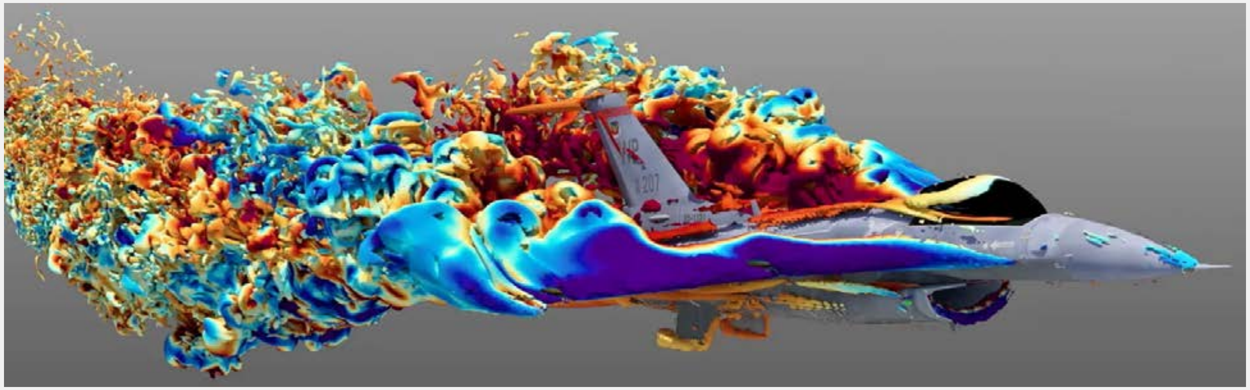


High Fidelity Multi-Disciplinary Simulation and Reduced Order Modeling in the Design and Assessment of Military Aircraft

NATO RTO AVT-324 Specialists Meeting on "Multidisciplinary Design Approaches and Performance Assessment of Future Combat Aircraft", Quebec, Canada, 27-28 April 2020

Dr. Scott A. Morton, CREATE Air Vehicles Project Manager
Dr. Robert L. Meakin, Associate Director for CREATE
DoD HPCMP, US Army ERDC Information Technology Laboratory

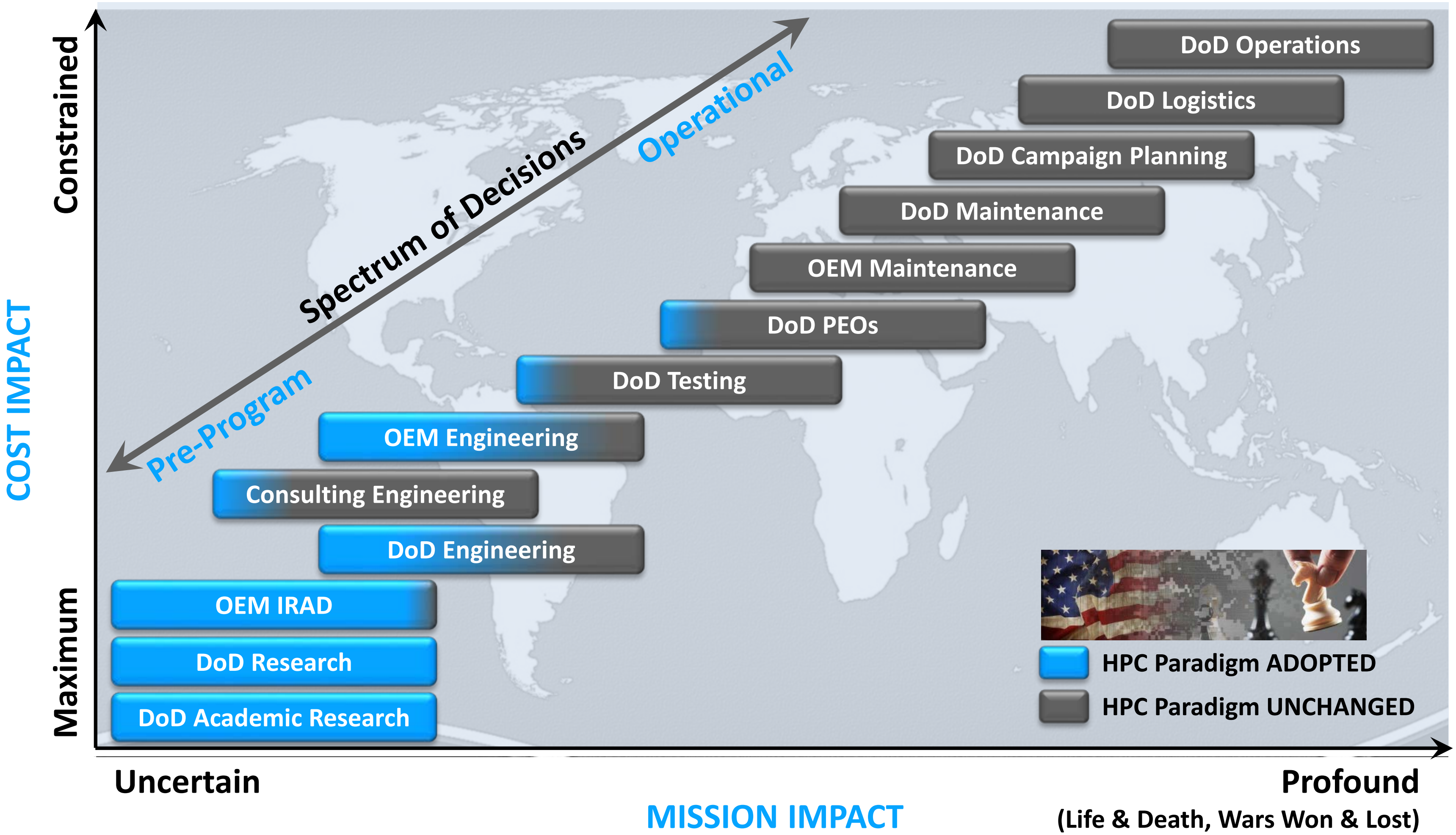
Overview

- **A Vision for Physics Based Digital Engineering (PBDE)**
  - Where Can We Use PBDE?
  - What is the Vision for PBDE?
  - Definitions for Elements of the PBDE Vision
- **Software Engineering for PBDE**
  - Physics Based Analytics
  - Digital Surrogates
  - Data Driven Analytics
  - Data Acquisition and Curation
  - Decision Support Apps
- **A Combat Air Vehicle Example Following the PBDE Vision**
- **Concluding Remarks and Discussion**

An Introductory Thought: "Speed of Relevance"

If a given technology is unable to deliver actionable data when it is needed, it is not relevant.

Physics-Based Digital Engineering Assessment of Relevance in 2019

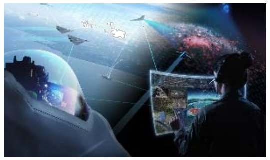


A Vision for Physics-Based Digital Engineering

BIG IDEA: Lifecycle Decision Support using physics informed data analytics.







Acquisition → Maintenance → Service Life Extension → Operations & Logistics → Command

Digital Surrogates

ML/DL

Data-Driven Analytics | Physics-Based Analytics

Kestrel, Capstone, Navy FOAM, Mercury, SENTRi, Helios, NESM

APPROACH

Synthesize digital surrogates via physics informed data analytics. Leverage HPCMP CREATE™ physics-based simulation software and proven software engineering practices.

PAYOFF

Reliable decision support at the speed of relevance

Definition – What is a Digital Surrogate?

An "On Demand" source for technical information for weapon system…

Given (per subject weapon system)

- Design Data (Design specs – geometry/materials, operational envelope, etc.)
- IMOS Data (Inspection, Maintenance, Operational <history>, and Sensor Data)

Wanted (Timely Performance, State, and Signature information)

- Performance (Aeromechanical/Hydromechanical)
- State (Structural/Thermal)
- Signature (EM, IR, and Acoustic)

Digital Surrogates (Are synthesized using Data Driven and Physics-Based Analytics)

Data Driven Analytics – Derived from Machine Learning (ML) algorithms operating on IMOS Data and constrained by Physics.

Physics-Based Analytics – Derived from Physics Based compute engines operating on Design Data fused with IMOS Data.

"Decision Support Apps" Powered by Digital Surrogates

Actionable information, intuitively understood, highly automated

DDA and PBA software applications generally require HPC and are computationally expensive.

Digital Surrogates can be run on a hand-held device, or laptop, and when needed, respond at near instantaneous speeds to queries on system performance, state, and signature via purpose built "Decision Support Apps".

Given (for subject weapon systems)

- Digital Surrogate (system specific)
- Decision Maker Roles & Operational Requirements (e.g., Captain/Pilot, Battle Group Commander, Theater Commander, etc.)

Wanted (for targeted Decision Makers)

"App" that provides needed decision information…

- On demand
- Intuitive format

Examples…

Heads-Up Display App

Battle Group Readiness App
(Roll-up of readiness state of all systems in battle group)

Unmanned Naval Vessel
Apps that enable remote control and at sea operations.

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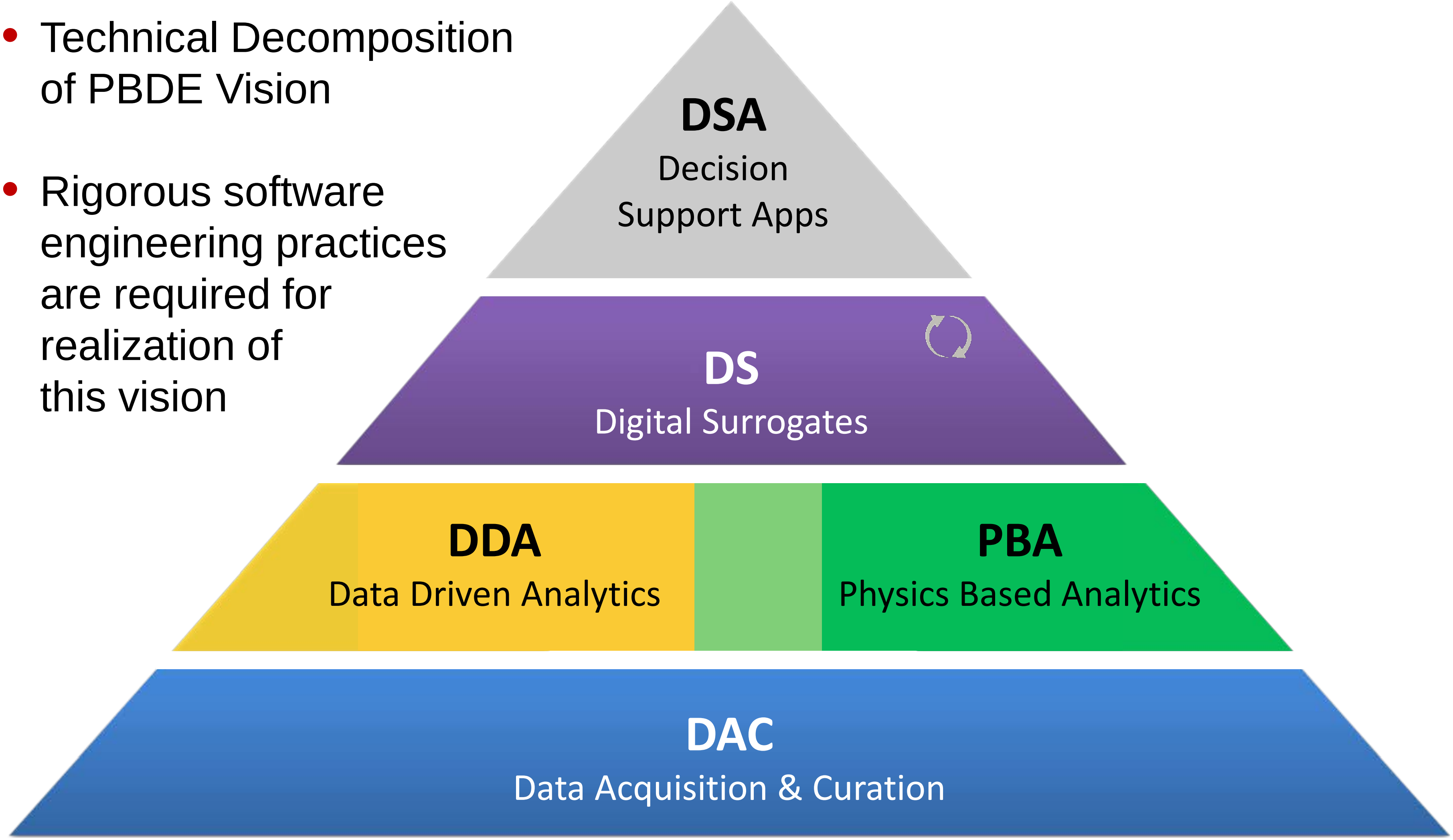
Software Engineering

- Technical Decomposition of PBDE Vision
- Rigorous software engineering practices are required for realization of this vision



Technical Decomposition

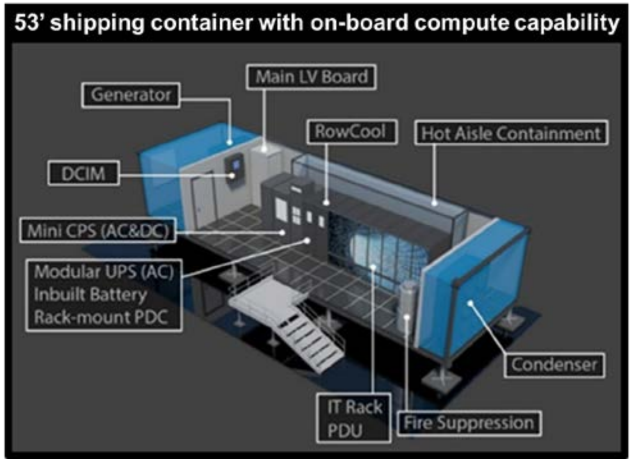
“DAC” – Data Acquisition and Curation

- Ability to READ “legacy format” IMOS data (Inspection, Maintenance, Operational history, and Sensor)
- Ability to “CURATE” and archive resulting IMOS data
- Ability to sense additions/changes to IMOS database (from legacy sources of data)
- Ability to establish and maintain VERSION CONTROL of curated IMOS data.

Key Issues

- Data Inventory
  - What data is available for the targeted (weapon) system?
  - Where is the data? (all in one place?)
  - How is the data stored (server, format, etc.)?
  - What legacy process(es) feed each data component?
- Data Accessibility
  - Is the data “network visible”?
  - What constraints to data access are there?
    - UNCLASS/CLASS
    - IP
    - Other

“HPC in a Container”



Software is Portable

Software needed to
generate Digital Surrogates can reside wherever the data is!

Technical Decomposition

“PBA” – Physics Based Analytics

Relative to targeted military systems…

- Ability to faithfully represent system domain (material, geometry, meshing)
- Ability to compute performance, state, and signature attributes through multi-disciplinary, physics-based, virtual tests
  - Variable (but consistent) fidelity physics
    - Solid Mechanics
    - Fluid/Aero Mechanics
    - Wave Mechanics (EM, IR, Acoustics)

  (Solid Mechanics and Fluid/Aero Mechanics: Includes thermodynamics and multi-phase & chemically reacting flows)
- Ability to construct/refine Digital Surrogate based on physics

Key Opportunities/Issues

- Leverage HPC Software Products for Fluid/Aero Mechanics and Wave Mechanics, E.g. -

  Kestrel, Helios, SENTRi

- Technological advances in all mechanics domains are needed
- **Significant modernization of Solid Mechanics software is required**

Technical Decomposition

DDA
Data Driven Analytics

"DDA" – Data Driven Analytics

Relative to targeted military systems…

- Ability to infer/discover hidden patterns in multidimensional data (IMOS – Inspection, Maintenance, Operational history, and Sensor) that inform performance, state, and signature attribute assessment
- Ability to construct/refine Digital Surrogate based on physics informed data analytics, for example…
  - Sensor data (real and/or synthetic) for system performance, state, and signature attributes
  - Inspection/Maintenance/Operational data for system state attributes
- Ability to update/improve Digital Surrogate in light of new/additional data
- Ability to quantify uncertainties associated with info delivered via Digital Surrogates

Key Observations

- Operational use of military systems represent stochastic (uncertain) processes for which deterministic methods have real, but limited, decision-making value
- Advances in data-analytics (ML/DL) produce models which are typically purely data-driven.
  Such are promising in, for example, machine-vision (autonomy); fraud-detection (economics); microarray gene-expression (medicine) However, model predictions may be infeasible (false-positives) where systematic constraints do not exist, or are not applied.

