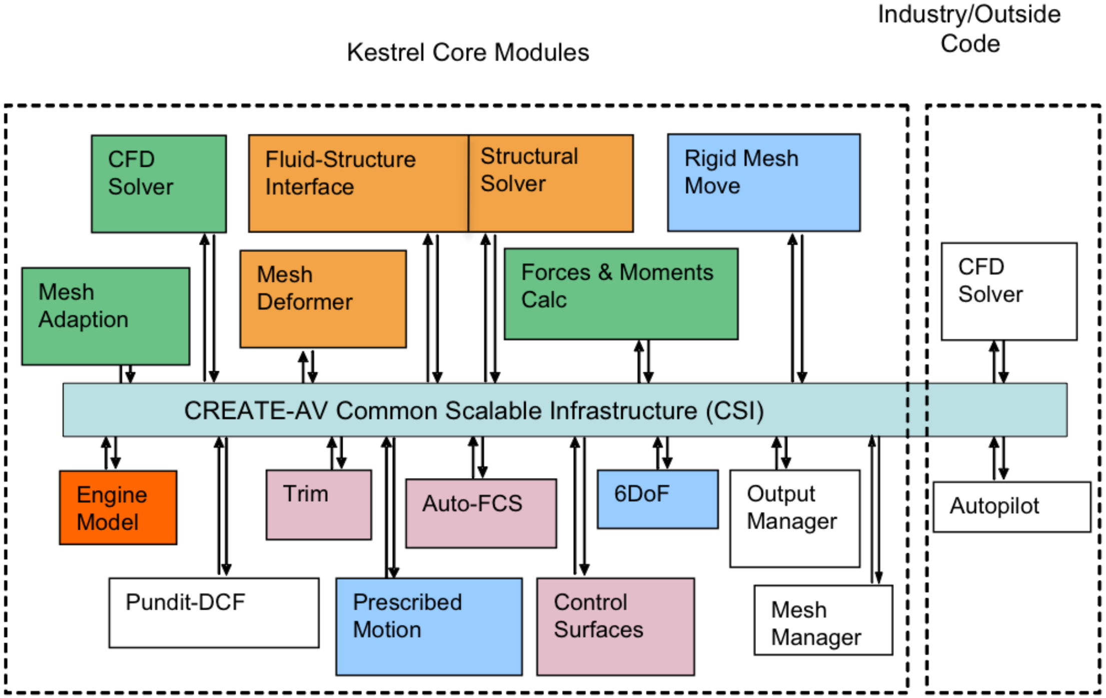
- **SID – construct a mathematical model of a system**
- **SID goal: determine the functional dependence b/w input and output**
- **Already applied to WT and FT data for:**
  - Flight simulation
  - Control system design
  - Dynamic analysis
- **Our approach: apply SID to CFD data**
- **Obtain both Static and Dynamic data from single computational maneuver**
- **Two methods: MVP and RBF**

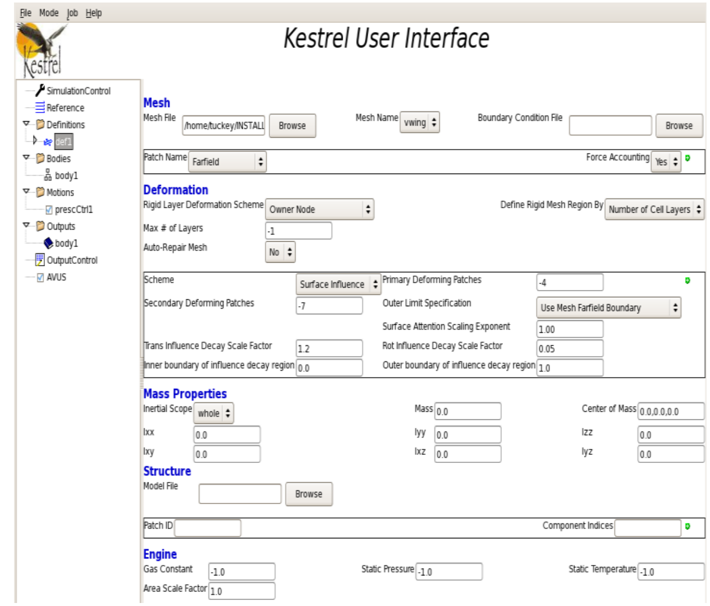


Compact Model Approach (cont.)



CSE Code (*Kestrel*) Architecture





- Unique Event Driven Infrastructure with Modular Components
- Unstructured Navier-Stokes CFD Solver (kAVUS)
  - Cell Centered, Finite Volume, 2nd Order Temporal and Spatial Solver
  - Hybrid Mesh – Tetrahedrals, Prisms, Pyramids, Hexahedrals
  - Euler, Laminar, and Turbulent Flow (SA, SST, SA-DDES, SST-DES)
  - Moving Mesh, Deforming Mesh Capable with GCL
- Rigid/Aeroelastic Prescribed and 6DOF Predictive Motion Capable
- UI for pre-processing **pre-flight** capability to build complex motions
- UI for post-processing **SYSID model building** and data analysis

Baseline Aerodynamic CG Loads Modeling Using System Identification

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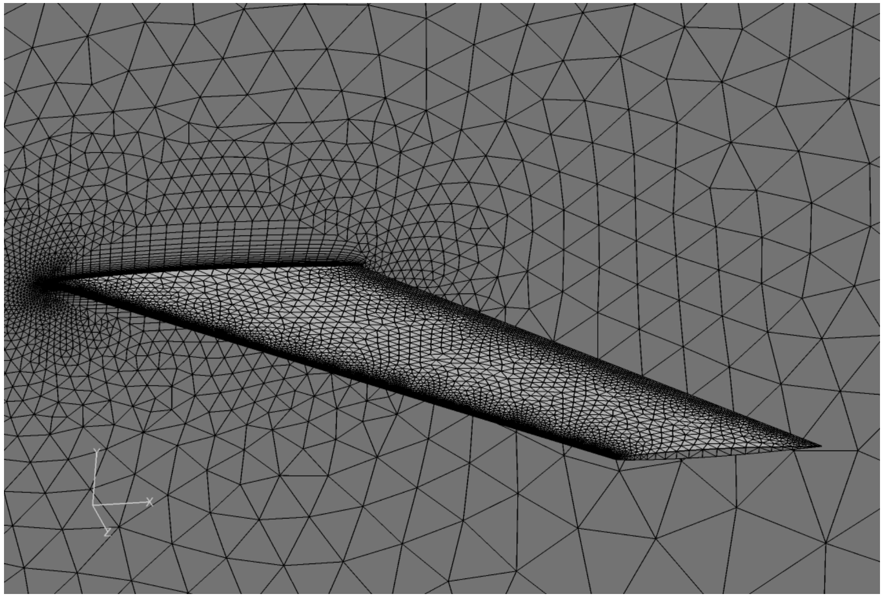
AGARD 445.6 Wing Simulations



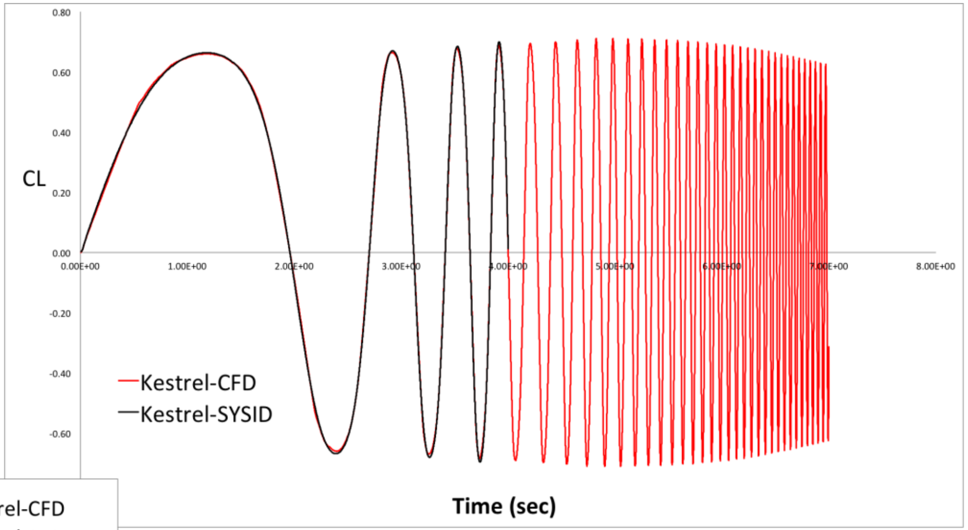
- **Half-span grid with:**
  - 2,974,944 cells
    - 2,101,020 prisms
    - 848,184 tets
- **Flow conditions:**
  - M_∞=0.95, P_∞=0.66 lb/in^2, T_∞=464.2R
- **Numerical parameters:**
  - Δt=0.0002s
  - 5 Newton sub-iterations
  - SA-DDES
- **Sinusoidal Pitch Chirp Training Maneuver**
  - α = 0$\pm$10 deg, frequency varying from 0.2 to 20 cycles/sec
- **Used System Identification to "fit" the data**

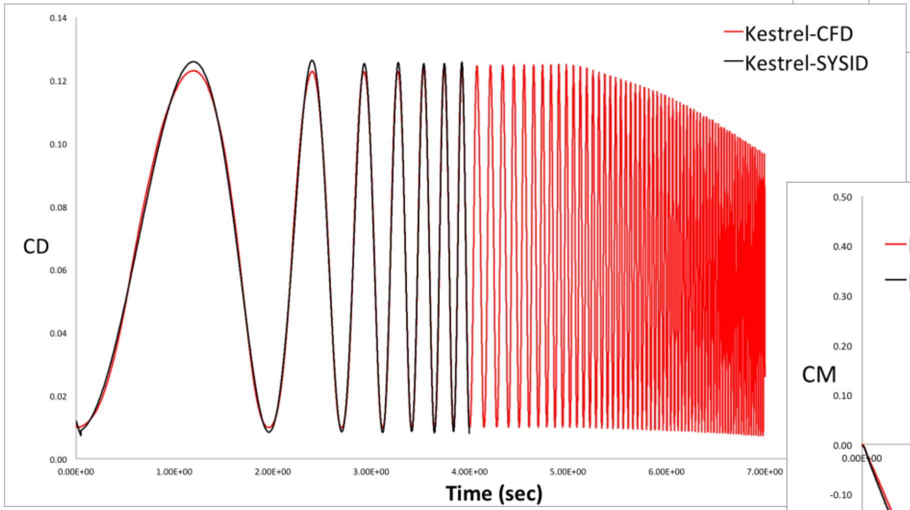
$$\begin{aligned}C_L(a,q,\dot q) &= C_1 + C_2 a + C_3 a^3 + C_4 a^2 q + C_5 a q \dot q + C_6 q + \\ &C_7 q \dot q^2 + C_8 q^3 + C_9 a \dot q^2 + C_{10} q^2 \dot q + C_{11} \dot q^3 + C_{12} a^2 + \\ &C_{13} a^2 \dot q + C_{14} a q^2 + C_{15} a q + C_{16} q^2 + C_{17} \dot q^2 + C_{18} \dot q\end{aligned}$$

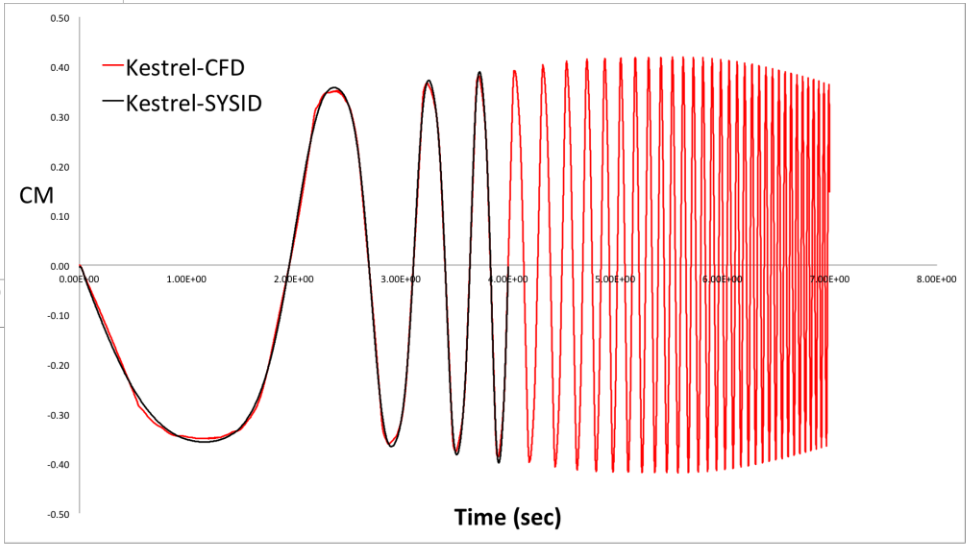
$$\begin{aligned}C_D(a,q,\dot q) &= C_1 + C_2 a^2 + C_3 a \dot q + C_4 \dot q^2 + C_5 q \dot q + C_6 q^2 + \\ &C_7 a q + C_8 a^3 + C_9 a + C_{10} a^2 \dot q + C_{11} \dot q + C_{12} q^2 \dot q + \\ &C_{13} a q^2 + C_{14} q + C_{15} \dot q^3 + C_{16} q^3 + C_{17} a^2 q\end{aligned}$$

$$\begin{aligned}C_M(a,q,\dot q) &= C_1 + C_2 a + C_3 a^3 + C_4 a^2 q + C_5 a q \dot q + C_6 q \dot q^2 + \\ &C_7 q^3 + C_8 a \dot q^2 + C_9 q^2 \dot q + C_{10} q + C_{11} \dot q^3 + C_{12} a^2 + \\ &C_{13} a^2 \dot q + C_{14} q^2 + C_{15} \dot q^2 + C_{16} a q + C_{17} a q^2 + C_{18} \dot q\end{aligned}$$

