



Comparisons of CFD Solutions of Static and Maneuvering Fighter Aircraft with Flight Test Data

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Overview

Application of CFD to aircraft stability & control (S&C)

- Background
- Air Force SEEK EAGLE Office (AFSEO)
- The problem...
- Suggested approach
- Examples:
 - Static: F-16XL (CAWAPI) / F-18
 - Maneuvering: F-16C
- Conclusion

Background

- Virtually every new a/c and armament program encounters unexpected S&C problems
 - Current S&C modeling techniques inadequate
 - Complex S&C issues require nonlinear, CFD-in-the-loop simulations with control surfaces modeled
- New CFD methods combined with HPC resources ...
 - address S&C problems that previously were untenable
 - overcome experimental gaps
 - complement experiments
 - result in safer flight testing
 - reduce amount of wind tunnel and/or flight testing



Saab JAS39 "Gripen"



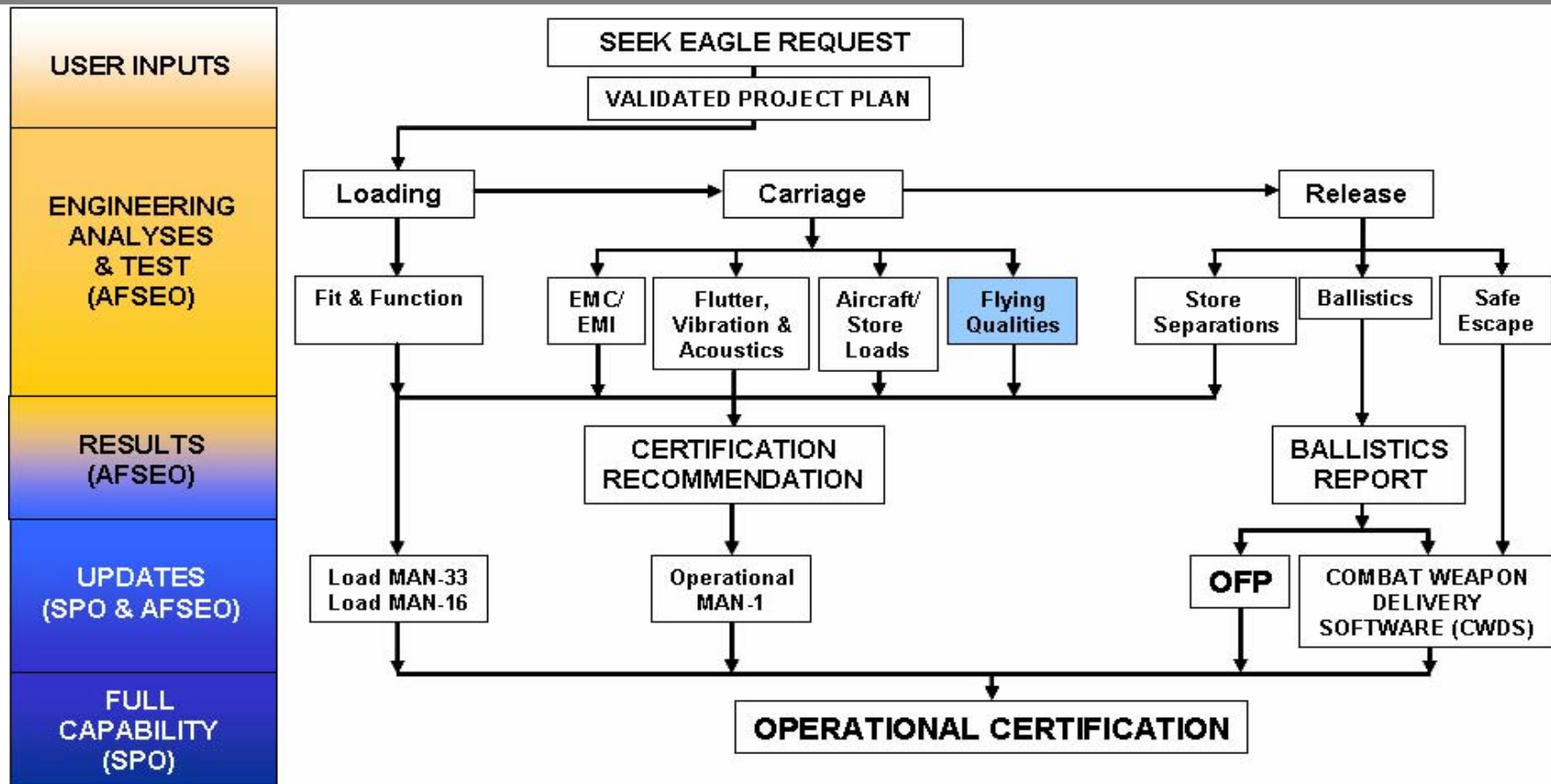
Store separation test

Play

Computational S&C Approaches

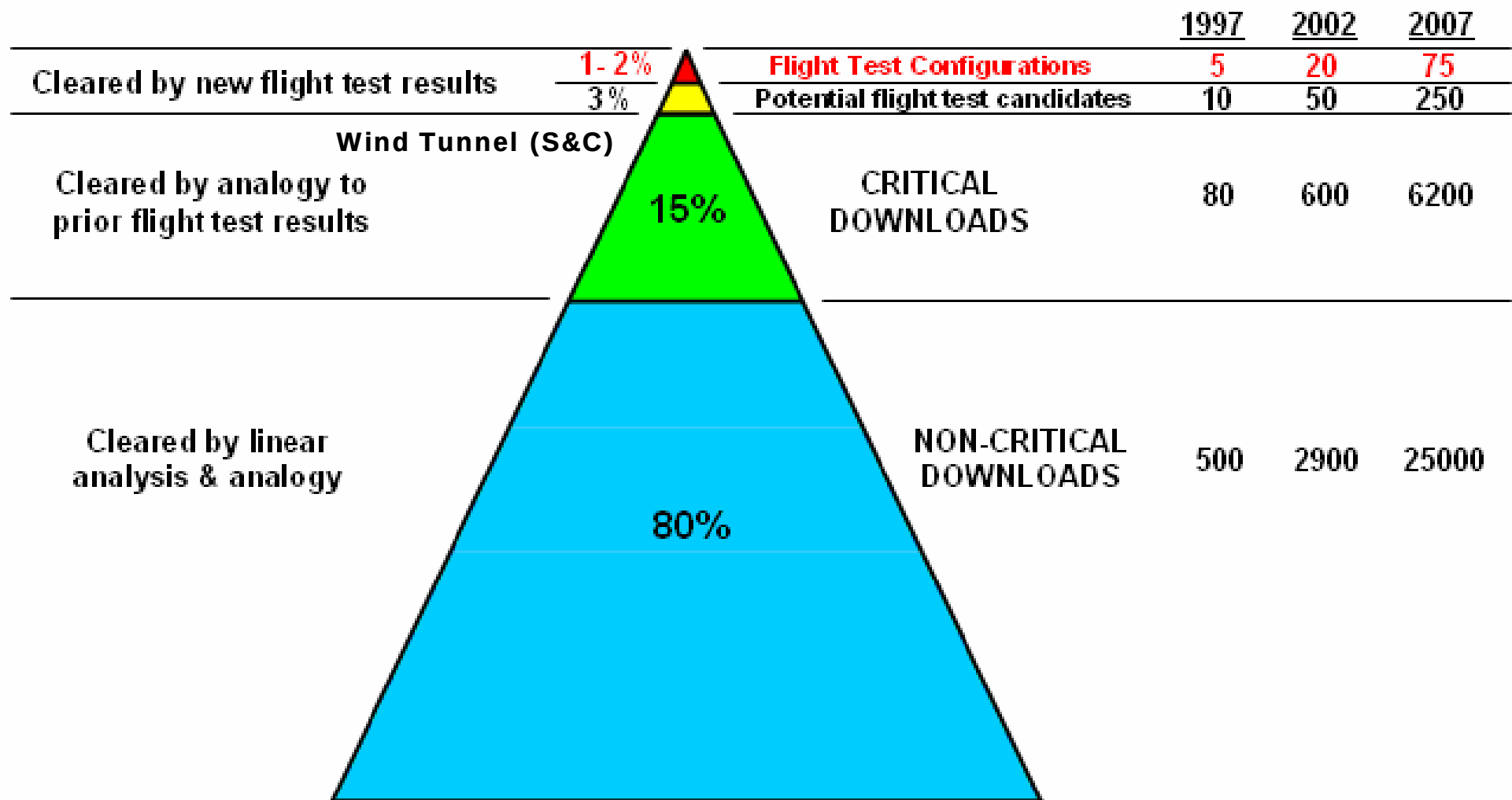
- “Brute-force” approach to filling an aerodynamic database (Murman *et al*, Rogers *et al*)
 - 30,000 solutions → 256 procs/16 mill cells → 158 years
 - Only static data at discrete points
- Data fusion approach (Tang *et al*)
 - Intelligent agents to combine low/high order solutions
- Automated Cartesian-based methods (Murman)
- Reduced-frequency approach to dynamic derivatives (Murman)
- Many, many others...
- New RTO task group → AVT 166

USAF SEEK EAGLE Office (AFSEO)



- The SEEK EAGLE program is the standard for the aircraft-stores certification process for the US Air Force
- Provides Quick Reaction Certifications (QRC), Certification Recommendations (CR), and Flight Clearances (FC)

The AFSEO Problem...



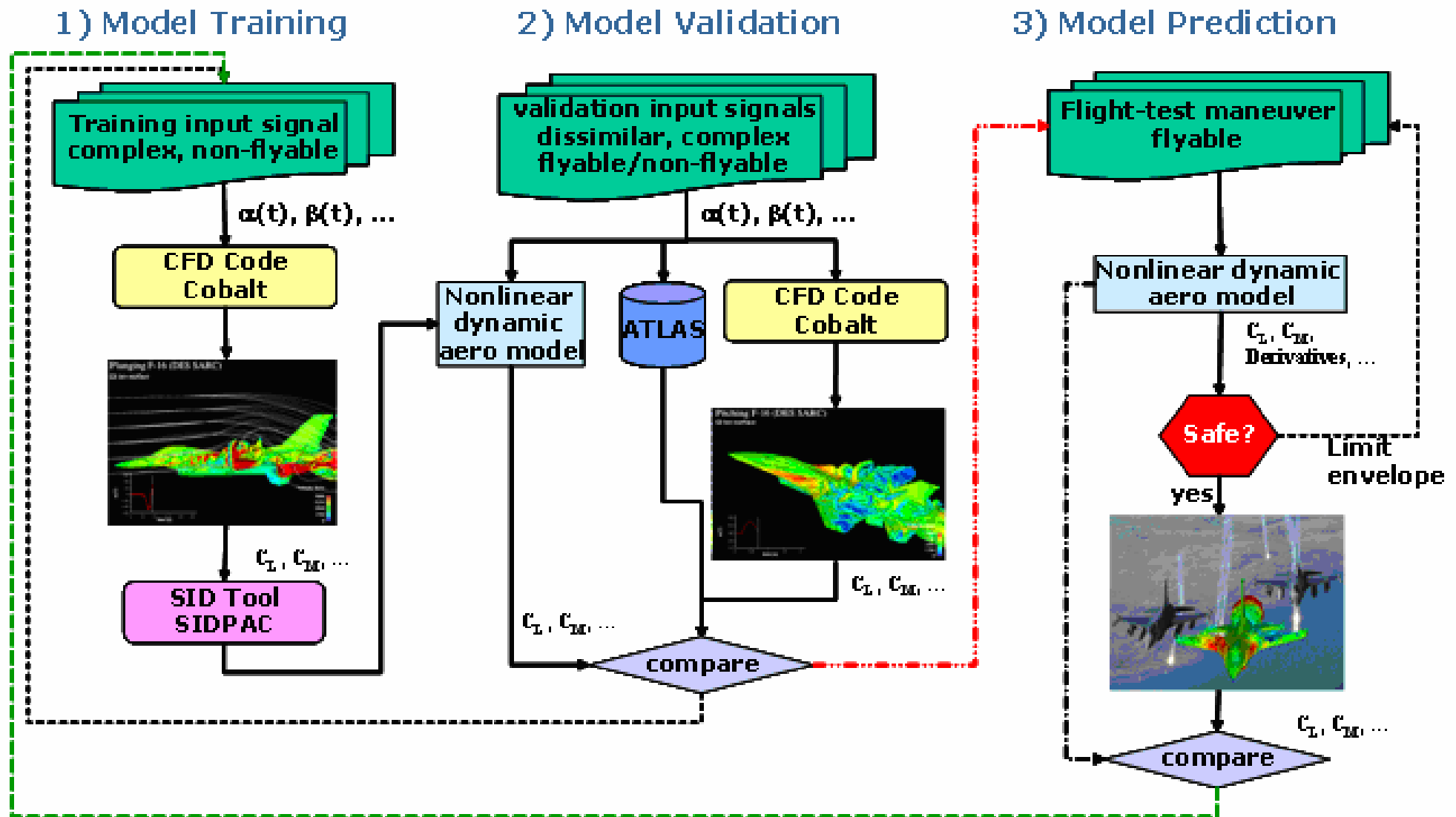
...and Other Issues

- F-16 and F-22 ATLAS aerodynamic database limitations:
 - Limited in the number of configurations
 - Only symmetric configurations available
 - No data for modern stores and suspension equipment
- Unable to predict where instabilities occur in the flight envelope (if at all)
- Long history of flight test programs where lots of \$\$ spent to find absolutely nothing