Must account for physics and uncertainty with adaptable data-driven models that are constrained by applicable physics (to eliminate inadmissible portions of feature-space).

"DS" – Digital Surrogates

Relative to targeted military system…

- Ability to identify the key performance, state, and signature parameters
- Ability to generate and "train" Digital Surrogate **using DDA/PBA compute engines**
- Ability for Digital Surrogate to continuously learn (e.g. from sensor data, maintenance/ inspection data)
- Ability to signal need for Digital Surrogate re-training
- Ability to publish Digital Surrogate updates (viz., post training, or re-training)
- Ability to synchronize with Apps (inform Apps of changes to Digital Surrogate resulting from updates or continuous learning)

Key Issues

- Whoever "owns" the data must be the one to generate the surrogates
  - e.g., if OEM owns IMOS data (and GOV has no access)…
    - GOV provides DDA, PBA, and DS software to OEM
    - OEM provides/maintains trained Digital Surrogates to/for GOV

Technical Decomposition

"DSA" – Decision Support Applications

Relative to targeted military system…

- Ability to RAPIDLY build new Apps
  - by developers
  - by end users
- Ability to build and maintain a standard set of Apps
- Ability to accept Digital Surrogate synchronization information with Apps

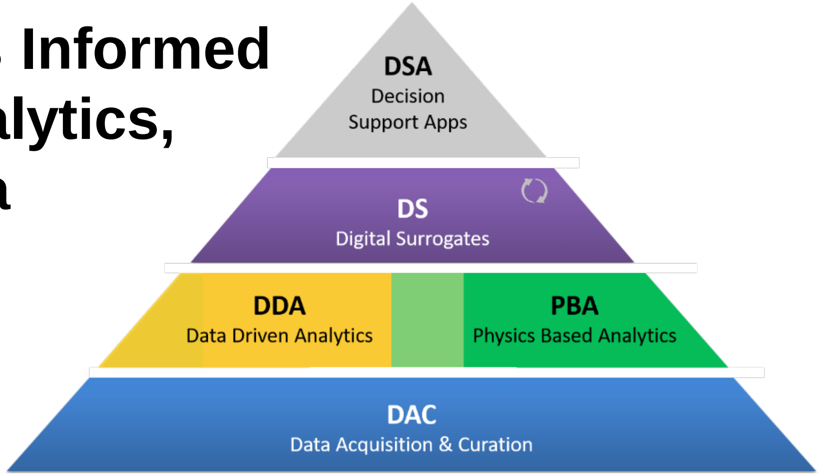
Key Issues

- The number of possible Apps is virtually unlimited
- App synchronization implies ability for secure real-time communication between App in use by decision maker and weapon system associated with Digital Surrogate in question

Physics Based Digital Engineering

- **Combat Air Vehicle Example**

- **Look at example Apps, Physics Informed Surrogates, Physics Based Analytics, Data Driven Analytics, and Data Acquisition and Curation**



Physics Based Analytics - Aerodynamics

DOD HPC MODERNIZATION PROGRAM

PBA
Physics Based Analytics

- **Models are built to impact decision making in air vehicle design, development, and sustainment**
  - Examples – Aerodynamics, Stability and Control (S&C), Propulsion, Structures
- **High Fidelity CFD Models typically…**
  - Take supercomputer resources to run depending on the fidelity of the mesh
  - Take flight conditions, surface and external volume meshes with boundary condition attributions as inputs
  - Compute the surface and volume aerodynamics of the vehicle using a finite volume or finite element solution algorithm
  - May be coupled with a structural solver, propulsion module, 6DOF solver, chemistry solvers for non-ideal gases, and conjugate gradient heat transfer solver to compute multiphysics simulations

DS
Digital Surrogates

- **Reduced Order Loads Models typically…**
  - Are derived from simulations using the high fidelity CFD solver, sometimes coupled with other physics models (e.g. S&C 6DOF, Structures, Propulsion)
  - Run faster than real time and can span the air vehicle envelope

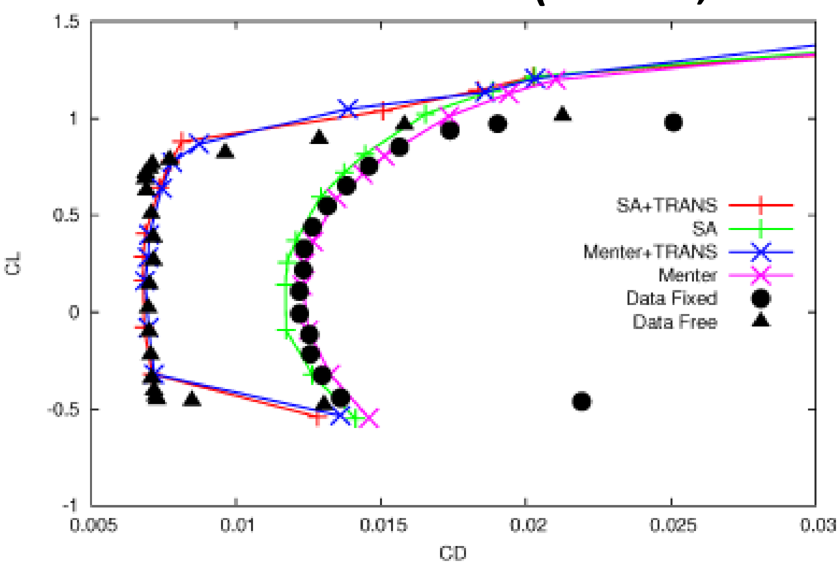
Aerodynamic Model Enablers

Turbulence Transition Modeling

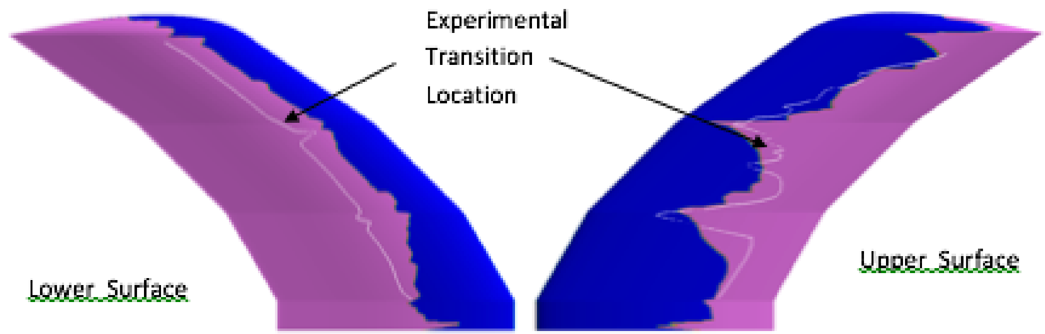
PBA
Physics Based Analytics

- **Mature 1- and 2-eqn turbulence models and options**
  - Steady/unsteady RANS, unsteady DDES, compressibility correction for high-speed shear layers, QCR, automatic wall functions
  - Proven accuracy for cases of interest to DoD fixed-wing community
  - Consistent implementation in KCFD and SAMAir
- **Local-correlation 1-eqn transition model based on intermittency by Menter et al (2014) in KCFD (SA/Menter)**
  - Correlations for natural, bypass, cross-flow, and separation-induced transition

S809 Wind-Turbine Airfoil (M = 0.1, Re = 2m)



Sickle Wing (Petzold and Radespiel)
M = 0.156, Re = 2.744m, -2.6 deg AOA



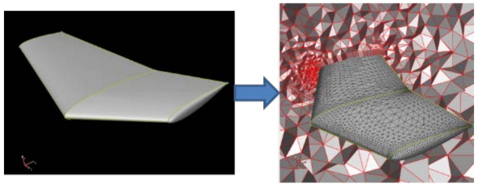
Aerodynamic Model Enablers

Automatic Mesh Generation

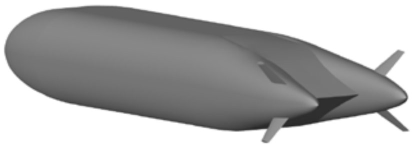
PBA
Physics Based Analytics

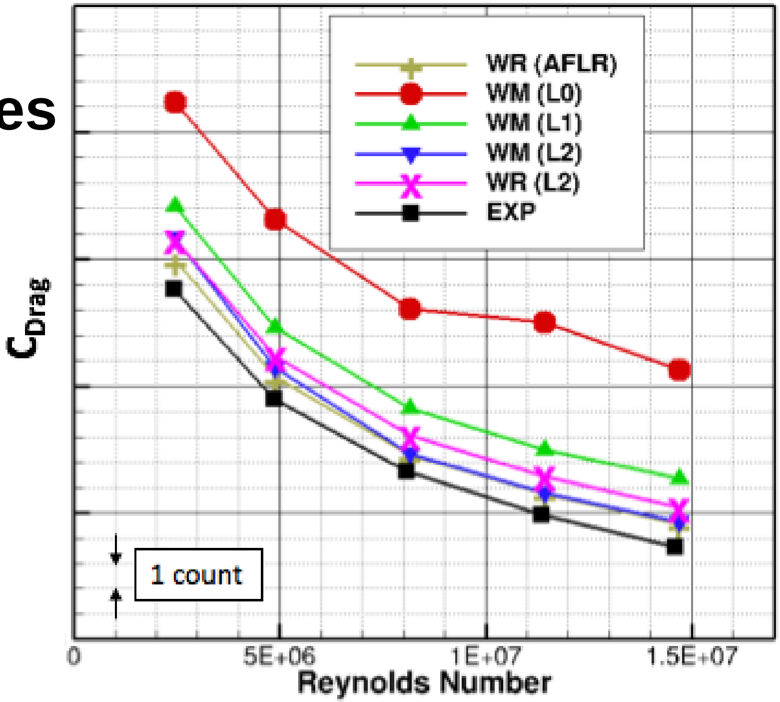
DOD HPC MODERNIZATION PROGRAM

- **Kestrel job inputs inform unstructured meshing process powered by CREATE Capstone SDK**



- **Automatic surface feature detection helps to target an appropriate surface mesh topology and resolution**
- **Easy to vary overall grid resolution**
- **Series-66 geometry with appendages**
  - Multiple resolution levels of both wall-modeled and wall-resolved grids
  - Grid sizes ranging from 800k to 8m
  - Automatic detection of cusps and problem edges and introduction of edge boundary layers into the mesh





Aerodynamic Model Enablers

PBA
Physics Based Analytics

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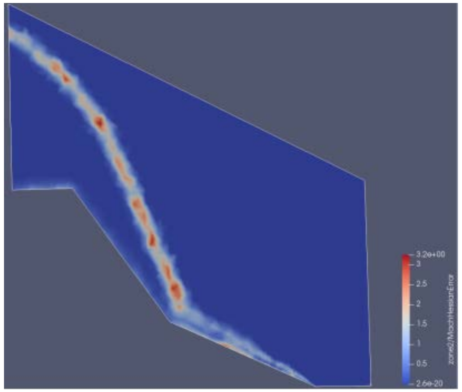
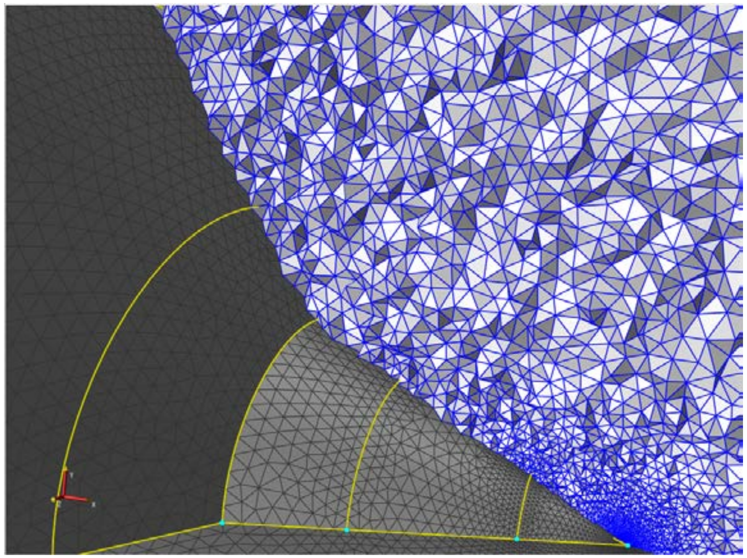
Automatic Mesh Refinement (AMR)

- **Collaboration with CREATE-MG (Capstone) team**
- **Leverages new Mach Hessian error indicator and robust ability to restart on different mesh (v10.1)**
- **AMR repeats until the convergence of error indicator or a maximum mesh size is reached**
- **Initial capability targeted for v11.0 (May 2020)**

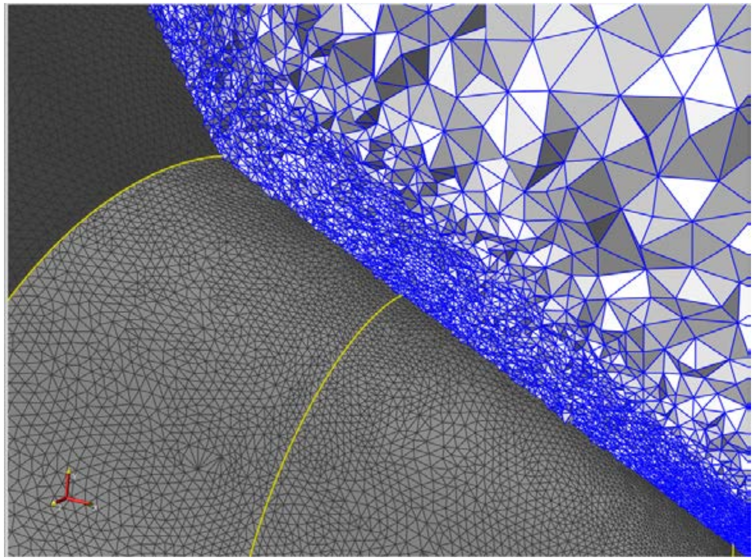


Mach Hessian Error
Viz Output

CUBRC Double-Cone Geometry, Mach 12.5
Refine every 1000 iterations from 2000 to 4000 iterations



Initial Mesh (all tet, no BL)



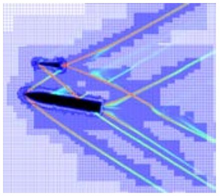
Adapted Mesh (all tet)