Sinusoidal Pitch Chirp Training Maneuver

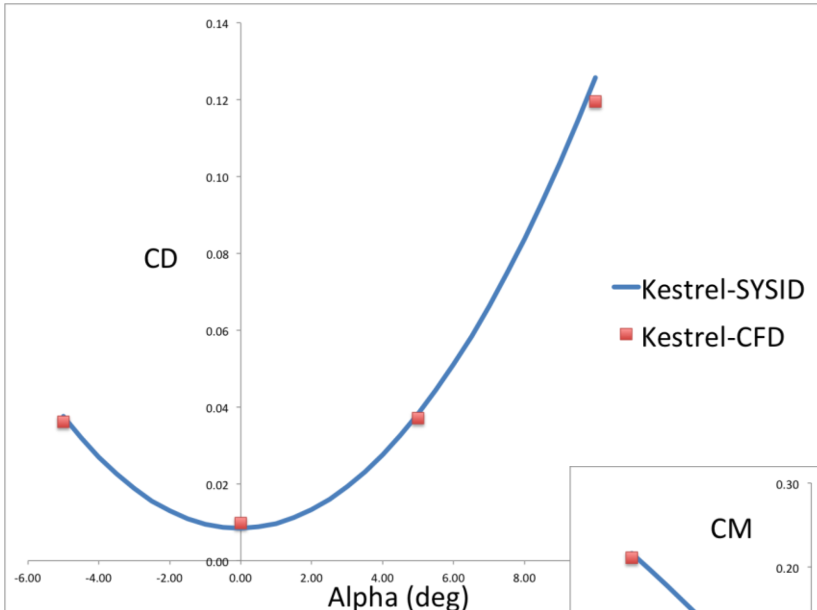


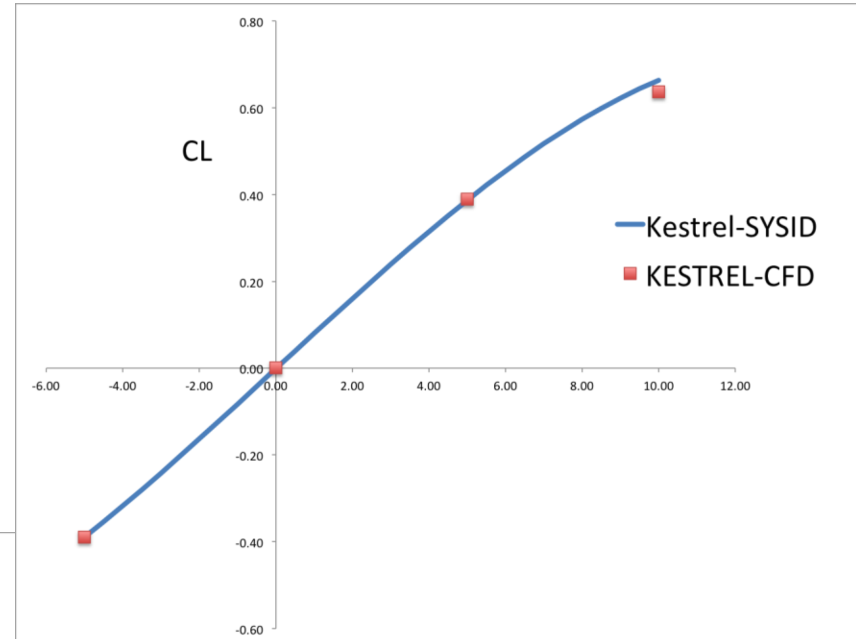


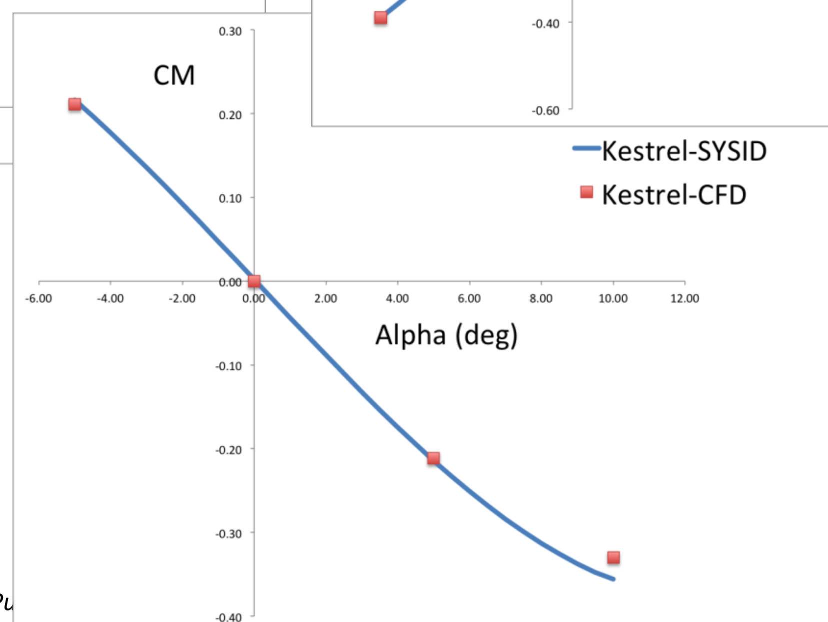


Sinusoidal Pitch Chirp Training Maneuver

- **Comparison of System Identification Generated Model from the Training Maneuver with CFD Static Solutions**







Complex Configuration Aerodynamic CG Loads Modeling Using System Identification

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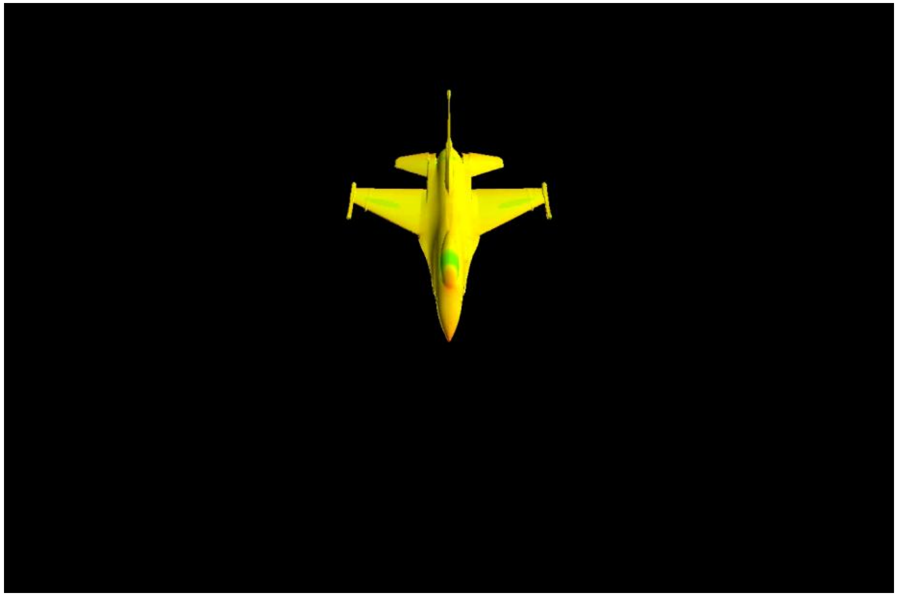
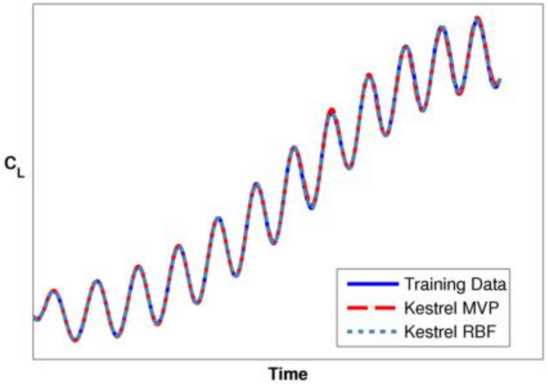
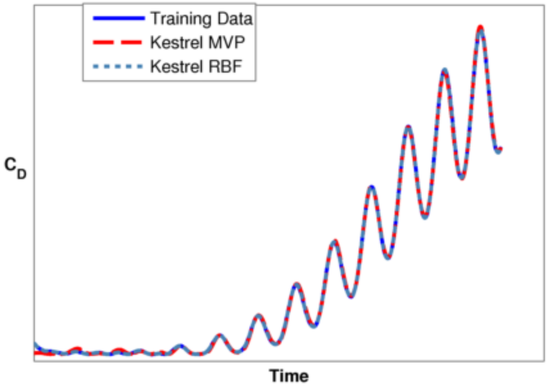
F-16C Static SID Analysis

Lockheed Performance Data vs. SYSID (Kestrel)

- **Composite Pitch-Roll-Yaw Chirp**
  - α = 0-25 deg, β = 0±2 deg, $\dot{\phi}$ = 0±70 deg/sec
  - Multiple rotations
- **Input signals orthogonal**
- **Requires full span F-16C grid**
- **Conditions: M=0.6**
- **Compare against Lockheed Martin Flight Test & Performance Data**
  - LM: tip AIM-9s; CFD/SID: tip LAU-129s







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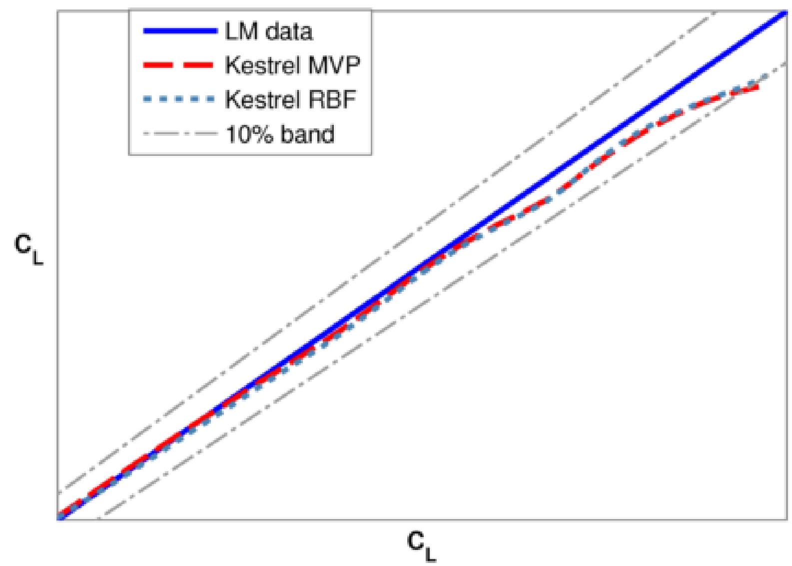
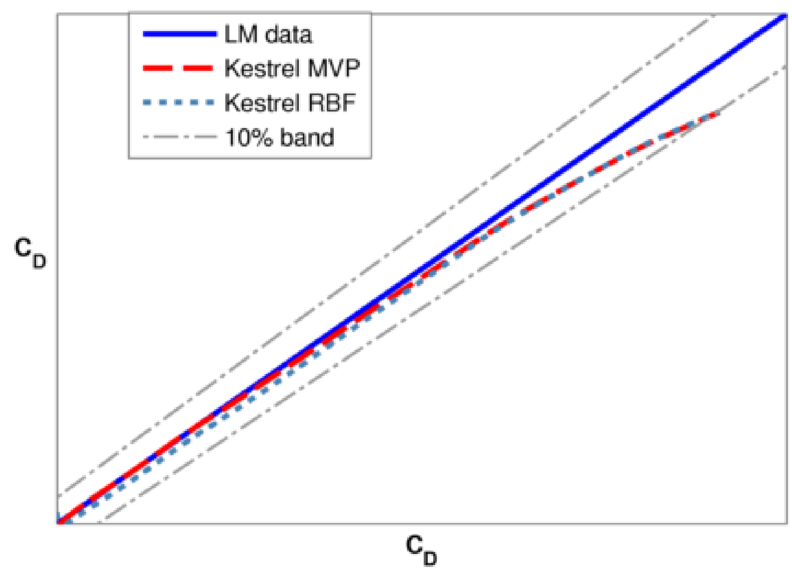




Extension to Surface Loads Modeling Using Proper Orthogonal Decomposition (POD) and System Identification