Suggested Approach

- Focus on specific flight conditions (if possible)
- Simulate closed-loop, full-scale a/c at critical conditions with a single, complex and efficient maneuver (possibly non-flyable)
- Generate nonlinear, dynamic reduced-order models for aerodynamic loads
- Use model for S&C analysis, flight simulation, control system design, etc.
 - Continuous data
 - Derivatives computed analytically
 - Allows SEEK EAGLE Office flexibility to handle **any new configuration** and **independence from contractors**

Suggested Approach



Examples

Flow Solver - *Cobalt*

Numerical Modeling

- Unstructured, cell-centered, finite volume CFD code
- Hybrid grids (arbitrary elements), overset grids
- Space discretization:
 - Godunov's first-order accurate exact Riemann solver
 - Second-order accuracy through least-squares reconstruction
- Time discretization:
 - Point-implicit with Newton sub-iterations for time accuracy
- 6DOF and ALE for rigid body motion

Physical Modeling

- Compressible Euler and NS, laminar and RANS
- Equilibrium air physics
- Turbulence models:
 - Spalart-Allmaras (SA)
 - Mentor's SST
 - Wilcox's 1998 $k-\omega$
 - Detached Eddy Simulation (DES) for S-A and SST
 - Curvature corrections (SARC)

F-16XL

- RTO AVT-113 (CAWAPI)
- Comprehensive validation of CFD methods against available flight test database
- Time-accurate DES calculations at full-scale flight Reynolds numbers



Morton, S.A., McDaniel, D.R., and Cummings, R.M., "F-16XL Unsteady Simulations for the CAWAPI Facet of RTO Task Group AVT-113," AIAA Paper 2007-0493, Jan. 2007.

F-16XL (CAWAPI)

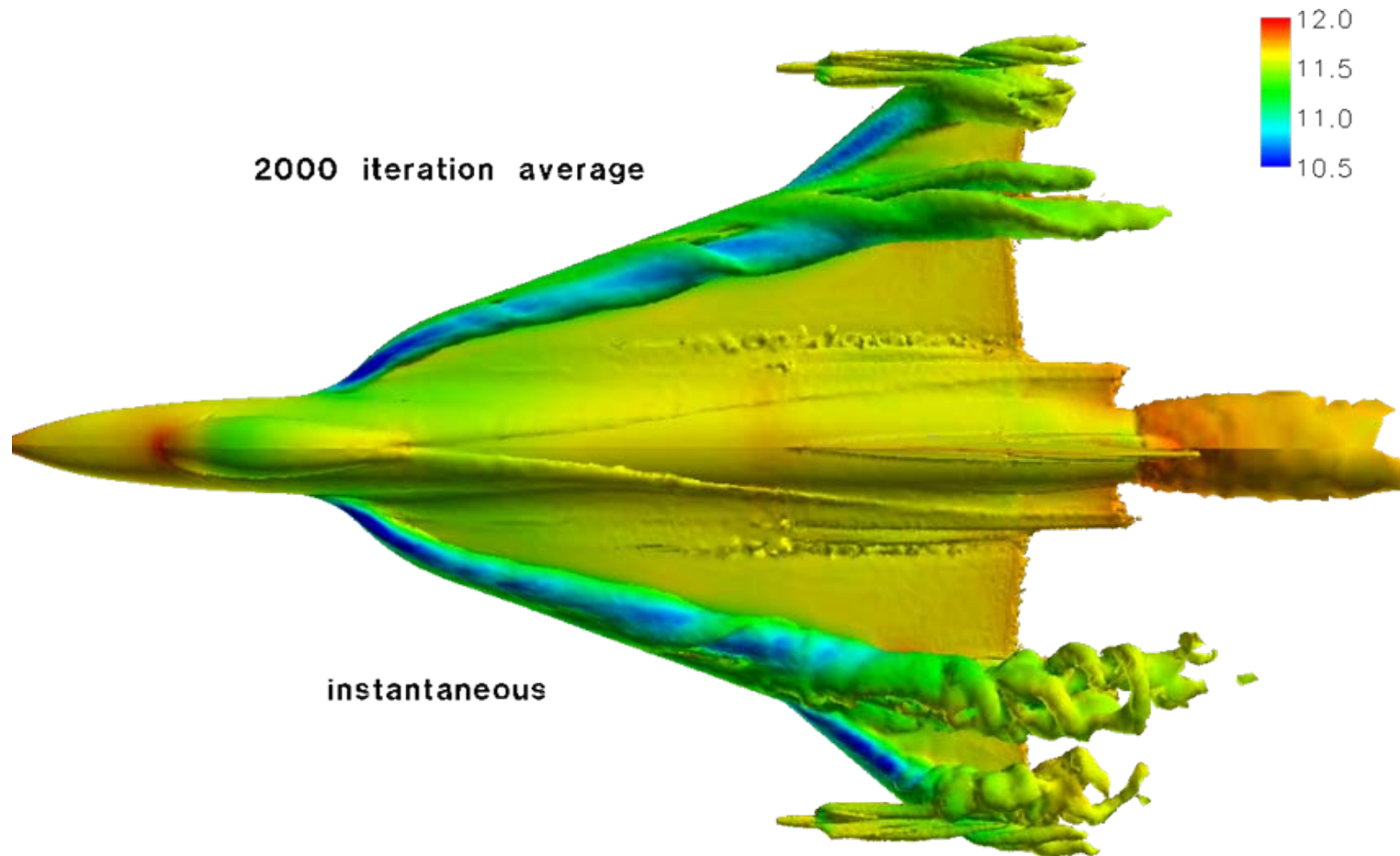
F-16XL SARCDES Solution at FC7

Alpha = 11.89 deg

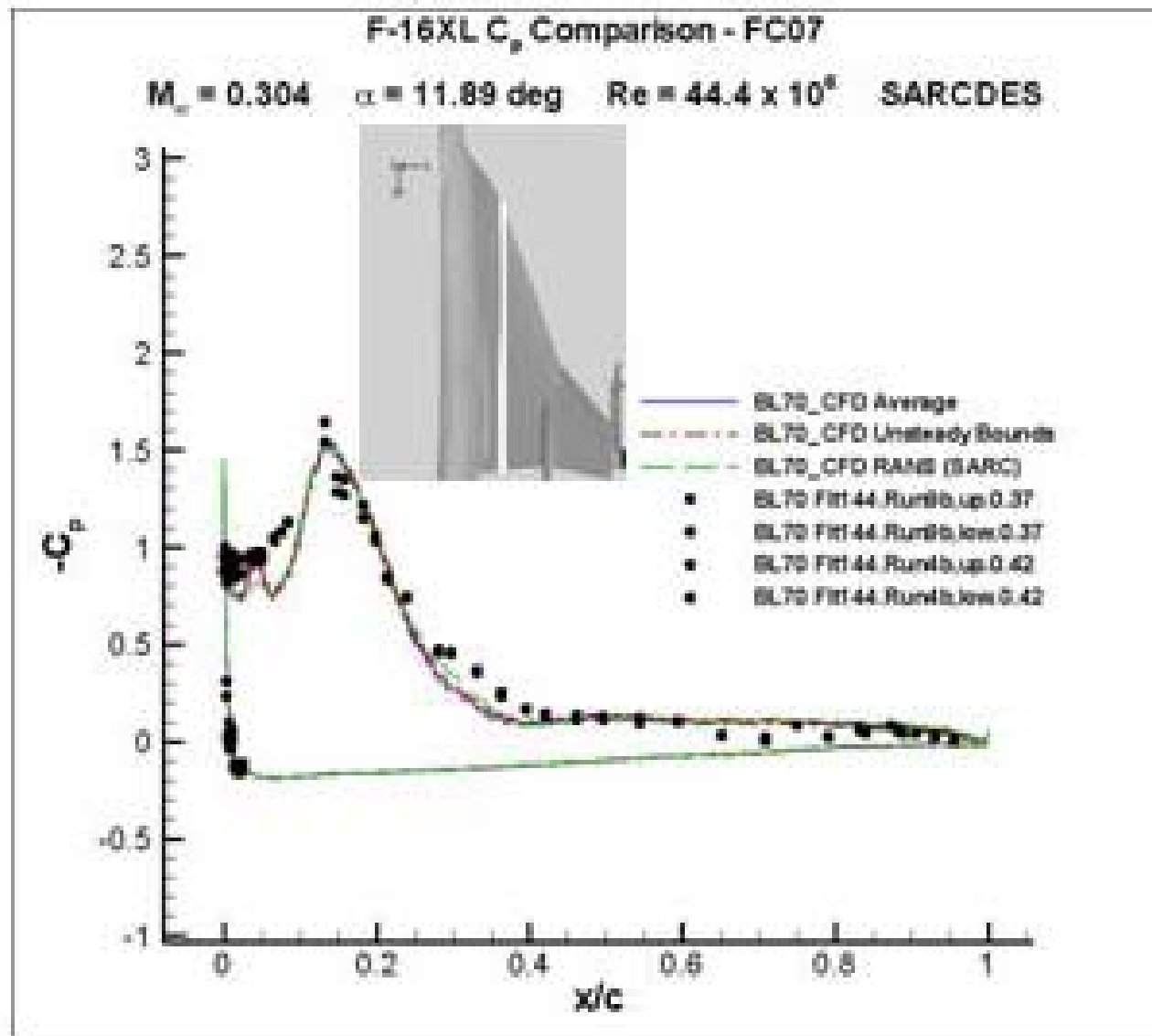
Mach = 0.304

Re# = 44.4E6

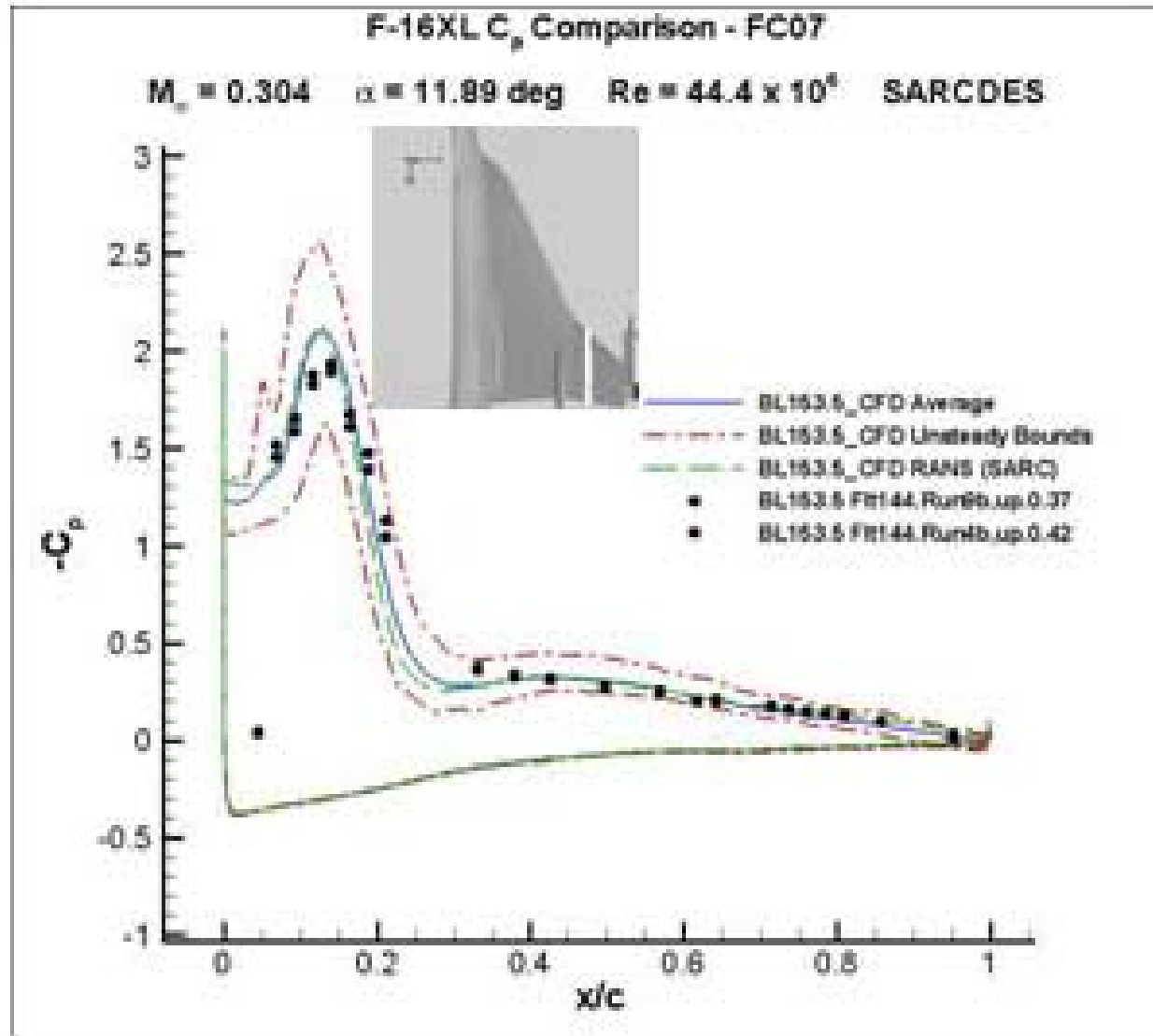
Vorticity Magnitude Iso-Surface (250 1/sec) Colored By Pressure (psi)