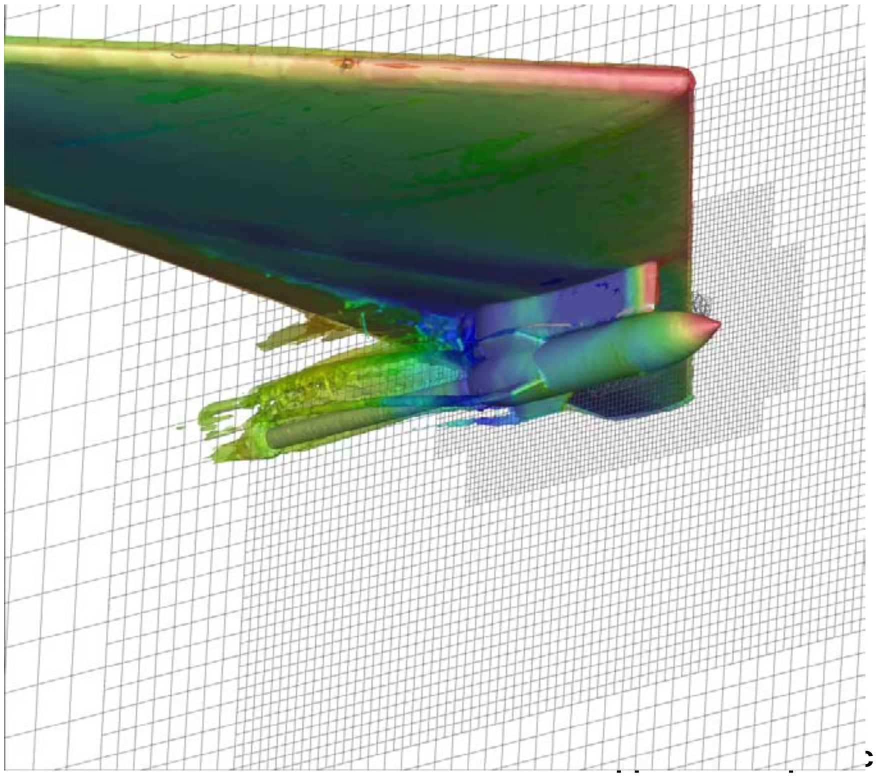
Aerodynamic Model Enablers

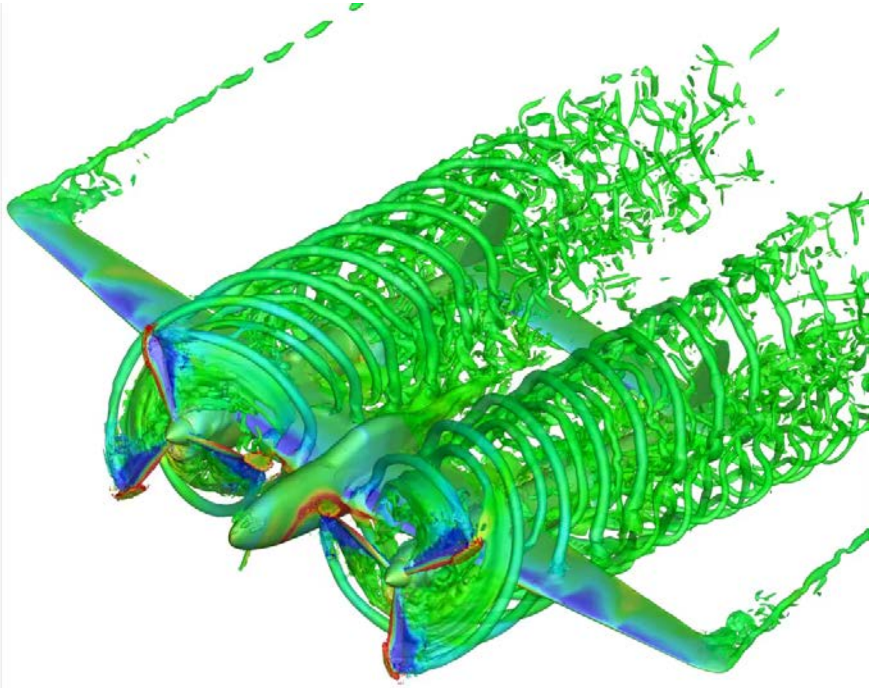
Near-body/Off-body Flow Solutions

PBA
Physics Based Analytics

- **Hybrid Near-Body/Off-Body solution capability**
  - 3rd/5th-order hybrid unstructured/Cartesian mesh overset
  - 1- and 2-equation turbulence models consistent with near-body solver
  - Implicit time integration
  - Adaptive Mesh Refinement (vorticity and shocks)







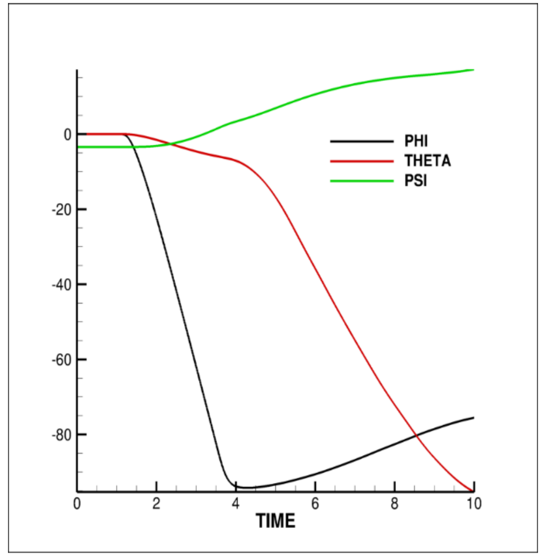
Physics Based Analytics – S&C

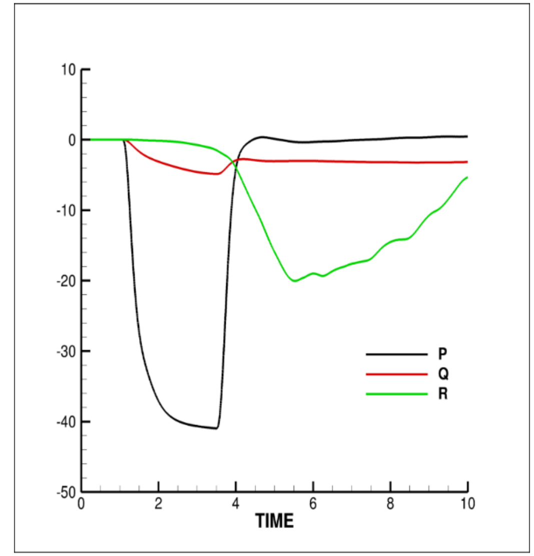
- **The Stability and Control Model is typically a 6 Degree of Freedom (6DOF) solver that…**
  – Runs faster than real time and spans the vehicle envelope
  – Takes mass properties, vehicle configuration, and desired flight trajectory (e.g. stick inputs) or conditions as inputs
  – Uses information about vehicle aerodynamics, structures, and propulsion and the equations of motion to determine a vehicle's trajectory
  – Can incorporate "feedback control laws"
  – Can easily be improved for accuracy by replacing aerodynamics, structures, and propulsion data as higher fidelity information is known
- **Stability and Control Model can be used for…**
  – Stability and Control analysis and handling qualities evaluations
  – Sensitivity studies
  – Mission performance – fuel burn, available payload weight, etc.
  – Driver for "Pilot in the Loop" Simulators

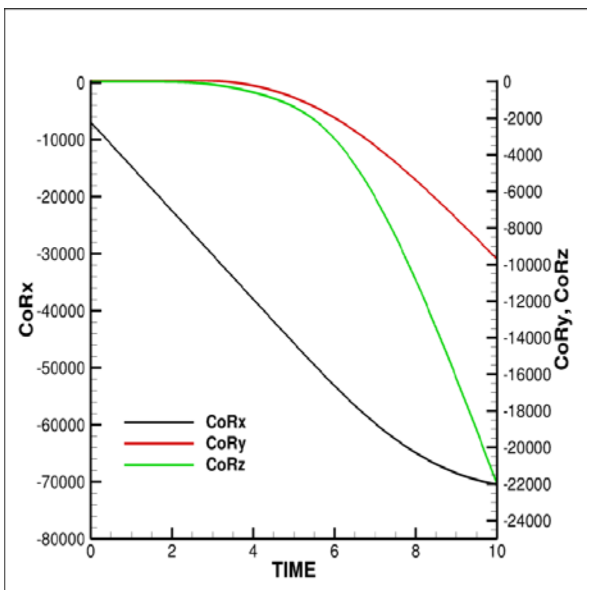
S&C Maneuver Analysis

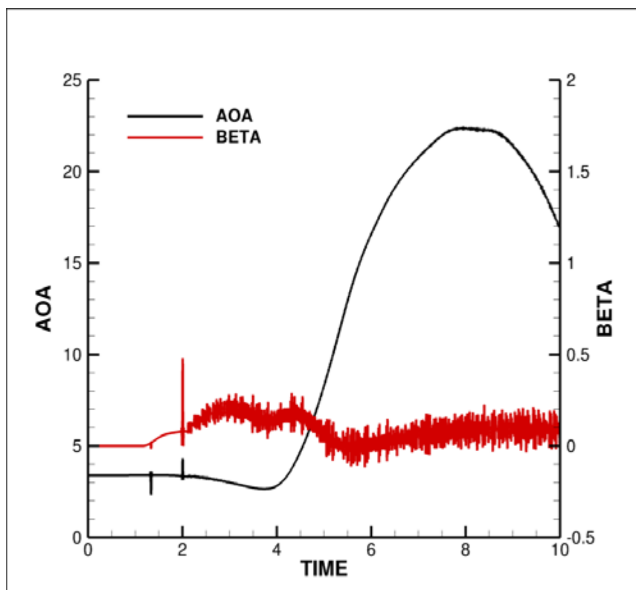
Wind-Up Turn

- **Prescribed Motion Wind-Up Turn (WUT) from ATLAS**
  - **10 second Maneuver**
  - **Level Acceleration to M=0.6**
  - **Roll Right to Max Bank Angle**
  - **Pitch to Establish High G Turn**
  - **Maintain Turn**





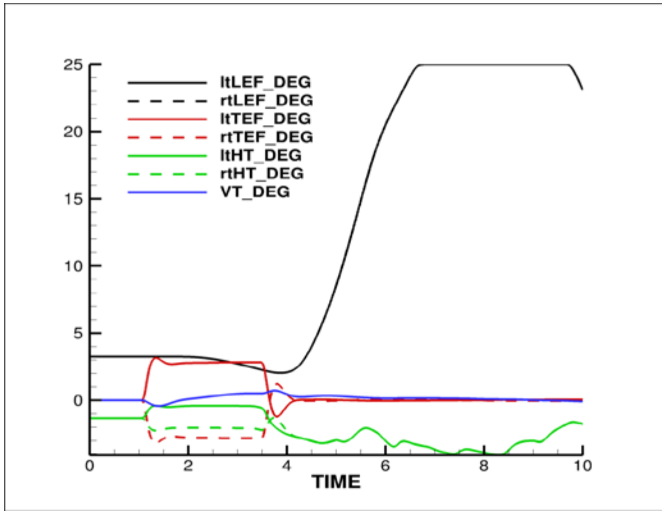


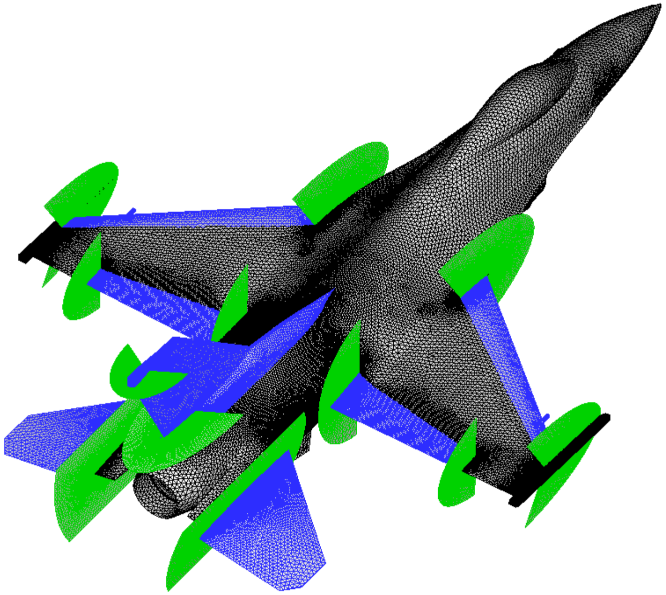


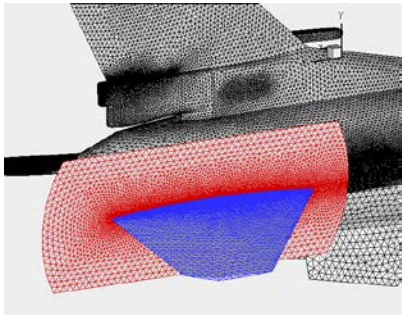
- **Descending Right Turn**
- **Resulting AOA and Beta**
- **Max Alpha Hold at 23 degrees**
- **Sideslip Between 0 and 0.2 degrees**
- **Noise in Sideslip due to Expanded Scale**

Maneuvering F-16 With Moving Control Surfaces

- **Unstructured Mesh with Control Surfaces**
  - 6.2M Tets, 6.9M Prisms, 190K Pyrs
  - Sliding Plane Interfaces for Control Surfaces
- **Prescribed Control Surfaces**
  - Leading Edge (LEF) and Trailing Edge Flaps (TEF)
  - Rolling Horizontal Tail (HT) and Vertical Tail (VT) with Rudder
- **Time History of Control Surface Motion**
  - Differential HT's and TEF's to Roll (1-4 sec)
  - Equal Lft/Rt HT for Pitch
  - Equal Lft/Rt LEF for High AOA







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Maneuvering F-16 With Moving Control Surfaces

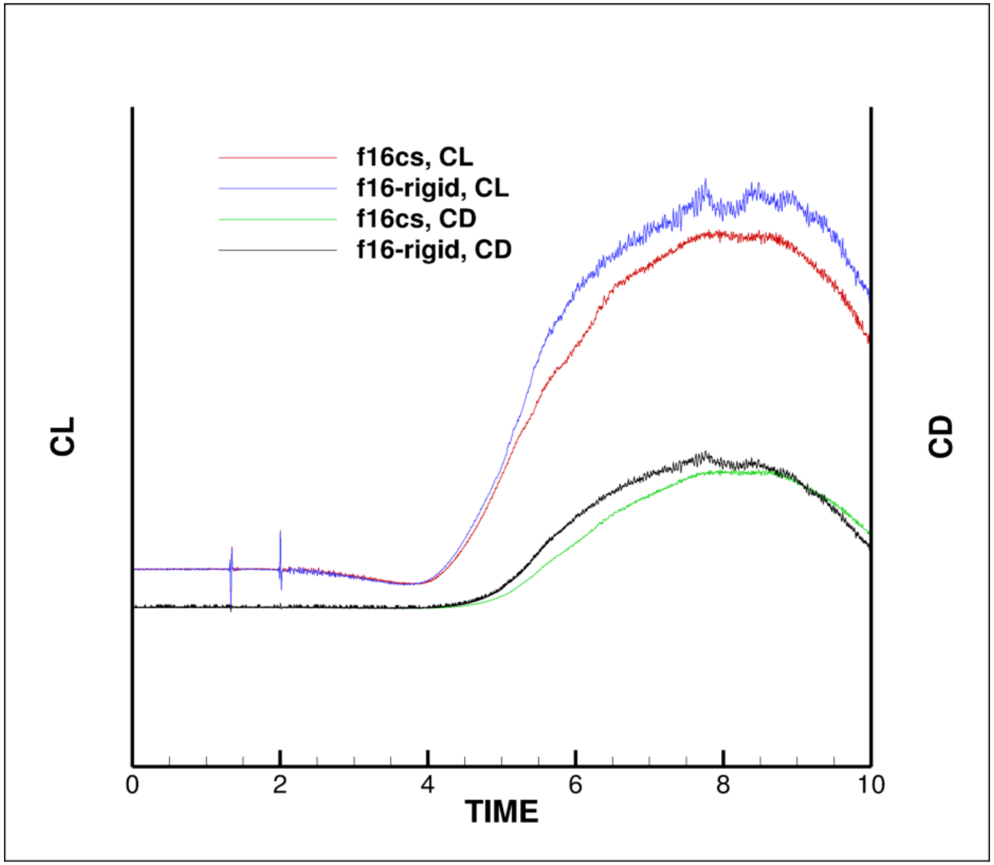
PBA
Physics Based Analytics

- **Iso-surface of Vorticity Magnitude (100/sec) Colored by Pressure**

Maneuvering F-16 With Moving Control Surfaces

PBA
Physics Based Analytics

- **Comparison of Lift and Drag Coefficients w/ w/out Control Surfaces**
  - **Almost no difference until pitch up**
  - **Fairly large difference in CL and CD from 5 to 10 seconds**
  - **Pitch up and LEF lowering requires large tail movement, reducing overall lift**
  - **Control surfaces also impact drag**
  - **Low frequency oscillations and high frequency chatter reduced with LEF extensions, probably due to less separated flow from increased camber**
  - **Measurable differences demonstrate the need for modeling control surfaces during the design process**



