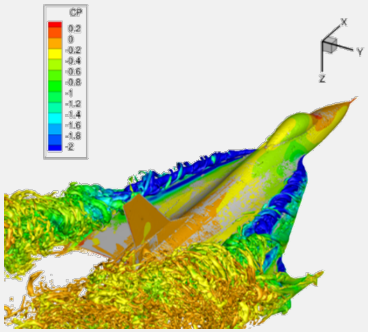
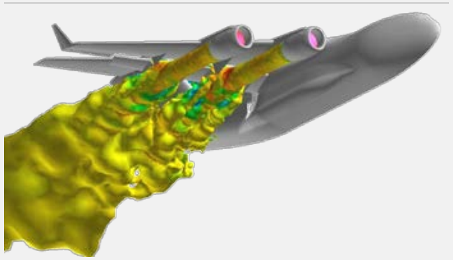




A Ten-Year Retrospective on Building CREATE Air Vehicle Tools Consistent with Much of the CFD2030 Vision

Scott A. Morton, CREATE-AV Project Manager
CFD2030 Integrating Committee

DOD HPC MODERNIZATION PROGRAM

Overview

- **Some History…**
- **Kestrel overview**
- **Kestrel and the Vision 2030 CFD capability**
  - Emphasis on physics-based predictive modeling…
  - Management of errors and uncertainties…
  - Higher degree of automation in all steps of analysis process…
  - Ability to utilize massively-parallel, heterogeneous, and fault-tolerant HPC architectures…
  - Capability to tackle capability- and capacity-computing tasks…
  - Enables complex multidisciplinary analyses and optimizations...
- **The Future...**
- **Summary**

Some history…

- **In FY07 the DUSD for Acquisition funded a POM initiative to improve acquisition simulation tools for ships, aircraft, antennas, and meshing/geometry → CREATE was born**
- **The CREATE-AV team developed three products starting 1Oct07 → Kestrel and Helios with a propulsion module, Firebolt, and a design code DaVinci**
- **Requirements for the software were gathered from all of the major DoD acquisition agencies that could use an HPC simulation tool with the bottom-line requirements-**
  - Easy to use, accurate enough to make decisions, a/c in operational scenarios
- **There are over 650 active licenses of the software in FY18**
  - Kestrel (575), Helios (75)
- **Kestrel and other CREATE products may be viewed as a validation of the CFD 2030 Vision report findings**

Kestrel Overview

DoD HPCMP CREATE™– AV Kestrel

Kestrel is the fixed-wing product of the CREATE™-AV program

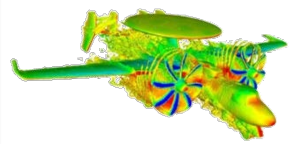
- Born from requirements gathered in 2007/08 to address modeling & simulation deficiencies in the DoD acquisition process
- Multi-mesh/multi-solver paradigm
  - Unstructured near-body (FV and SUPGFE)
  - High-order Cartesian off-body
  - Adaptive Mesh Refinement
  - Fast overset connectivity
- Full spectrum of aircraft type
  - Fighter, Bomber, Tanker, Transport, UAV
- Full spectrum of flight conditions/missions
  - Low-speed, transonic, supersonic
  - Cruise, maneuver, take-off/land, refueling, formation flight, store carriage and release, pilot ejection, precision air-drop, and more…

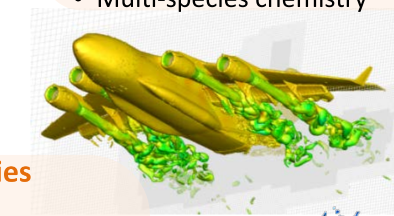
Kestrel

Version 8

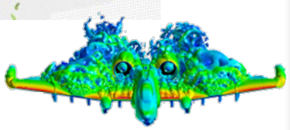
Capabilities

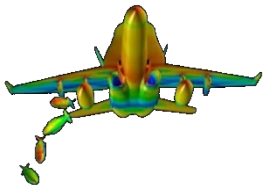
High-fidelity coupled physics
- Aerodynamics
- Structural Dynamics
- Propulsion
- Flight Control Systems
- Multi-species chemistry





Key Technologies
- Multi-mesh paradigm
- Adaptive mesh refinement
- High-Order Unstructured solver
- High-order Cartesian solver
- Non-ideal gas closure models
- Python-based common software infrastructure
- Generalized interface for externally developed "plug-in" capability modules



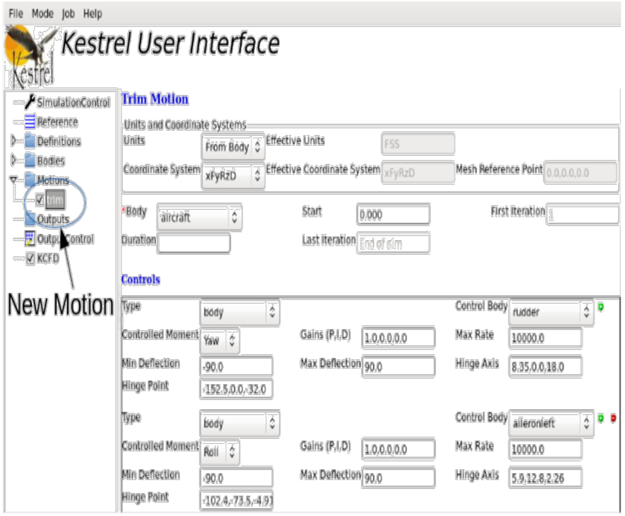


Expanding Footprint of Kestrel Adoption

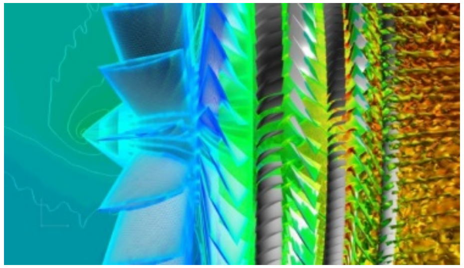
- 575 active license holders (as of 1 Jan 2018)
- 21 Defense Orgs (Labs, Engineering and Test Centers) actively using Kestrel
- All major manufacturers actively evaluating Kestrel
- 5 Orgs affiliated with Other Federal Agencies using Kestrel to support US Gov't Programs
- 4 select US Academic Institutions and the Service Academies using Kestrel to support DoD Programs

Kestrel Architecture

- **Plan for change, *manage* the chaos…**
- **Kestrel User Interface (KUI/Carpenter)**
  - Pre-processing
    - Job setup and validation
    - Mesh manipulation
  - Post-processing
    - Tracking file plotting and manipulation
    - Reduced-order model building



- **Kestrel Run-Time Execution Software**
  - Common Scalable Infrastructure (CSI)
    - Unique event-driven infrastructure
    - Data Warehouse – generic data definition and automatic language translation
  - Modular Components
    - Written in Python/C/C++/FORTRAN
    - CFD Solver, mesh motion, propulsion, visualization, etc.
    - Support for proprietary, user-developed components via SDK



Distribution A: Approved for Public release; distribution is unlimited.

CFD2030 Vision

(1) Emphasis on physics-based predictive modeling.

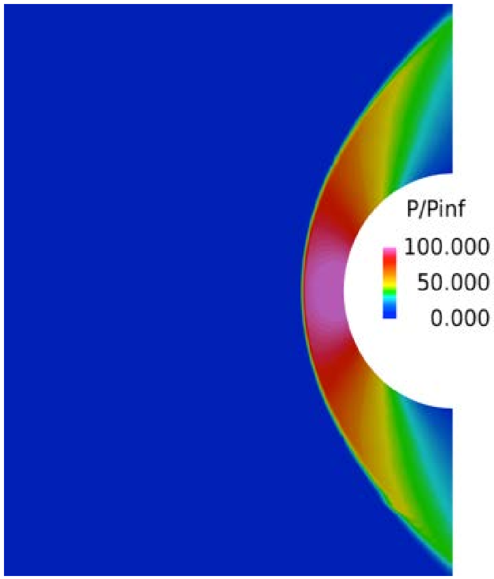
(2) Management of errors and uncertainties.

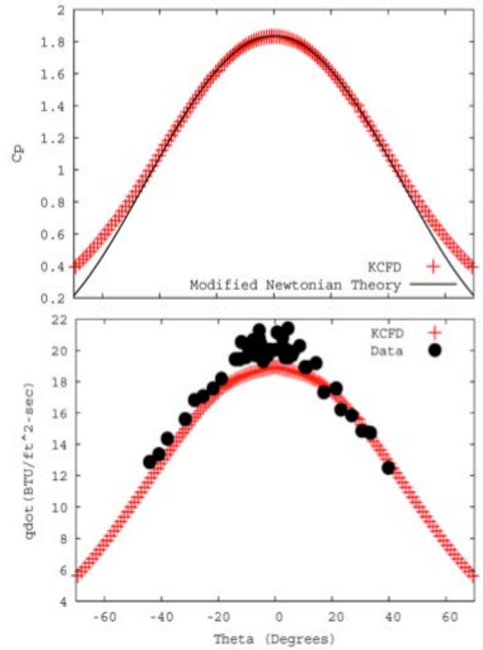
Accuracy…

DOD HPC MODERNIZATION PROGRAM

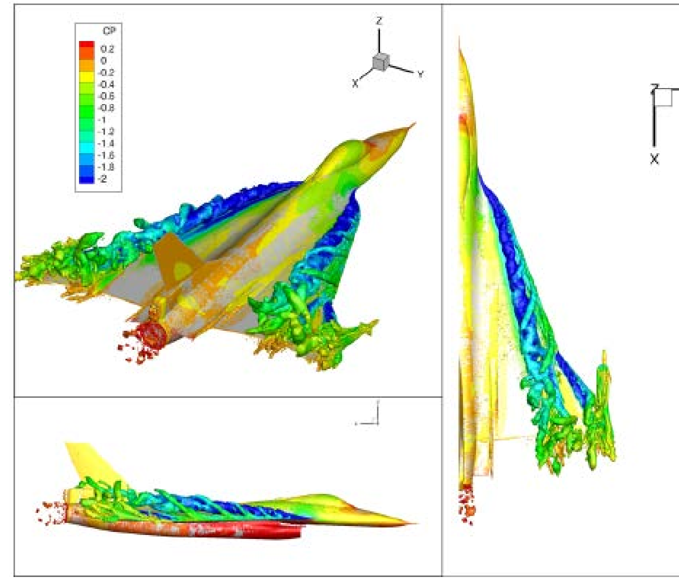
Centered on physics-based predictive capability...

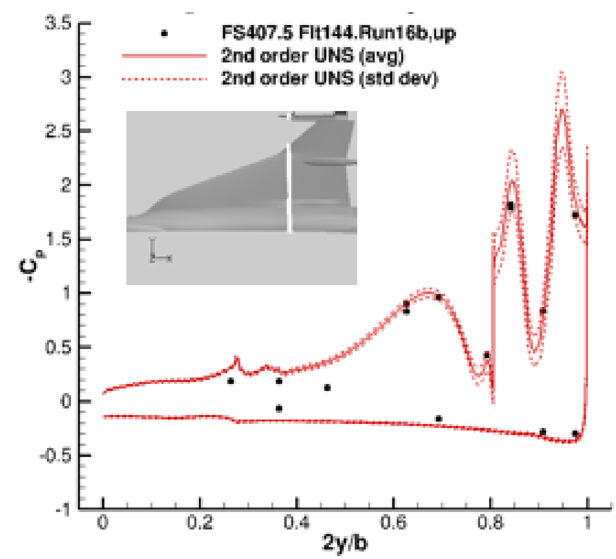
Holden Cylinder - Mach 16.01



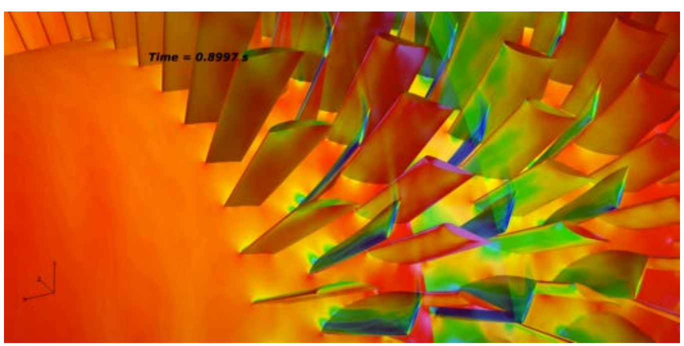


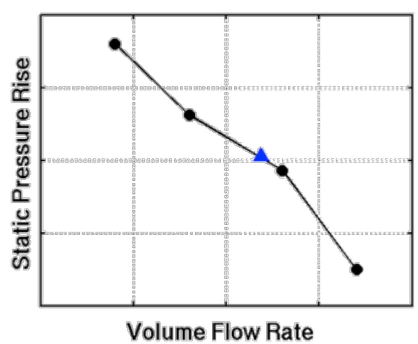
F-16XL Unsteady Solution @ 20° AOA
SA-DDES, M=0.242, 10k ft





C1 Compressor from AEDC 16T



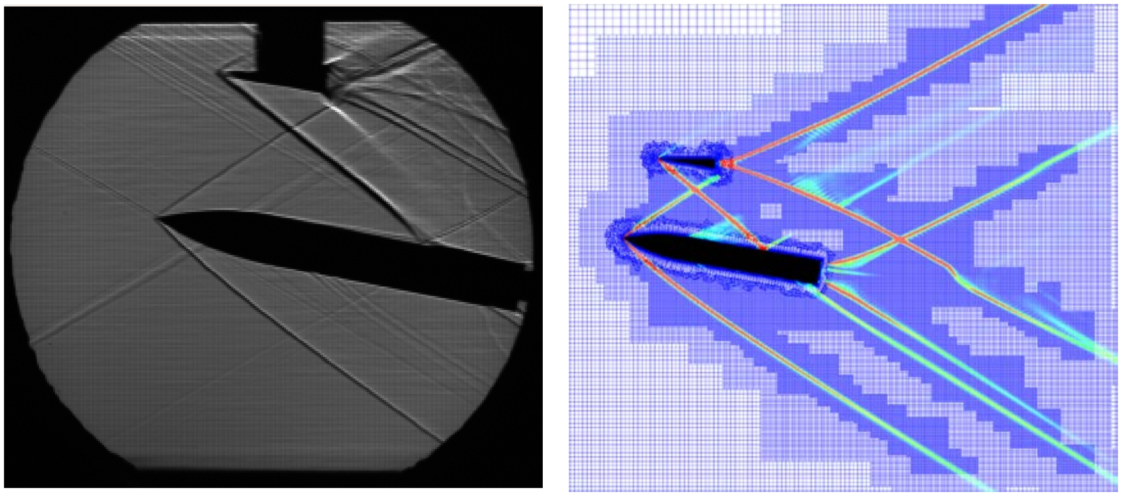


Distribution A: Approved for Public release; distribution is unlimited.