F-16XL (CAWAPI)

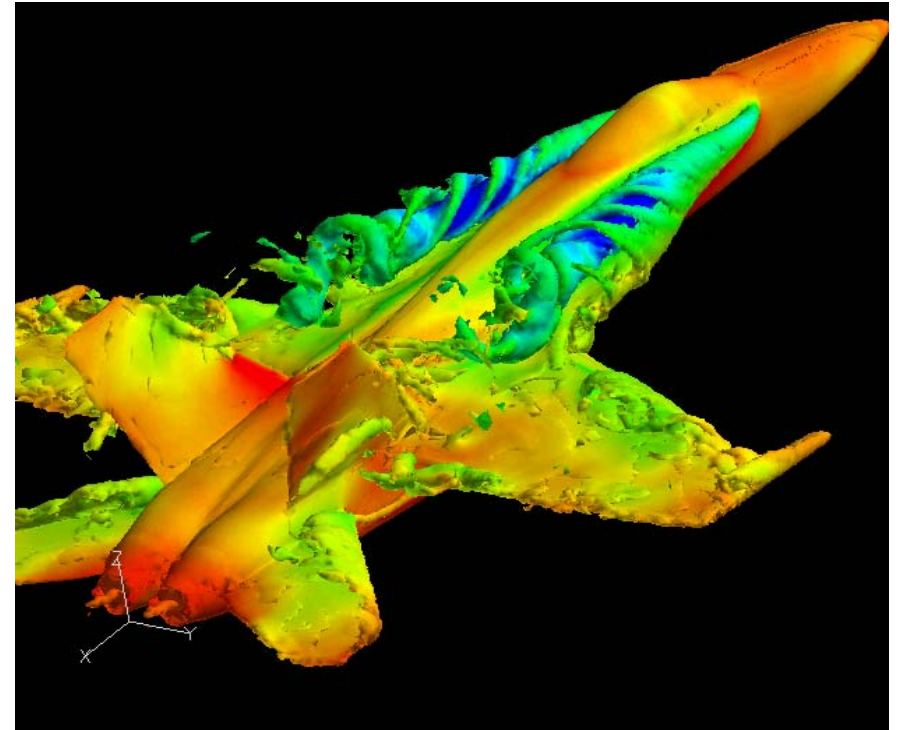


F-16XL (CAWAPI)



F-18C (HARV)

- High Angle of Attack Research Vehicle (HARV) – NASA-Dryden
- Rich source of flow viz, surface pressures, and aeroelastic data
- Numerical investigation to try and accurately predict flow impinging on vertical tails ($M=0.28$, $Re\#=13E6$, $\alpha=30$ deg)

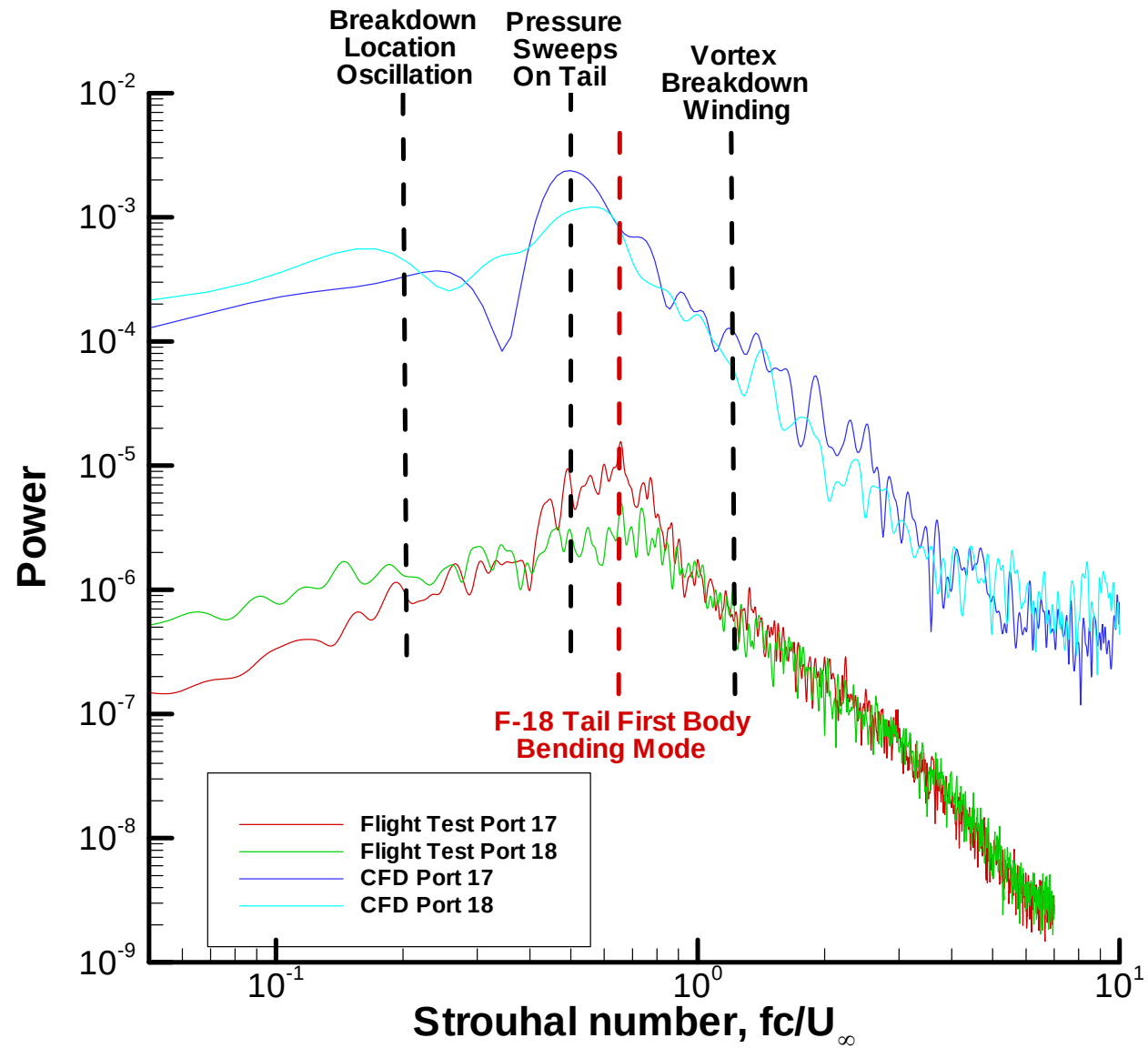


Morton, S.A., Cummings, R.M., and Kholodar, D.B., "High Resolution Turbulence Treatment of F/A-18 Tail Buffet," AIAA Paper 2004-1676, April 2004.

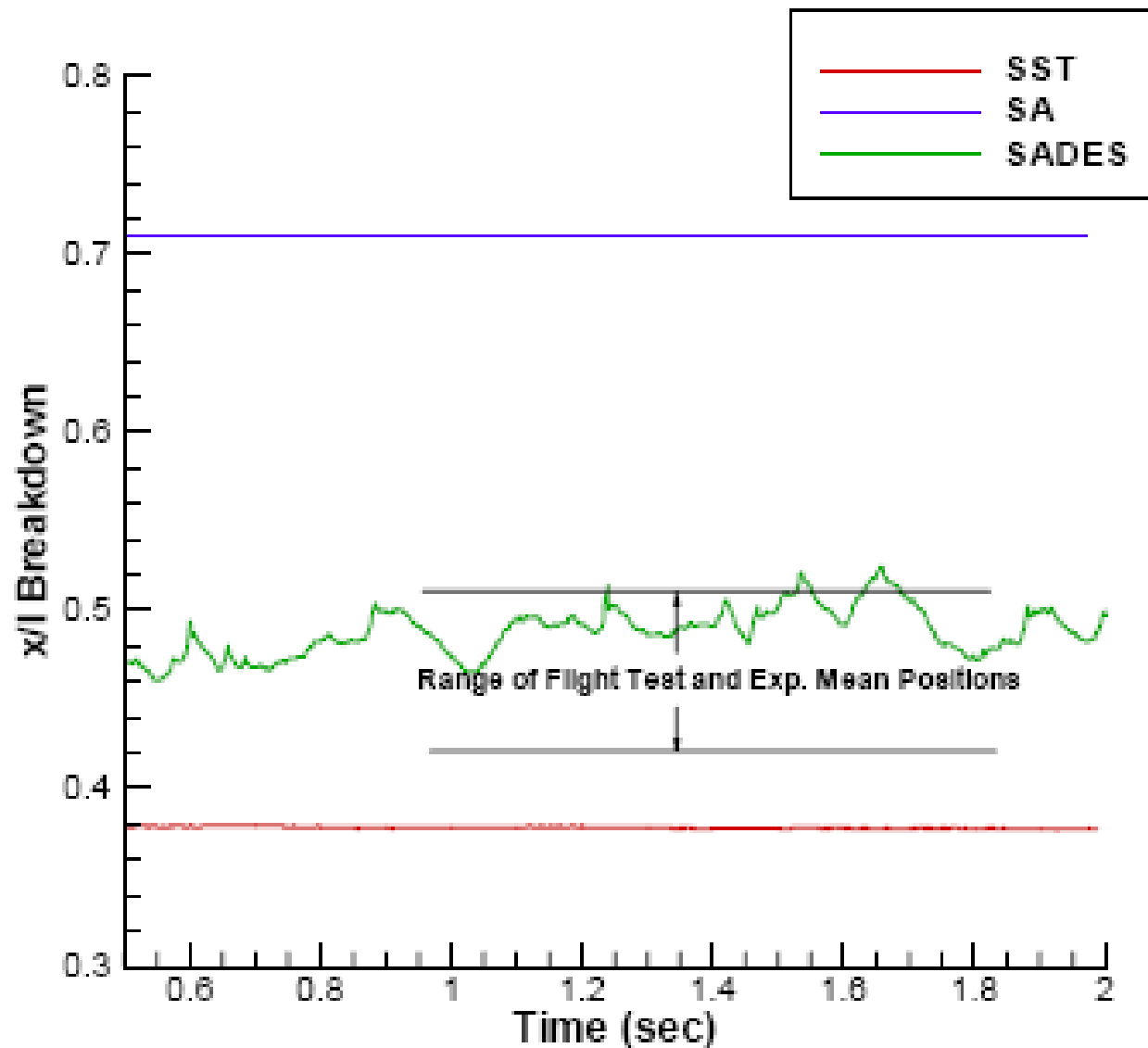
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F-18C (HARV)