Physics Based Analytics - Propulsion

PBA
Physics Based Analytics

- **The Propulsion Model has two variants**
  - High fidelity turbomachinery integrated into a CFD solver
  - Engine cycle deck
- **Turbomachinery are geometry/mesh components (e.g. compressor or turbine rotor/stators, combustor) in the flowfield path of a high fidelity simulation tool**

DS
Digital Surrogates

- **The Engine Cycle Deck typically…**
  - Runs faster than real time and spans the vehicle envelope
  - Takes flight conditions, compressor face conditions, exit nozzle conditions, and vehicle configuration as inputs
  - Uses information about the engine and with one-dimensional engine pressure and temperature ratios through the engine stations, along with bleed losses and installation losses, determines compressor face and exit nozzle mass flow, velocity, and temperature data, as well as fuel burn and installed thrust
  - Can be run offline, integrated into a high fidelity simulation tool (FORTRAN or NPSS Model) with pseudo-time accuracy with or without transient behavior, or integrated into an S&C 6DOF Model to provide thrust

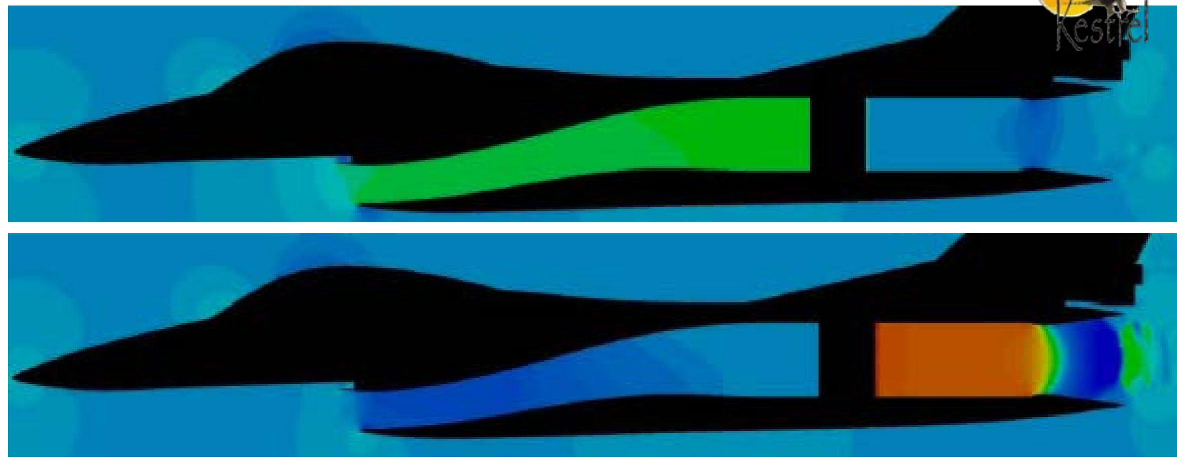
Propulsion Integration

PBA
Physics Based Analytics

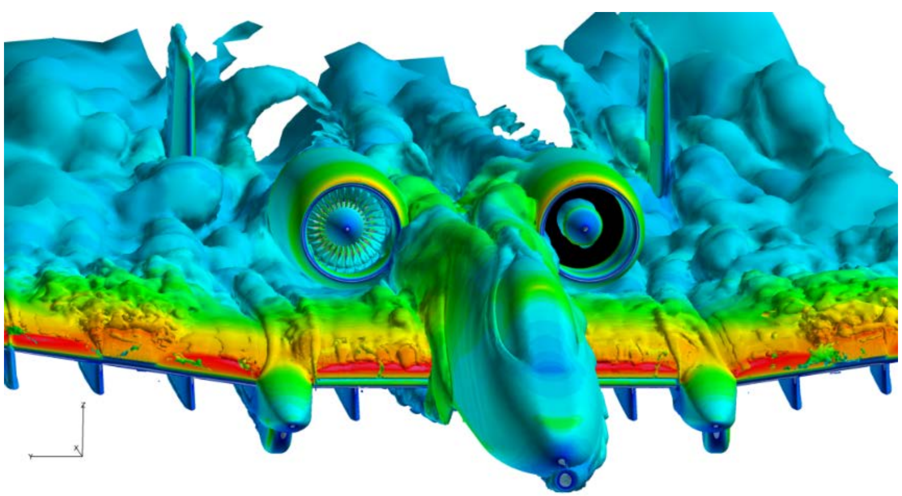
F-16
0.6 Mach
20k feet
6 deg AOA
F110-100 0D transient engine model

30° PLA

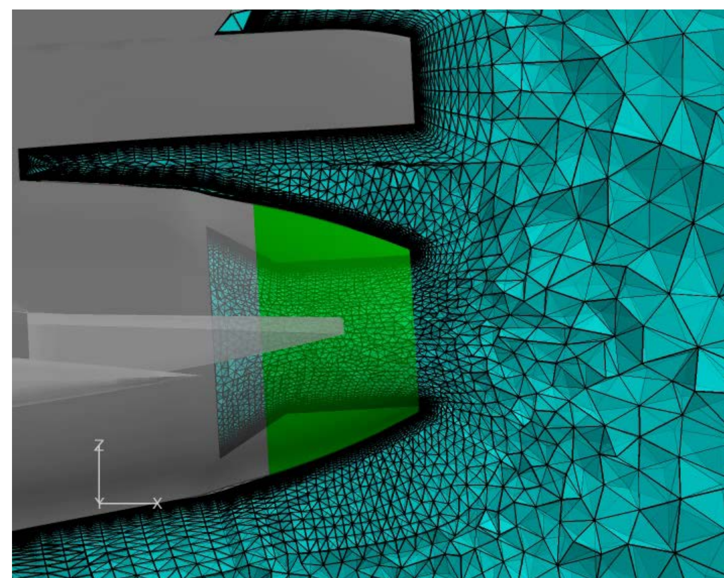
85° PLA



A-10 Inlet Distortion - 21° AOA



Variable Inlet or Nozzle Geometry
F-16XL/F-110 Variable Throat and Exit Plane

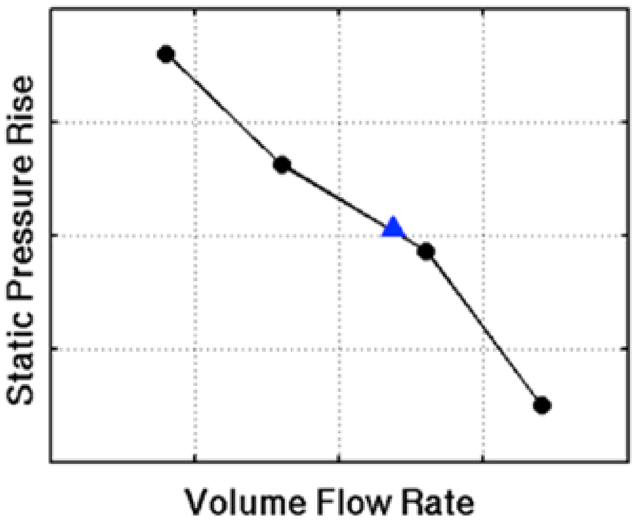


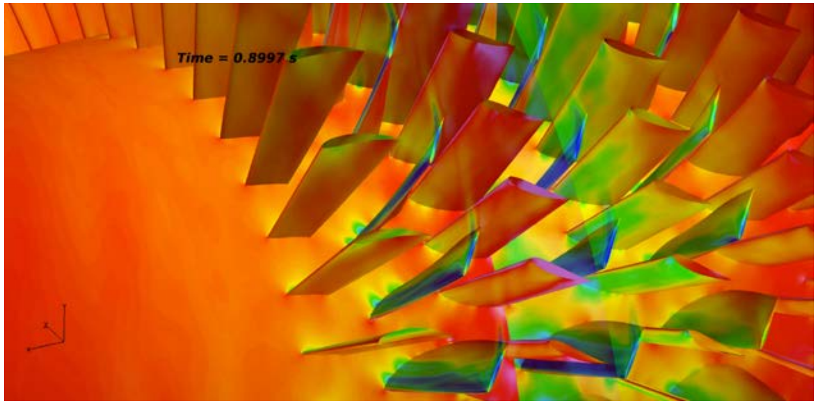
Propulsion Integration

PBA
Physics Based Analytics

C1 Compressor AEDC 16T

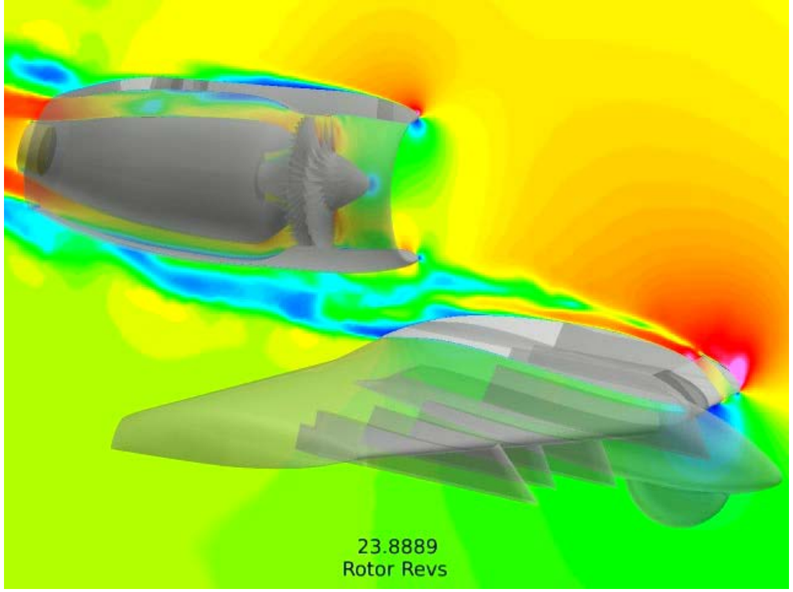
8 blade rows, 333 blades

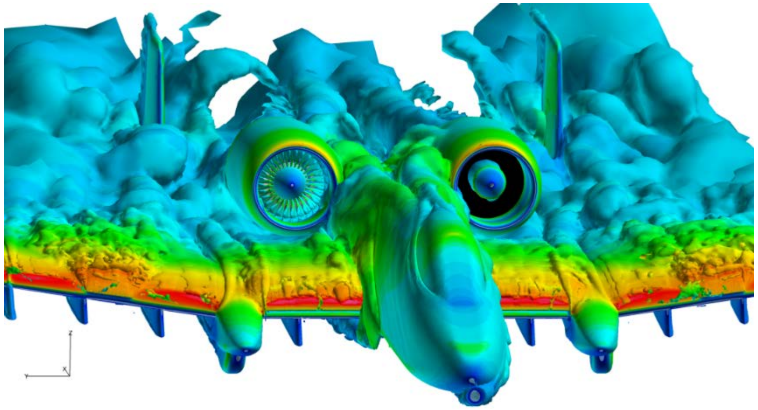




A-10 Inlet Distortion at 21° AOA

Full annulus TF34 fan stage with static BC core flow





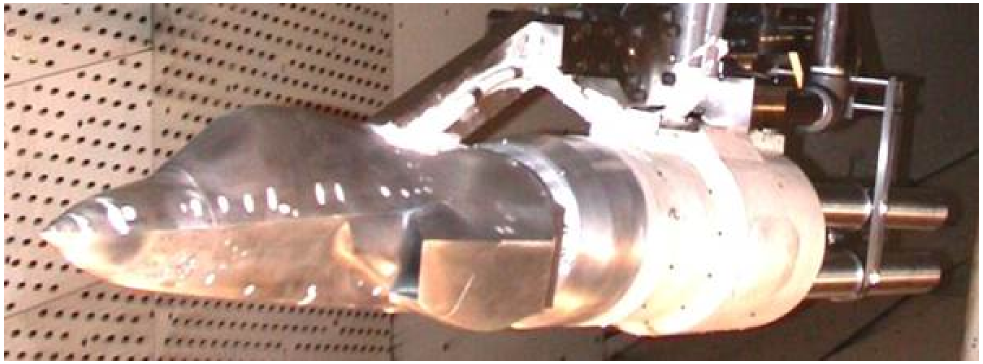
Propulsion Integration

PBA
Physics Based Analytics

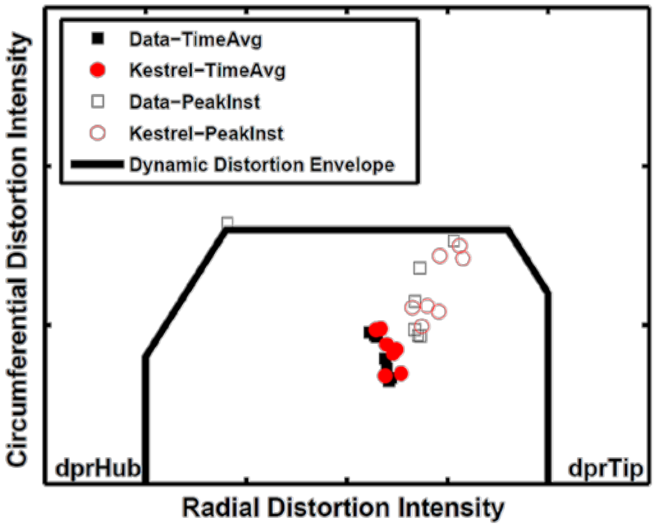
DOD HPC MODERNIZATION PROGRAM

Kestrel

- **Dynamic distortion analysis of complex inlet systems**

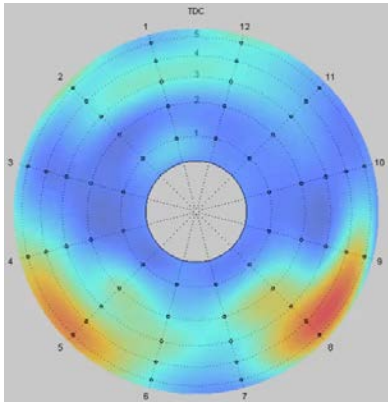


12% scaled model of actual weapon system containing forebody, complex inlet, and AIP in AEDC 16T

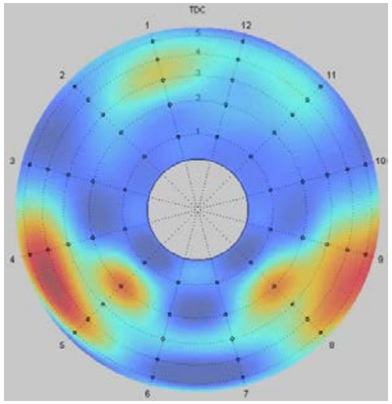


Mach= 0.90, AoA=5º

Data

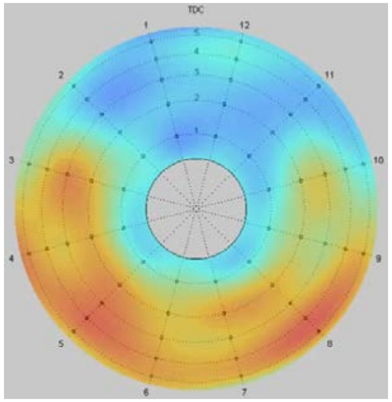


Kestrel

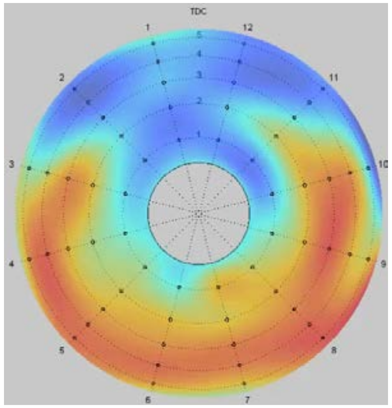


Mach= 0.90, AoA=30º

Data



Kestrel



*Klepper et al., "Dyanamic Jet Simulation Demonstration for Airframe-Propulsion Integration using HPCMP CREATE^{TM}-AV Kestrel," ASME Turbo Expo 2017, GT2017-63072.