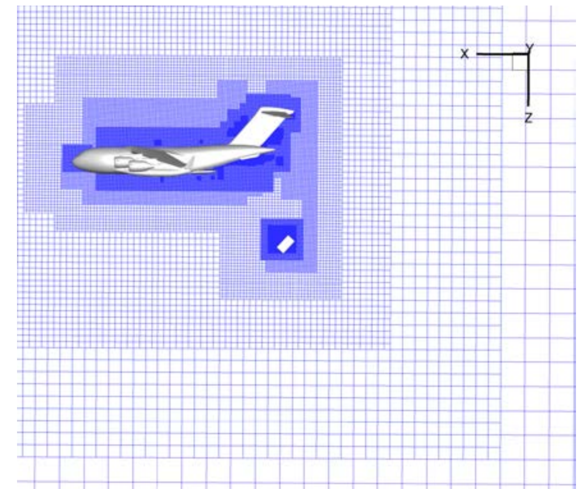
Automated management of errors and uncertainties…

- # Off-body Cartesian AMR + high-order capabilities

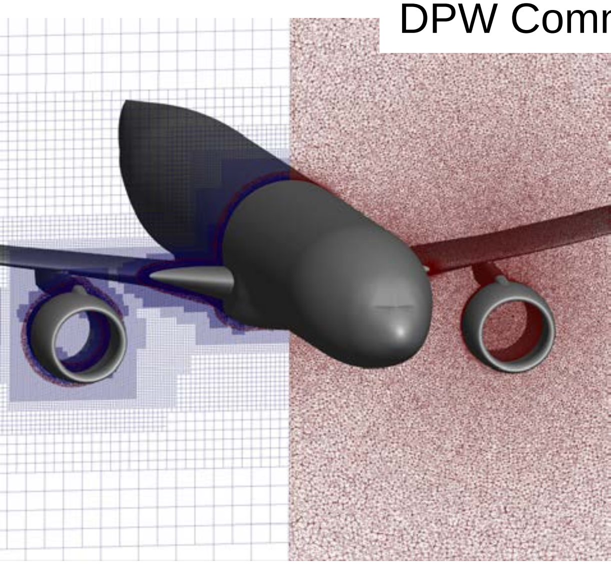
SBLI Investigation w/ Mach 2.0 ogive cylinder (FL State Univ)

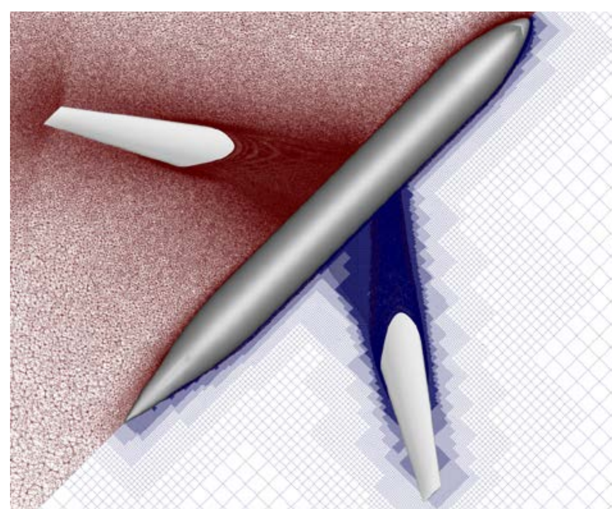


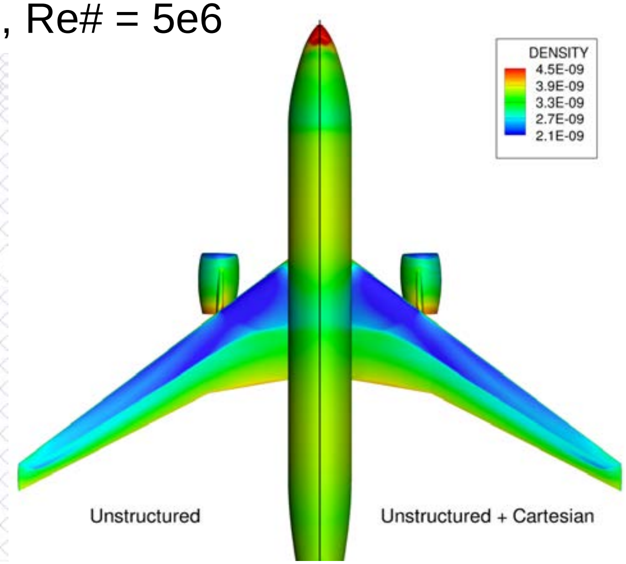
C-17 Cargo Drop



DPW Common Research Model, Mach 0.85, Re# = 5e6



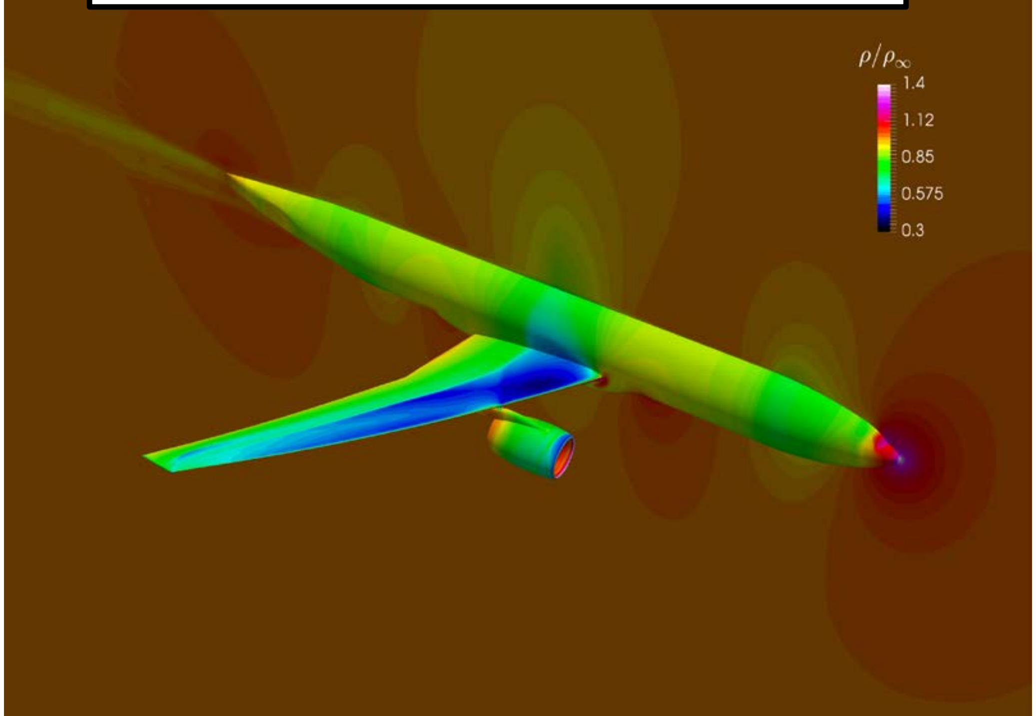




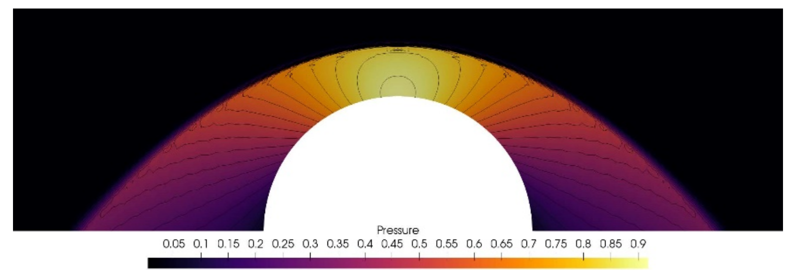
Automated management of errors and uncertainties…

- **New Kestrel unstructured flow solver component (COFFE)**
  - Streamline-Upwind/Petrov-Galerkin (SU/PG) FEM technique
  - Strong solver → machine zero convergence
  - Path to high-order unstructured capability
  - Adjoint consistent → provide sensitivities for design optimization, error control, etc.

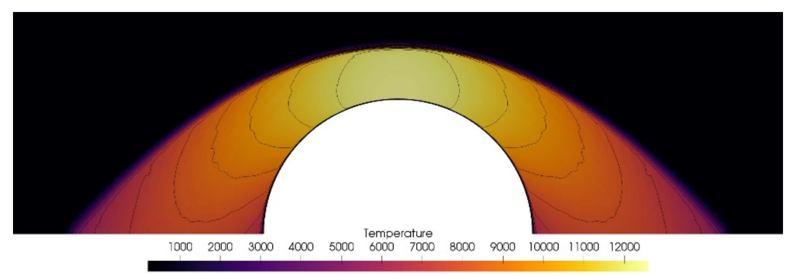
Density contours for P2 solution on CRM



Mach 17 Cylinder P2 solution



Pressure



Temperature

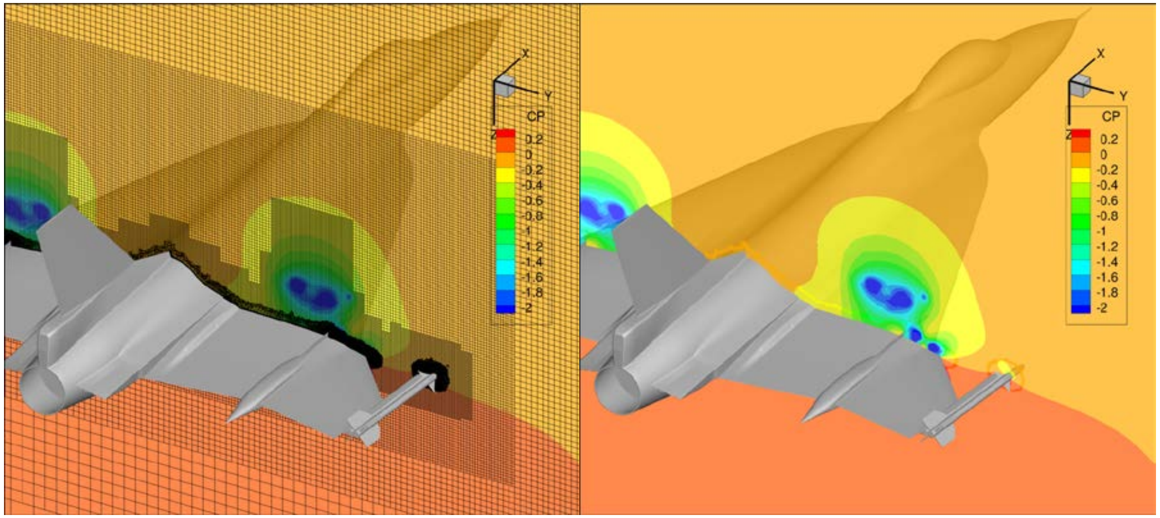
CFD2030 Vision

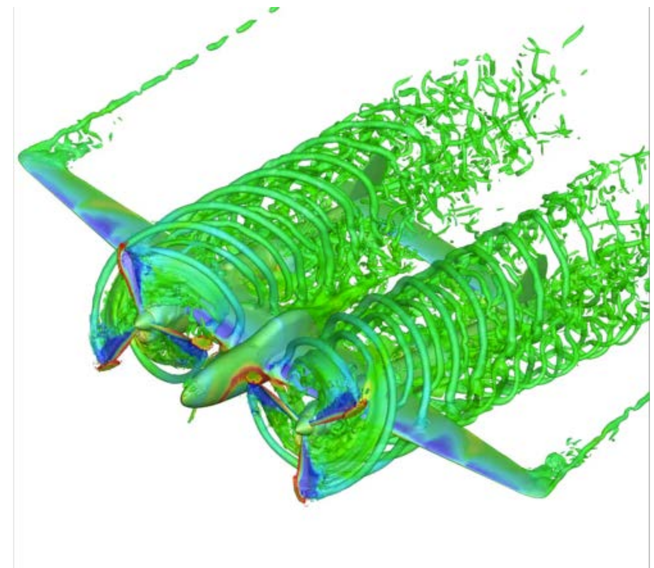
(3) A much higher degree of automation in all steps of the analysis process.