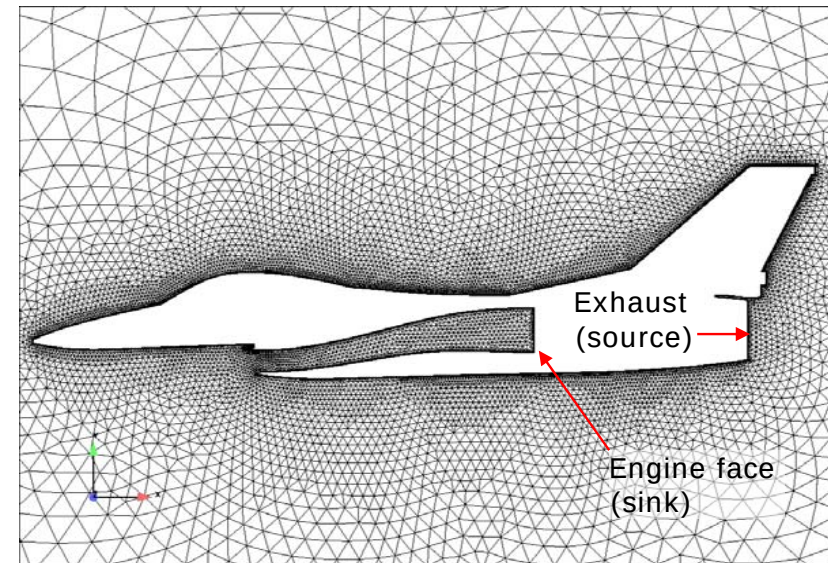
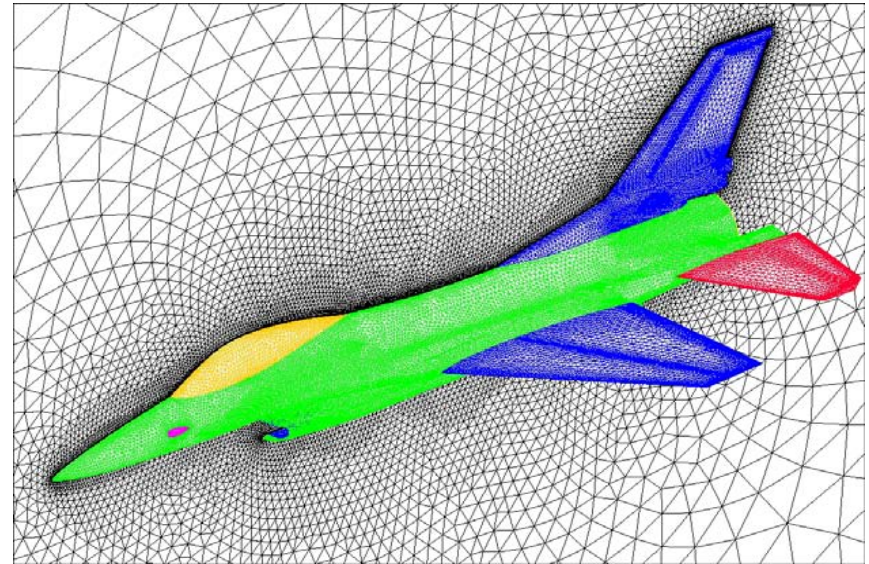


F-18C (HARV)



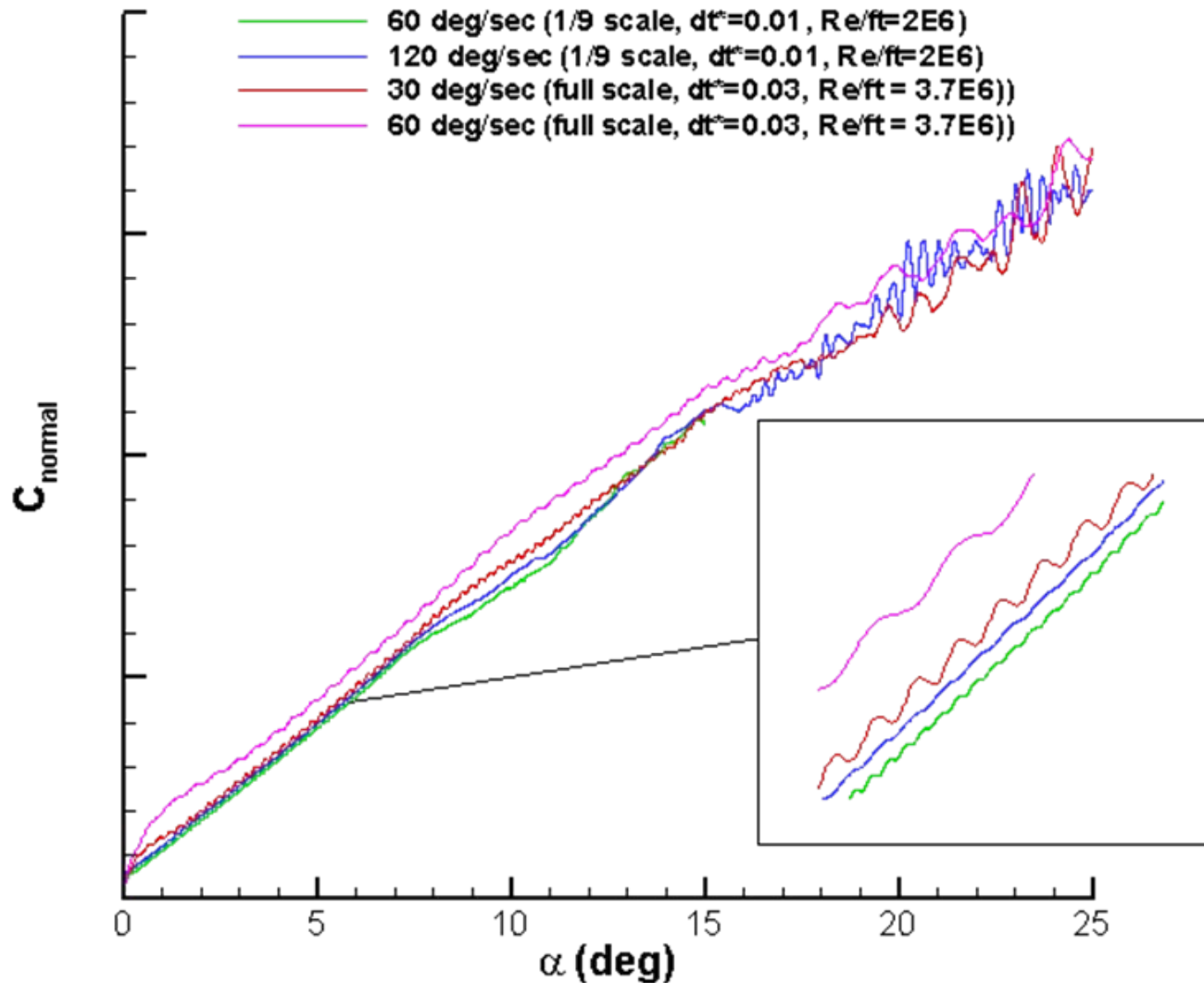
Full-Scale F-16C Motion Simulations

- Half-span grid with 3.4×10^6 cells and prismatic layers
- Cells concentrated in the strake vortex
- Forebody bump, diverter, ventral fin modeled
- Engine mass flow modeled
- Flow conditions:
 - $M_\infty = 0.25/0.60$
 - $Re = 14.7 \times 10^6 / 42 \times 10^6$
- Numerical parameters:
 - $\Delta t = 0.0004s / 0.0002s$ ($\Delta t^* = 0.01$)
 - 5 Newton sub-iterations
 - DES based on SA with RC



α -Sweeps & Dynamic Scale Effects

- Angle of attack sweeps at various pitch rates



Aircraft System Identification (SID)

- Normally applied to flight-test data to generate aerodynamic models (assumed time-invariant)
- Can use SID techniques to analyze CFD data computed for aircraft in prescribed motion
- **S**ystem **I**dentification **P**rograms for **A**ircraft (SIDPAC) by Klein/Morelli at NASA-Langley



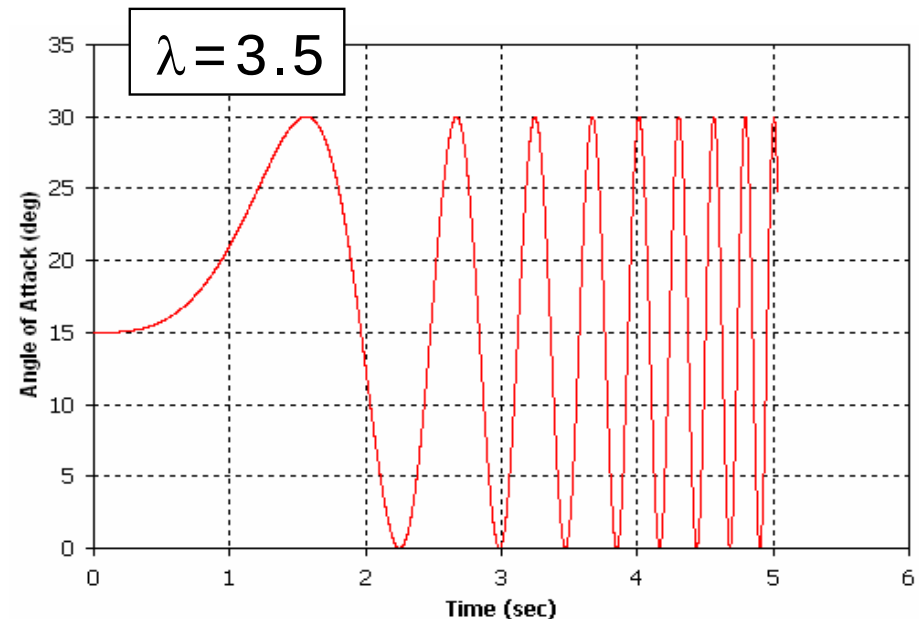
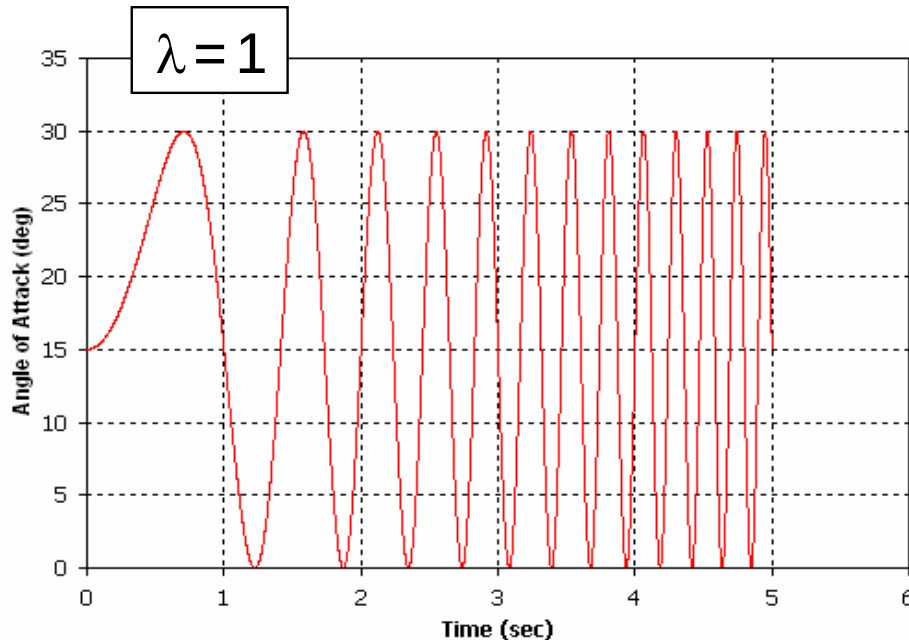
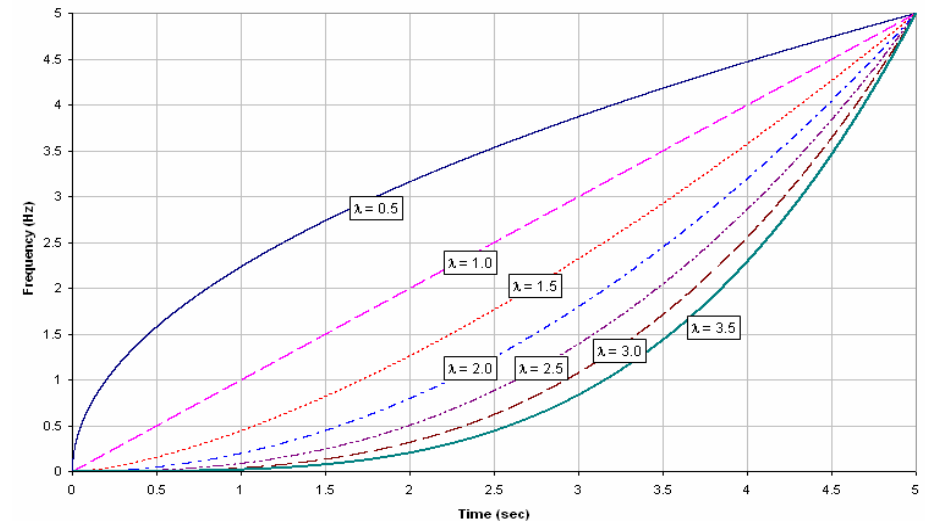
Pitch Chirp Training Maneuver

- Chirp Training Maneuver:

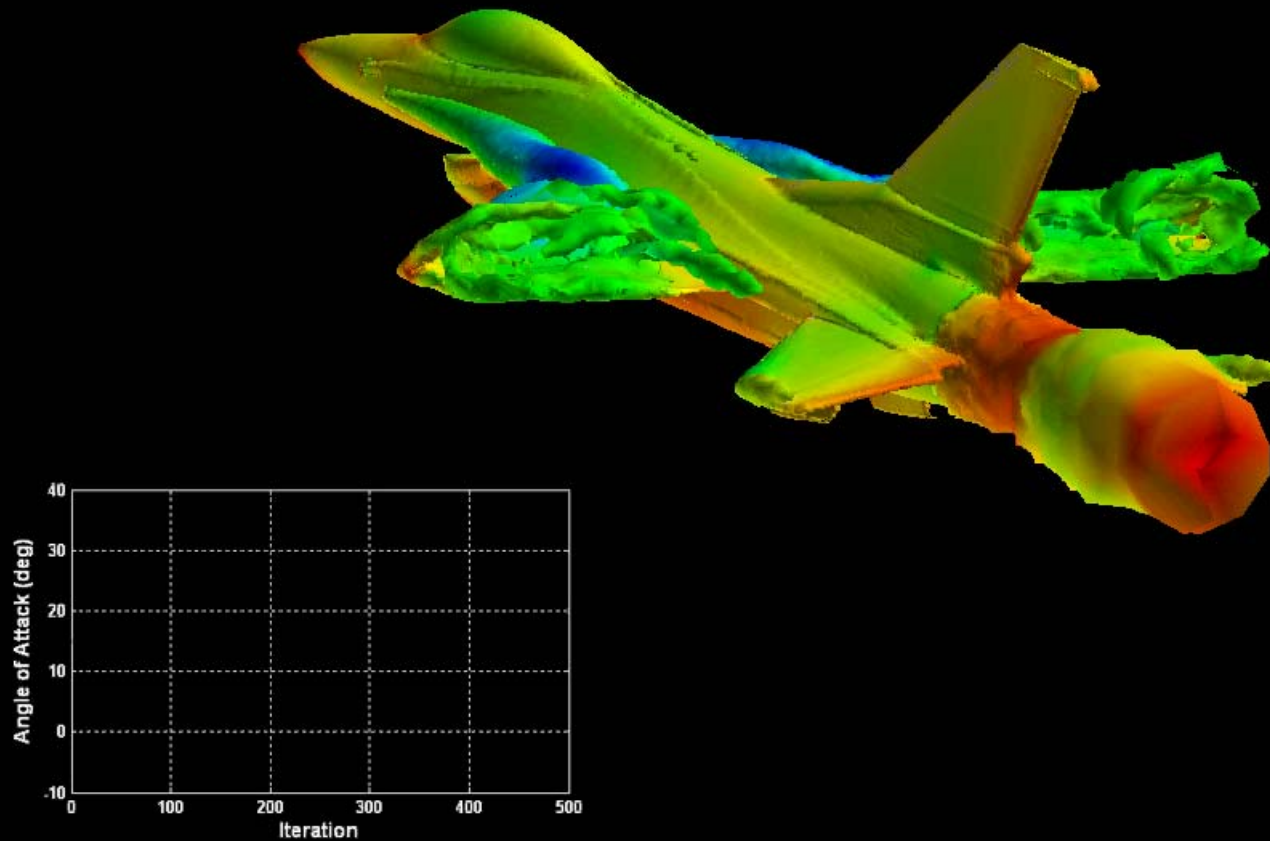
$$s(t) = \cos\left(2\pi\left(\frac{\beta}{\lambda+1}t^{\lambda+1} + f_1t + \frac{\phi}{360}\right)\right)$$

$$\beta = \left(\frac{f_2 - f_1}{t_2^\lambda}\right)$$

- Vary λ to dwell on the lower frequencies to capture static behavior



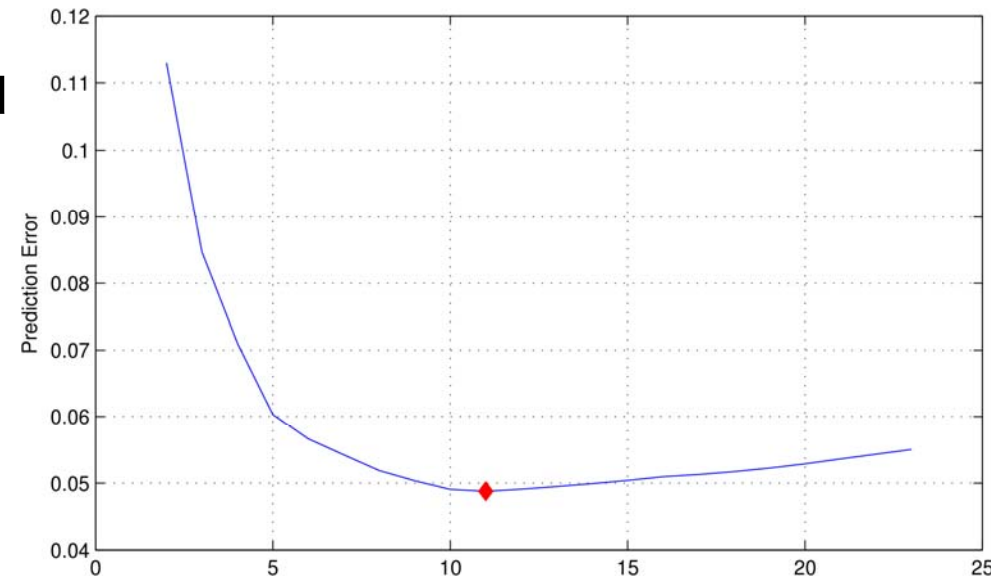
Pitch Chirp ($\lambda=1.0$)



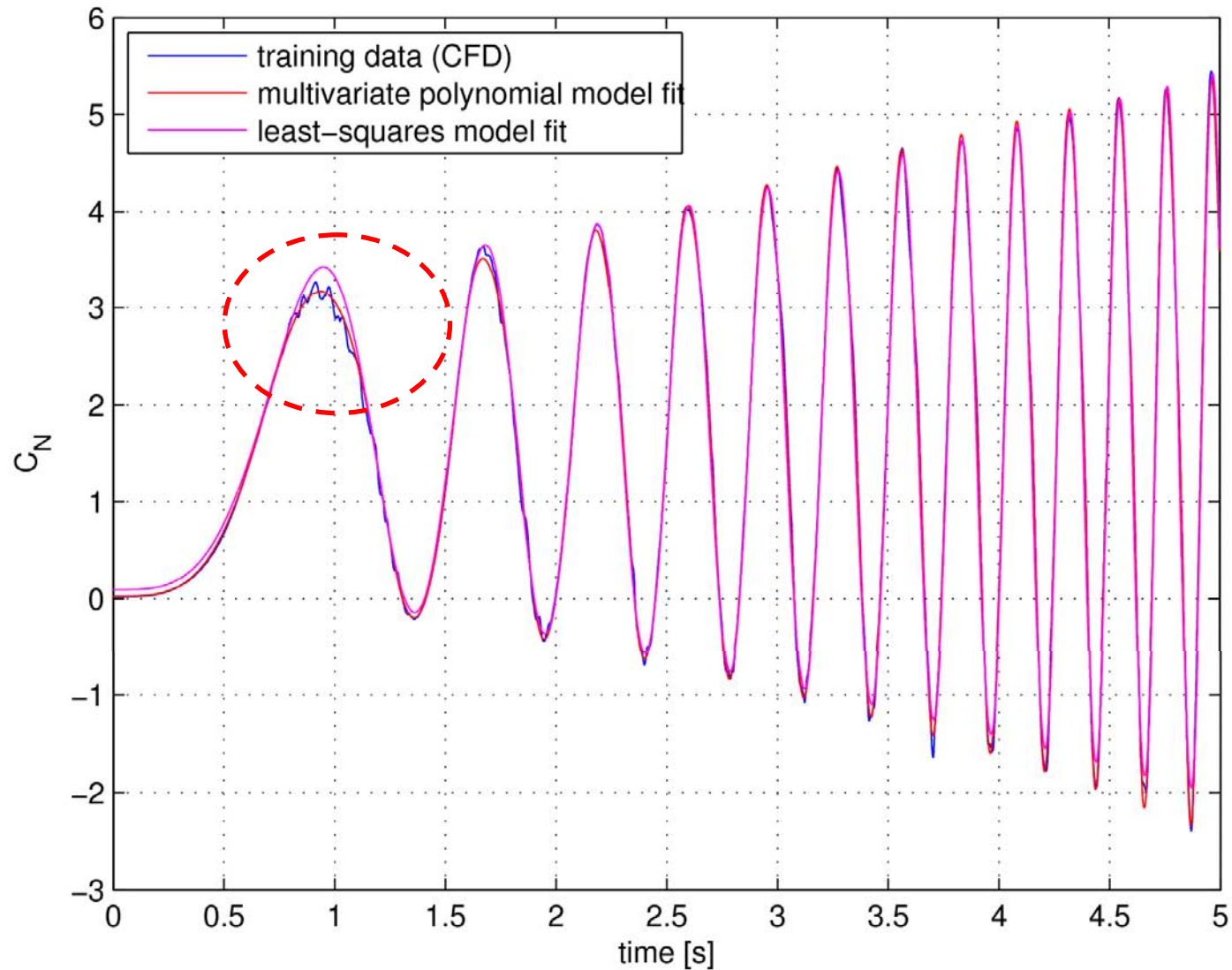
Play

SID of Pitch Chirp

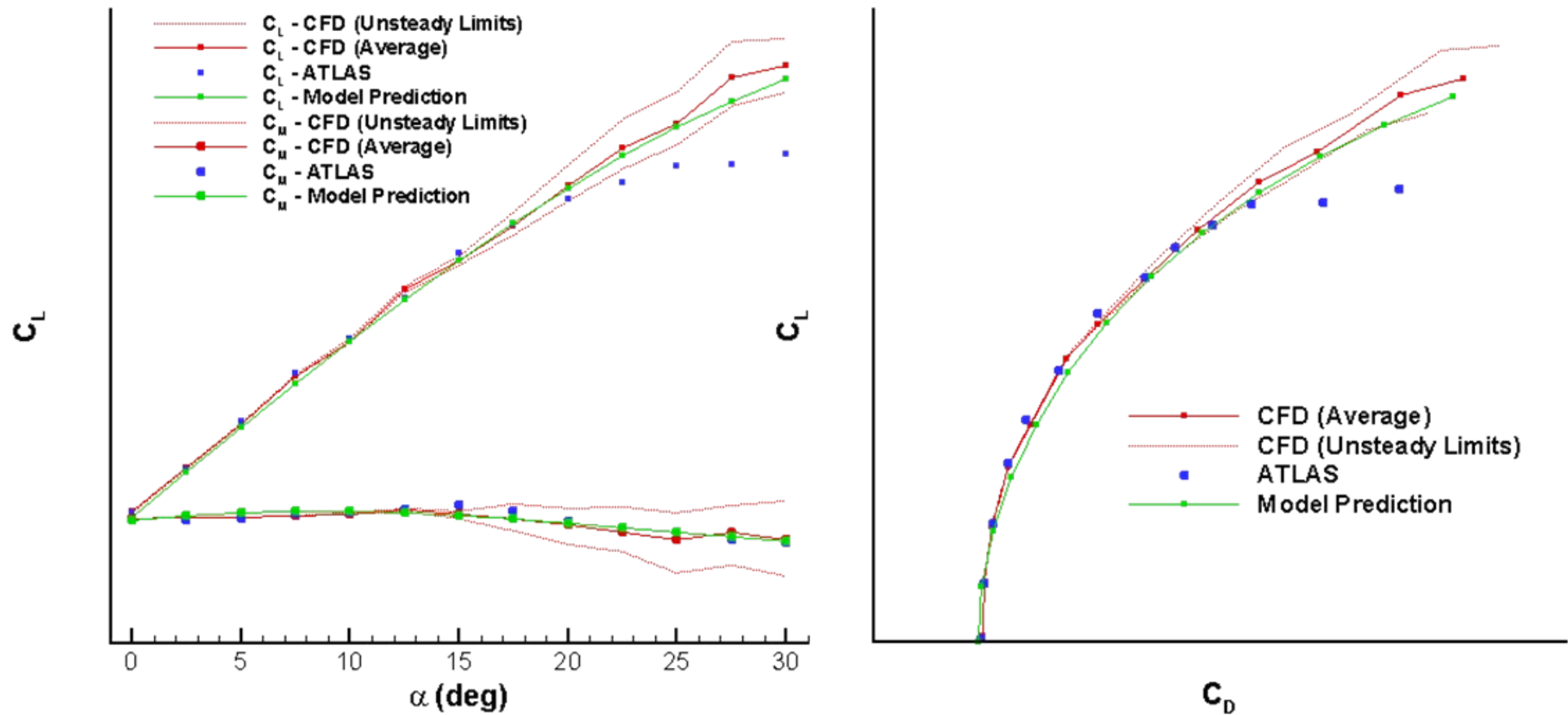
1. Least-squares linear model: $C_{N_{\text{lesq}}} = C_0 + C_{N_\alpha} \alpha + C_{N_q} q + C_{N_{\dot{q}}} \dot{q}$
2. Nonlinear multivariate polynomial model: $C_{N_{\text{mof}}} = C_0 + C_1 \alpha + C_2 q + C_3 \dot{q} + \dots$
 $+ C_4 \alpha^2 + C_5 \alpha^4 + C_6 \alpha q^2 + C_7 \alpha \dot{q} + \dots$
 $+ C_8 q \dot{q} + C_9 q^2 \dot{q} + C_{10} q^3 + C_{11} \dot{q}^2$
 - Model structure determined using multivariate orthogonal functions generated by Gram-Schmidt orthogonalization, ordered by dynamic programming
 - Retained modeling functions expanded into ordinary multivariate polynomial
 - Parameters estimated using maximum likelihood technique