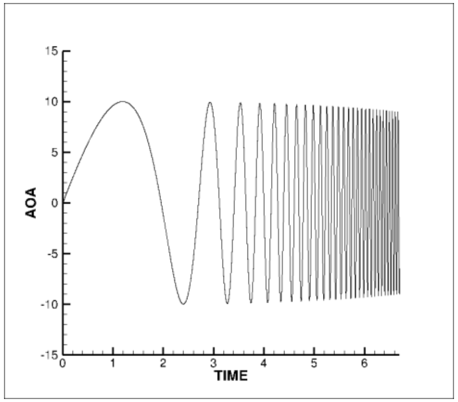
DOD HPC MODERNIZATION PROGRAM

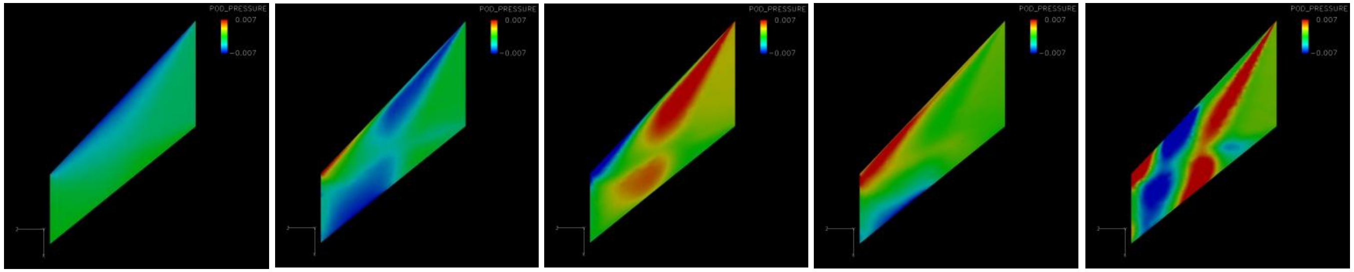
Modified Approach for Surface Loads Model Development

- Perform a training maneuver similar to the CG loads method and collect loads (pressure or forces) at each surface mesh location as a function of time
- Perform a Proper Orthogonal Decomposition (POD) of the surface loads to determine a set of aero surface modes and companion POD coefficients as a function of time
- Perform a System Identification analysis of the maneuver inputs (α, β, ϕ, P, Q, R, …) and POD coefficient outputs to determine a functional form of the POD coefficients
- Resulting model is predictive, compact, efficient, accurate on and off-design, and easy to re-generate with new configurations
- Things to work on…
  - Need for improvement in training maneuvers designed for surface load generation
  - System Identification methods for fitting the POD coefficients

Loads Model Development Example: AGARD 445.6, M=0.95

- **Simulated a pitch sinusoidal chirp**
  - **Initial/final frequencies of 0.2/10 cycles per second**
  - **Initial/final amplitude of 10/5 degrees**
- **POD of the training maneuver developed with 20 modes**
- **System Identification used to "fit" data**
  - **Multi-variate polynomial approach proved inadequate for POD coefficients (not an exhaustive study)**
  - **Neural network approach proved fruitful**
- **Compared POD/SYSID prediction with CSE for a sinusoidal pitch with 10 deg amplitude and 2 cycles/sec frequency**



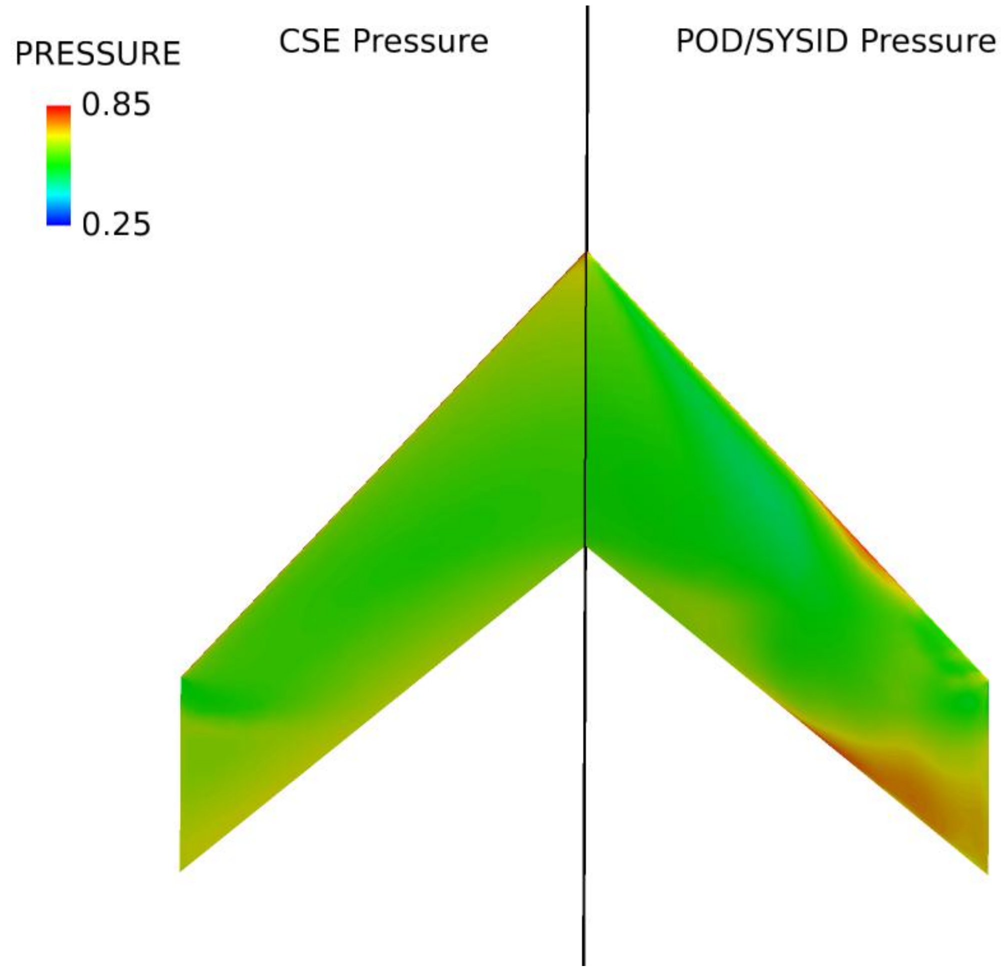


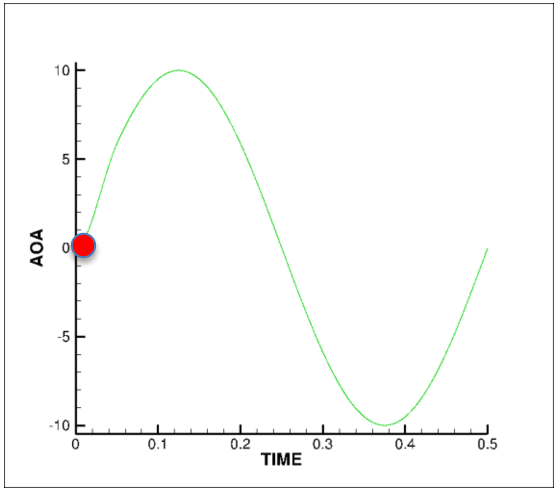
POD Mode 1 POD Mode 2 POD Mode 3 POD Mode 4 POD Mode 5

AGARD 445.6 Wing

Comparison of Surface Pressure for CSE to POD/SYSID

2 Cycles/Sec Pitch Maneuver





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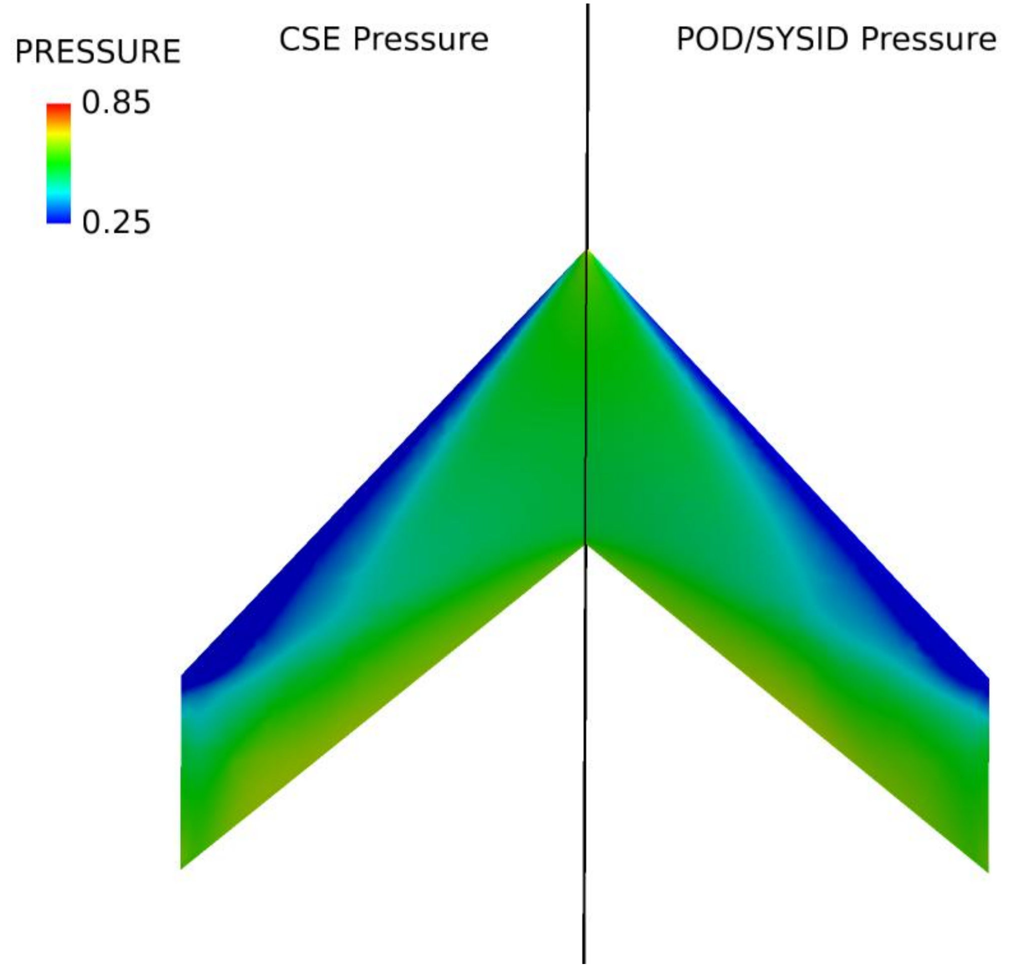

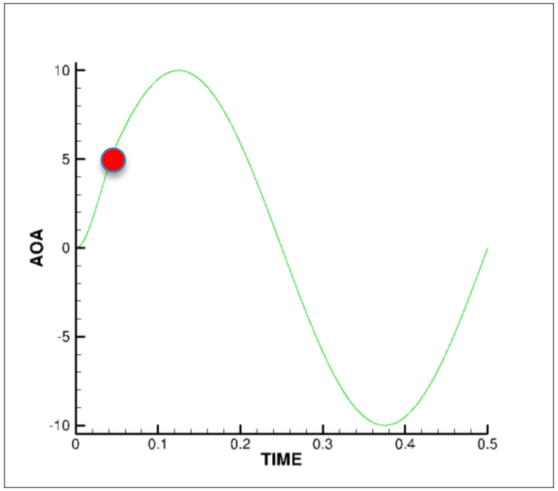

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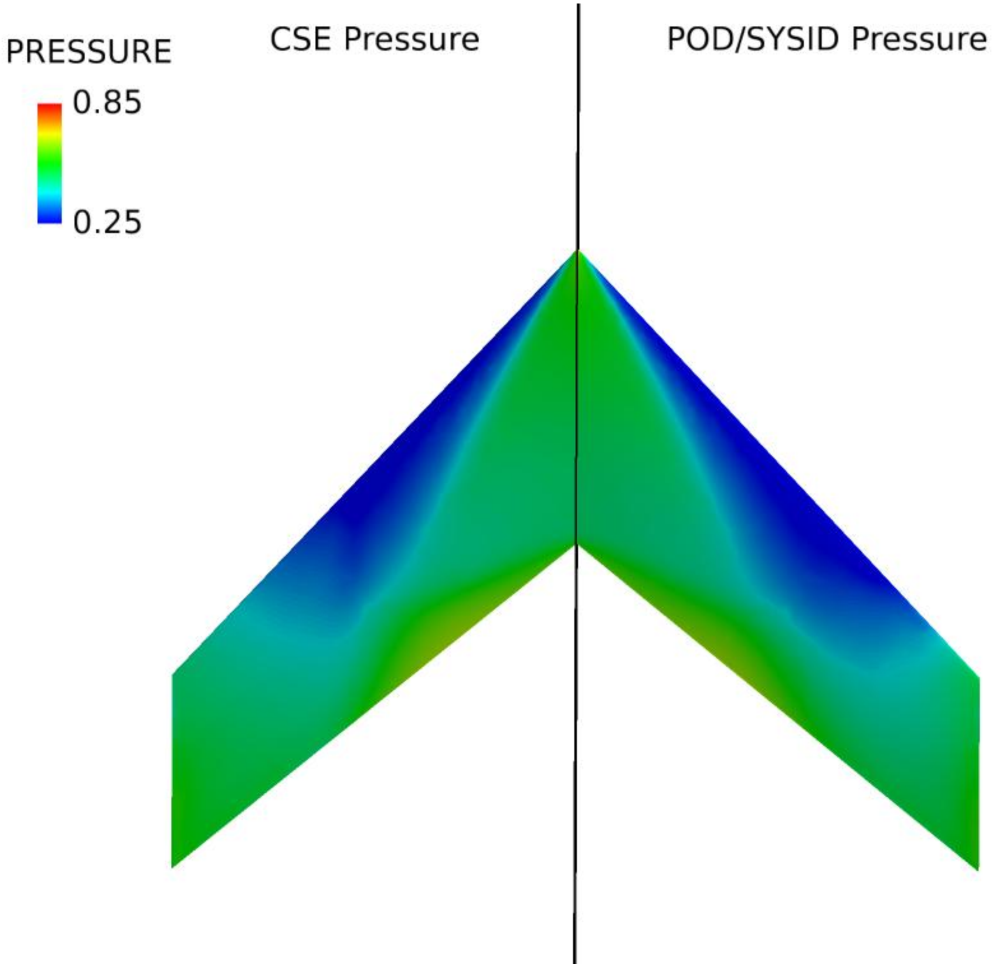