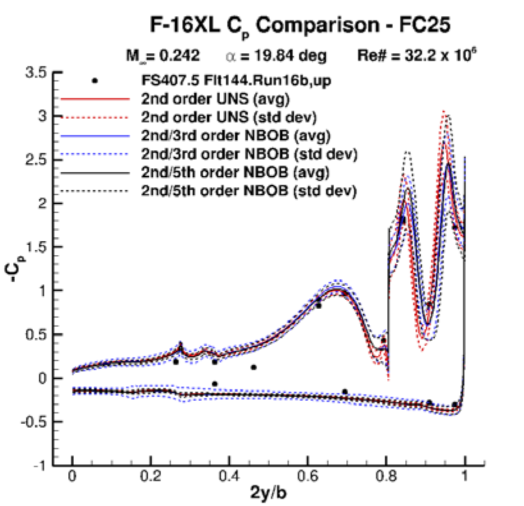
Automation…

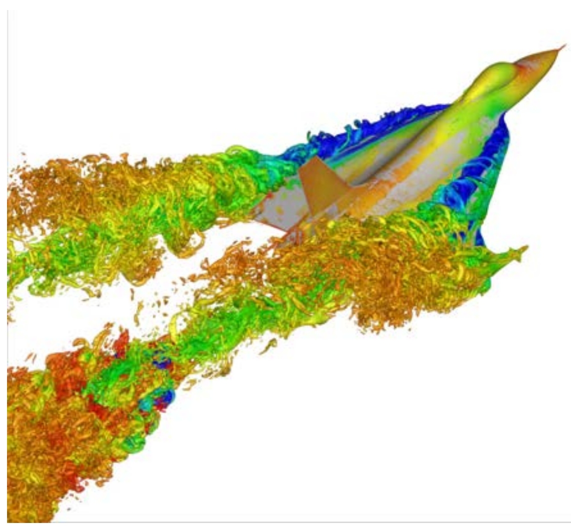
Higher degree of automation in all steps of analysis process…

- **Near-Body/Off-Body Solver Paradigm – Unstructured NB/Cartesian OB**
- **Auto-Generated Off-Body Cartesian Mesh with Automatic Mesh Refinement**

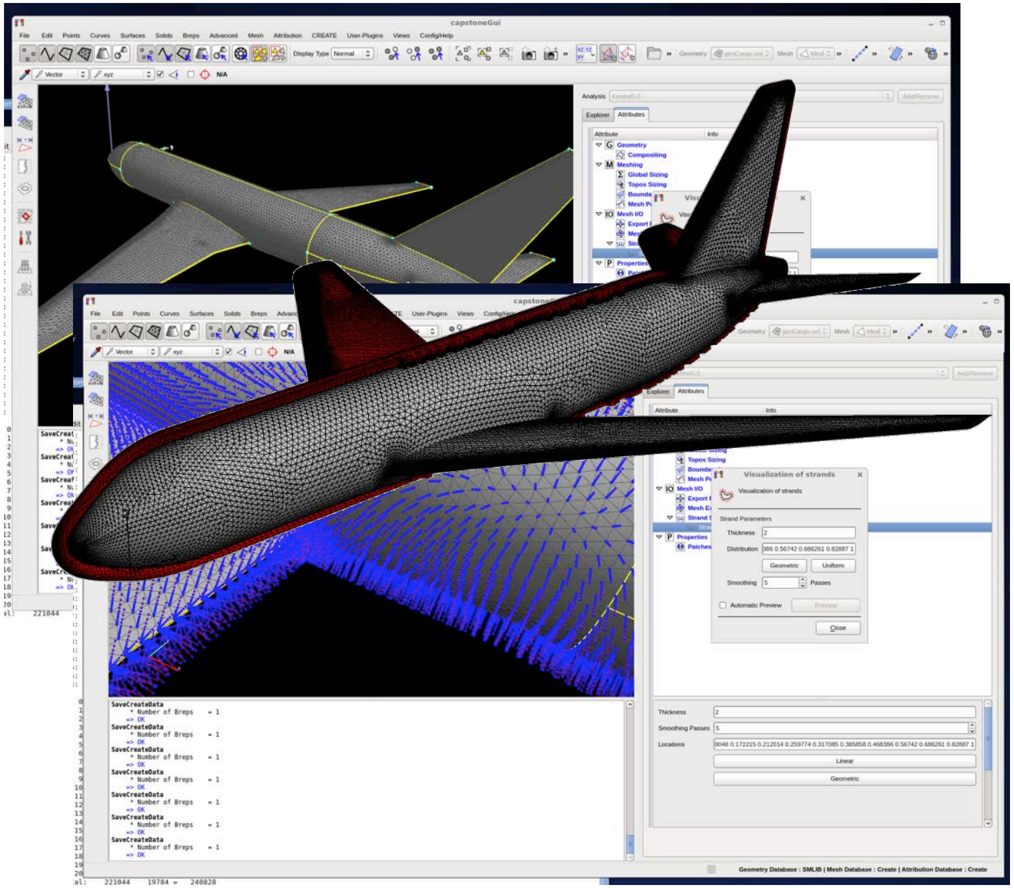


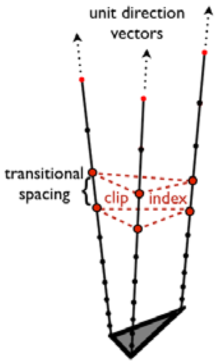


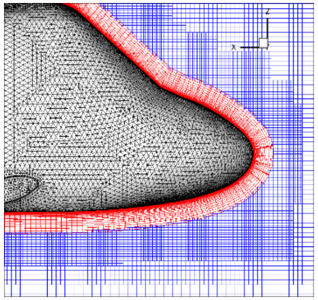




- **Body Conformal Mesh generation continues to be a bottleneck…**
- **Automatic strand-based near-body + Cartesian off-body is a potential game-changer**







- **<u>Automated</u> near-body mesh generation**
  - Multi-strand generation from CAD *R. Haimes. B. Roget, J. Sitaraman*
- **Hv7 introduced mStrand with offline strand mesh generation utilities**
- **Hv8 added intersecting strands, OSCAR, and run-time mesh generation**

CFD2030 Vision

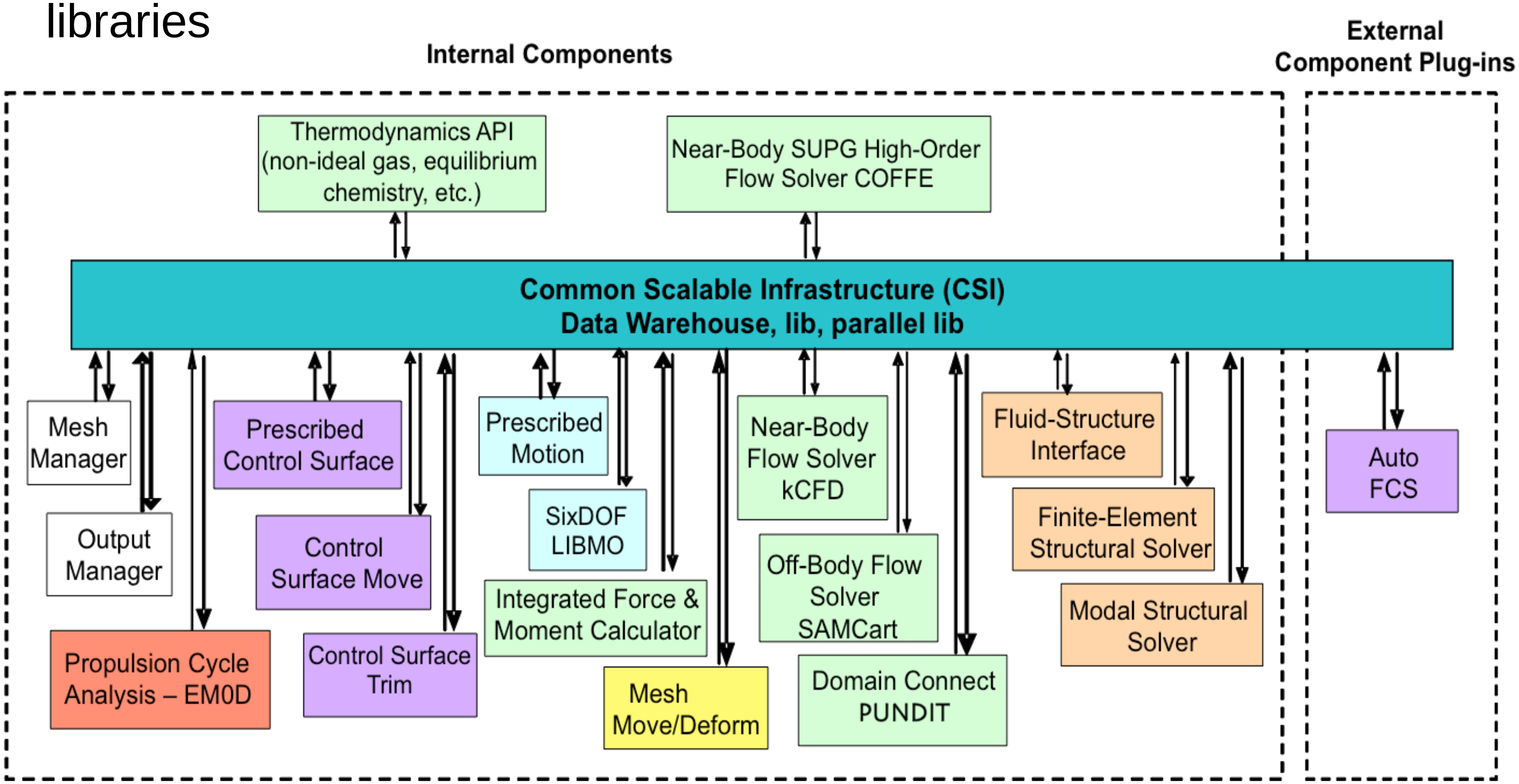
(4) Ability to utilize massively-parallel, heterogeneous, and fault-tolerant HPC architectures.

Compute Machine Architecture Changes…

DOD HPC MODERNIZATION PROGRAM

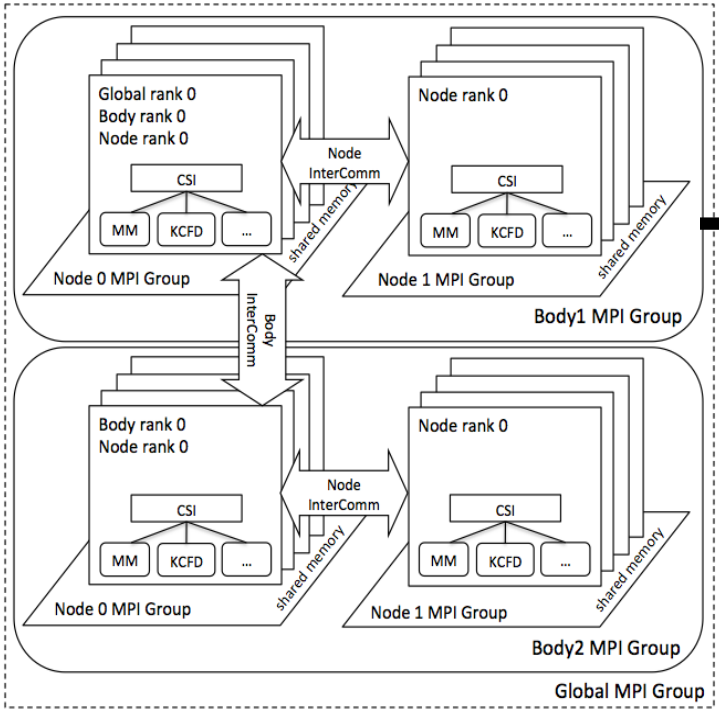
Kestrel designed around assumption of future change:

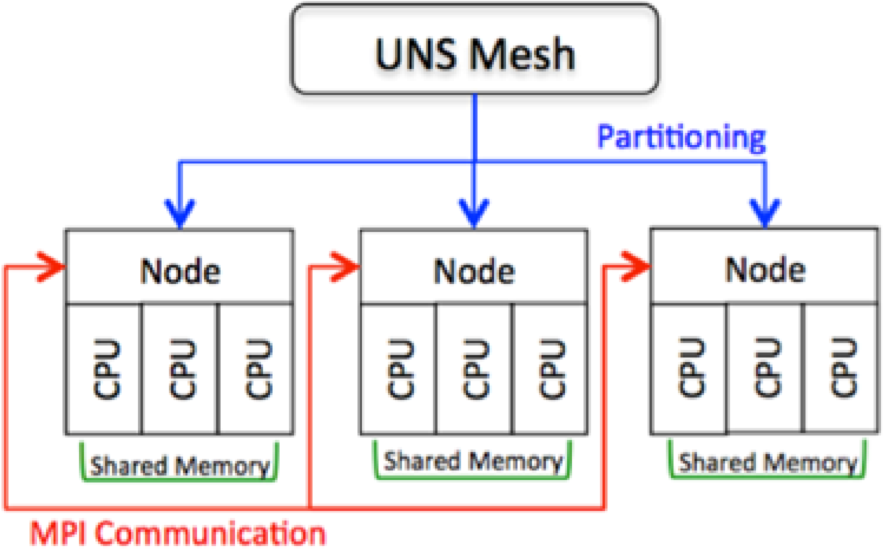
- New algorithms, higher-fidelity physics, incorporation of new disciplines
- Components easily replaced/modified as needed with minimal disruption
  - Modularity supports reworking particular modules for new architectures
- Multi-language data management via WAND – Python, C, C++, Fortran
- MPI abstracted with YOGI – allows single executable for many machine libraries



Effectively leverages most capable HPC hardware…

- **Direction of emerging HPC hardware is still unclear though a many-integrated-core paradigm is evident**
- **Kestrel able to operate in a fine *or* coarse zone decomposition and communication context**
- **Portability/resiliency key: PToolsRTE, AVTOOLS, YogiMPI, HealthChecker**





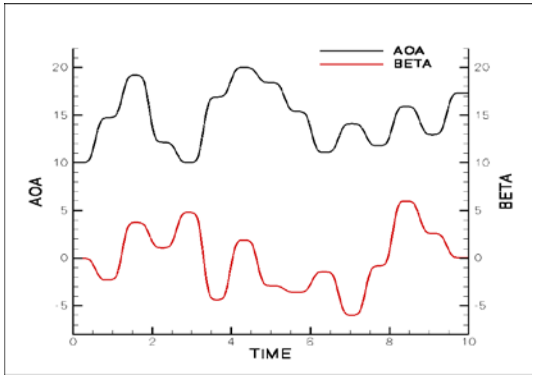
Coarse-grain domain decomposition

CFD2030 Vision
(5) Capability to tackle capability- and capacity-computing tasks.