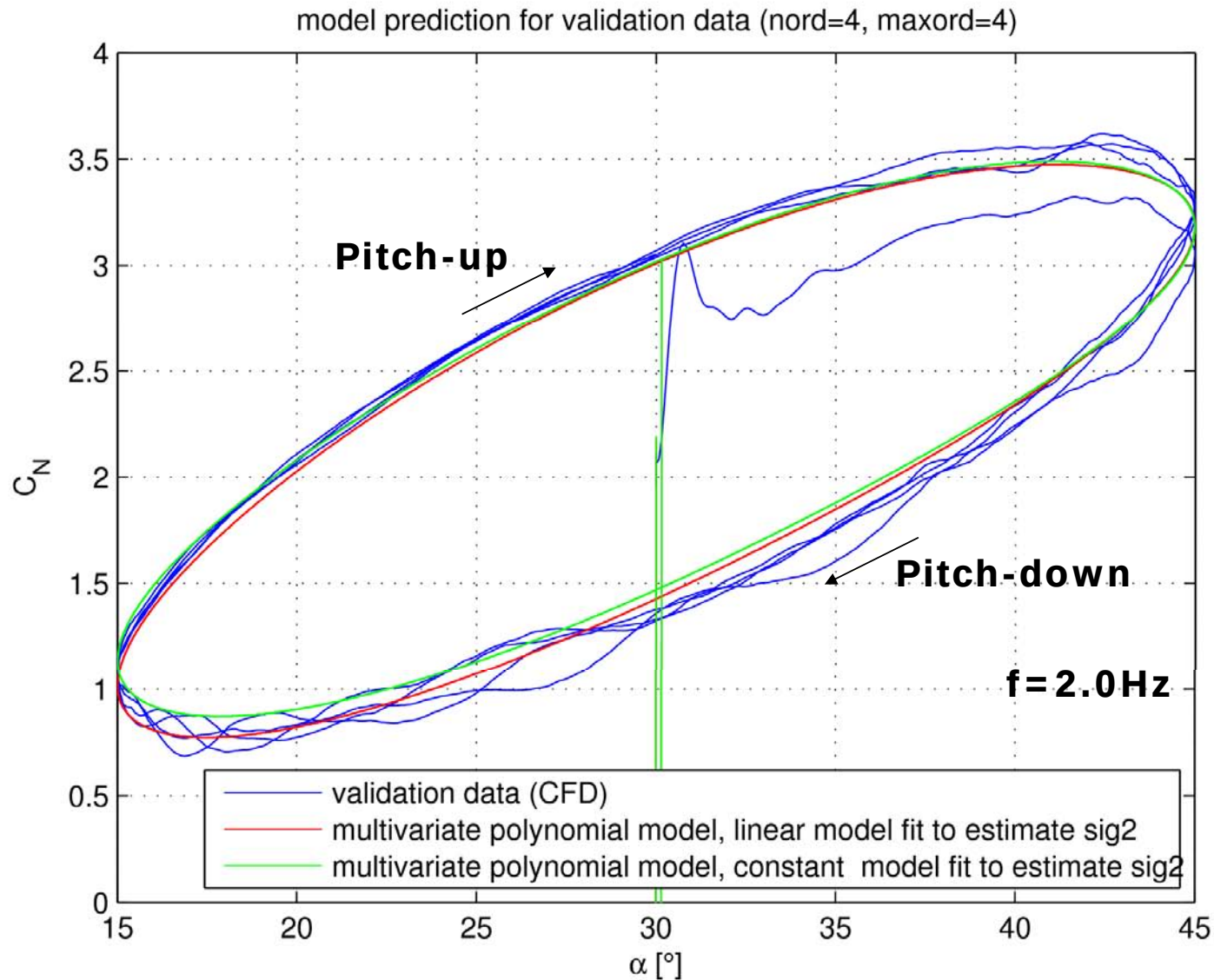
System ID of Pitch Chirp



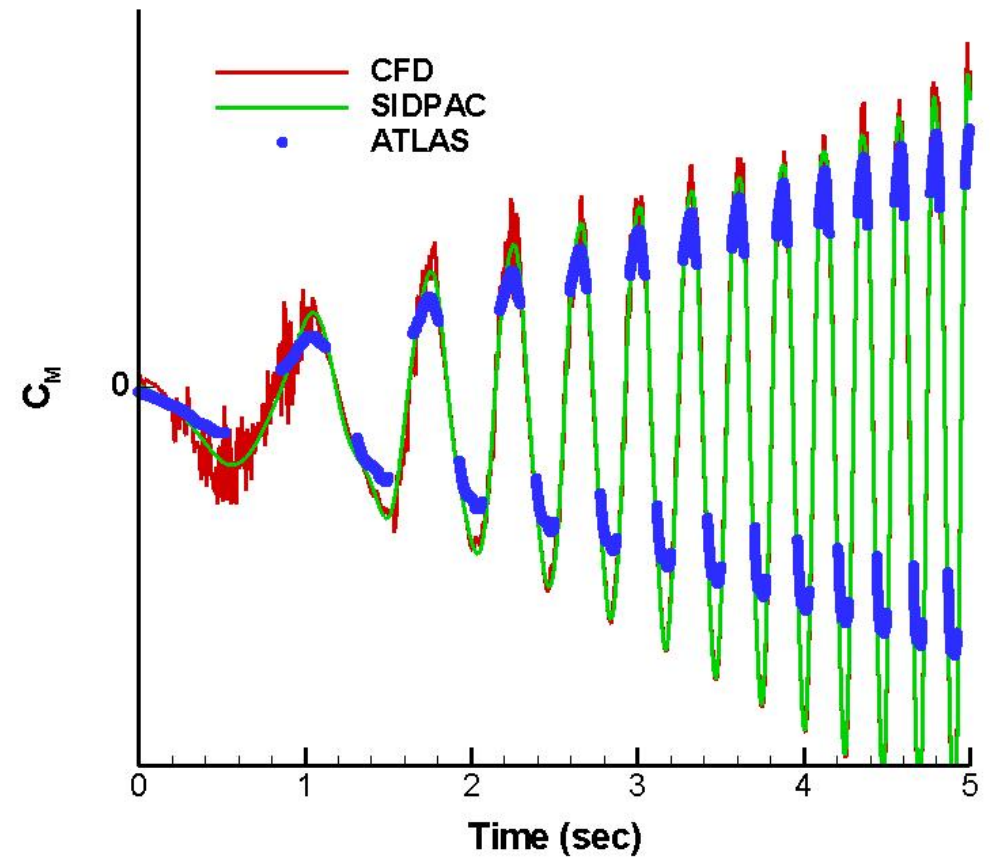
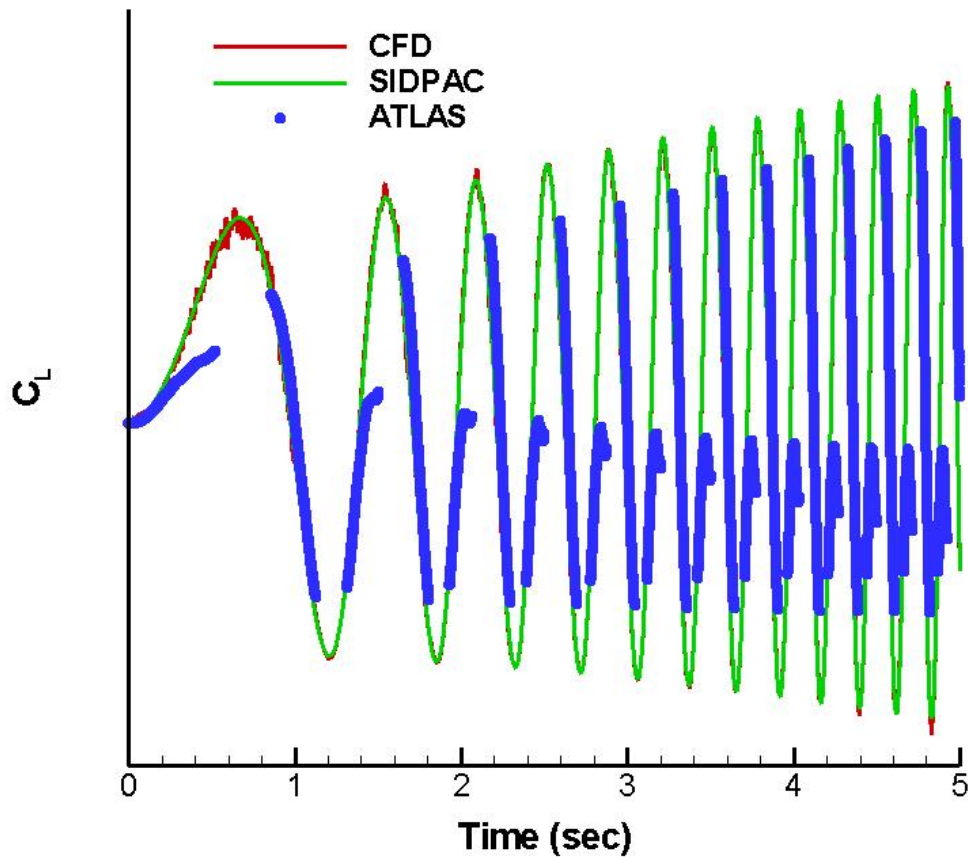
Static Validation vs. CFD / ATLAS



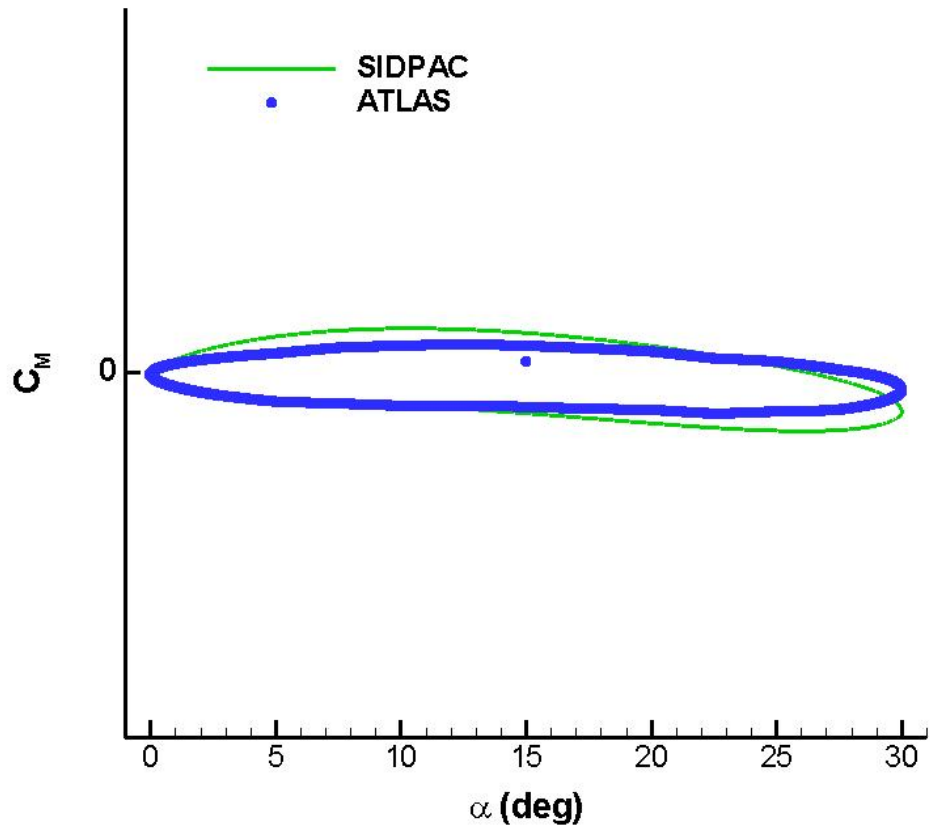
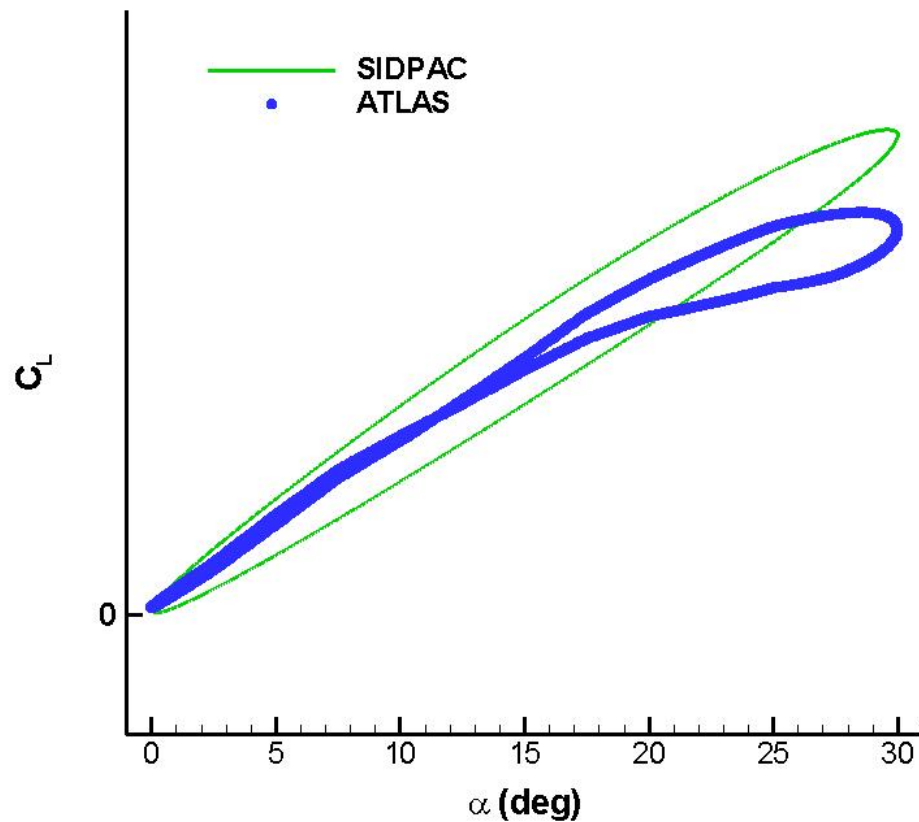
Dynamic Validation vs. CFD