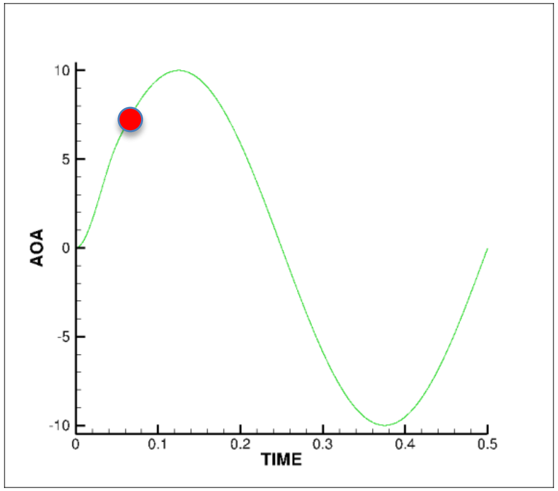

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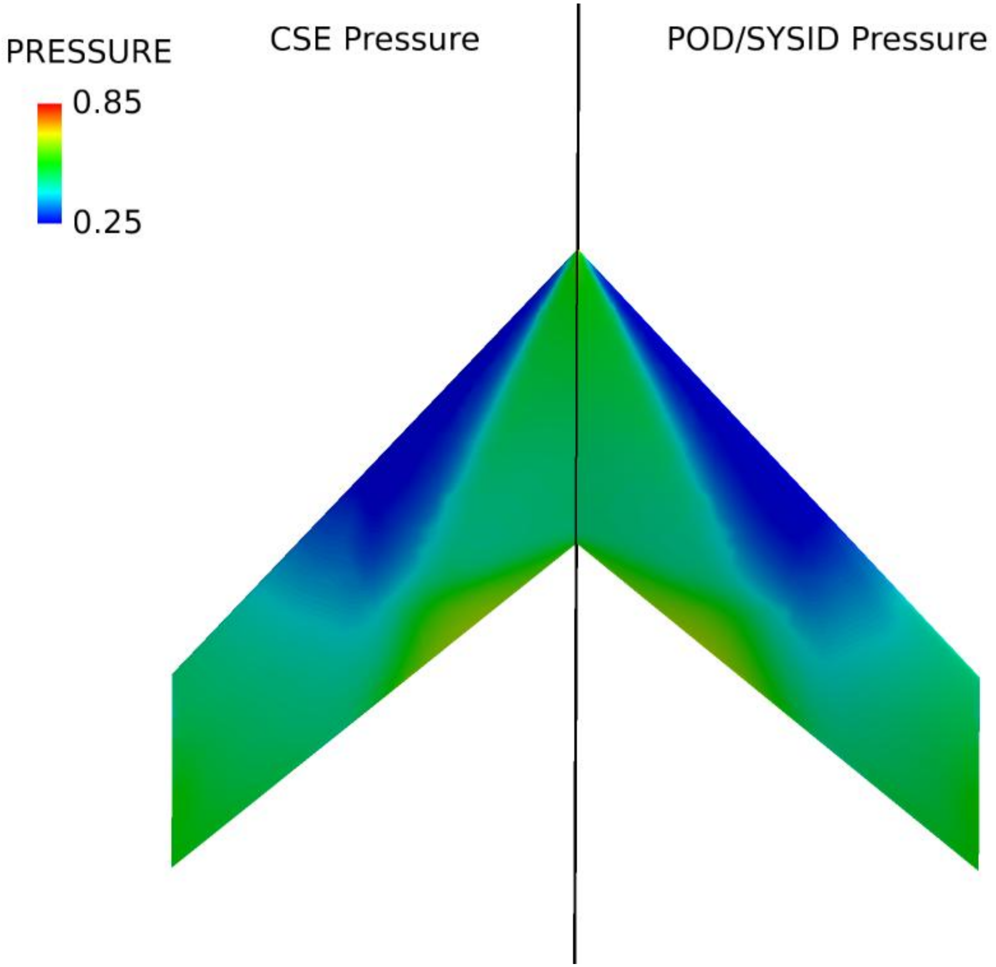

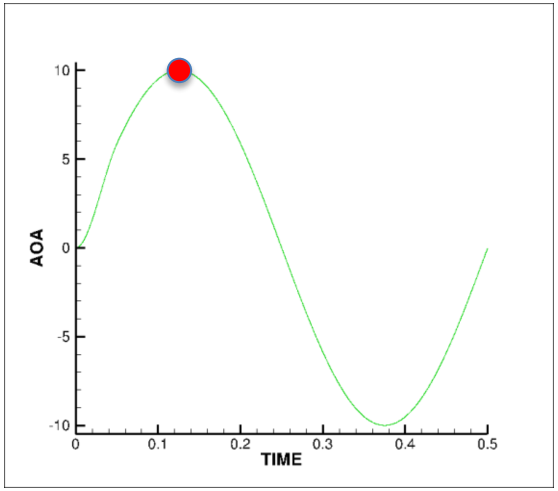

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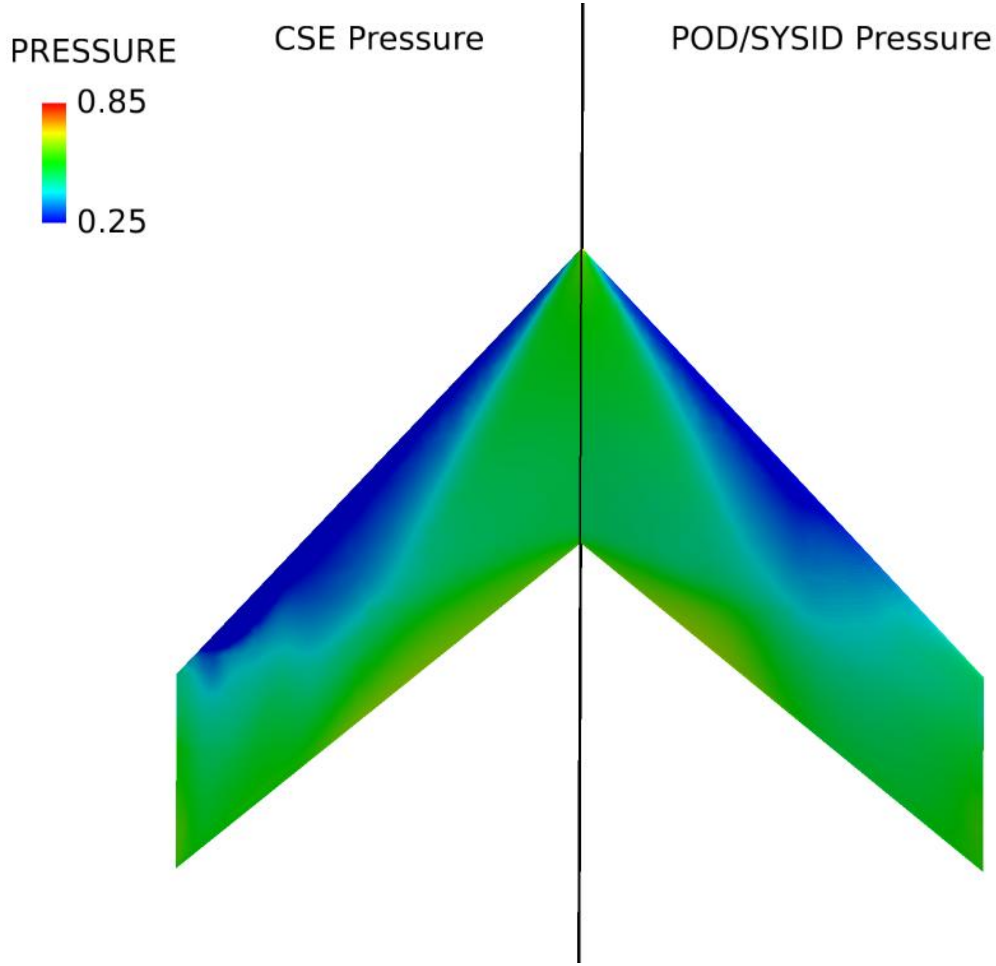

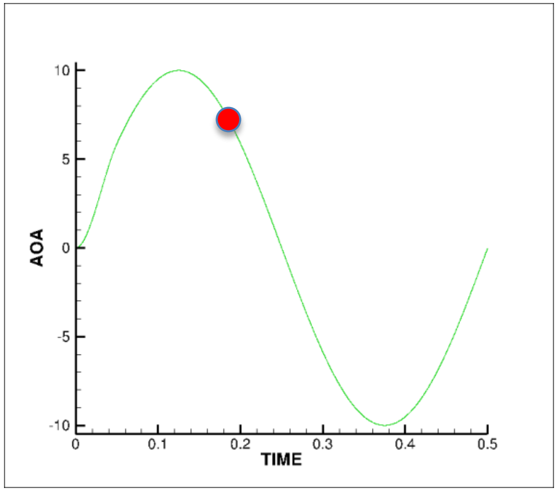

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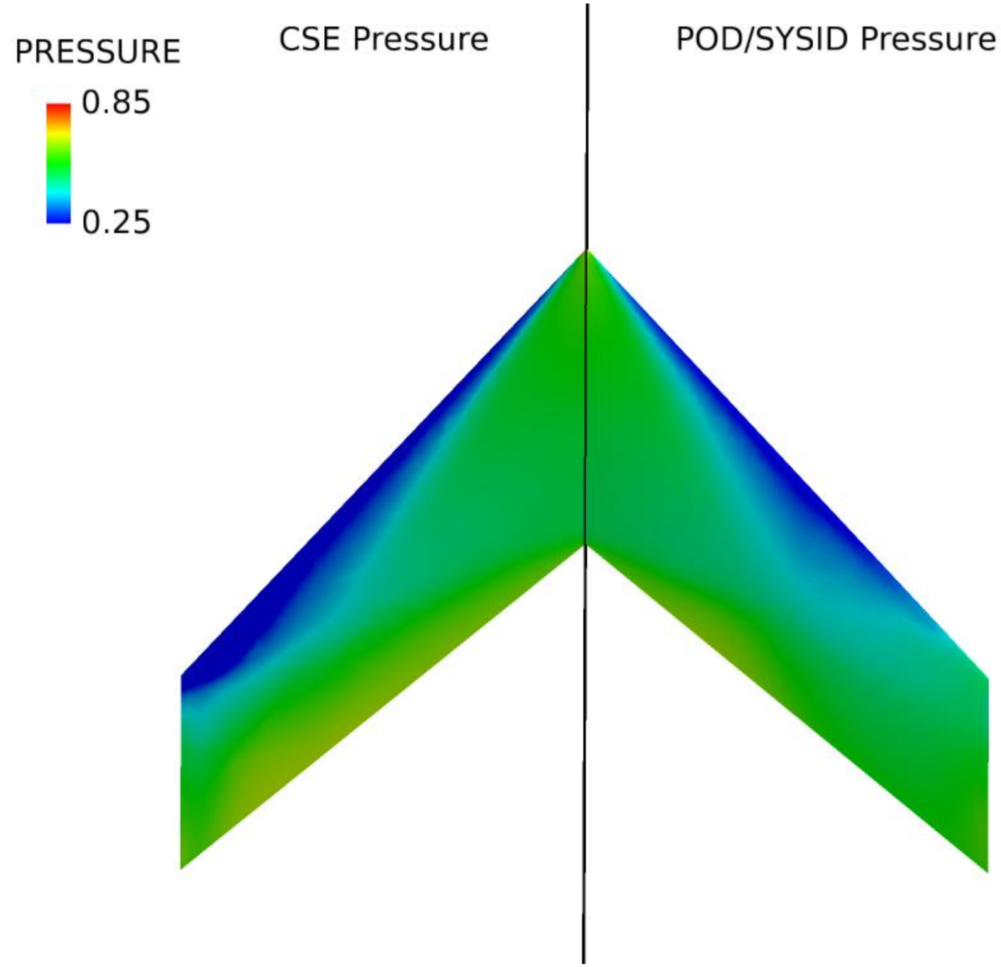