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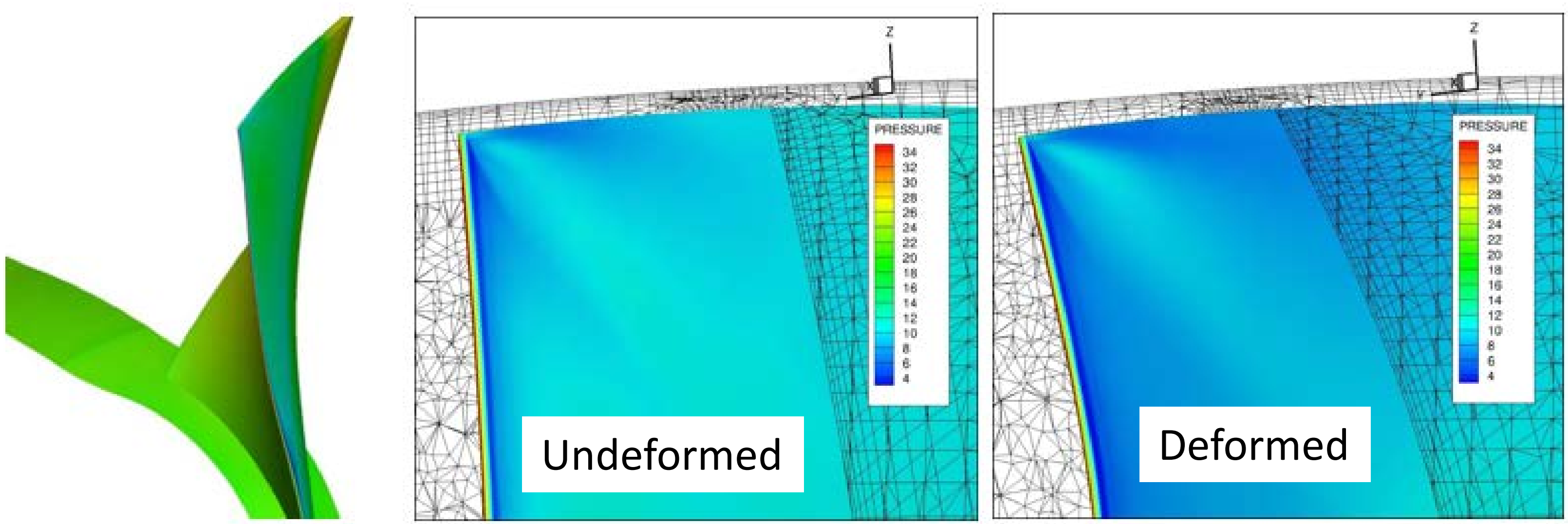
Propulsion Integration

PBA
Physics Based Analytics

- **Compressor or Turbine Blade Fluid-Structure Interaction**
- **Internal flow/turbomachinery, bodies in close proximity**
  - Applications have surpassed existing algebraic mesh deformation techniques in terms of robustness and/or ease-of-use
- **Parallel improvements to Winslow Smoothing technique**
- **Implementation of Radial Basis Function technique**
  - Constrained surface mesh deformation using “two-pass” approach

Rotor 67 Tip Gap Region, Std Day, M=0.5, 16043 RPM (Prescribed Mode Shape)



Physics Based Analytics - Structures

PBA
Physics Based Analytics

- **Two variants of Structures Models**
  – Finite Element Structural Model with a High Fidelity Simulation Tool
  – Modal Structural Model
- **The Finite Element Structures Model typically…**
  – Takes from work station to supercomputer resources to run depending on the fidelity of the mesh
  – Takes flight conditions, internal structure meshes with material property attributions, and external loads as inputs
  – Computes the structural deformation, as well as, internal stress and strain of the structure using a finite element solution algorithm
  – It may be coupled with an aerodynamic solver and/or a conjugate gradient heat transfer solver to compute fluid-structure, thermal-structure, or fluid-thermal-structural interactions

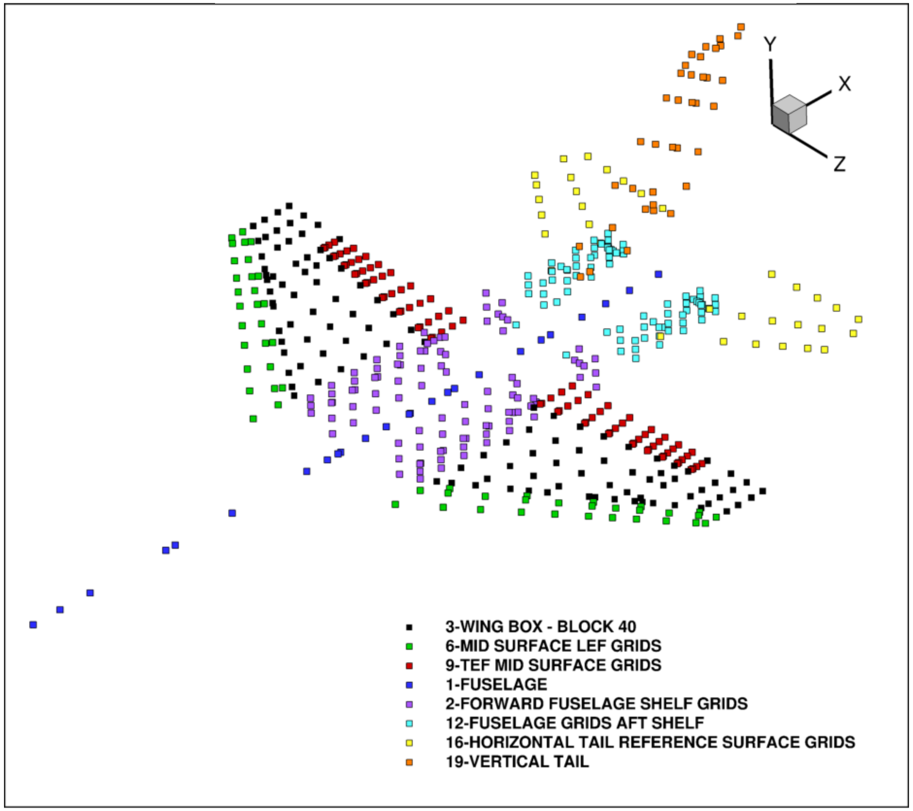
DS
Digital Surrogates

- **The Modal Structural Model typically…**
  – Is a linearized Reduced Order Model derived from the Finite Element Model through an eigenvalue analysis
  – Runs orders of magnitudes faster than the Finite Element Model

Aeroelastic Maneuver Analysis
F-16 in a WUT

PBA
Physics Based Analytics

- **Unstructured Mesh with No Control Surfaces**
  - 6.5M Tets, 3.8M Prisms, 19.5K Pyrs
- **Modal Structural Model**
  - 1,422 structural nodes
  - 26 modes
- **Prescribed Motion Wind-Up Turn (WUT) from ATLAS**
  - 10 second Maneuver
  - Level Acceleration to M=0.6
  - Roll Right to Max Bank Angle
  - Pitch to Establish High G Turn
  - Maintain Turn



Aeroelastic Maneuver Analysis F-16 in a WUT

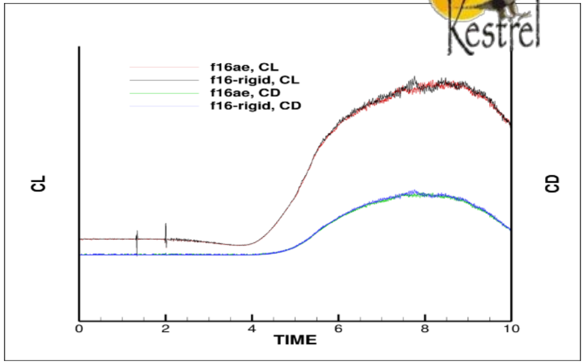
PBA
Physics Based Analytics

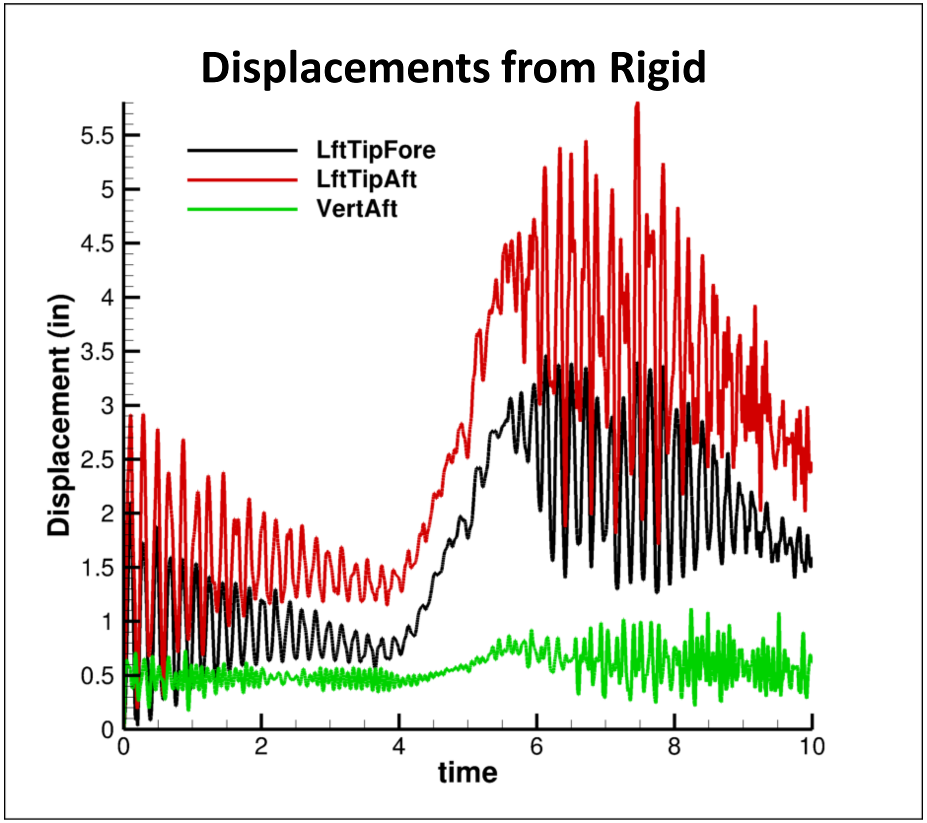
- **Aircraft Surface Colored by Pressure with a Reference Rigid Body Colored Grey**

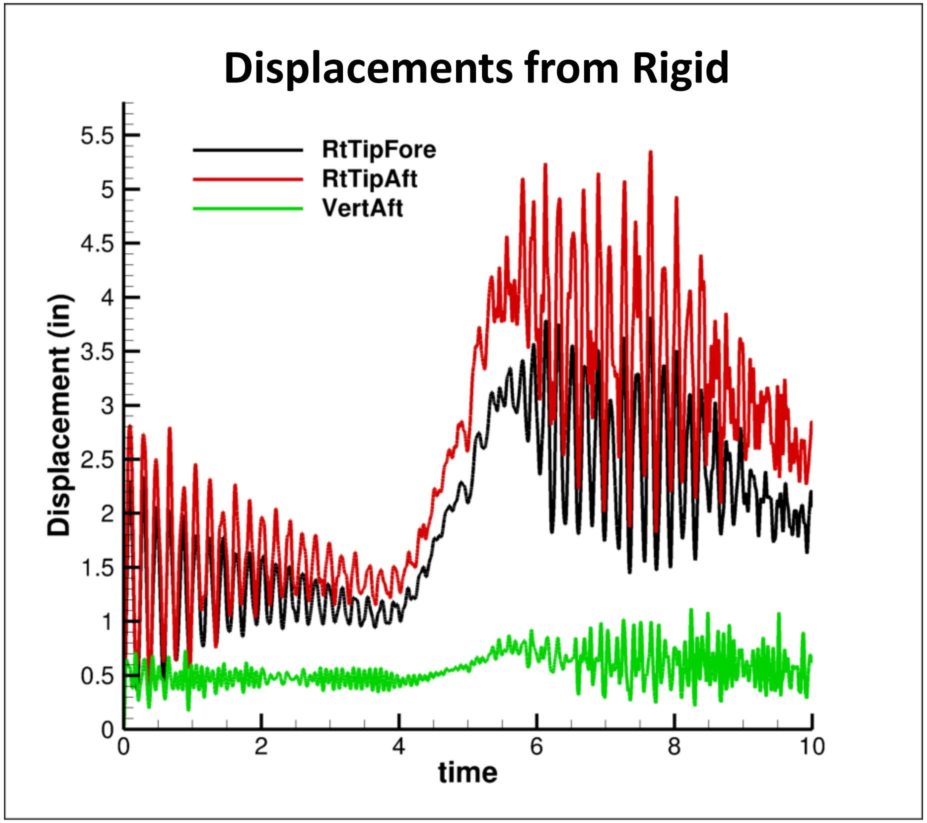
Aeroelastic Maneuver Analysis F-16 in a WUT

PBA
Physics Based Analytics

- **Displacements of the Left and Right LAU-129 Tip Launcher Fore and Aft and Vertical Tail Aft Points**
- **Lift and Drag Coefficients for Aeroelastic and Rigid F-16**



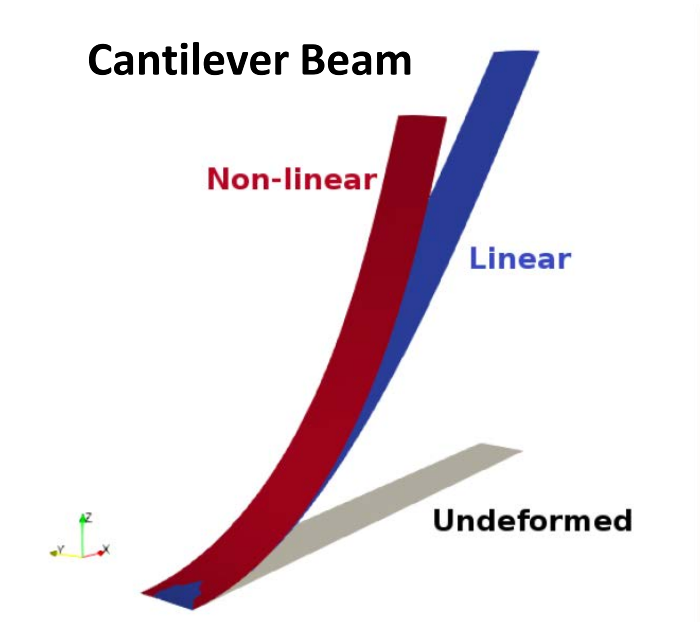




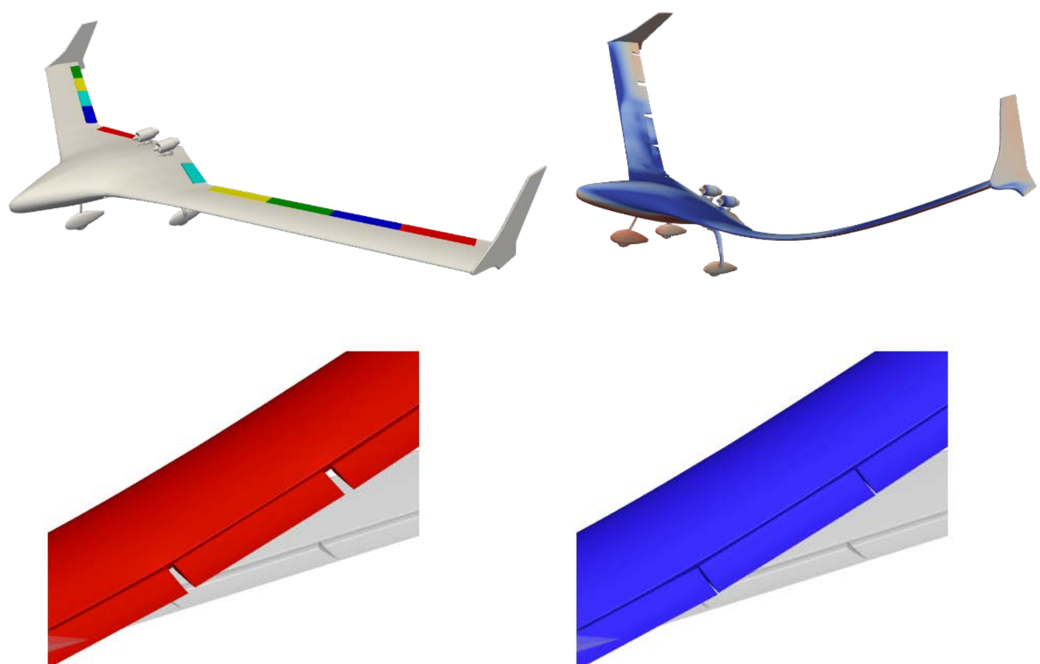
Elastic Structures Analysis

PBA
Physics Based Analytics

- **Scalable, high-fidelity FEM solver - Sierra/SD**
  - Nonlinear transient analysis capability
  - Accurate loads transfer for large FSI problems
- **Child bodies may use parent body structural model**