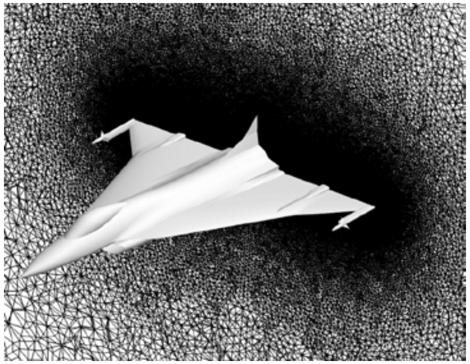
Model Building…

Reduced-Order Modeling

- **Effective use of ROMs convert multi-day high-resolution simulations to real-time model calculations**



Automated Maneuver Generation to Minimize Parameter Correlation



CFD Model

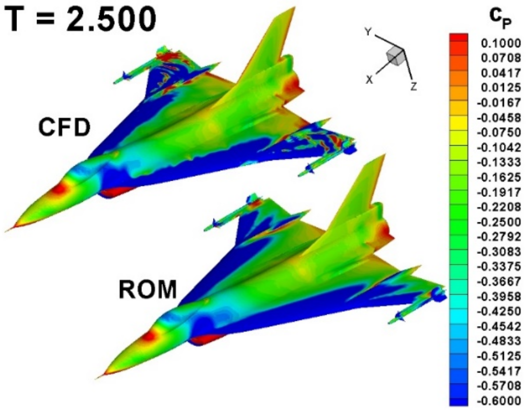
Polyomial (Integrated Loads):

$$C_L = f(\alpha, \beta, p, q, r, \dots)$$

POD-Based (Distributed Loads):

$$q(x,t) = a_n(t)\phi_n(x)$$

ROM Constructed Using On-Design Data

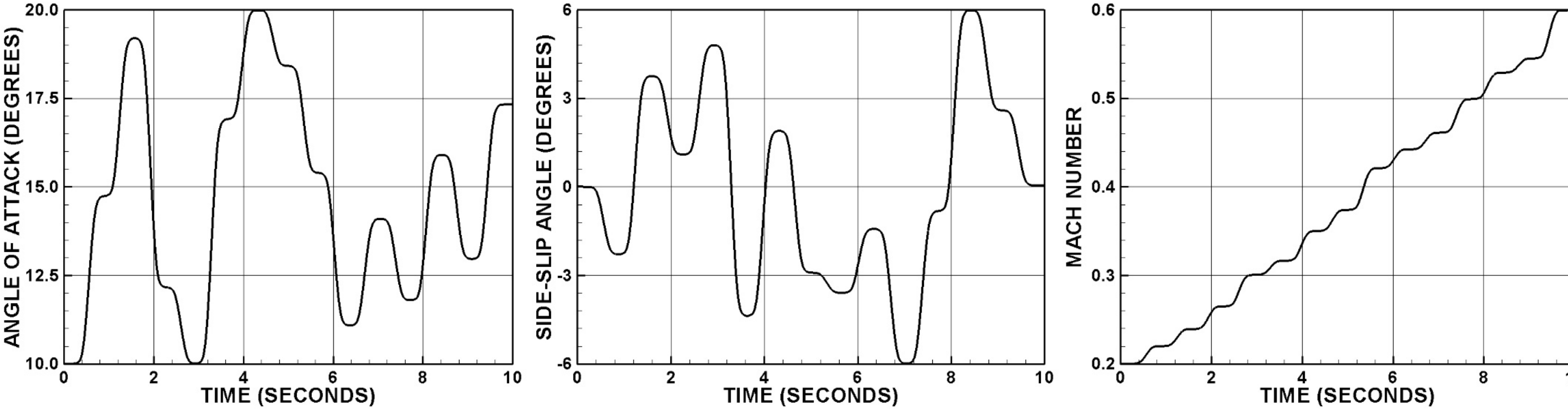


ROM Used For Integrated/Distributed Aero Predictions at Off-Design Conditions

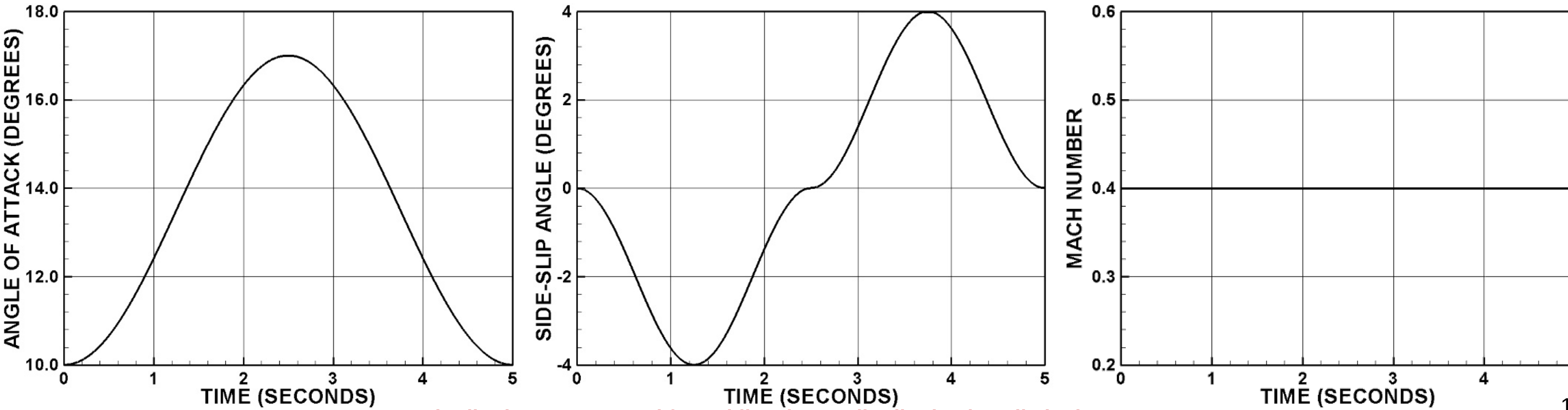
POD-Based Reduced-Order Modeling

Collaboration with Dr. Hal Carlson (Clear Sciences Corporation)