Dynamic Validation vs. ATLAS

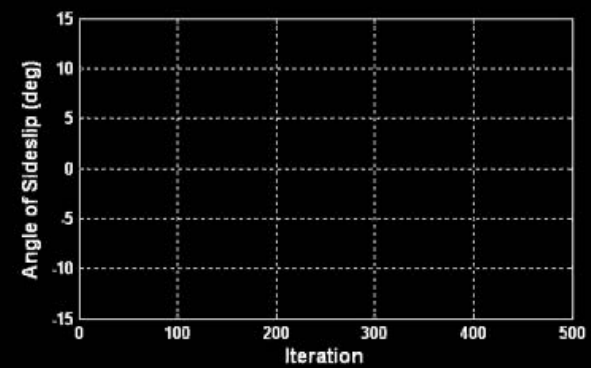
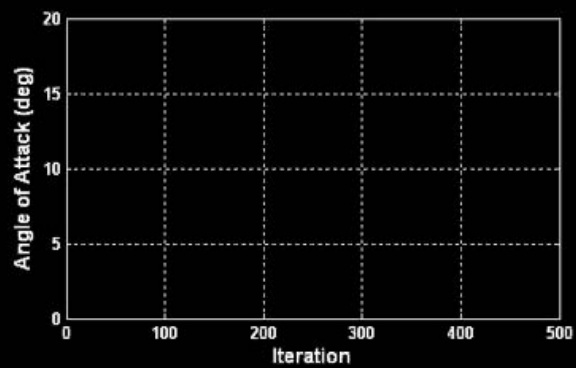


Dynamic Validation vs. ATLAS



1 Hz pitch oscillation about $\alpha = 15$ deg

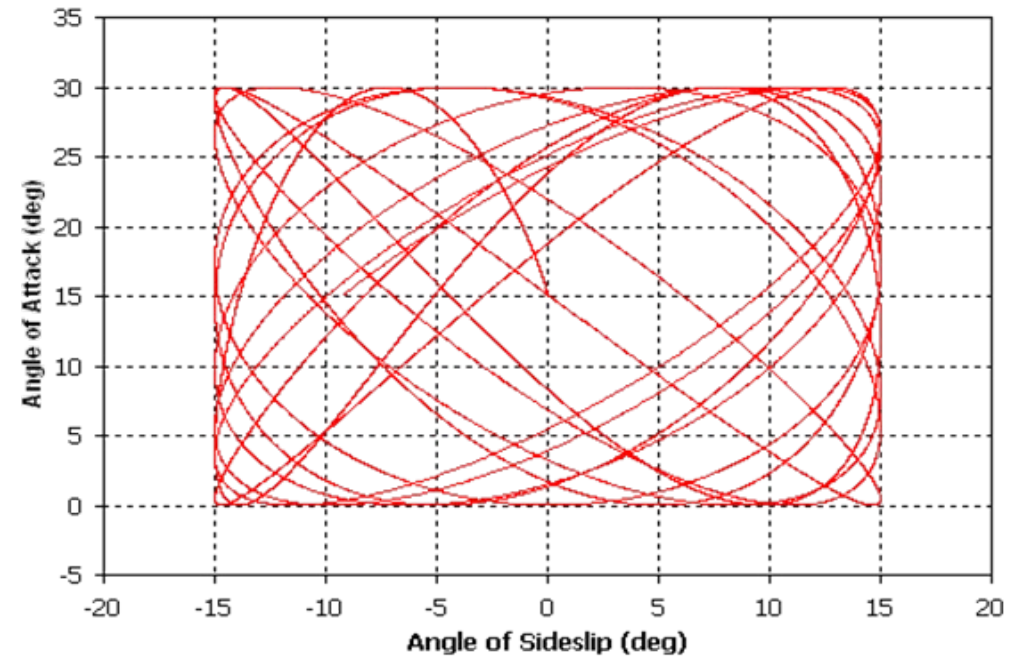
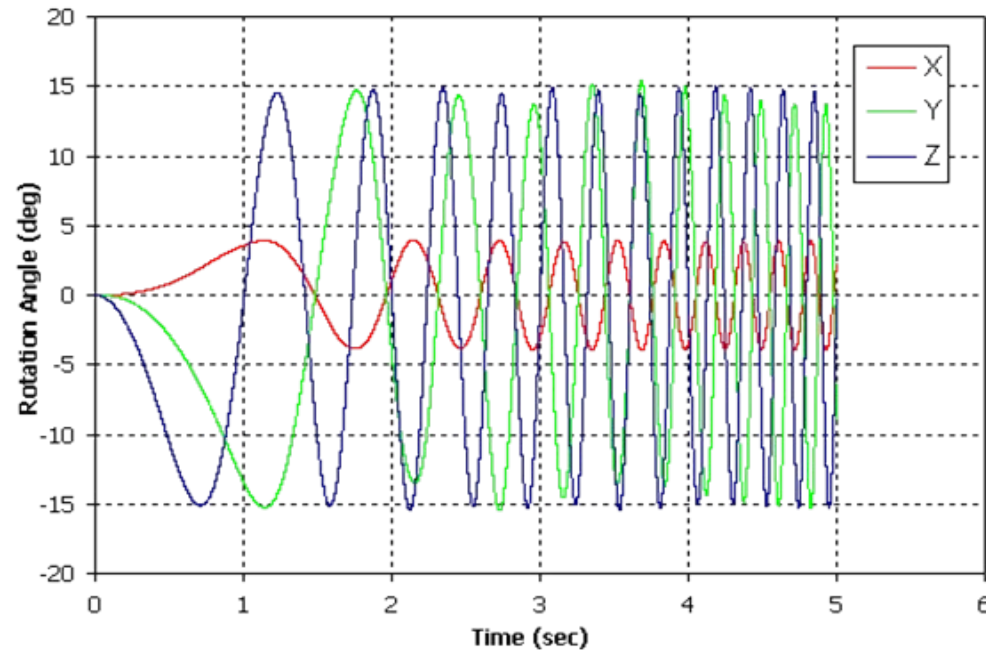
Yaw ($\lambda=1.5$)



Play

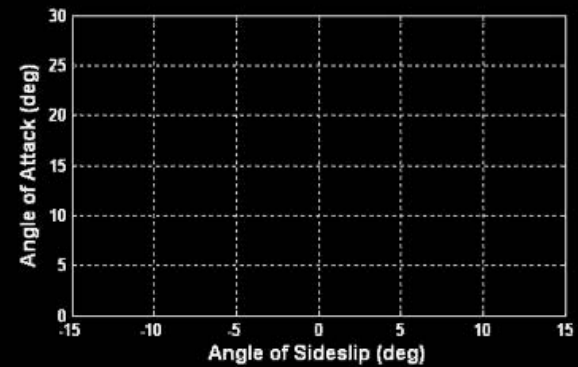
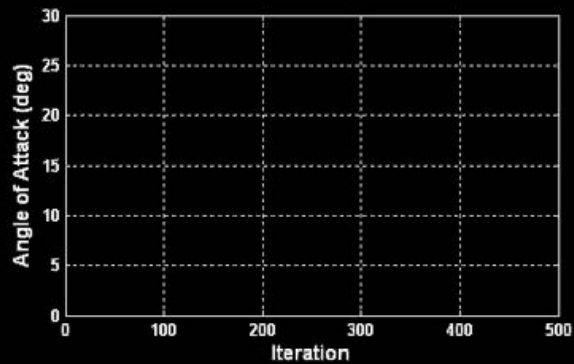
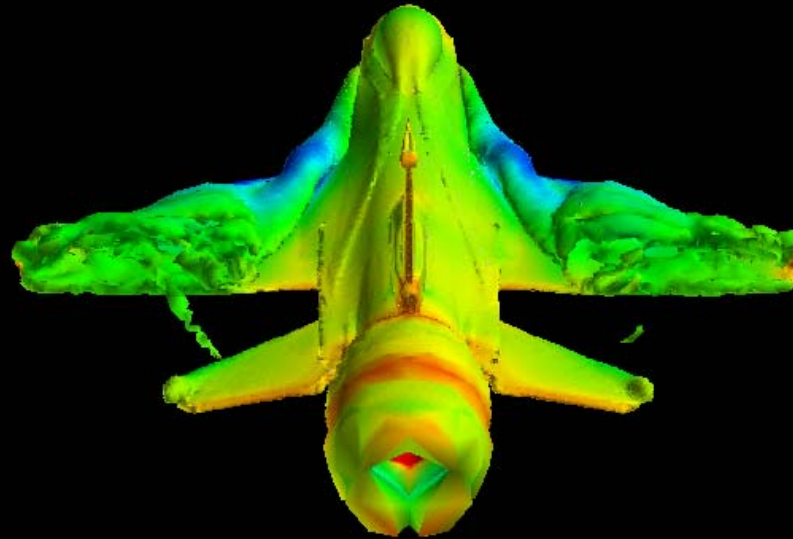
Composite Pitch-Yaw Chirp

- Single motion input to create a model including motion about two axes $\rightarrow \alpha = 15 \pm 15$ deg, $\beta = 0 \pm 15$ deg
- Input signals are made orthogonal by setting λ to 1.0 for pitch and varying λ until dot product of the two signals is zero resulting in λ of 1.47 for yaw signal



$$C_L(\alpha, \beta, p, q, r) = C_1 + C_2\alpha + C_3q + C_4p^2 + C_5\alpha q^2 + C_6\beta pq + C_7\beta p + C_8\alpha^2 q + C_9r + C_{10}\alpha\beta^2 + C_{11}\alpha^3 + C_{12}pr + C_{13}\beta^2 p + C_{14}\beta^2 q + C_{15}p + C_{16}\beta^2$$