NASA X-56 w/ 10 Overset Controls

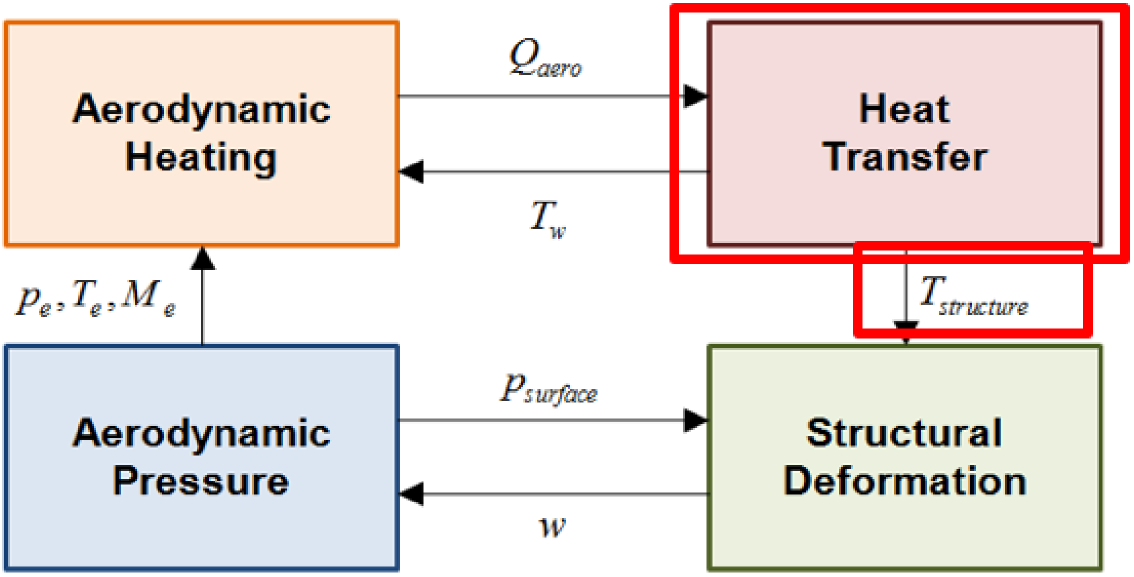


Parent-only FSI

Multi-body FSI

Coupled Heat Transfer in Structures

- Important for hypersonic vehicle simulations
- 1-D transient conduction BC in KCFD
- Initial integration of Sierra/TF "Aria"
- Temperature effects on material properties in Sierra/SD
- Assessment of material response and ablation solvers



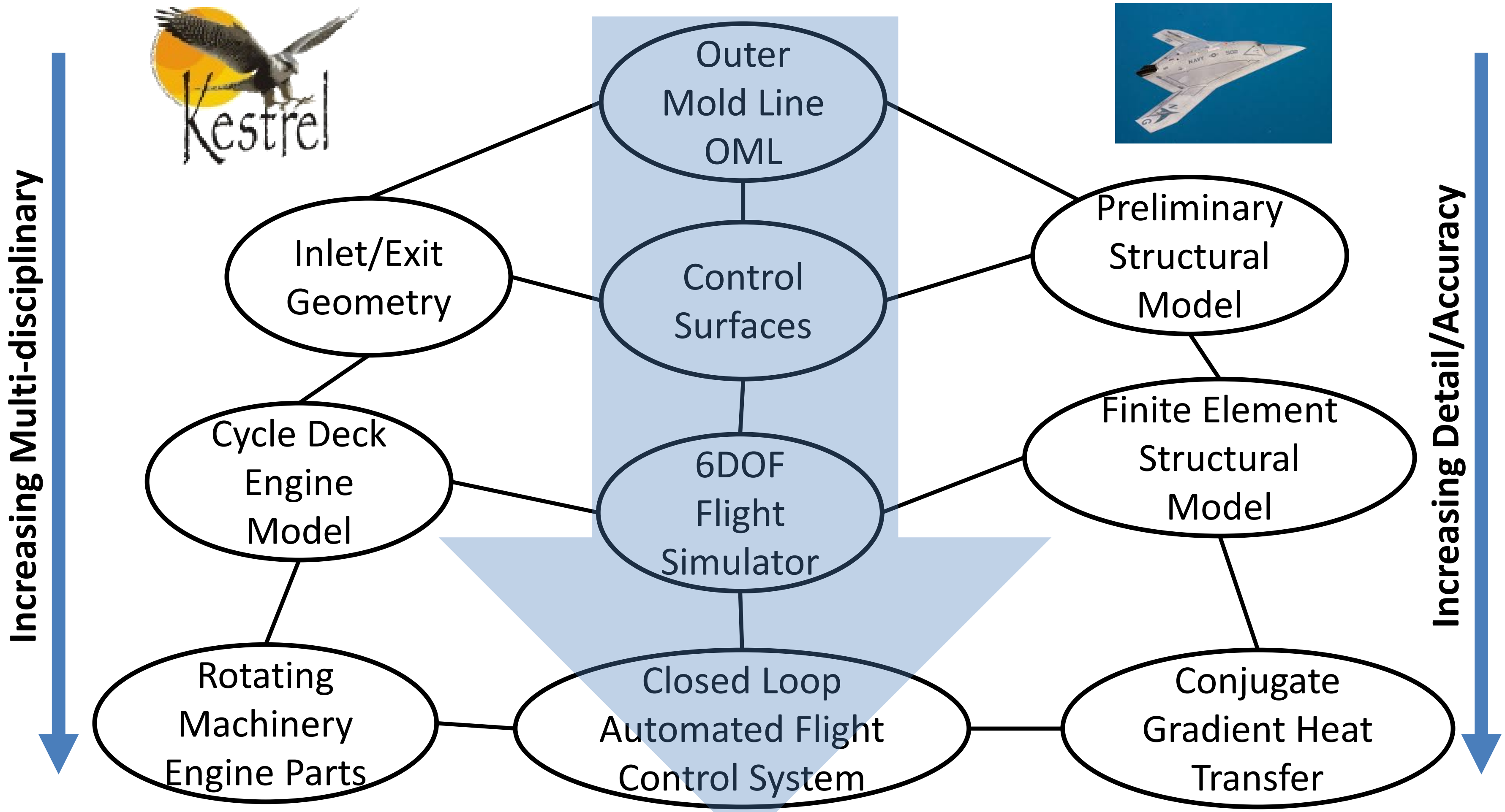
Chona, R., AFRL, Aug 2015

Physics Based Analytics

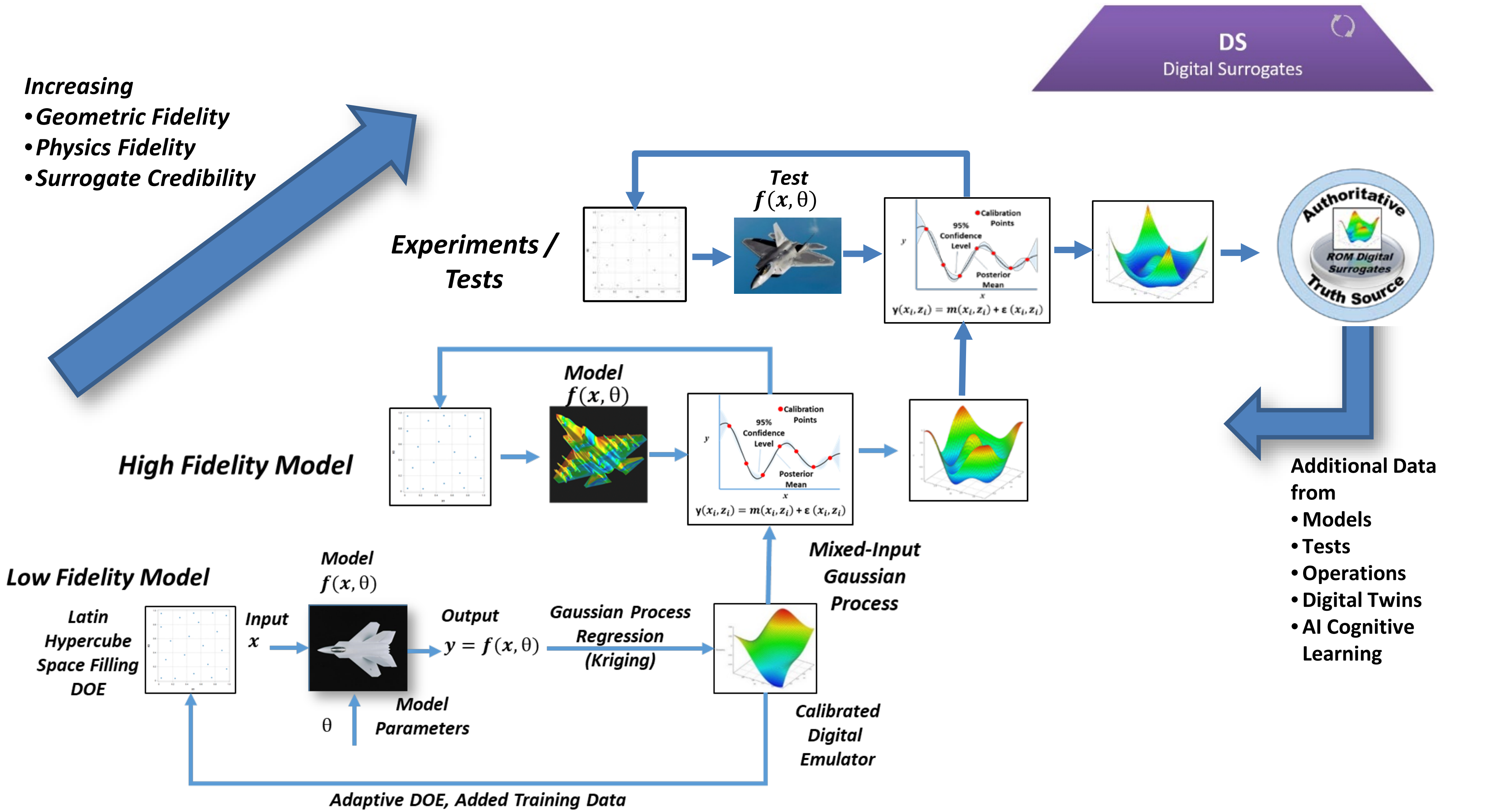
PBA
Physics Based Analytics

DOD HPC MODERNIZATION PROGRAM

- **During the design process we can eliminate poor design choices by increasing the fidelity of the PBAs as more information is known (objects and connection notional)**



Example of Developing an Authoritative Digital Surrogate Reduced Order Model for Aerodynamics

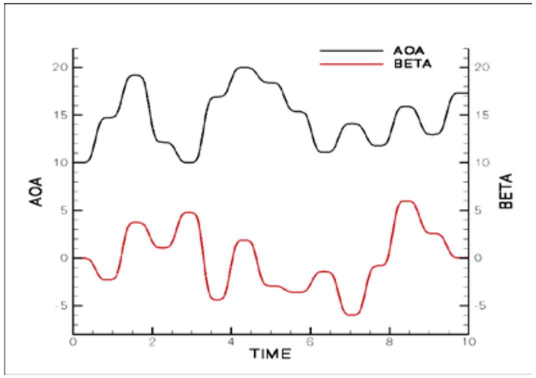


Edward M. Kraft, "Development and Application of a Digital Thread / Digital Twin Aerodynamic Performance Authoritative Truth Source," AIAA-2018-4003. Aviation Systems Conference, Atlanta, GA, June 25-29, 2018

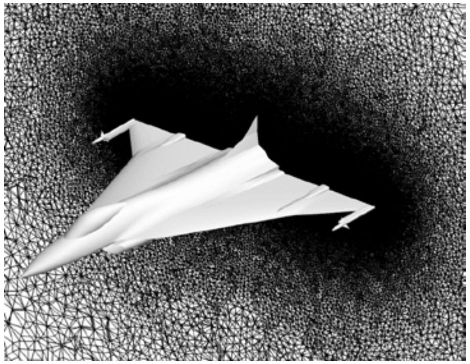
Digital Surrogates
Reduced-Order Modeling

DS
Digital Surrogates

- **Effective use of ROMs necessary for disruptive impact to acquisition programs**



Automated Maneuver Generation to Minimize Parameter Correlation



CFD Model

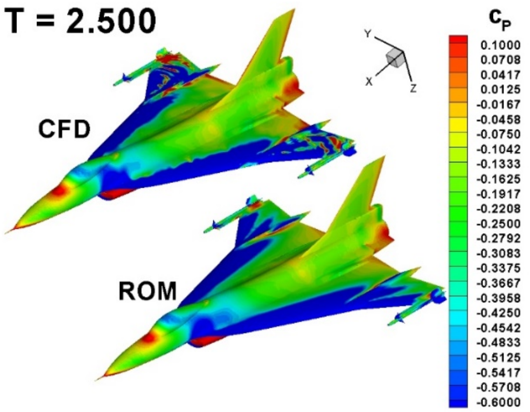
Polynomial (Integrated Loads):

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

POD-Based (Distributed Loads):