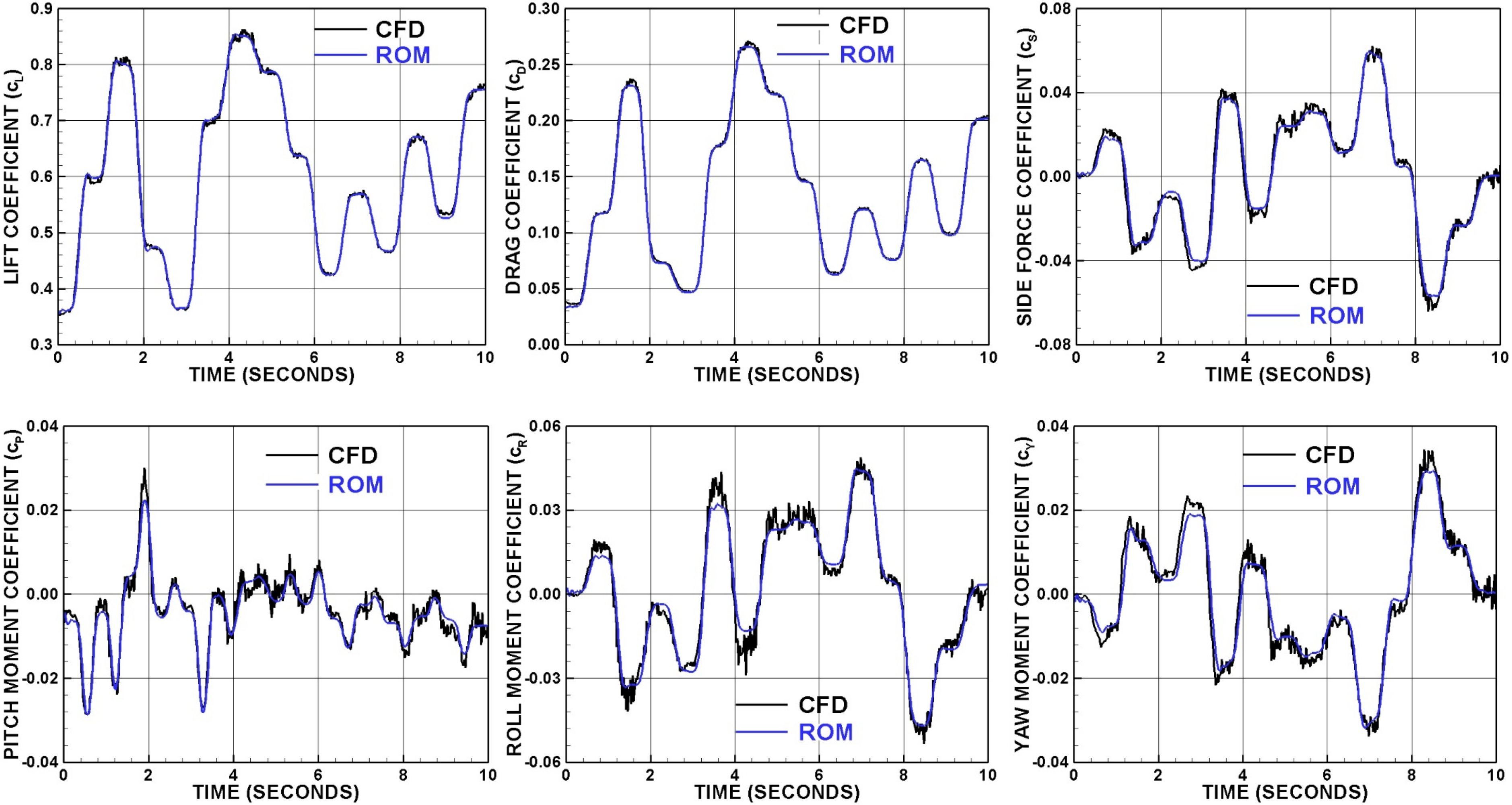
On-Design Training Maneuver



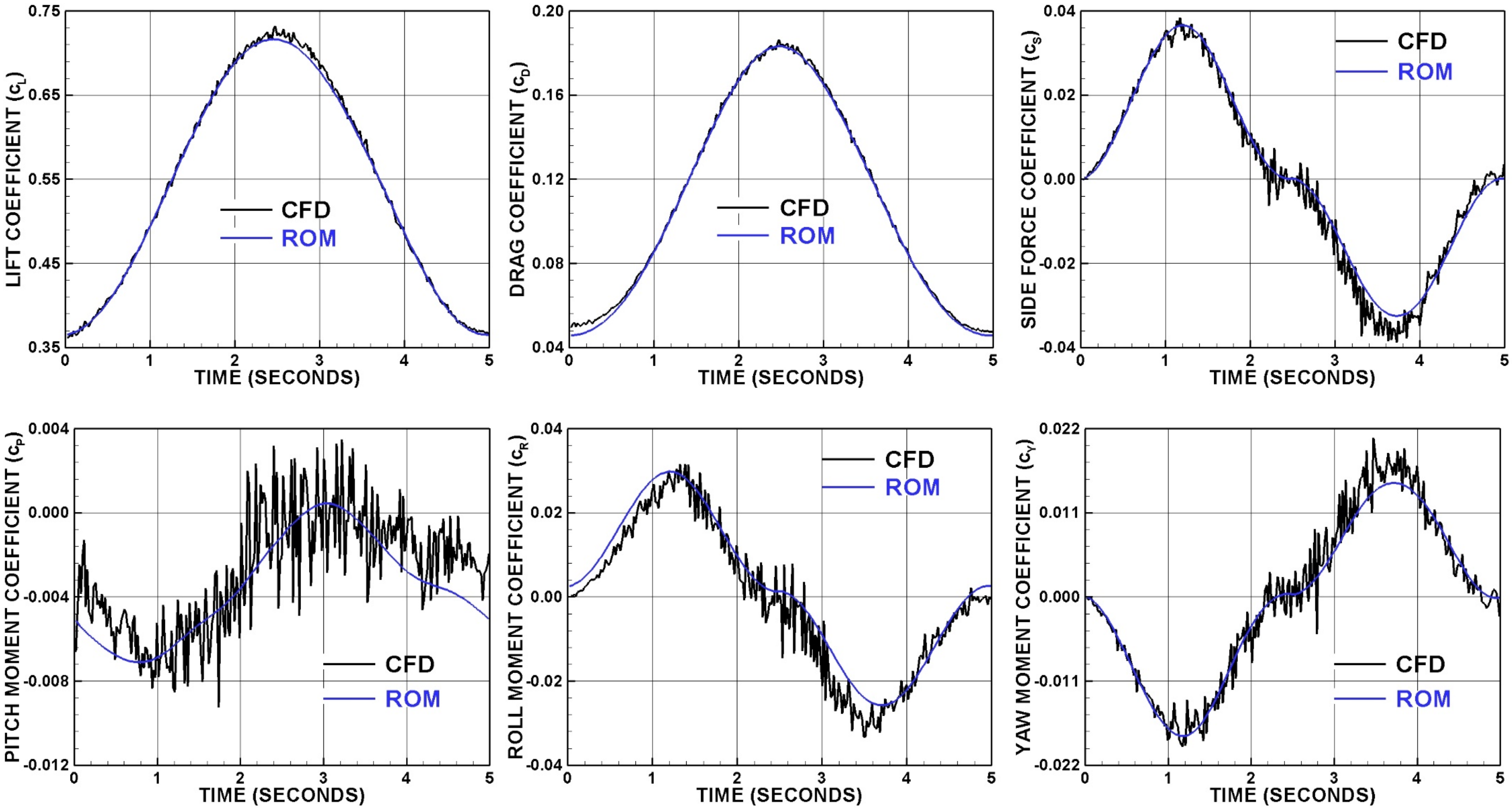
Off-Design Evaluation Maneuver



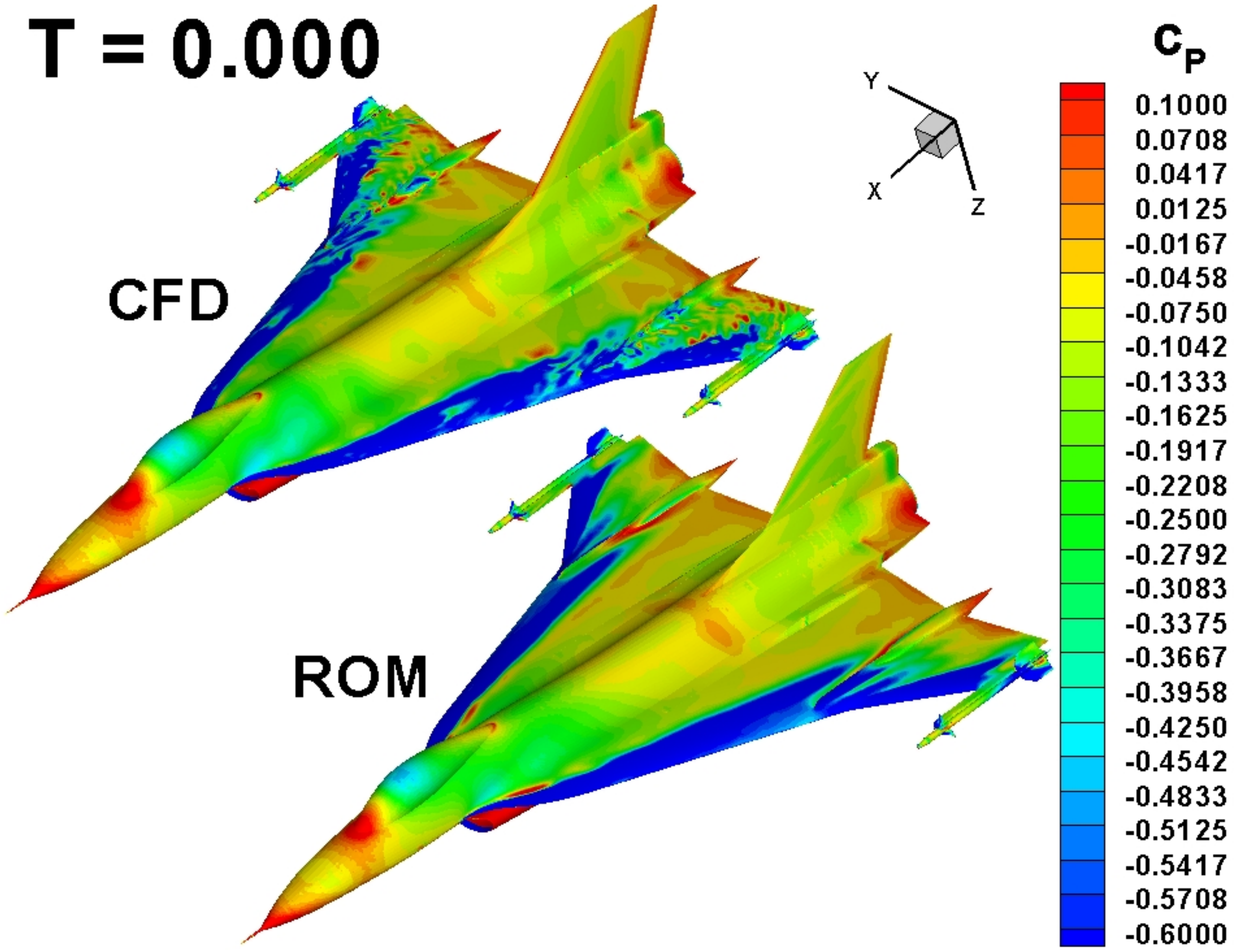
On-Design Training Maneuver Loads



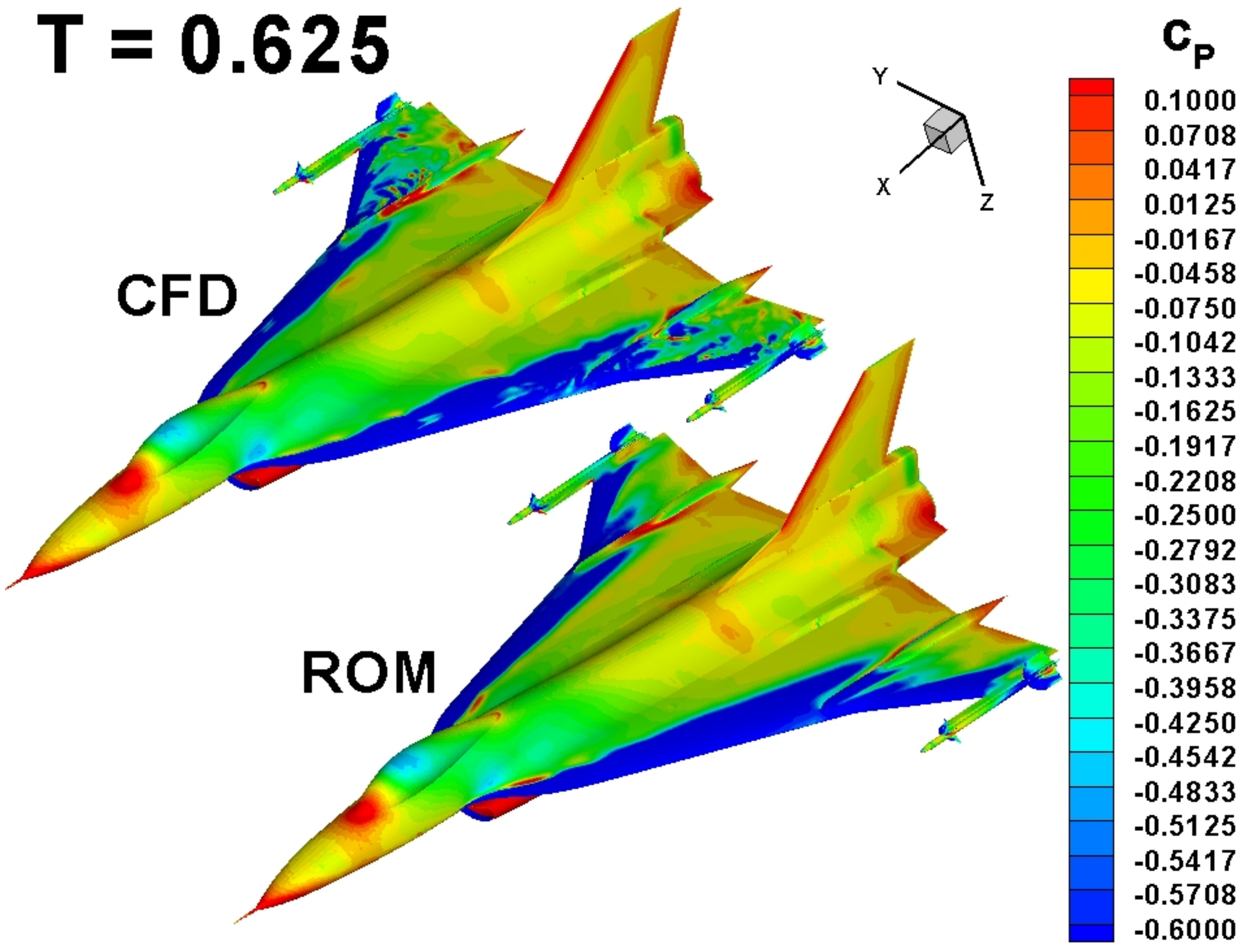
Off-Design Maneuver Integrated Loads



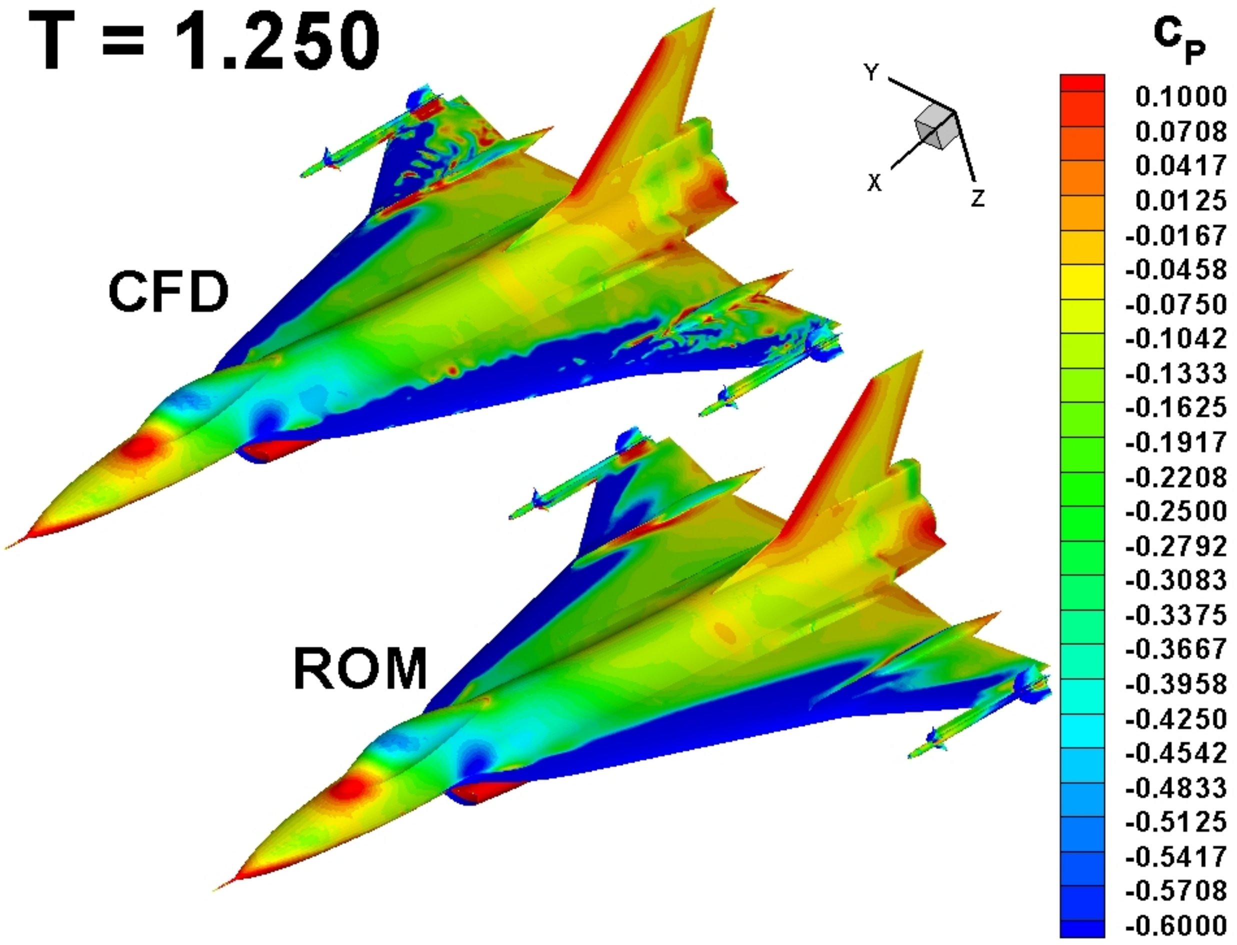
Off-Design Maneuver Loads



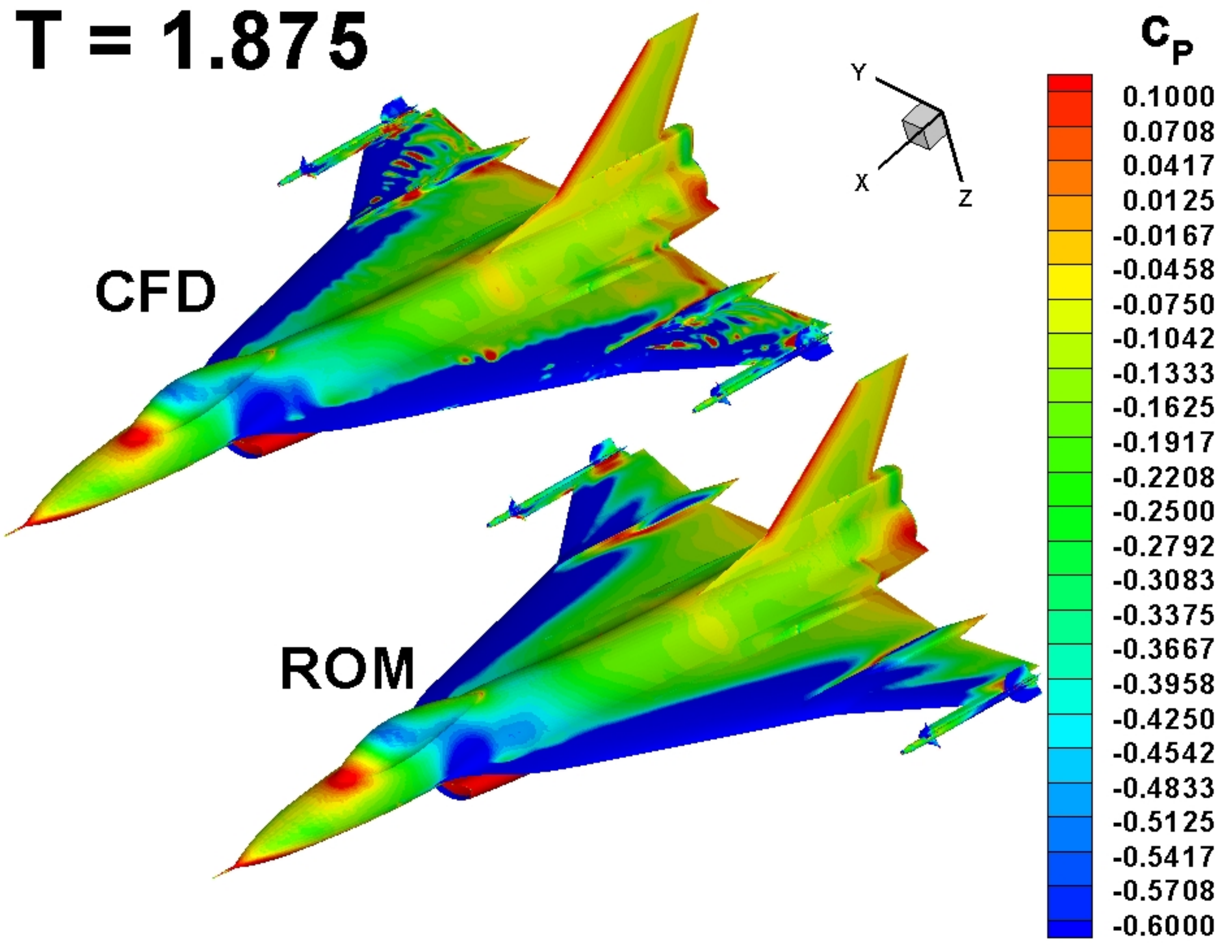
Off-Design Maneuver Loads



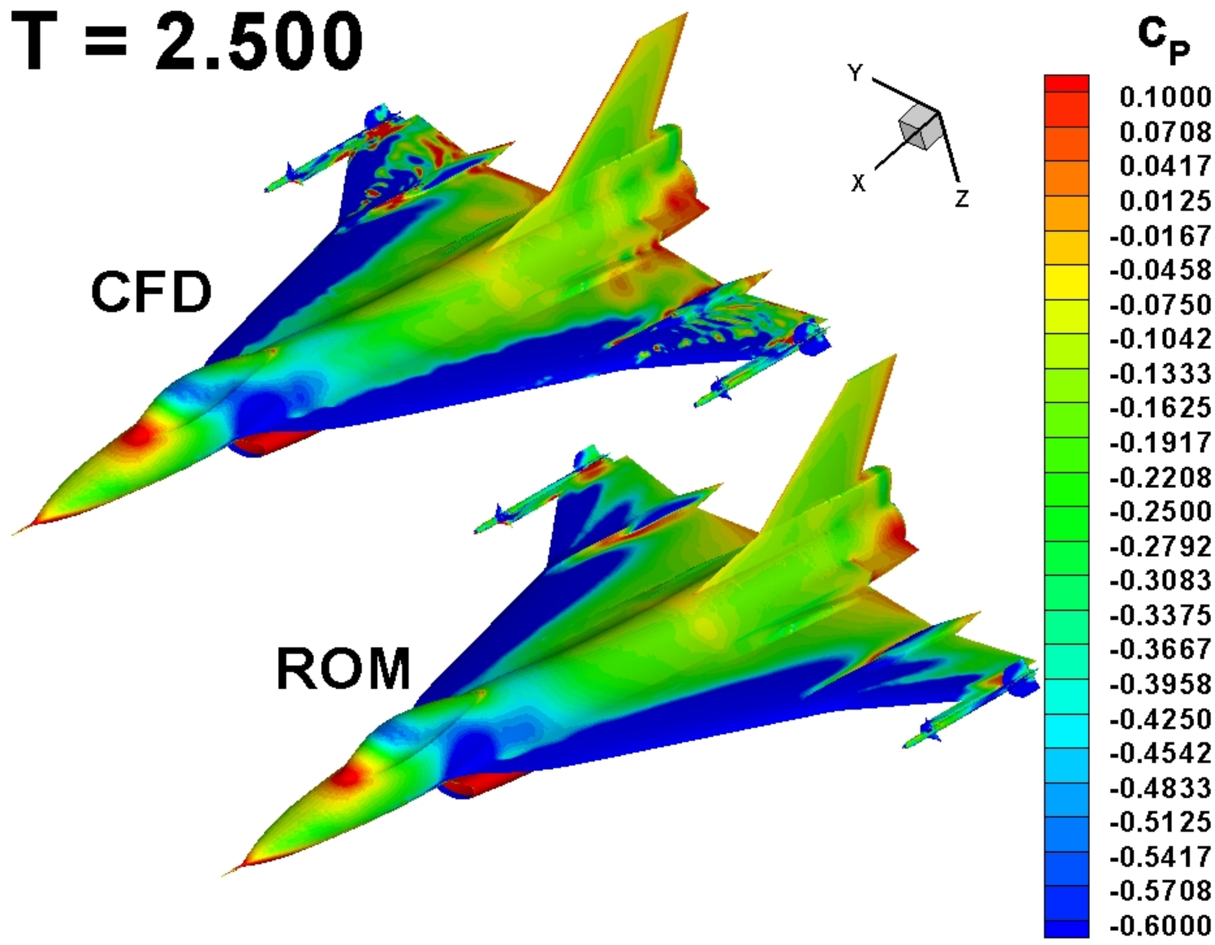
Off-Design Maneuver Loads



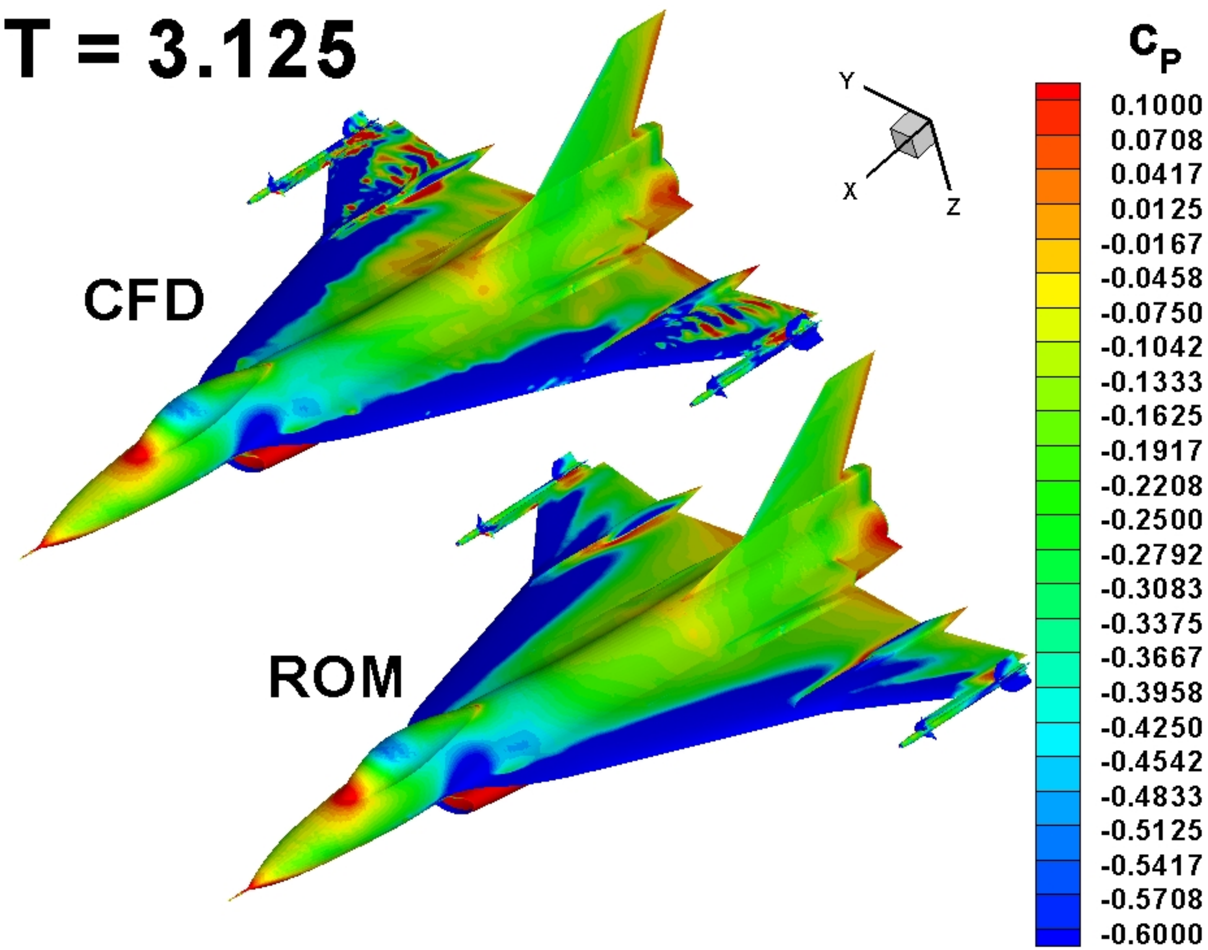
Off-Design Maneuver Loads



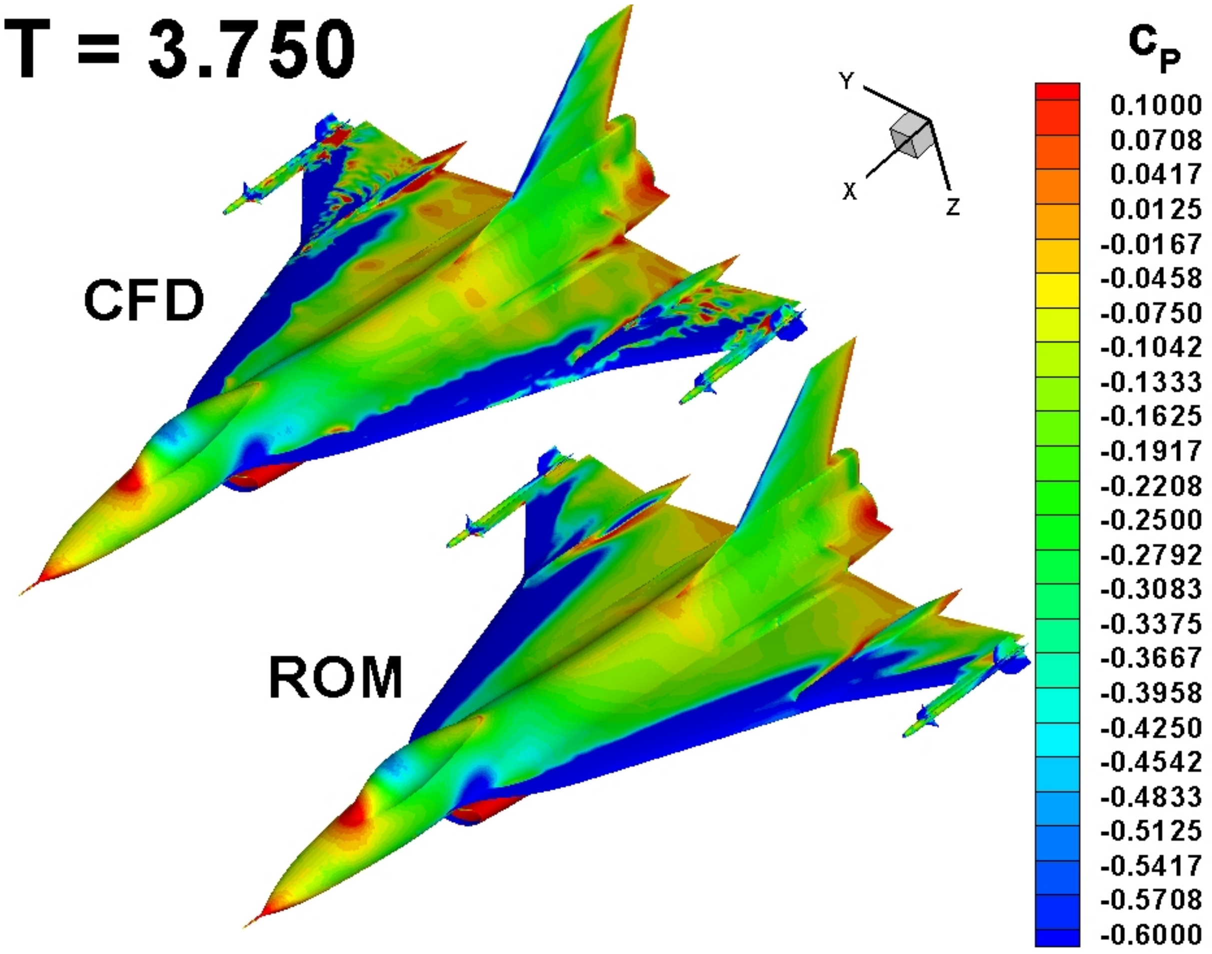
Off-Design Maneuver Loads



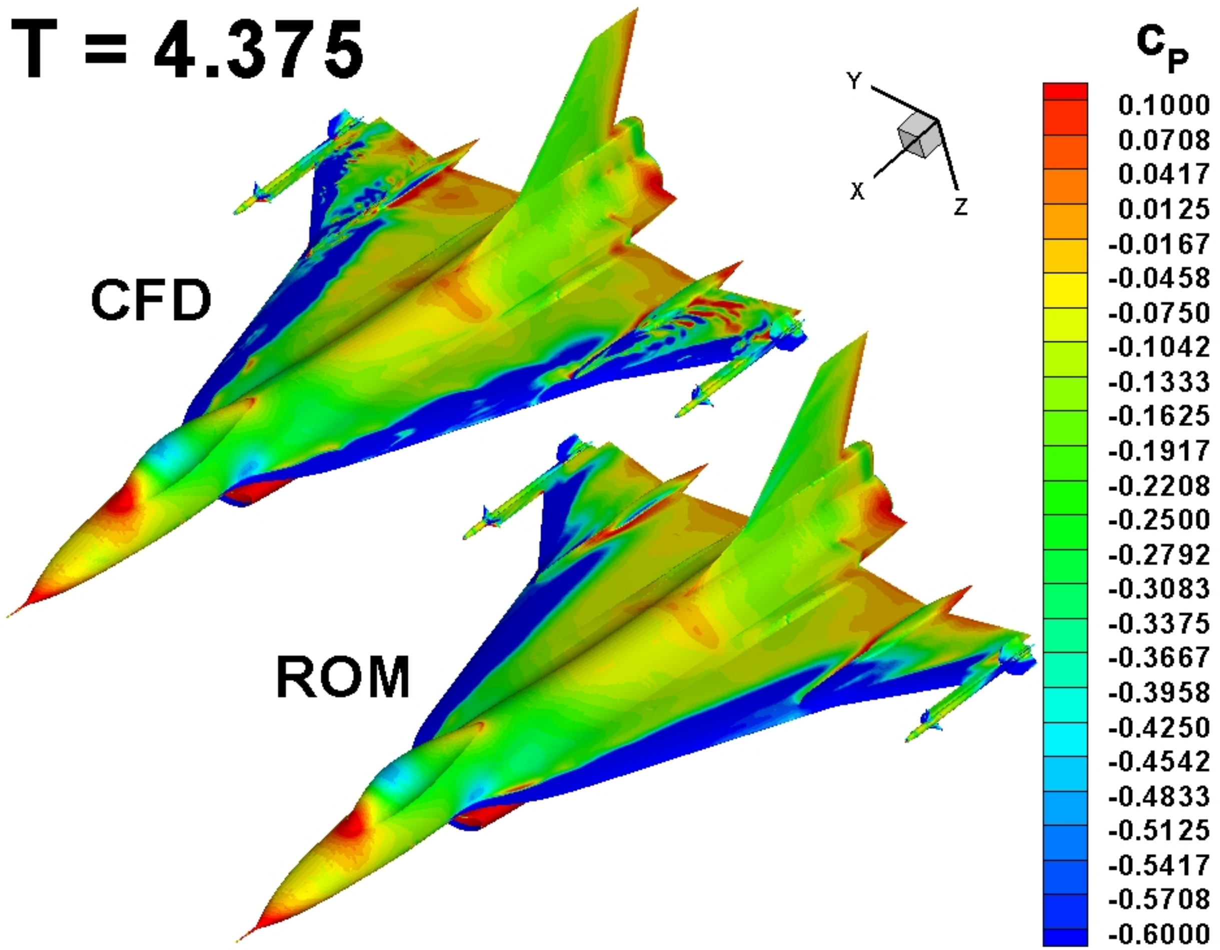
Off-Design Maneuver Loads



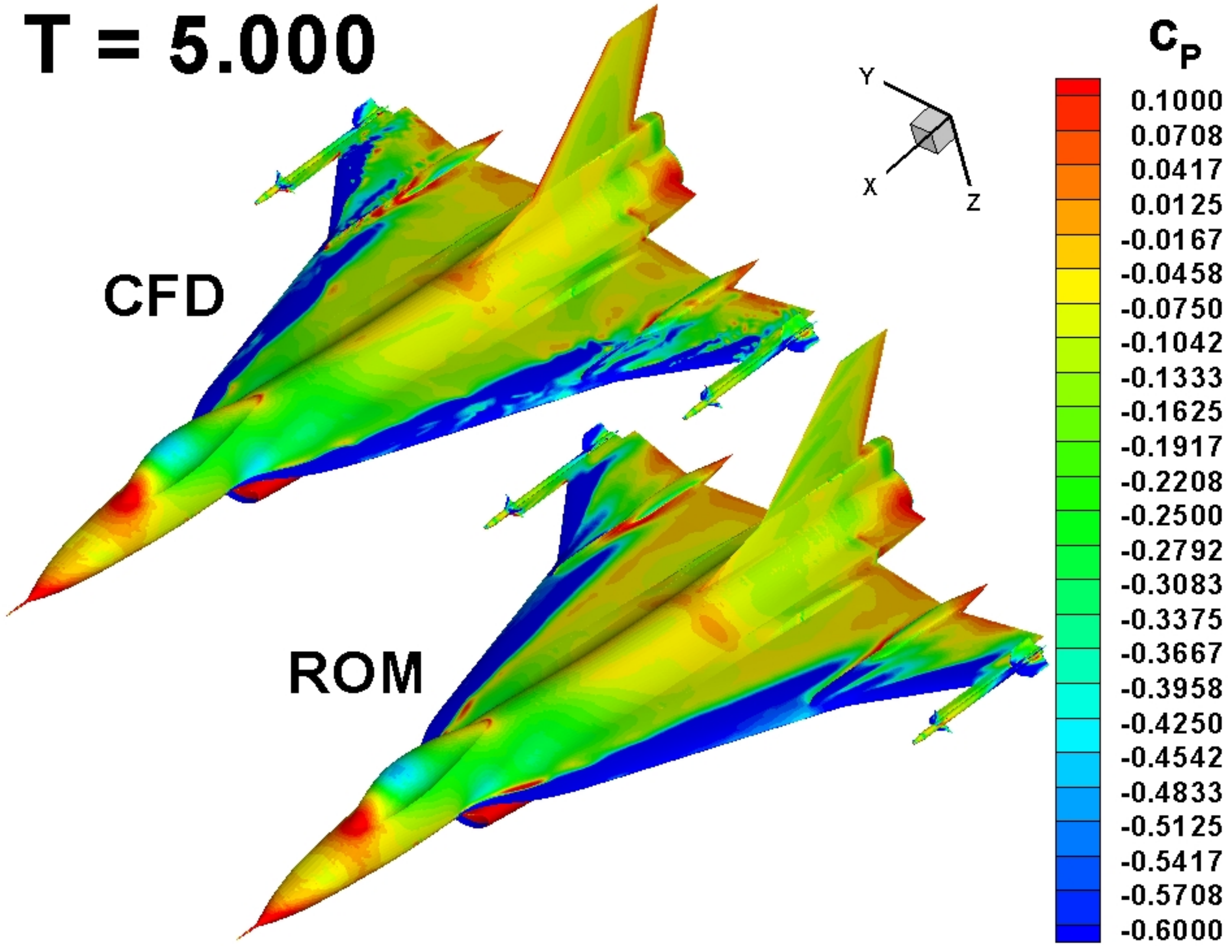
Off-Design Maneuver Loads



Off-Design Maneuver Loads

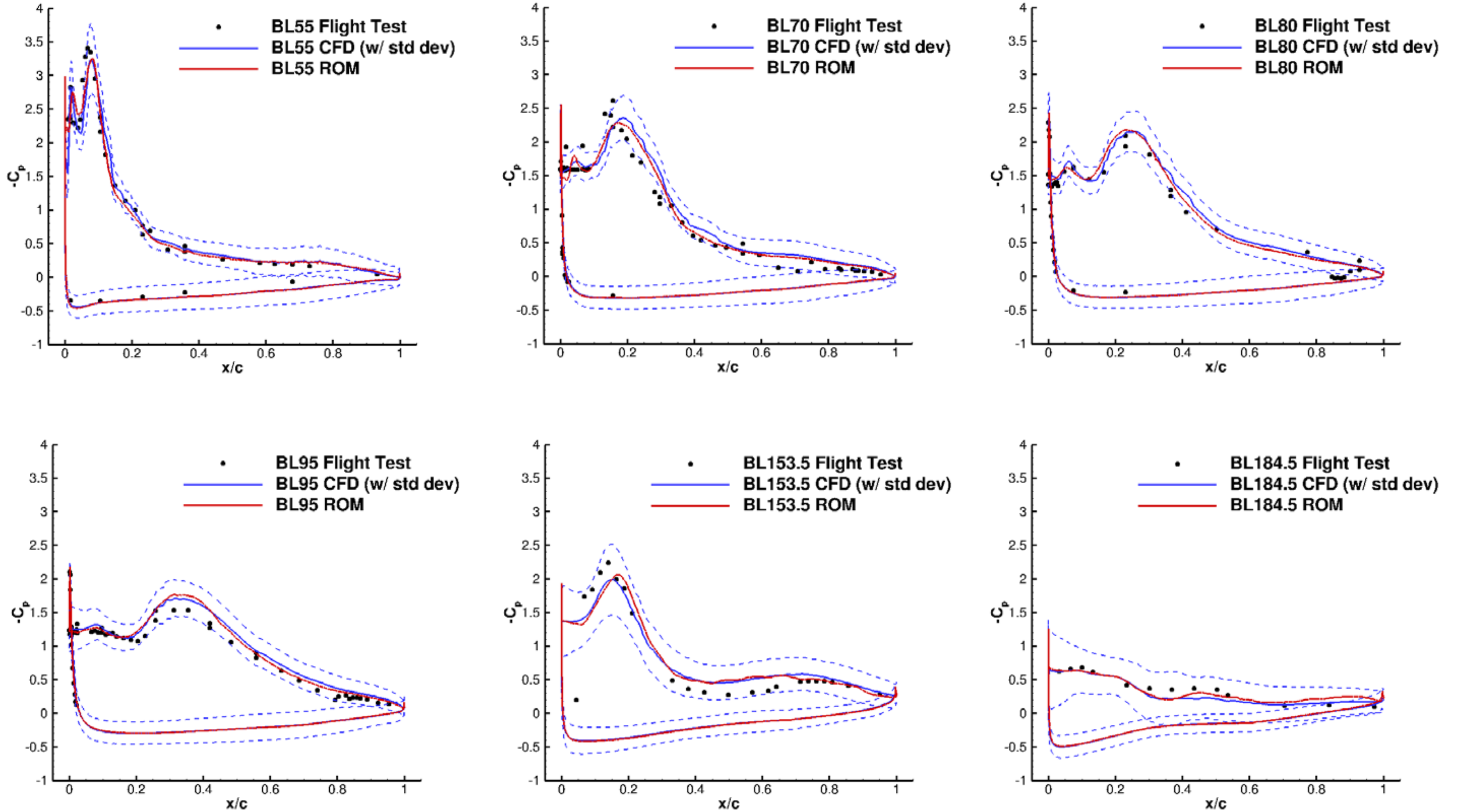


Off-Design Maneuver Loads



Off-Design Static Flight Condition Cp's

Flight Condition 25 Butt Line Stations



Distribution A: Approved for Public release; distribution is unlimited.

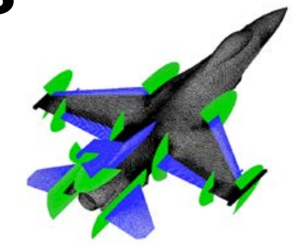
CFD2030 Vision

(6) Seamless integration with multi-disciplinary analyses that will be the norm in 2030

Multi-Disciplinary…

Kestrel Multi-Disciplinary Capabilities

Maneuvering Flight

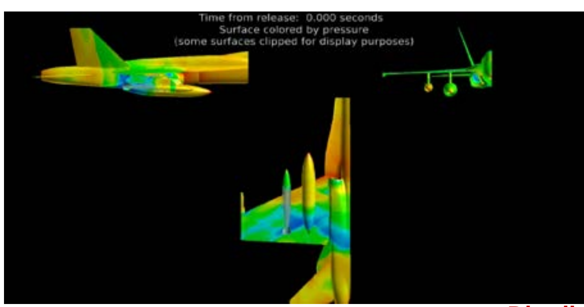


Single-Body (SB)

- Flow Solver → Rigid Body Motion → 6DoF + Constraints → Control Surface Motion → Auto-FCS "Black Box"