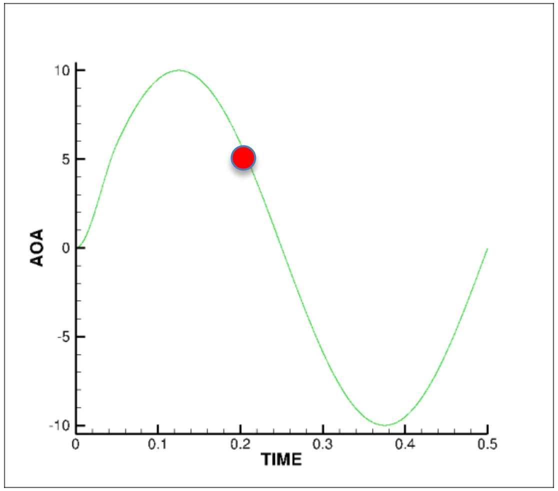

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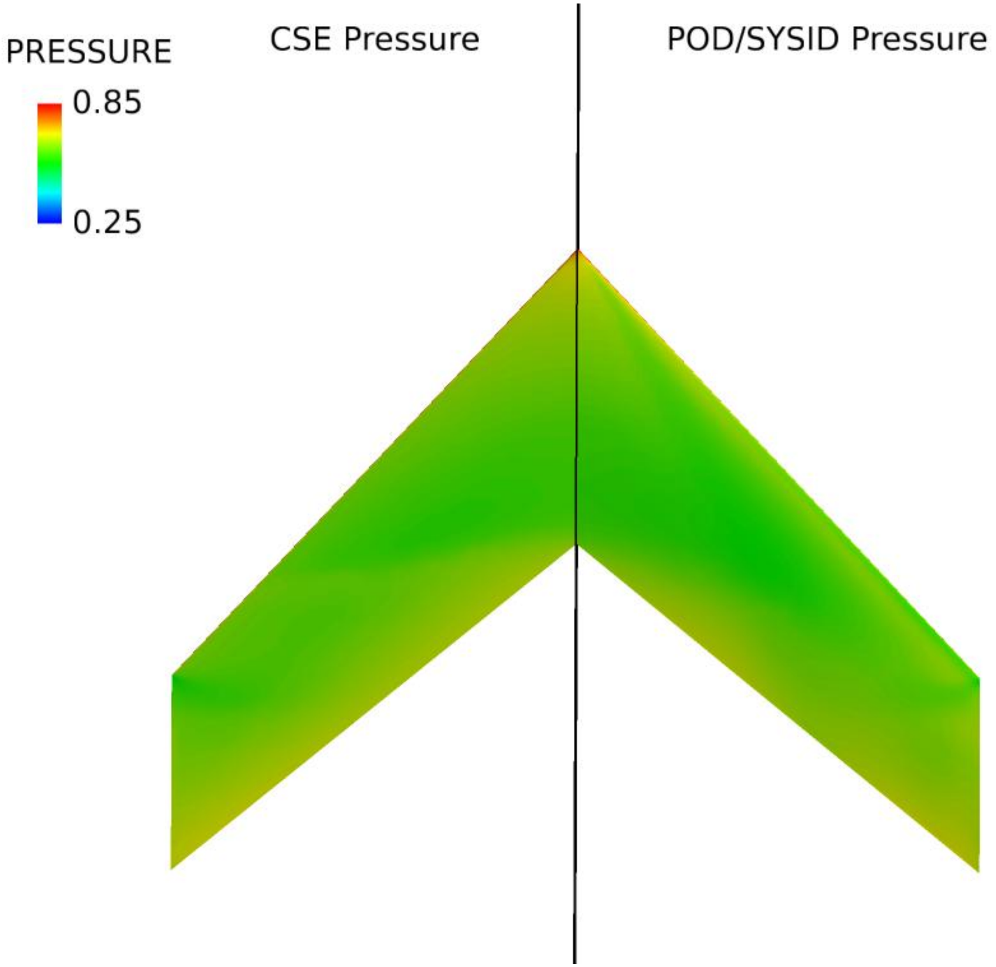

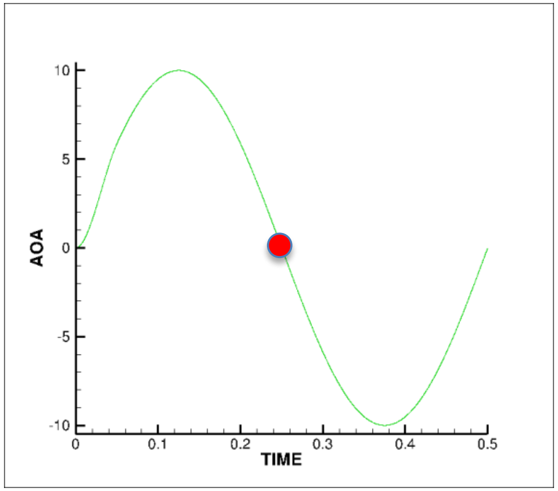

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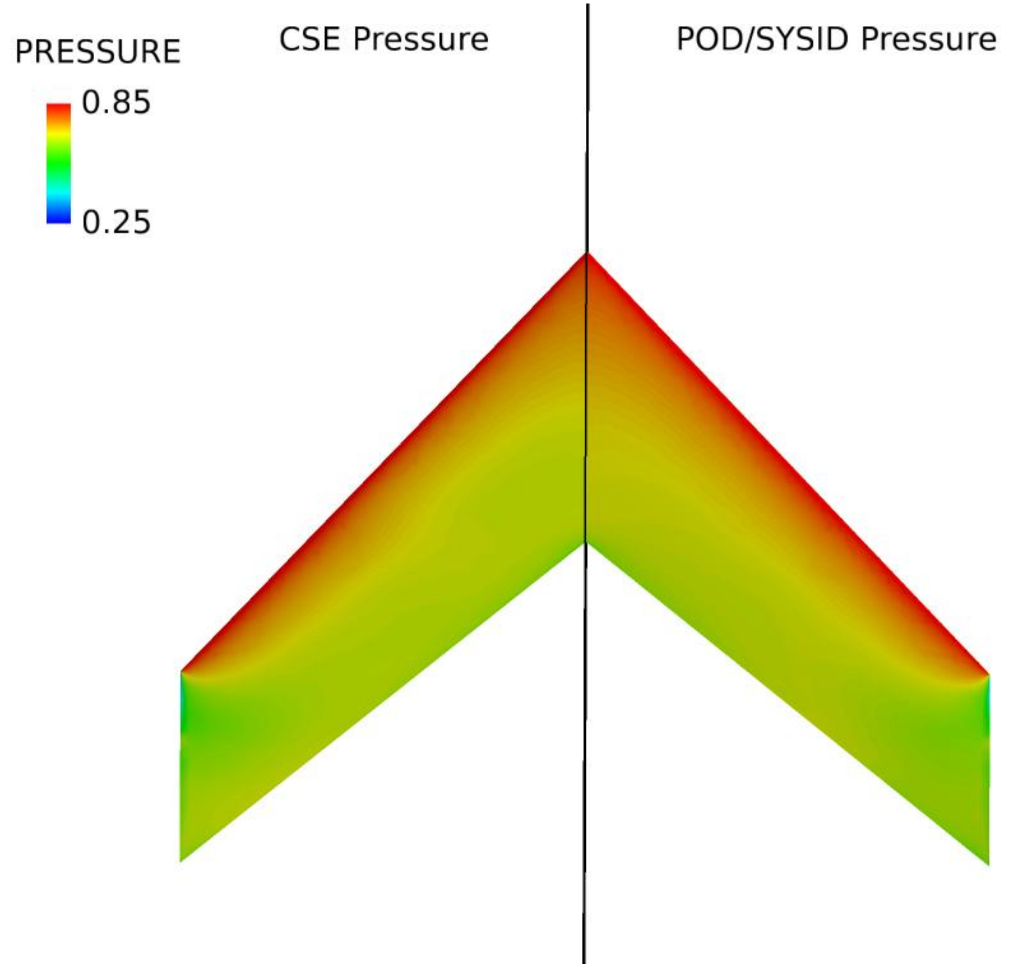

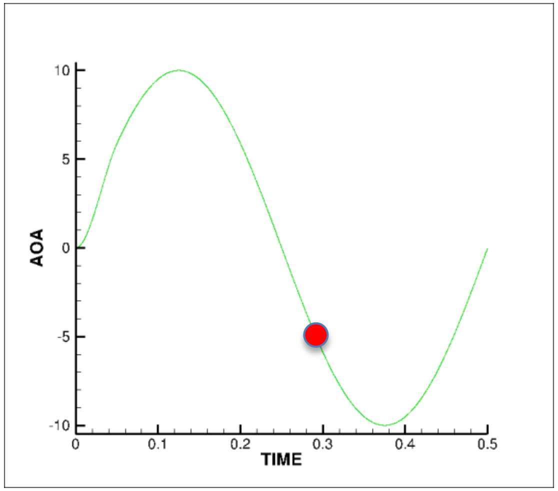

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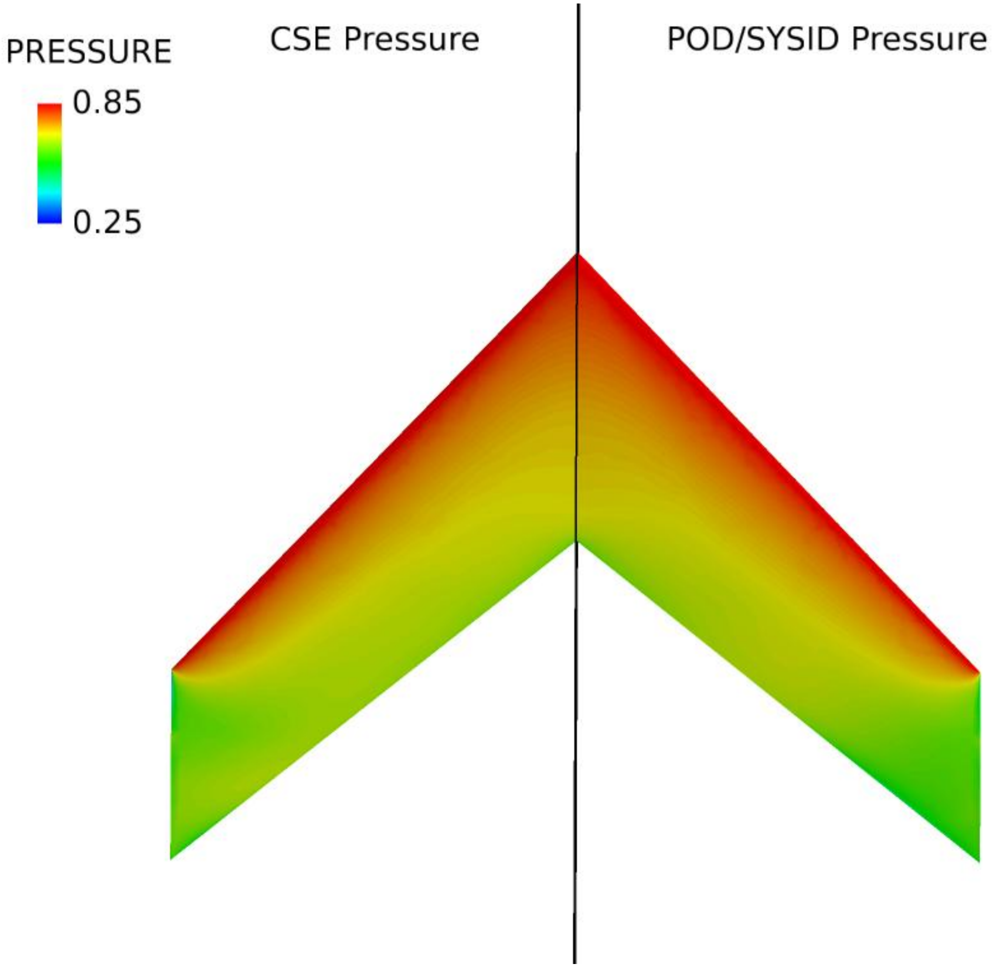