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

ROM Constructed Using On-Design Data

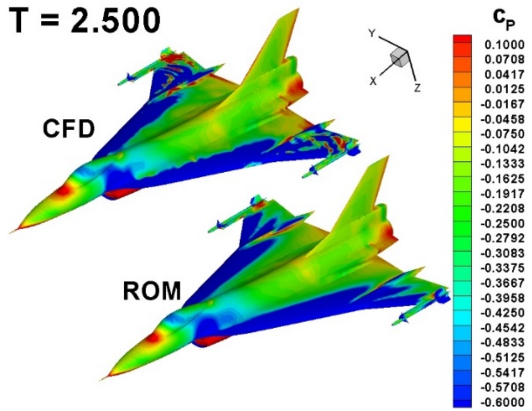


ROM Used For Integrated/Distributed Aero Predictions at Off-Design Conditions

Digital Surrogates
Reduced-Order Modeling

DS
Digital Surrogates

Distributed Loads Modeling

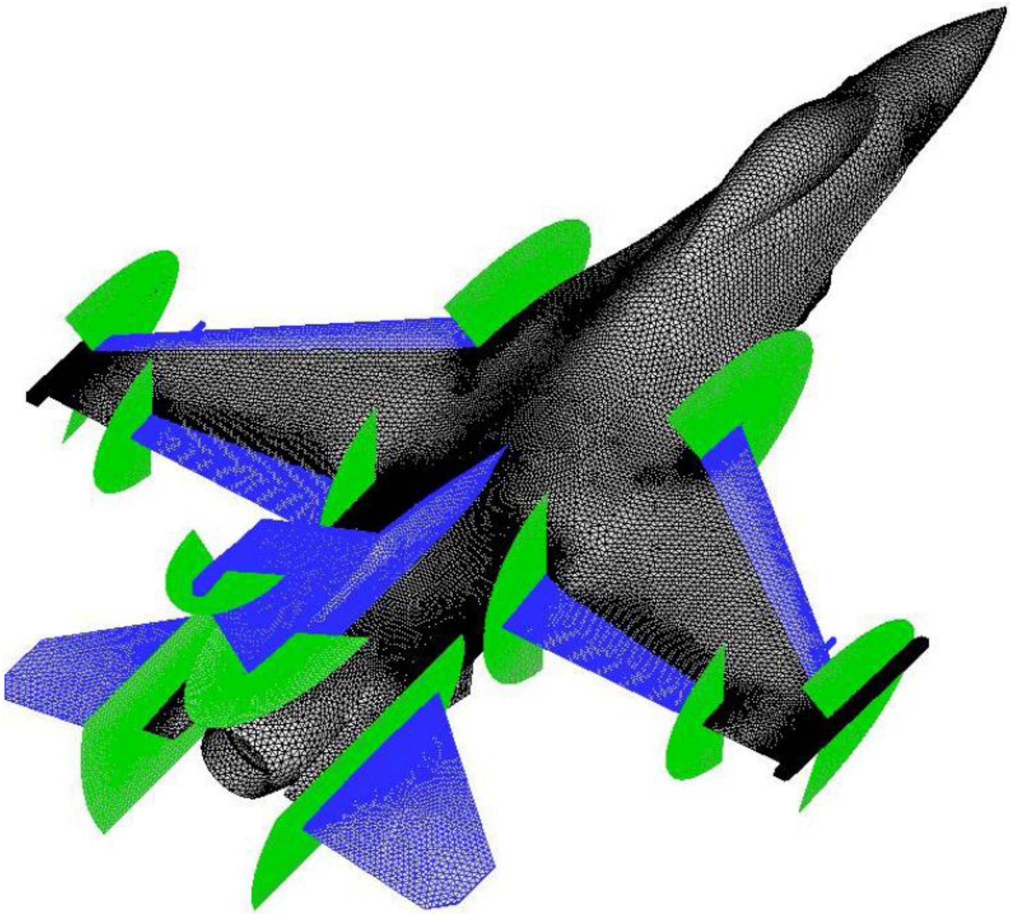


- **Two modeling methods developed, tested, and comparatively evaluated**
  - **Proper Orthogonal Decomposition (POD)**
  - **Eigensystem Realization Algorithm (ERA)**
- **POD method reduces the size of a high-fidelity, high-dimensional model by transforming from the physical (spatial) frame to a modal frame**
- **ERA balances the properties of controllability and observability where controllability is linked to system inputs (e.g., flight speed, altitude) and observability to system outputs (e.g., forces, moments)**
- **Each approach has strengths and weaknesses**

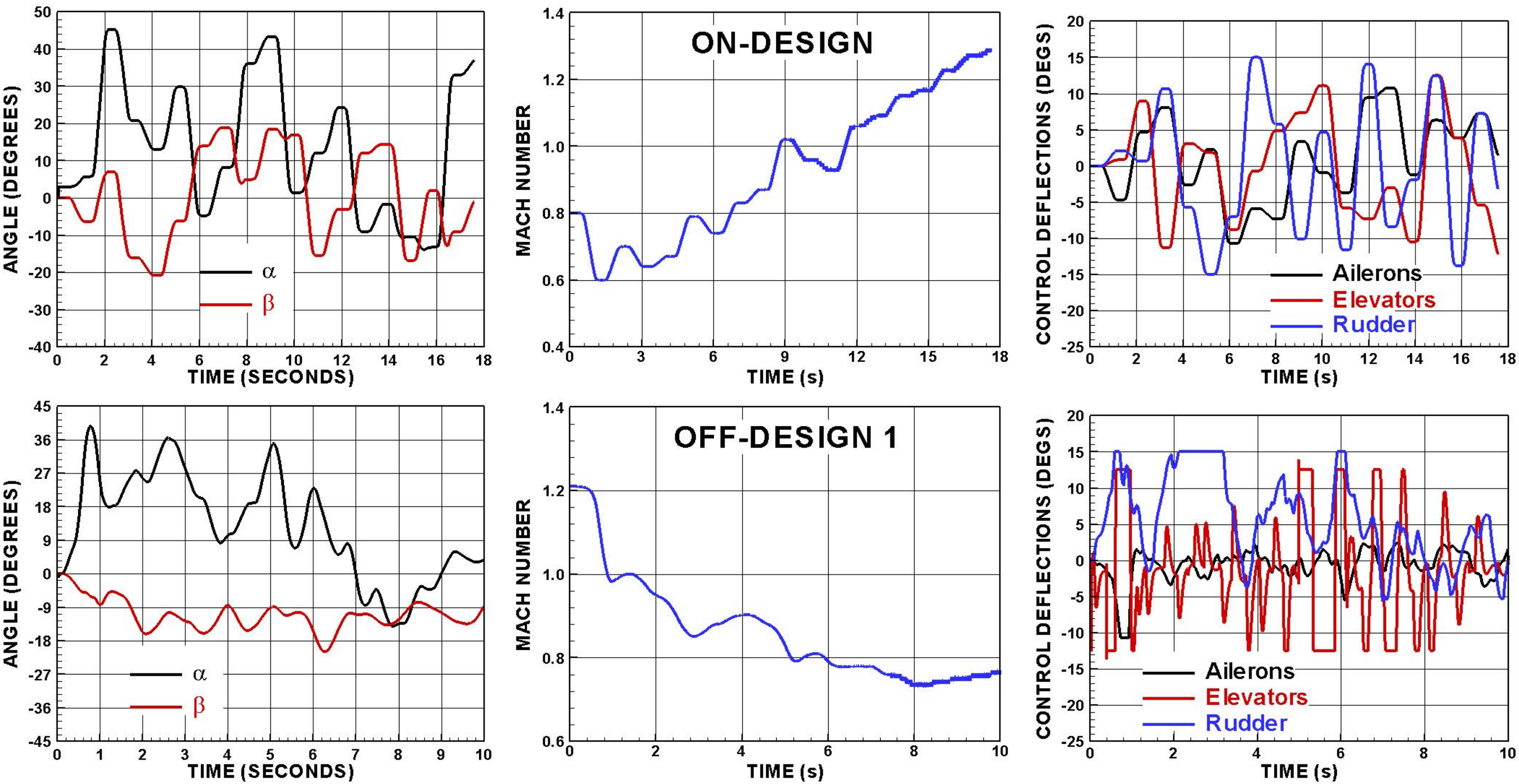
Example - F-16 with Moving Control Surfaces

DS
Digital Surrogates

- F-16 with control surfaces (ailerons, elevators, rudder)
- 14M nodes, 36M cells mesh
- Sliding interface planes
- Training and testing maneuvers for rigid aircraft include control surface motion, total aircraft motion, and variable flight speed



On- and Off-Design Maneuvers



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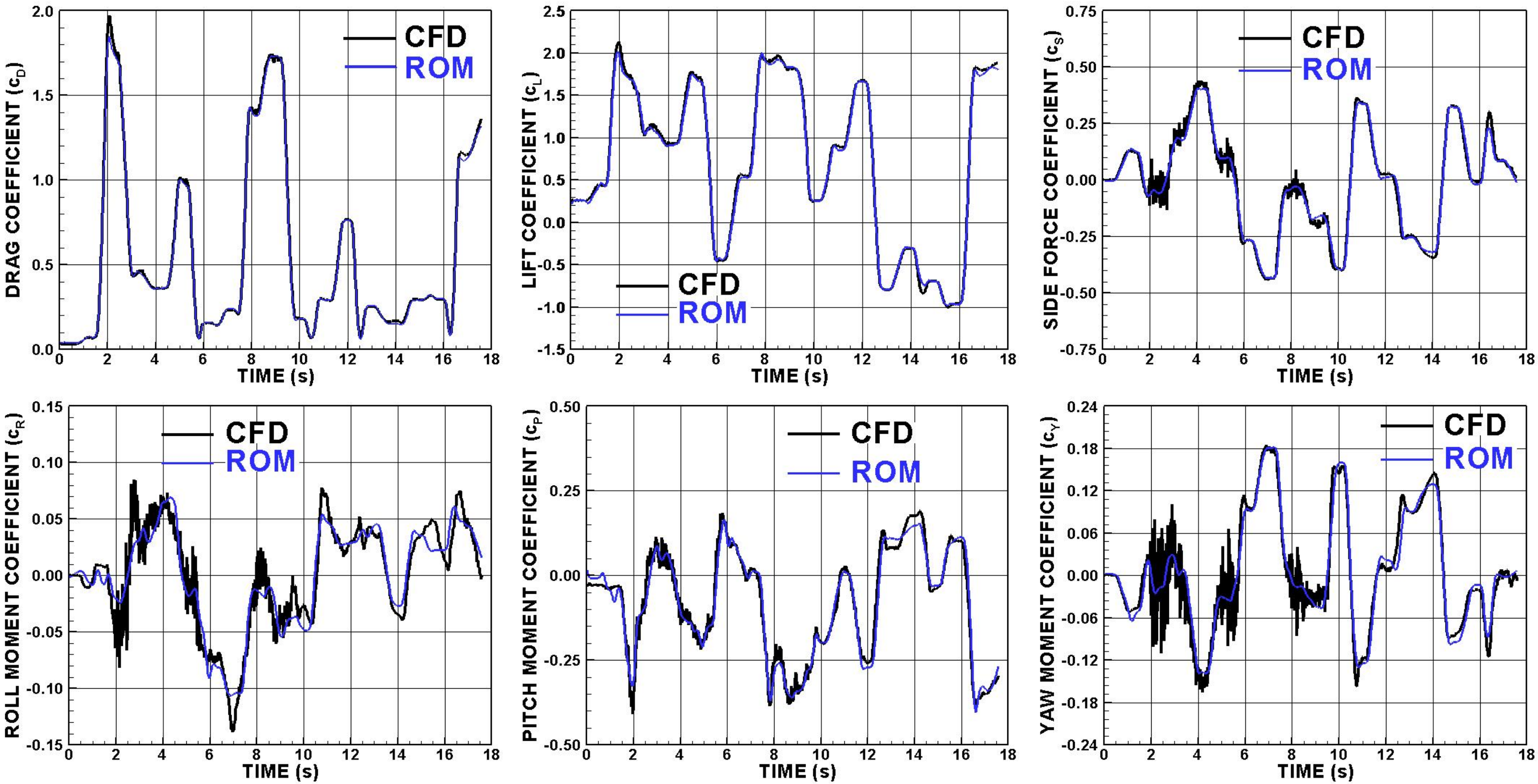
On-Design Maneuver



Clear Science Corp.

PRINCETON UNIVERSITY

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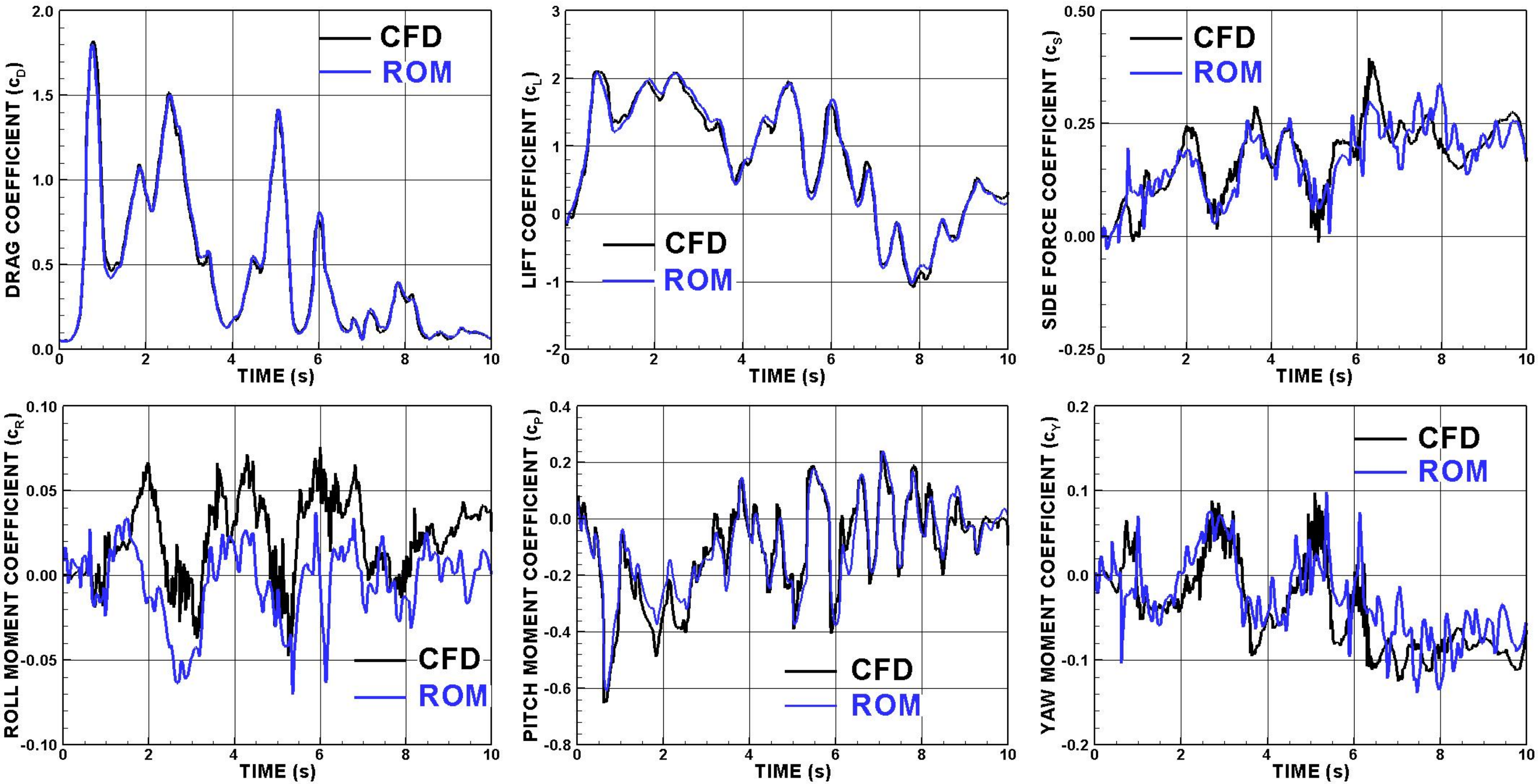
Digital Surrogates