- SB Static Mesh Unst. Aero
- SB Prescribed Maneuvering Unst. Aero
- SB Predictive Maneuvering Unst. Aero
- SB Predictive Maneuvering with DM Prescribed Control Surf Unst. Aero
- SB Predictive Maneuvering with Commanded Control Surf Unst. Aero

Multi-Body (MB)

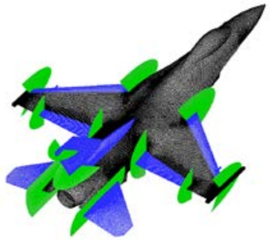
- NBOB Flow Solvers → PUNDIT Domain Connectivity → Rigid Body Motion → 6DoF + Constraints → Control Surface Motion → Auto-FCS "Black Box" → MB Collision and Response
- MB Static Mesh Unst. Aero
- MB Prescribed Relative Motion Unst. Aero
- MB Predictive Relative Motion Unst. Aero
- MB Predictive Maneuvering with DM/Overset Prescribed Control Surf Unst. Aero
- MB Predictive Relative Motion with Commanded Control Surf Unst. Aero
- MB Predictive Relative Motion with Collisions



Kestrel Multi-Disciplinary Capabilities

Single-Body (SB)

Maneuvering Flight



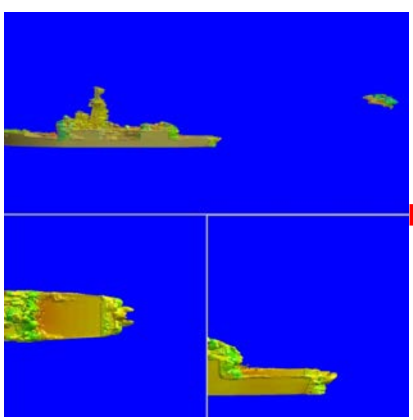
Flow Solver
Rigid Body Motion
6DoF + Constraints
Control Surface Motion
Auto-FCS "Black Box"

SB Static Mesh Unst. Aero
SB Prescribed Maneuvering Unst. Aero
SB Predictive Maneuvering Unst. Aero
SB Predictive Maneuvering with DM Prescribed Control Surf Unst. Aero
SB Predictive Maneuvering with Commanded Control Surf Unst. Aero

Multi-Body (MB)

NBOB Flow Solvers
PUNDIT Domain Connectivity
Rigid Body Motion
6DoF + Constraints
Control Surface Motion
Auto-FCS "Black Box"