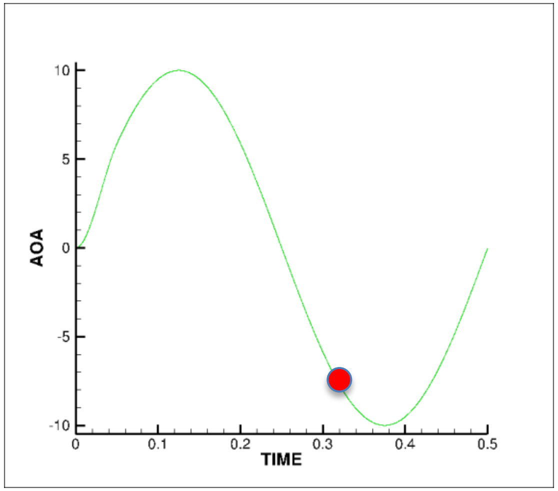

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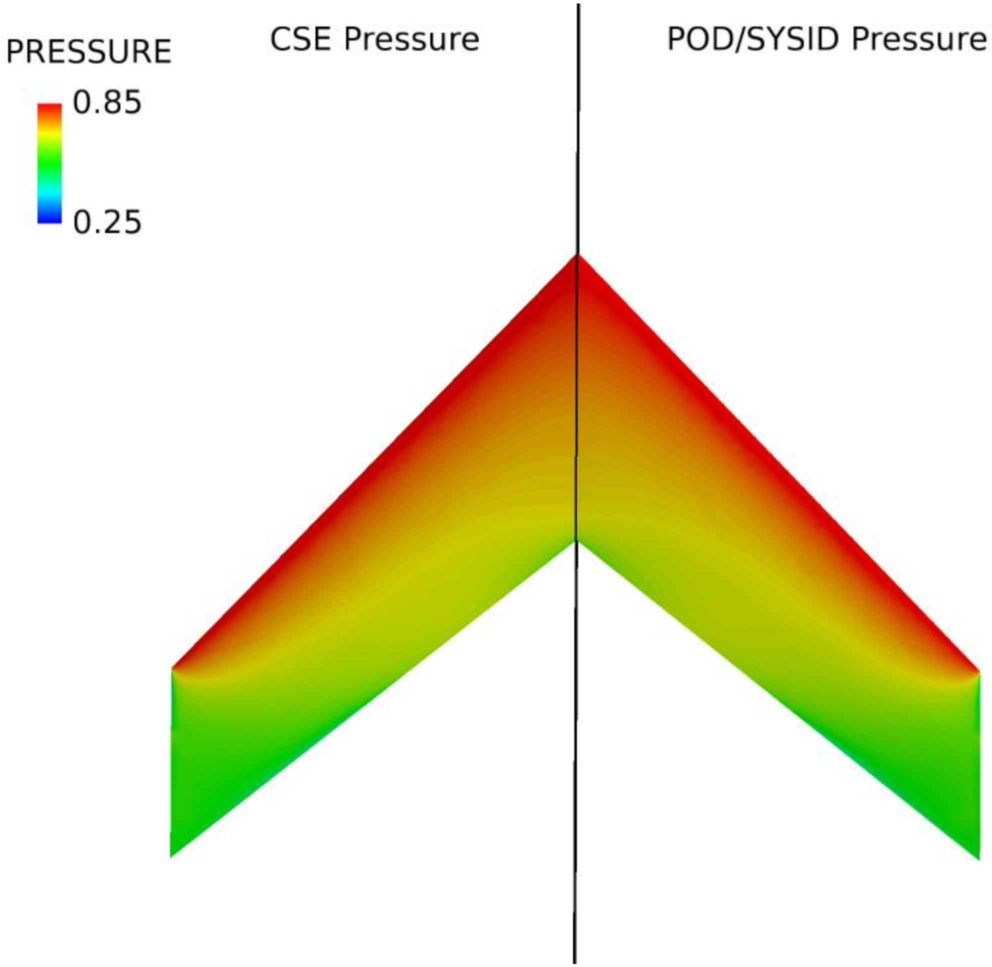
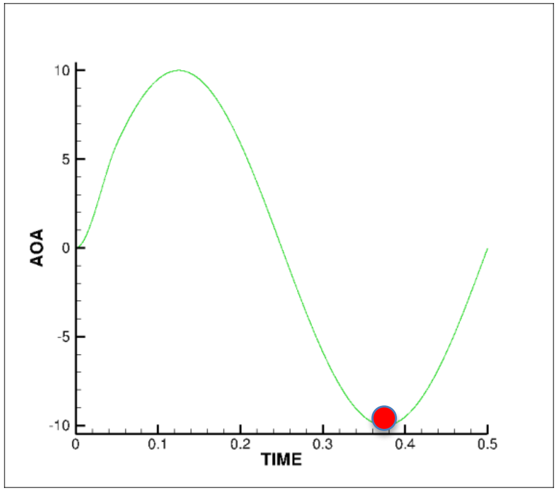
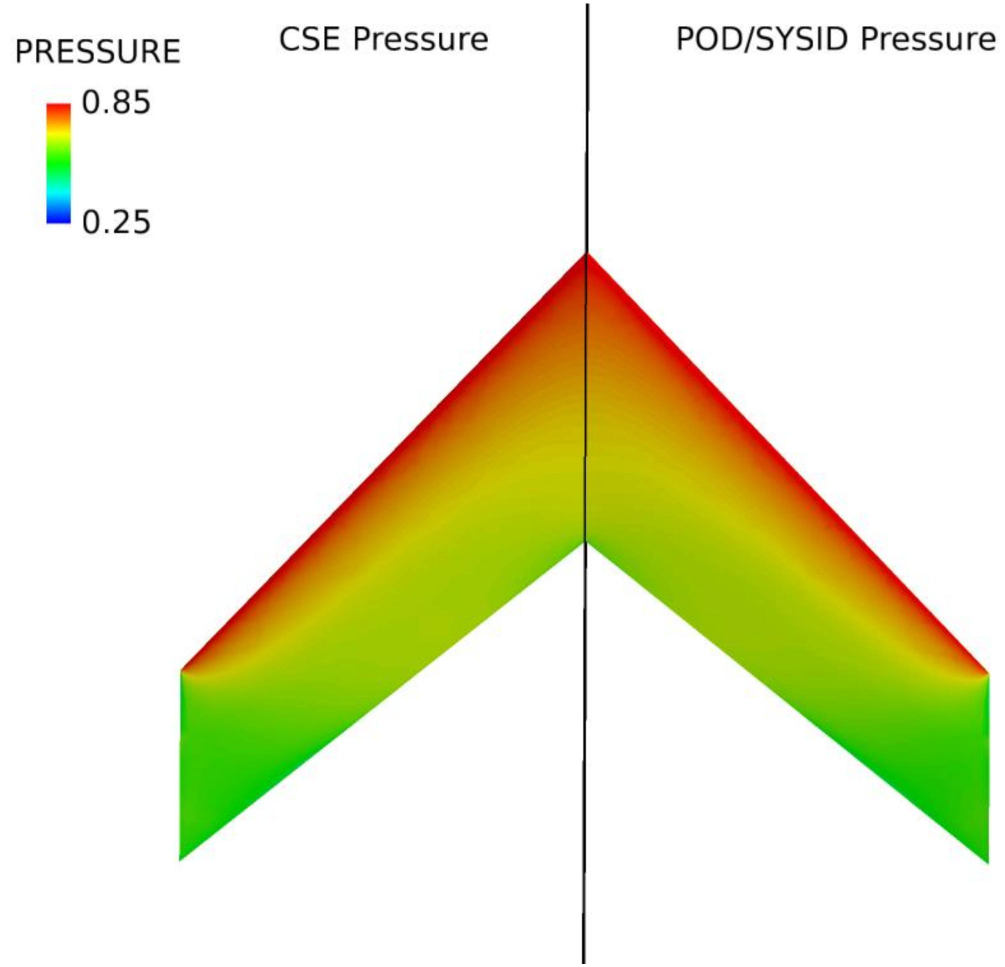


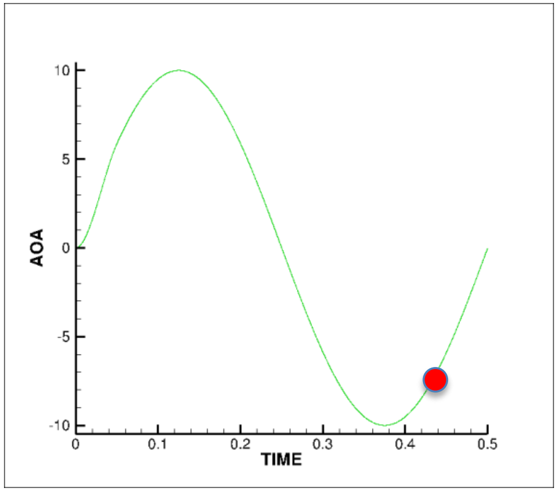


AGARD 445.6 Wing

Comparison of Surface Pressure for CSE to POD/SYSID

2 Cycles/Sec Pitch Maneuver





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AGARD 445.6 Wing

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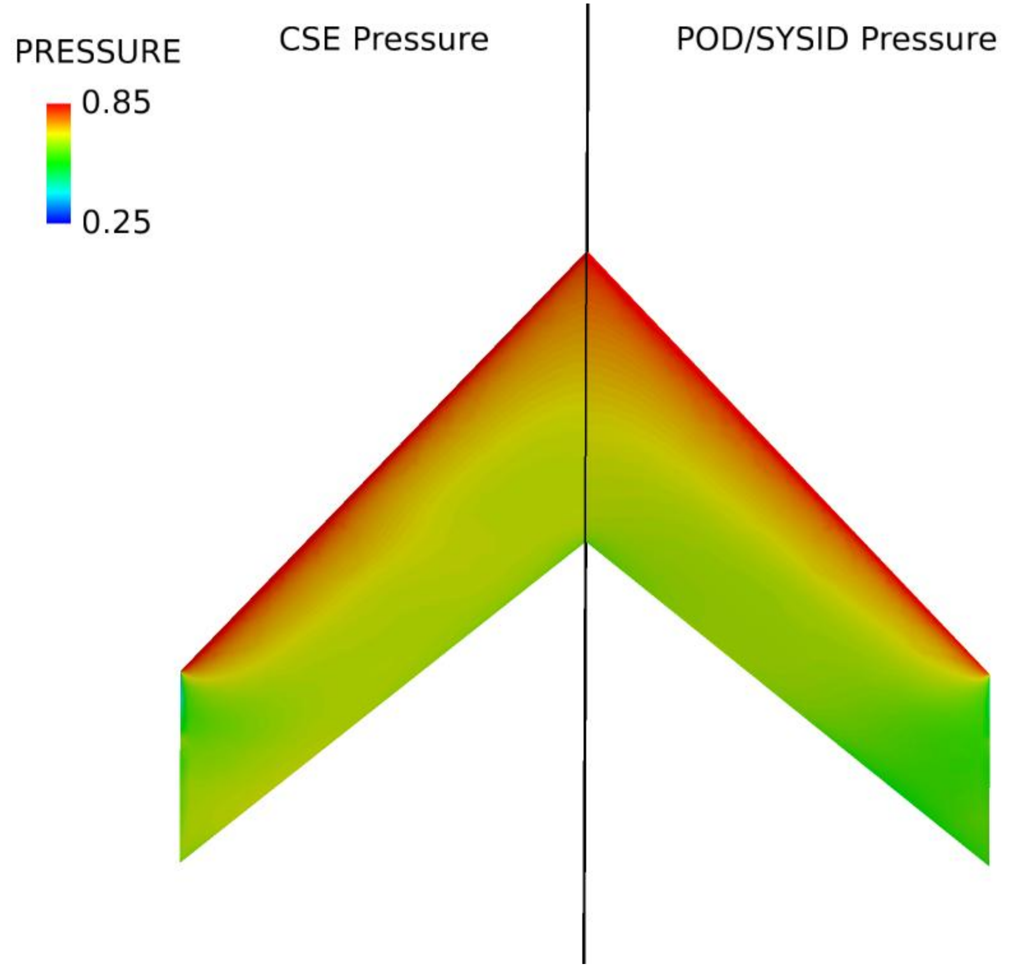