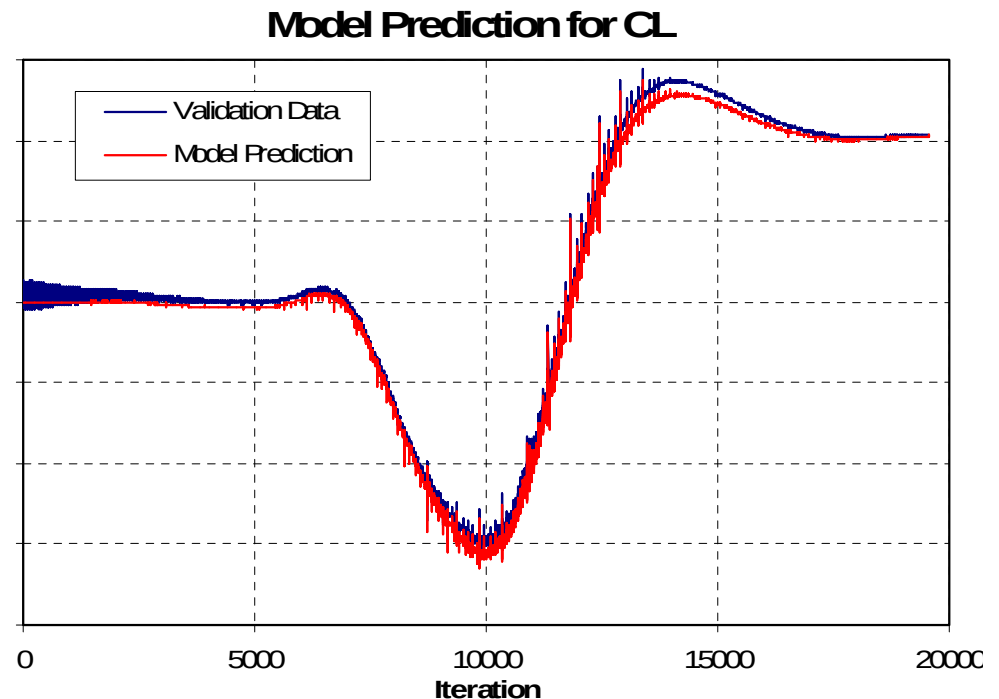
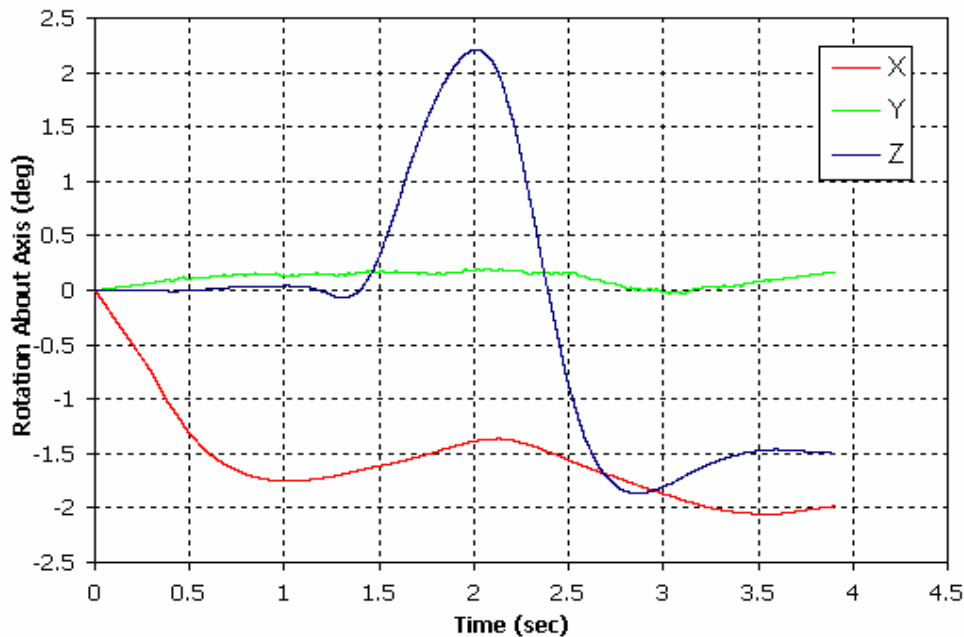
Composite Pitch-Yaw Chirp



Play

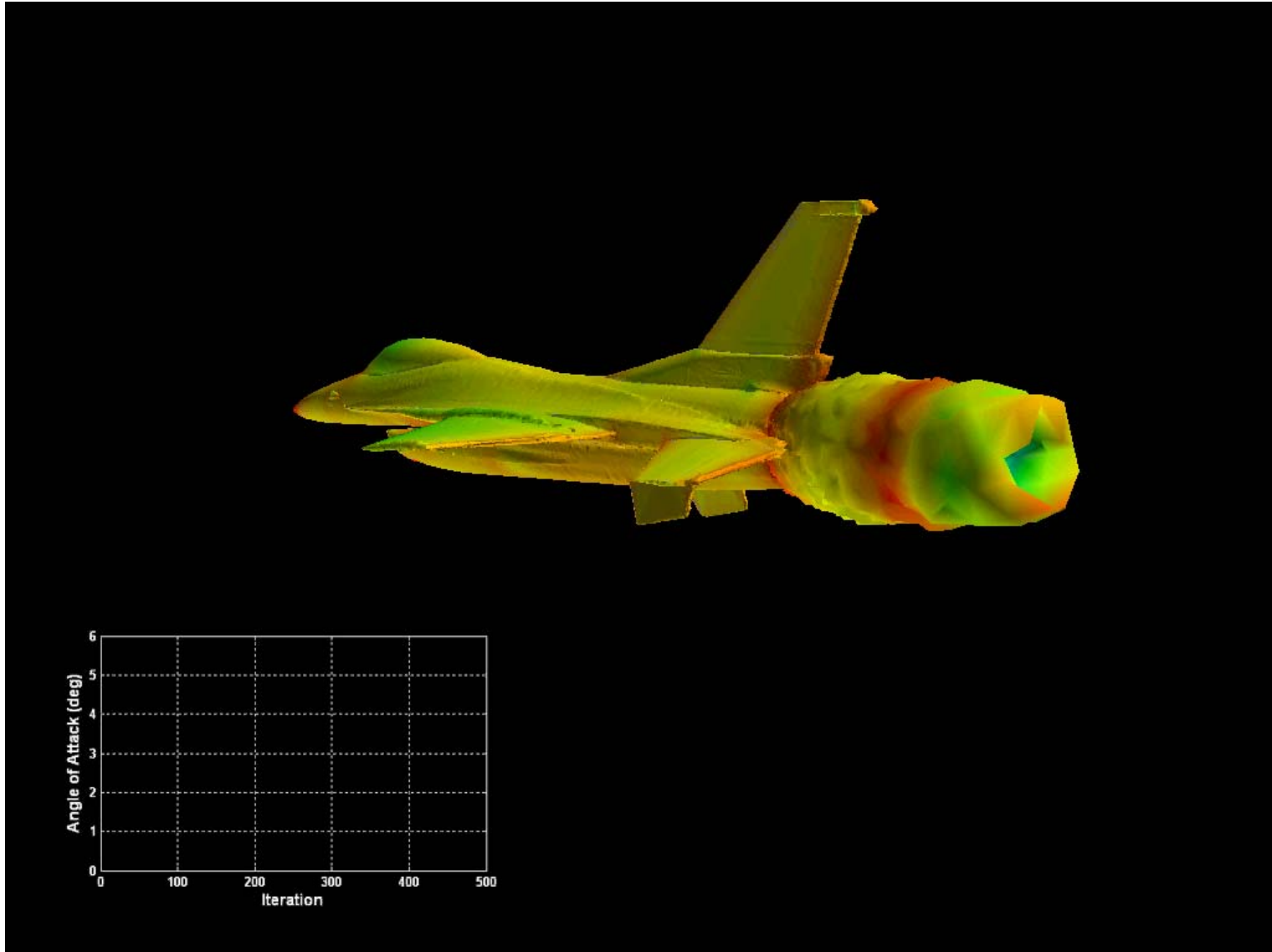
Pitch Doublet Flight Test Maneuver

- Gathered actual strip chart data from a flight test
- Created the motion file that forces the F-16C through translations and rotations giving similar/same behavior
- Predict maneuver with reduced-order model and compare



Pitch Doublet Flight Test Maneuver

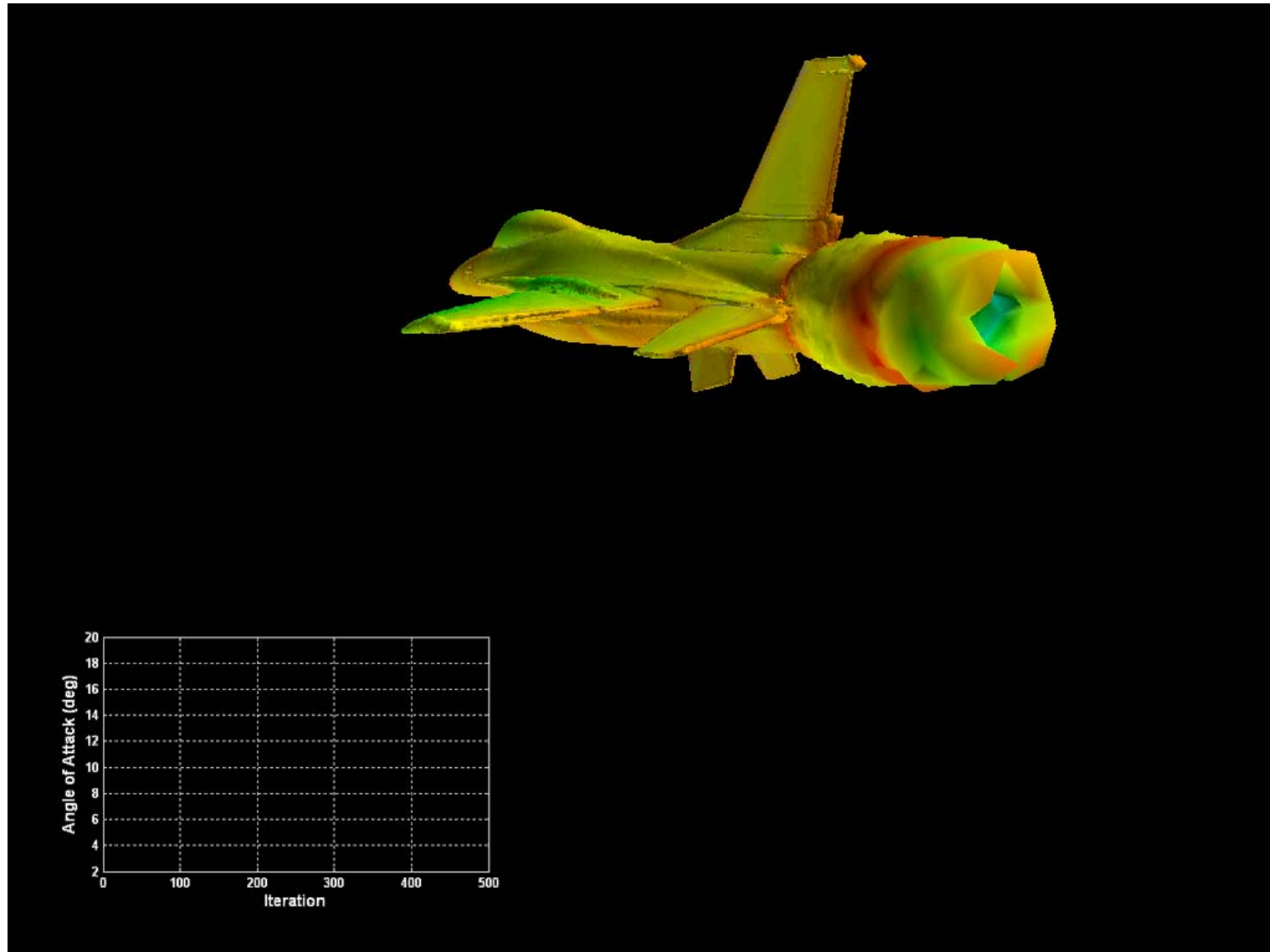
Simulation run at $M=0.6$ and $h=5,000$ ft with full span grid



Play

2.5g Wind-up Turn Flight Test Maneuver

Simulation run at $M=0.6$ and $h=5,000$ ft with full span grid



Play

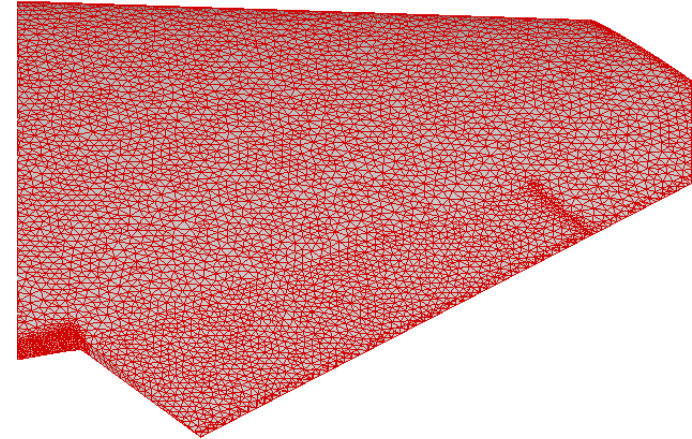
Conclusions and Ongoing Work

- State-of-the-art CFD techniques capable of predicting static, unsteady flow fields with complex aerodynamic behavior
- Motion+ modeling technique shows promise and has many benefits
- Goal is to direct/complement experimental techniques – not replace them
- Need good full-aircraft S&C experimental data for validation (AVT-166)

Ongoing Work:

- More accurate F-16C grid with stores and pylons
- Comparison of CFD and model predictions with ATLAS/flight test data
- Integration of moving control surfaces and inclusion into the SIDPAC modeling process
- Investigation of range of validity of models across flight envelope
- Aeroelastic deformation

F-16C Trailing Edge Flaperon, ± 30 deg



Acknowledgements

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- Project sponsored by the DoD HPC/Air Force SEEK EAGLE Office (AFSEO) Institute for High Performance Computing Applications for Air Armament (IHAAA)



Questions?