MB Collision and Response

MB Static Mesh Unst. Aero
MB Prescribed Relative Motion Unst. Aero
MB Predictive Relative Motion Unst. Aero
MB Predictive Maneuvering with DM/Overset Prescribed Control Surf Unst. Aero
MB Predictive Relative Motion with Commanded Control Surf Unst. Aero
MB Predictive Relative Motion with Collisions

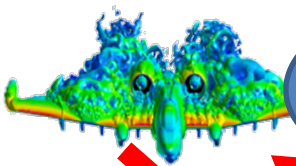


Kestrel Multi-Disciplinary Capabilities

Propulsion Integration

Single-Body (SB)

Flow Solver → Propulsion EM0D → Rigid Body Motion → 6DoF + Constraints → Control Surface Motion → Auto-FCS "Black Box"

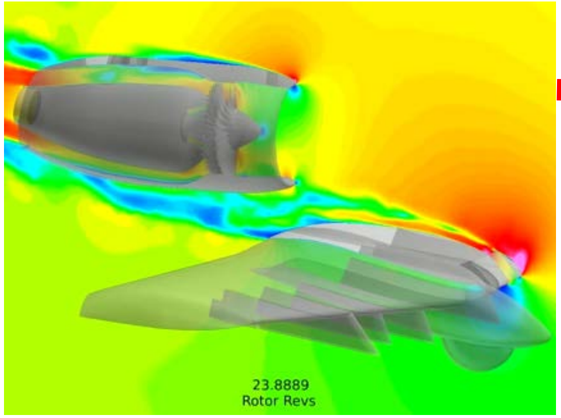


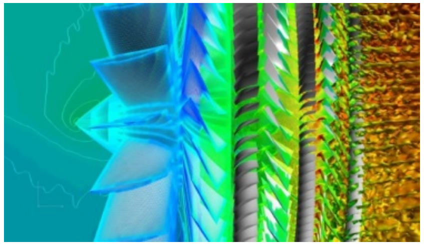
- SB Static Mesh Unst. Aero
- SB Prescribed Maneuvering Unst. Aero
- SB Predictive Maneuvering Unst. Aero
- SB Predictive Maneuvering with DM Prescribed Control Surf Unst. Aero
- SB Predictive Maneuvering with Commanded Control Surf Unst. Aero

Multi-Body (MB)

NBOB Flow Solvers → Propulsion EM0D → PUNDIT Domain Connectivity → Rigid Body Motion → 6DoF + Constraints → Control Surface Motion → Auto-FCS "Black Box"

- MB Static Mesh Unst. Aero
- MB Prescribed Relative Motion Unst. Aero
- MB Predictive Relative Motion Unst. Aero
- MB Predictive Maneuvering with DM/Overset Prescribed Control Surf Unst. Aero
- MB Predictive Relative Motion with Commanded Control Surf Unst. Aero





Distribution A: Approved for Public release; distribution is unlimited.