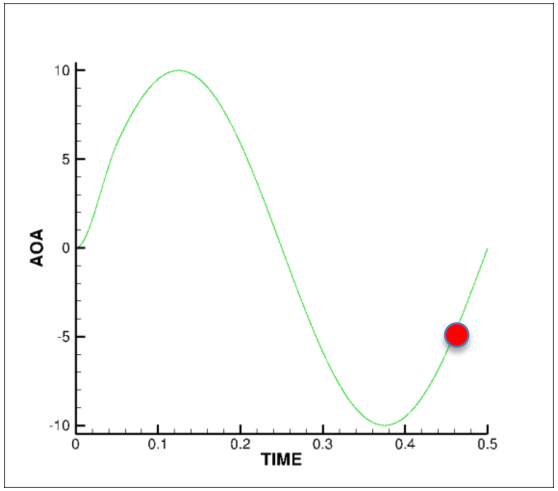

AGARD 445.6 Wing

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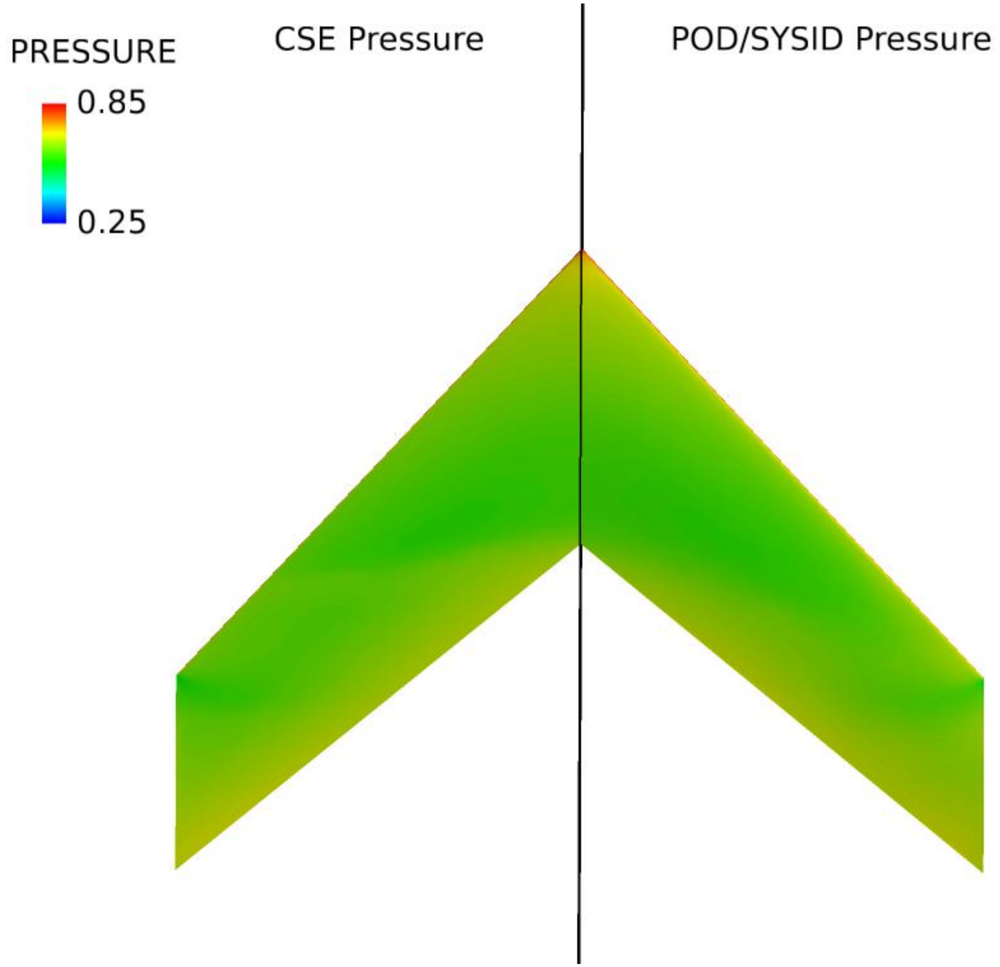
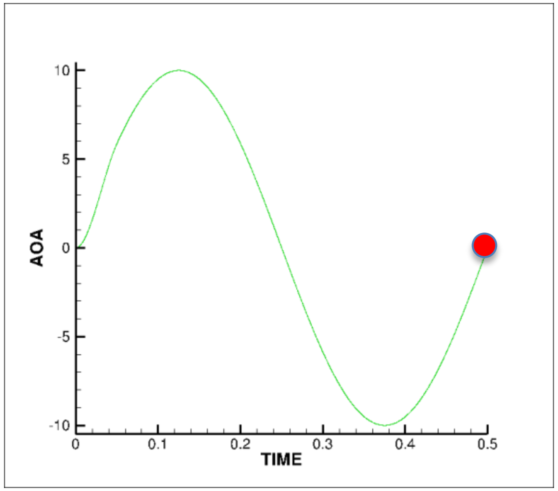


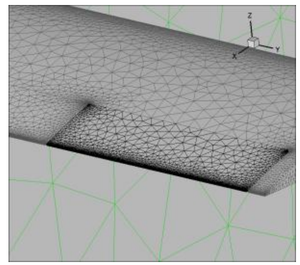


- **Started with only an OML**
- **Built a POD of a training maneuver**
- **Built a predictive SYSID of the POD**
- **Re-constructued a maneuver using the predictive SYSID/POD**
- **Compared well with CSE**

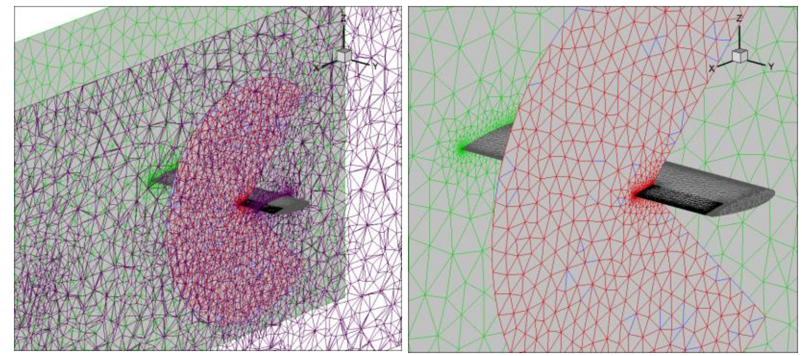
Ultimate Goal

- **Integrate all modules into high-fidelity tool capable of developing accurate models of full elastic aircraft configurations**

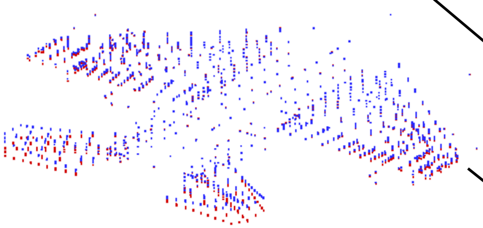
Fluid-Structure Interpolation



Control Surface Deformation

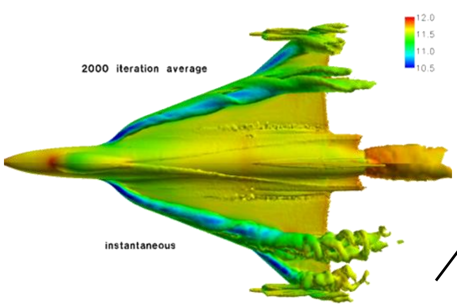


Fluid Grid Deformation

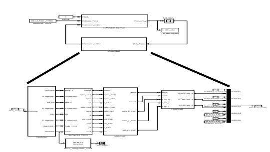


Structural Model

$$Loads = f(\bar{q}, M, a, a^2, q, aq, \dot{q}^2, \ldots)$$

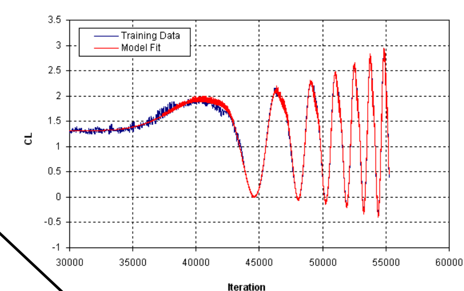


Aerodynamic Loads



Autopilot Integration

Engine Thrust Model



System ID

Conclusions & Outlook

- **Deficiencies in the current conceptual, preliminary, and detailed design process have been noted**
- **A new method has been proposed to address these deficiencies using CSE early in the design phase using**
  - **A system level high-fidelity CSE tool**
  - **High performance computing**
  - **Compact efficient models built from high-fidelity CSE**
- **Examples have been given of the method applied to CG loads and surface loads of a wing showing great promise for the method on realistic configurations**
- **Future work incorporating control surfaces, aeroelasticity, automatic flight control systems, and propulsion has been proposed**

Acknowledgements

- This work was supported in part by the DoD HPCMP CREATE Program with computational resources provided by the DoD HPCMP, MHPCC, AFRL, ARSC, and NAVO
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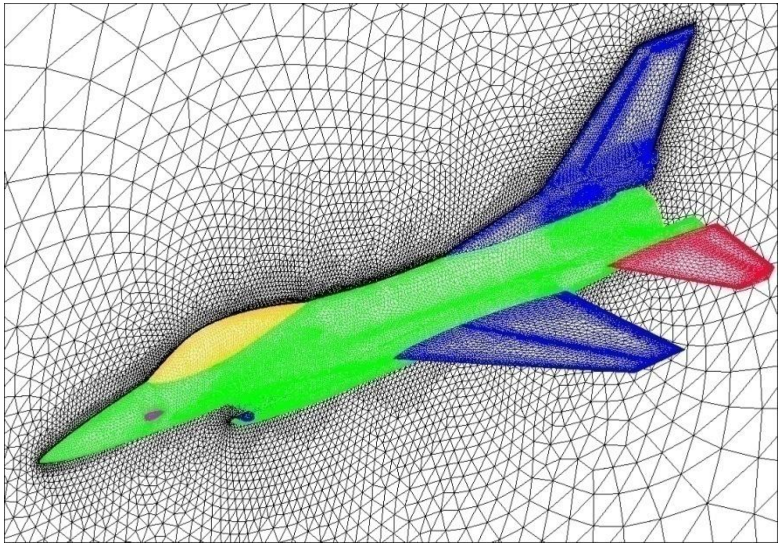
Questions?

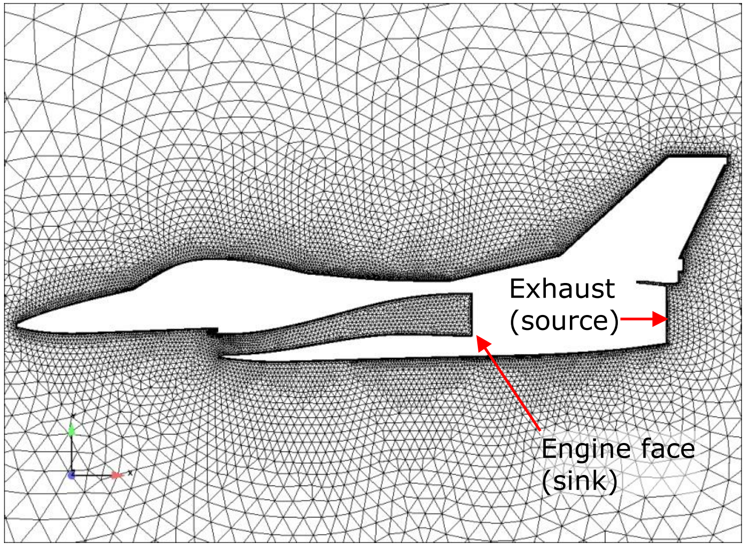
F-16 Aerodynamic CG Loads Modeling Using System Identification

DOD HPC MODERNIZATION PROGRAM

Baseline F-16 Simulations

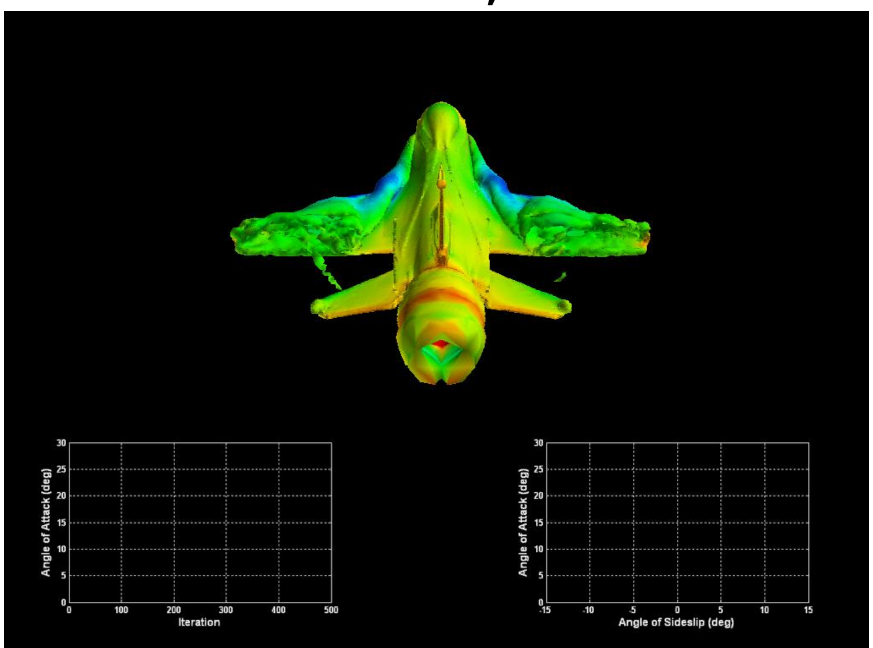
- **Half-span grid with:**
  - 790,109 nodes
  - 3,171,892 cells
  - 8 prismatic layers
- **Generated with NASA tool VGRIDns**
- **Cells concentrated in the strake vortex**
- **Forebody bump, diverter, ventral fin modeled**
- **Corrected engine mass flow modeled**
- **Flow conditions:**
  - M_∞=0.25, 0.6, .8, .9, .95, 1.2, 1.6, 2.0
  - *Altitudes = 5k, 10k, 20k, 30k*
- **Numerical parameters:**
  - Δt=0.0002s
  - 3 Newton sub-iterations
  - DDES based on SA with RC