DOD HPC MODERNIZATION PROGRAM

Kestrel

Off-Design Maneuver 1



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Reduced-Order Modeling

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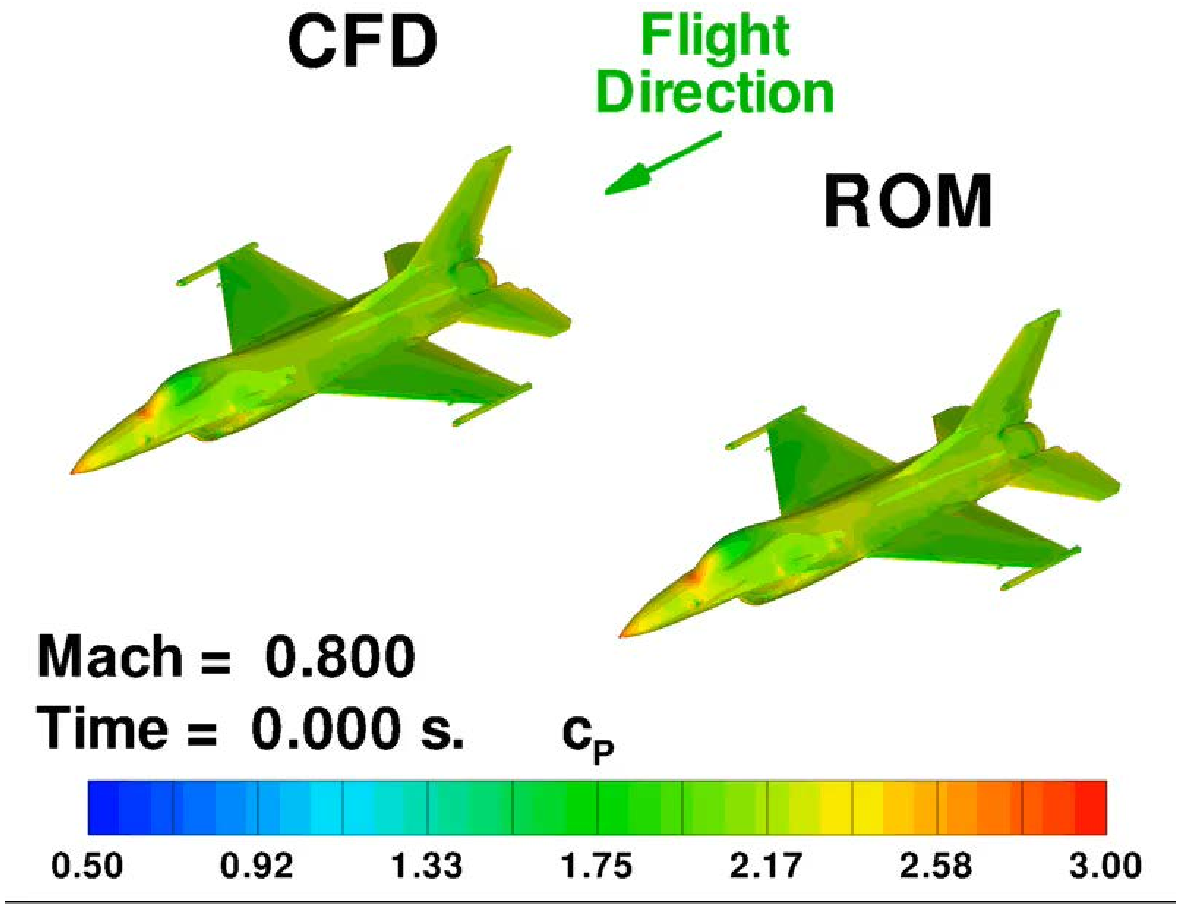
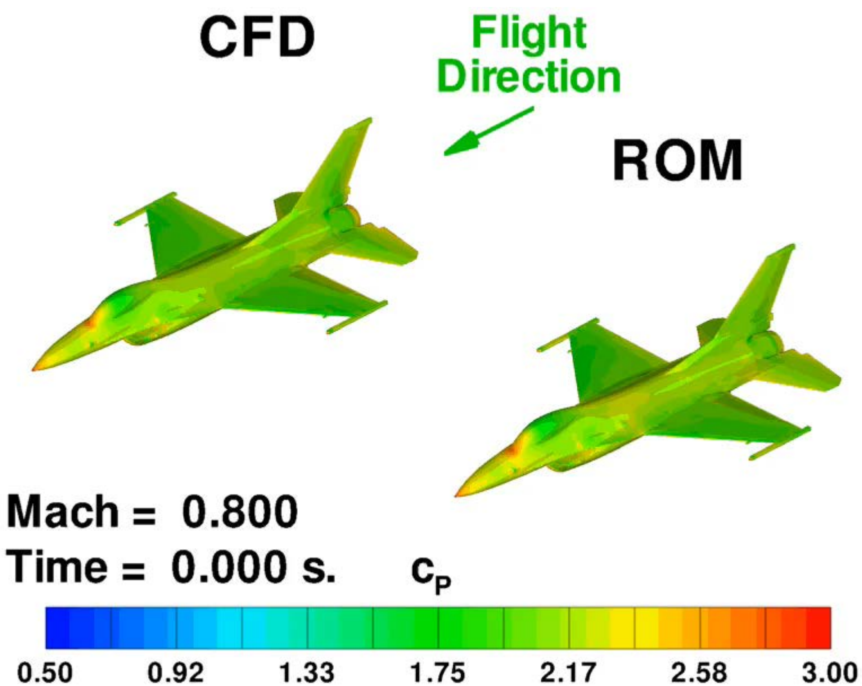
Kestrel

Training Maneuver for ROM Generation

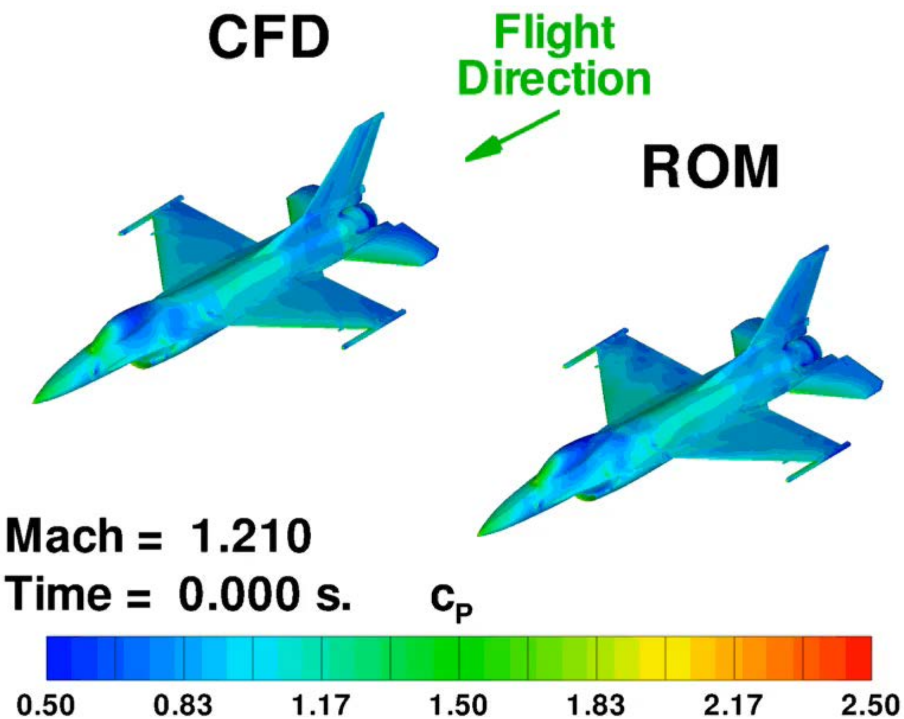


Reduced-Order Modeling

Playback Maneuver 1

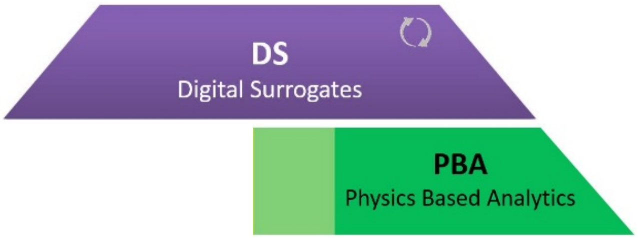


Playback Maneuver 2



Enhanced Surrogates through Data Driven Analytics

- **Surrogates shown up to this point have been based on PBA**



Enhanced Surrogates through Data Driven Analytics

- **Surrogates shown up to this point have been based on PBA**
- **There is also a wealth of information available (E.g. Ground test data, flight test data, fleet maintenance data)**

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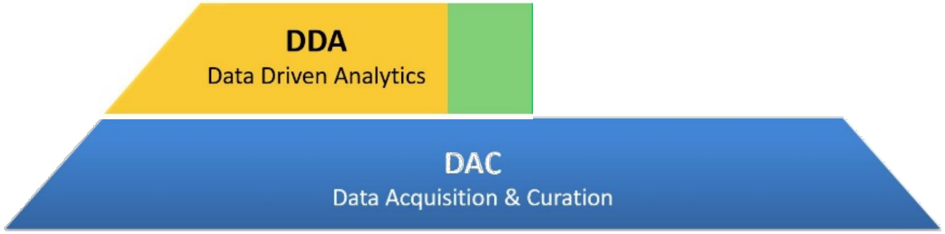

- Data can be curated/analyzed for use in surrogate generation

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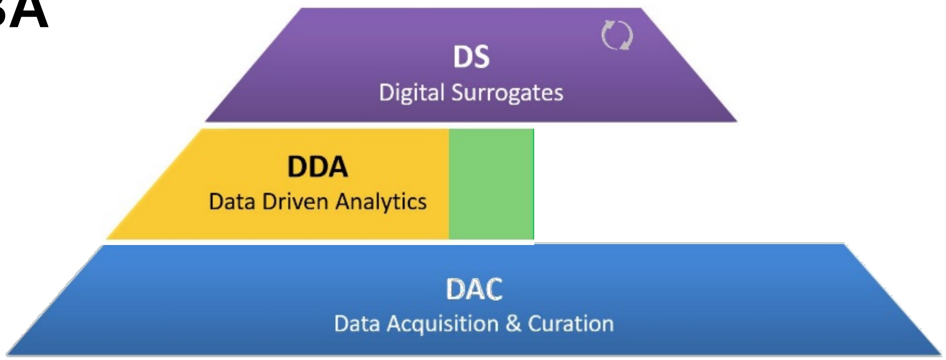
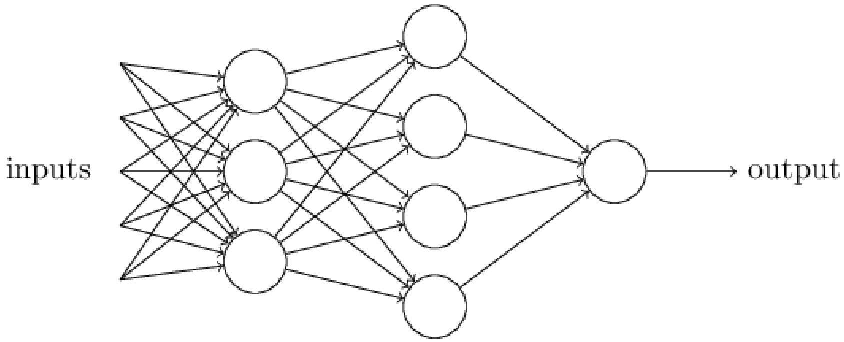
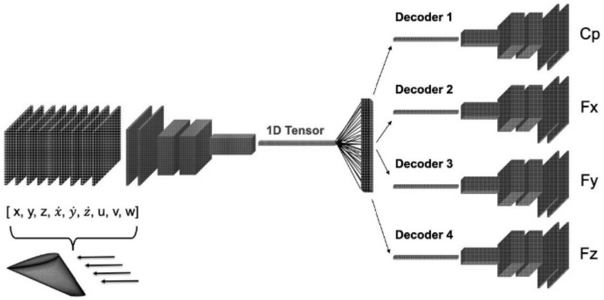


- Data can be curated/analyzed for use in surrogate generation
- Machine Learning/Deep Learning (ML/DL) can be used to create surrogates (requires a significant amount of data)





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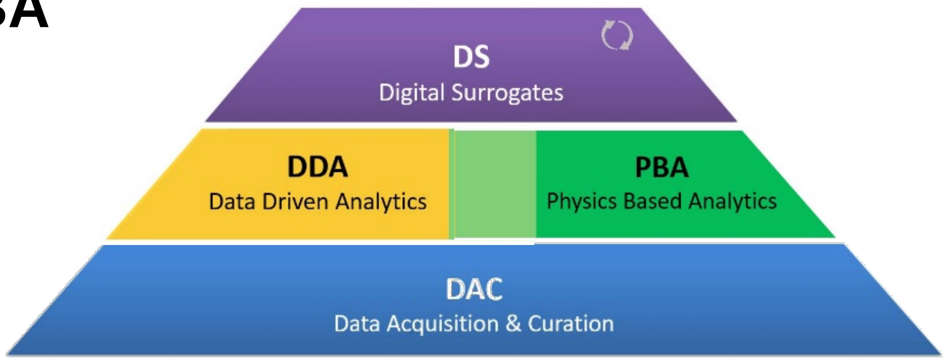
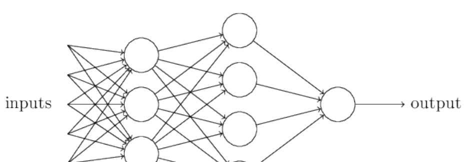
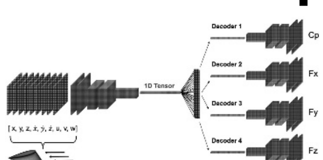


- Data can be curated/analyzed for use in surrogate generation
- Machine Learning/Deep Learning (ML/DL) can be used to create surrogates (requires a significant amount of data)
- The most powerful surrogates are “constrained” by the physics to create a combined DDA/PBA surrogate that accounts for the un-modeled physics/tail number specifics





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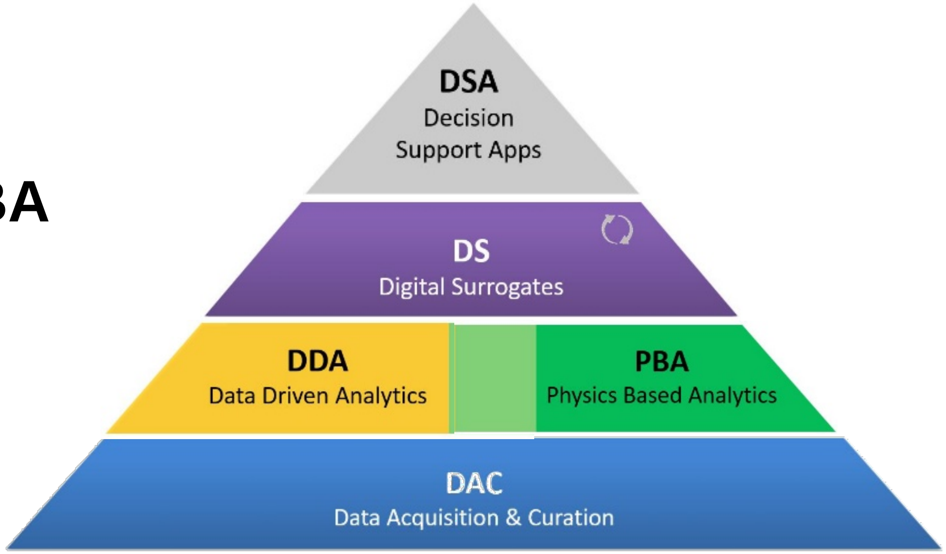
Enhanced Surrogates through Data Driven Analytics



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- **Machine Learning/Deep Learning (ML/DL) can be used to create surrogates (requires a significant amount of data)**
- **The most powerful surrogates are "constrained" by the physics to create a combined DDA/PBA surrogate that accounts for the un-modeled physics/tail number specifics**
- **Decision Support Apps can be built on this foundation of DDA/PBA – Mission Analysis, Structural Failure Analysis, etc.**

Concluding Remarks and Discussion

- The Physics Based Digital Engineering (PBDE) vision, such as described here, is the inevitable progression of technology (viz., high performance computing, physics, data analytics, and software engineering)
- The union of Machine Learning and Digital Surrogate Training via Physics-Based virtual test is what will deliver decision support data at the speed of relevance
- Machine Learning and Physics-Based virtual test both require HPC resources that can be reliably delivered by the HPC Modernization Program
- This PBDE vision can be applied to next generation combat air vehicle development through its Life-Cycle and specific examples have been shown
- Decision Support App software based on physics and system data can be pushed UP the leadership chain to aid in fast, accurate, decision making with high impact

Acknowledgements

- **Material presented in this presentation is a product of the CREATE-AV element of the Computational Research and Engineering for Acquisition Tools and Environments (CREATE) Program sponsored by the U.S. Department of Defense HPC Modernization Program Office**
- ***Huge*** **thanks to Dr. Saikat Dey, the CREATE-AV Development Team, the CREATE-AV Quality Assurance Team, Dr.'s Hal Carlson and Rolf Enger of Clear Sciences Corp. and all of our collaborators for their contributions to this presentation**
- **Thanks to the CREATE Management Team, the 96th Test Wing RNCS/RNCE, and AEDC for their financial management and facility support and the DoD HPCMP DSRC's for their computational resource support**

Questions?