Kestrel Multi-Disciplinary Capabilities

Single-Body (SB)

Aeroelasticity

Flow Solver

Propulsion EM0D

Modal/FE Structural Solver

SB Aeroelastic Unst. Aero

Rigid Body Motion

SB Predictive Maneuvering with DM Prescribed Control Surf FSI Unst. Aero

6DoF + Constraints

SB Predictive Maneuvering FSI Unst. Aero

Control Surface Motion

SB Predictive Maneuvering with DM Prescribed Control Surf FSI Unst. Aero

Auto-FCS “Black Box”

SB Predictive Maneuvering with Commanded Control Surf FSI Unst. Aero

Multi-Body (MB)

NBOB Flow Solvers

Propulsion EM0D

Modal/FE Structural Solver

PUNDIT Domain Connectivity

Rigid Body Motion

MB Static Mesh FSI Unst. Aero

6DoF + Constraints

MB Prescribed Relative Motion FSI Unst. Aero

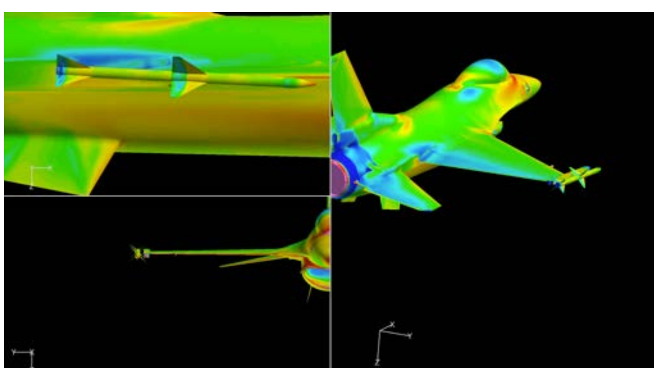
Control Surface Motion

MB Predictive Relative Motion FSI Unst. Aero

Auto-FCS “Black Box”

MB Predictive Maneuvering with DM/Overset Prescribed Control Surf FSI Unst. Aero

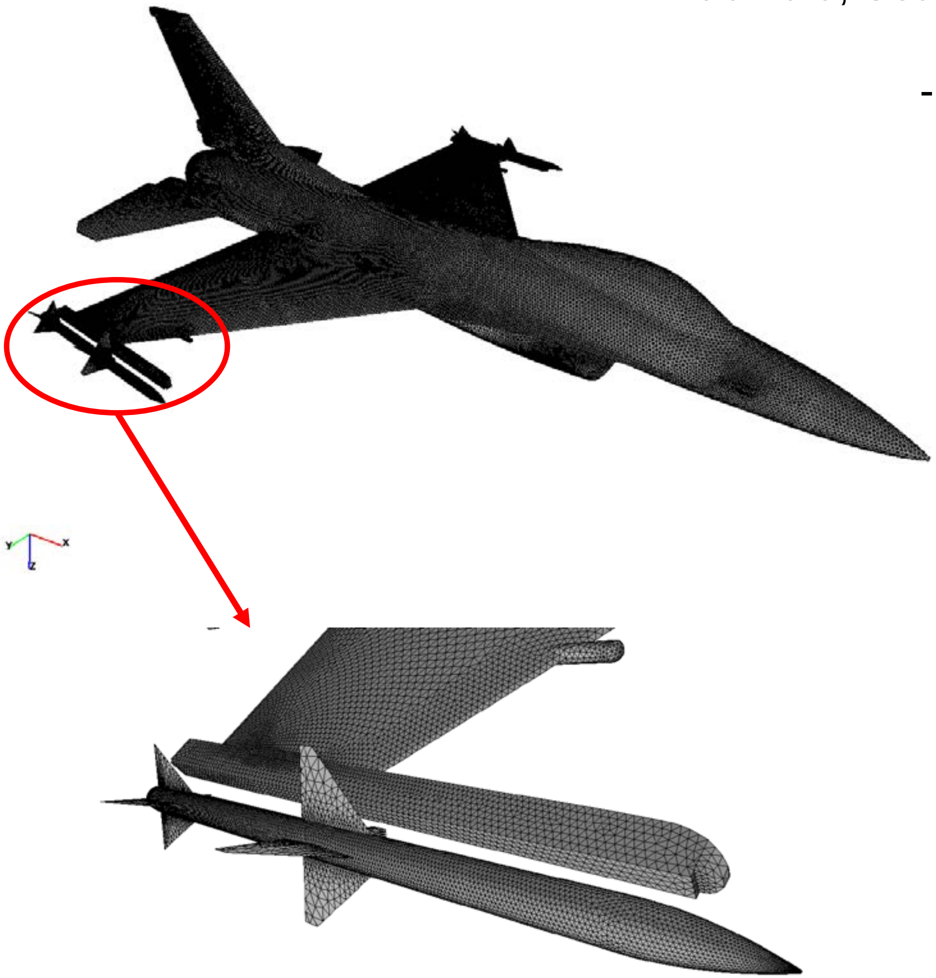
MB Predictive Relative Motion with Commanded Control Surf FSI Unst. Aero



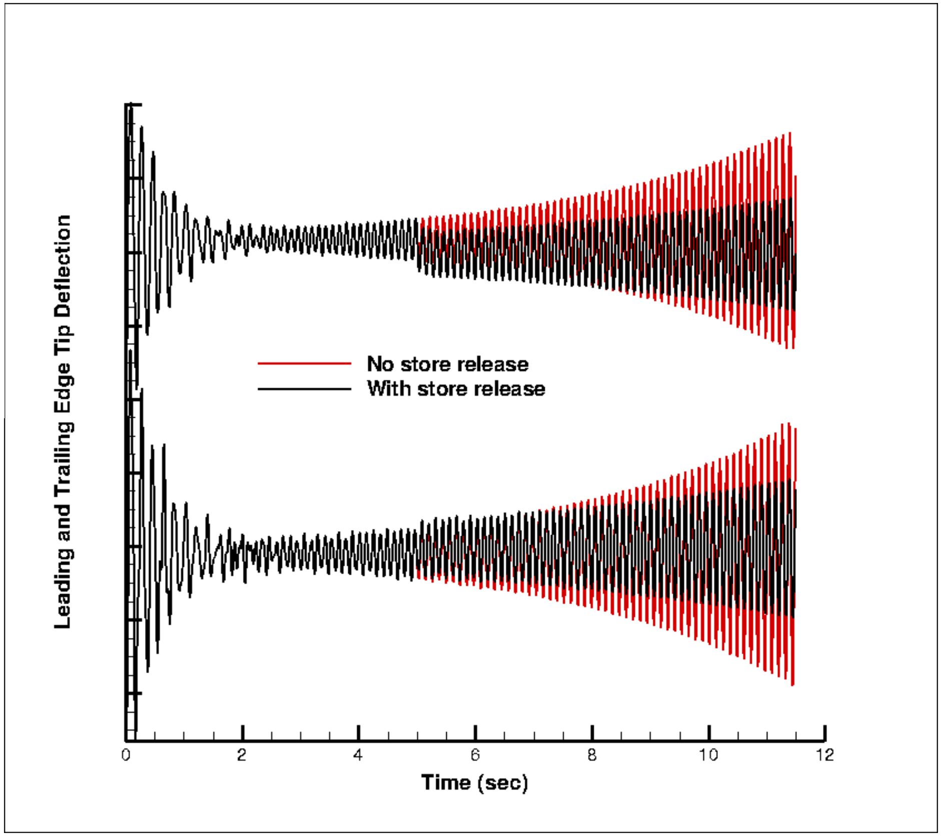
Distribution A: Approved for Public release; distribution is unlimited.

Enables complex multi-disciplinary analyses and optimizations…

Notional Sidewinder Release from Elastic F-16
Mach 0.9, Sea Level, SA+DDES

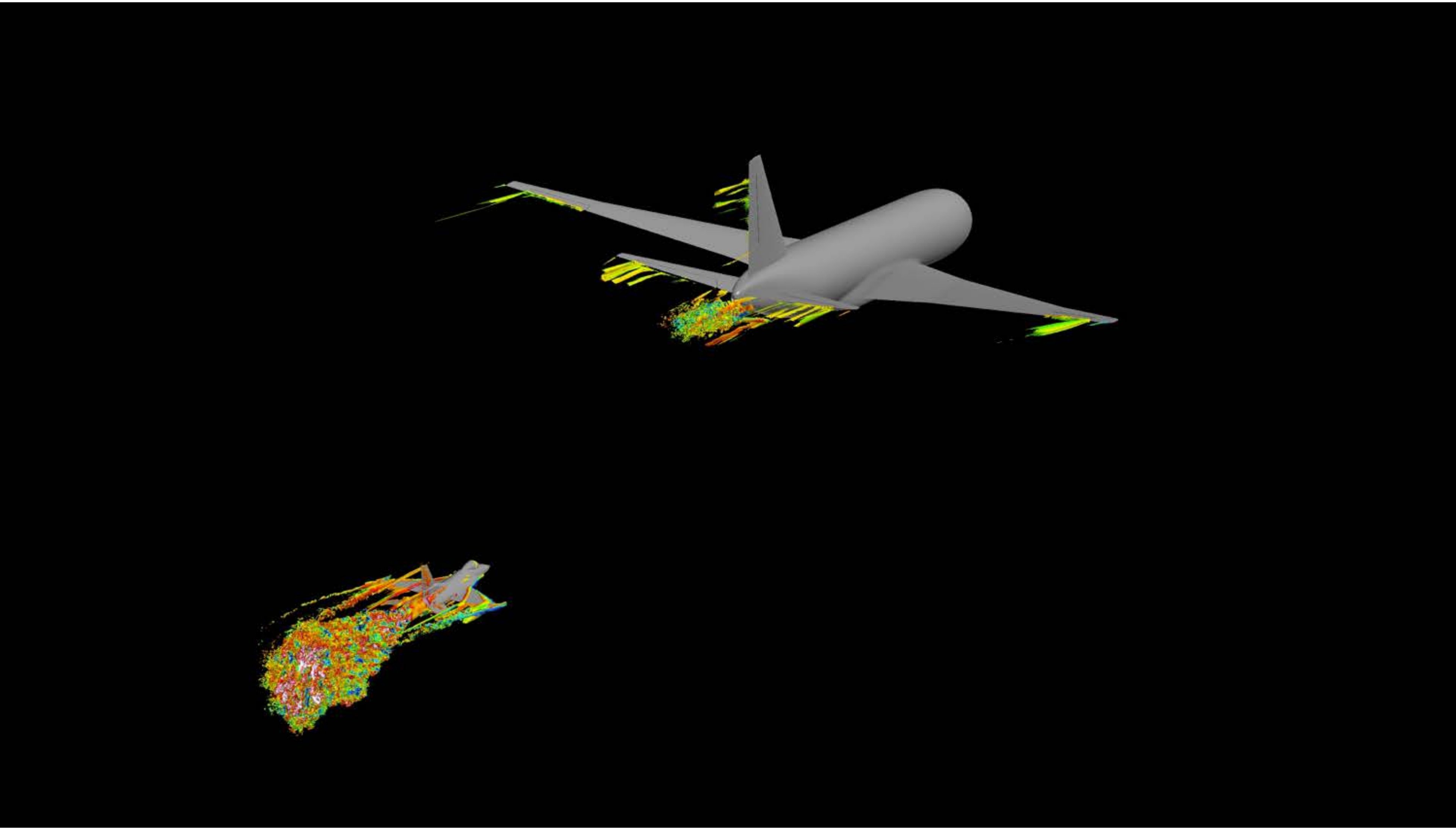


- Automatic body connection and force transferal



Kestrel Multi-Disciplinary Capabilities

Multi-Aircraft Interactions



The Future…

"To infinity and beyond!"

Buzz Lightyear

DOD HPC MODERNIZATION PROGRAM

The Future…

1) Emphasis on physics-based predictive modeling…

– Extending COFFE SUPG FE solver to implicit time-accurate, moving/deforming mesh, LES, transition turbulence, adjoint error estimation
– Adding a pseudo-compressible flow solver for very low Mach to support small UAV and submarine design applications

2) Management of errors and uncertainties…

– Adding feature-based and adjoint error-based adaptive mesh refinement to the near-body unstructured solvers
– Uncertainty Quantification for the a/c system simulations

3) A much higher degree of automation in all steps of the analysis process...

– Fully realize automatic solid geometry to surface and volume mesh based on run-time flight conditions

The Future…

4) Ability to utilize massively-parallel, heterogeneous, and fault-tolerant HPC architectures...

– Port to KNL processors for new machine architecture performance
– Implement parallel in time BDF scheme to reduce wall clock time

5) Capability to tackle capability- and capacity-computing tasks...

– Continue development of CG- and distributed loads-based reduced-order models from high-fidelity simulations for entire envelope

6) Seamless integration with multi-disciplinary analyses that will be the norm in 2030…

– Adding equilibrium/non-equilibrium chemistry, fluid-thermal-structural-interactions, and ablation for hypersonic vehicles

Summary

- **Kestrel program is a validation of the 2030 CFD findings**
- **Some Kestrel features and design elements pertinent to the CFD 2030 vision have been discussed**
- **Kestrel team not focused just on IF challenge problems can be solved, but also HOW USABLE is the approach**
- **Kestrel moving towards a comprehensive hypersonic capability….which represents a paradigm shift:**
  - WAS: Fairly mature technology (aerodynamics, structures, flight mechanics, propulsion) with lacking multi-disciplinary simulation
  - NOW: Immature technology (aerodynamics with chemistry, structures with thermal effects, ablation, etc.)
  - Collaborations and product agility are paramount

Acknowledgements

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- MANY thanks to the CREATE-AV development and management teams