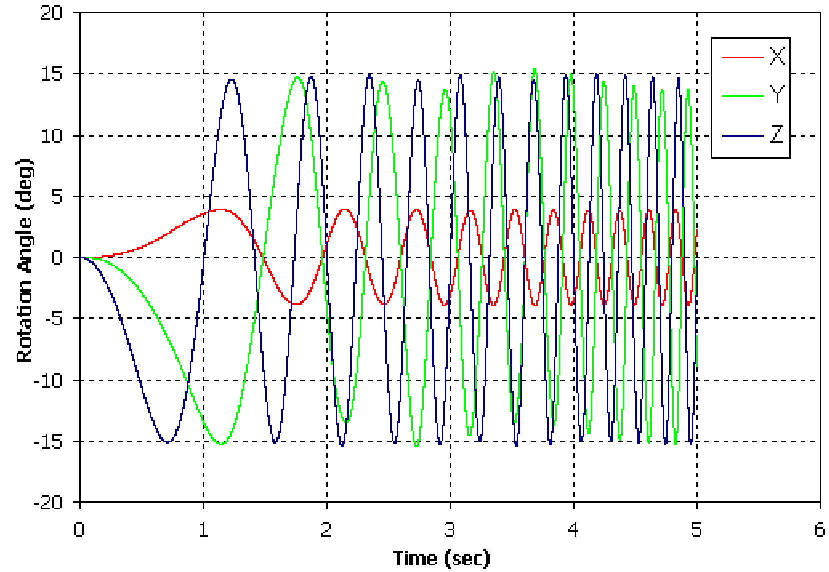


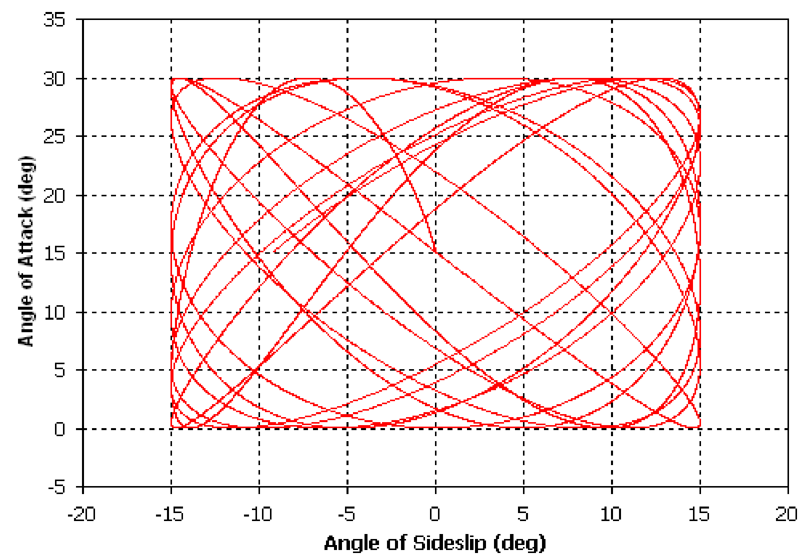


Multi-axis Training Maneuver Pitch-Yaw Chirp

- **Composite Pitch-Yaw Chirp maneuver allows a single motion input to create a model including motion about two axes**
  - $\alpha = 15 \pm 15$ deg, $\beta = 0 \pm 15$ deg
- **Input signals made orthogonal (dot product = 0)**
- **Requires full span F-16C grid**
- **Conditions: M=0.6, Alt.=5k ft.**





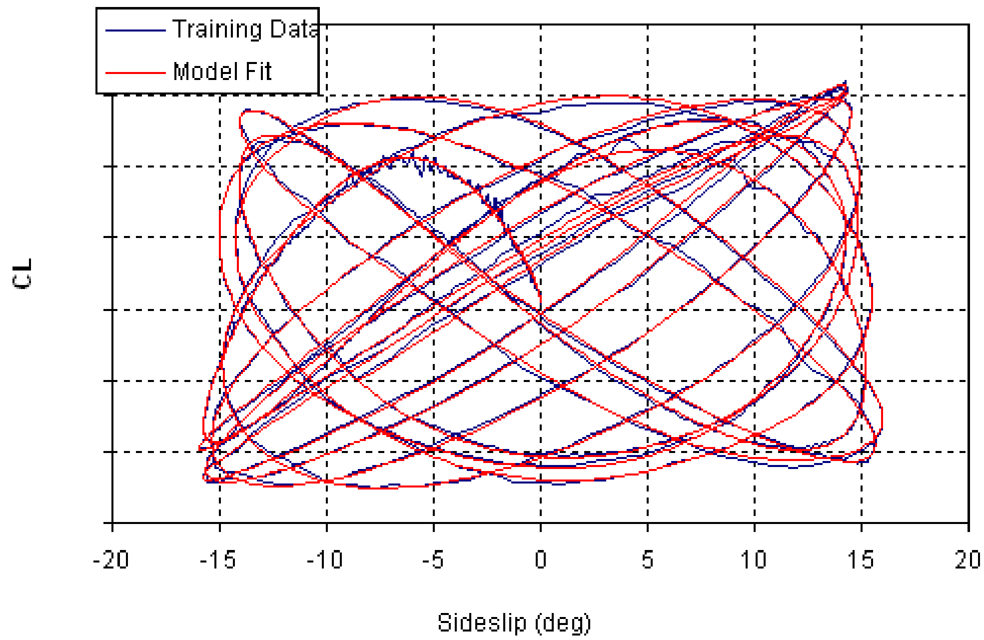


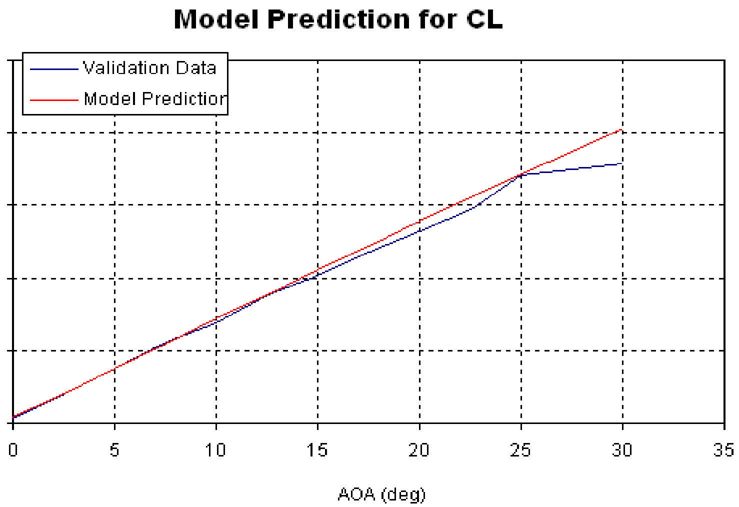
System ID Applied to Multi-axis Training Maneuver: Pitch-Yaw Chirp

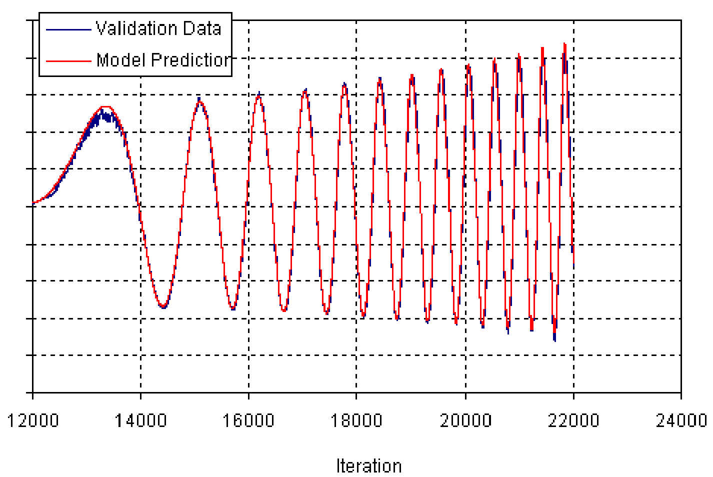
- **SIDPAC Model:**

$$C_L(\alpha,\beta,p,q,r) = C_1 + C_2\alpha + C_3 q + C_4 p^2 + C_5\alpha q^2 + C_6\beta pq$$
$$C_7\beta p + C_8\alpha^2 q + C_9 r + C_{10}\alpha\beta^2 + C_{11}\alpha^3 + C_{12} pr +$$
$$C_{13}\beta^2 p + C_{14}\beta^2 q + C_{15} p + C_{16}\beta^2$$

- **Validated against static C_L-α data and single axis motion pitch chirp**







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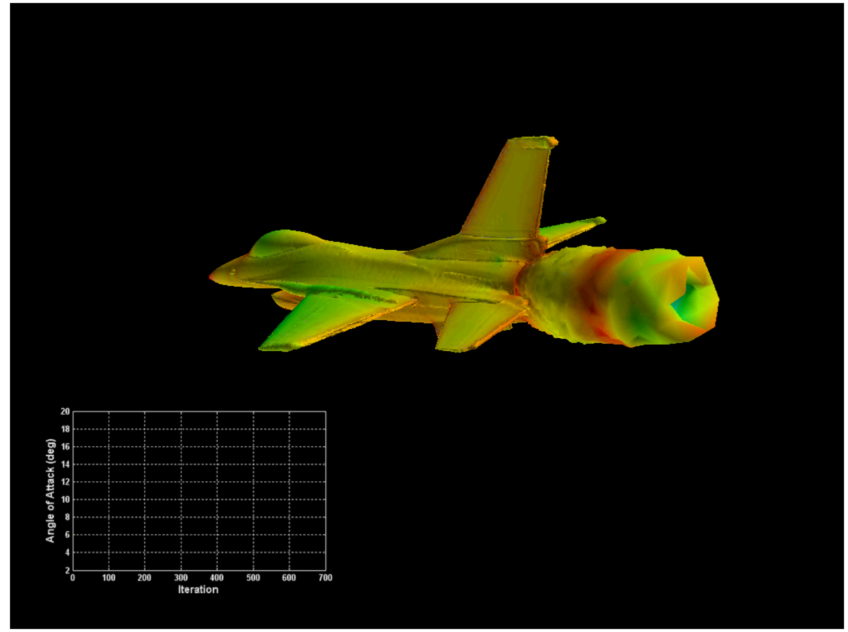
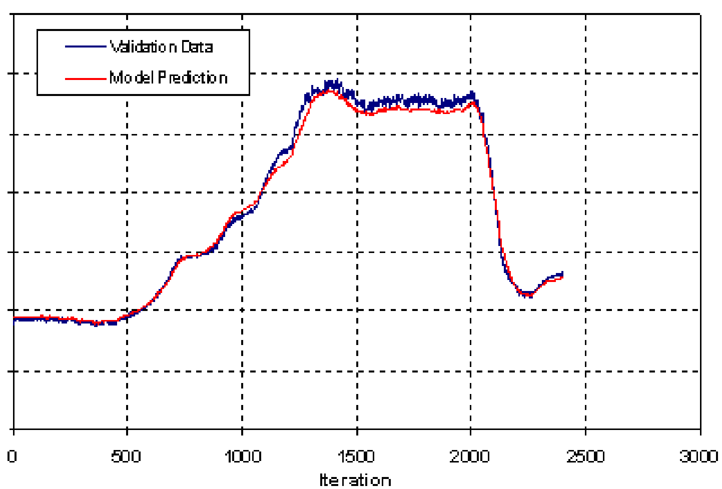
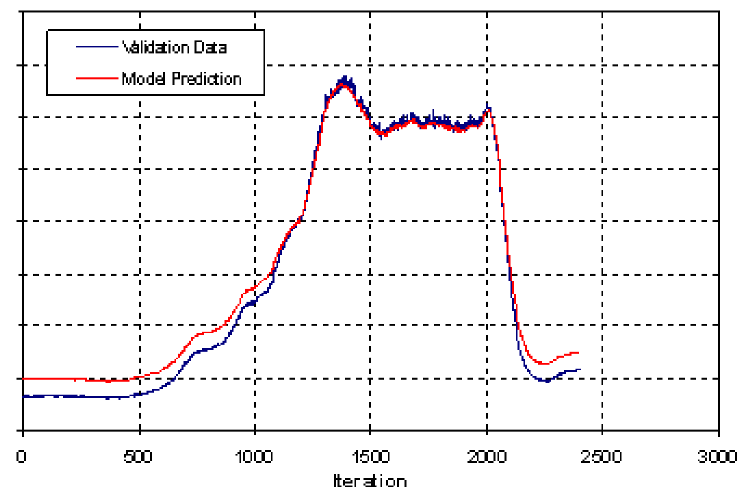
2.5g Wind Up Turn Flight Test Maneuver

- Prescribed motion based on flight test data (rotations only)
- Use reduced order loads model to perform maneuver & compare
- Good Lift prediction
- Drag prediction not as good as expected
- Conditions: M=0.6, Alt.=5k ft.





Lift



Drag

Training Maneuvers in 6-DoF

- **Incorporate both translation and rotation into the training maneuver to provide better regressor space coverage**
- **Much better drag model predictions resulted**