Integrity - Service - Excellence

Computational Aerodynamics at the US Air Force Academy

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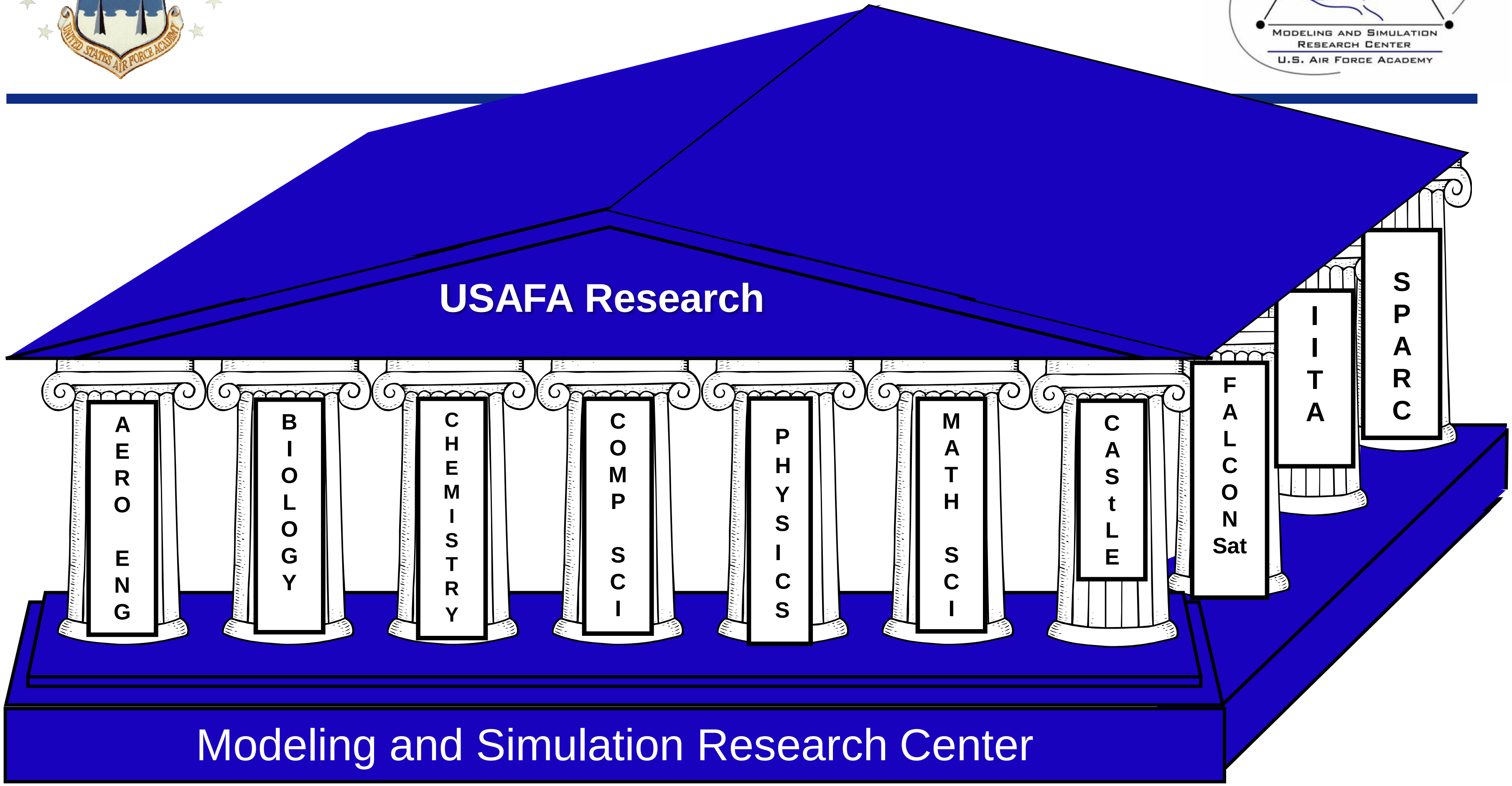
Asst. Professor of Aeronautics
Director, Modeling & Simulation Research Center

Agenda

- History and Heritage of the Modeling & Simulation Research Center
- Computational Fluid Dynamics in the Aeronautics Engineering Curriculum
- Research Highlights: Stability & Control Estimation Methods
- Summary

MSRC/HPC Research Concept

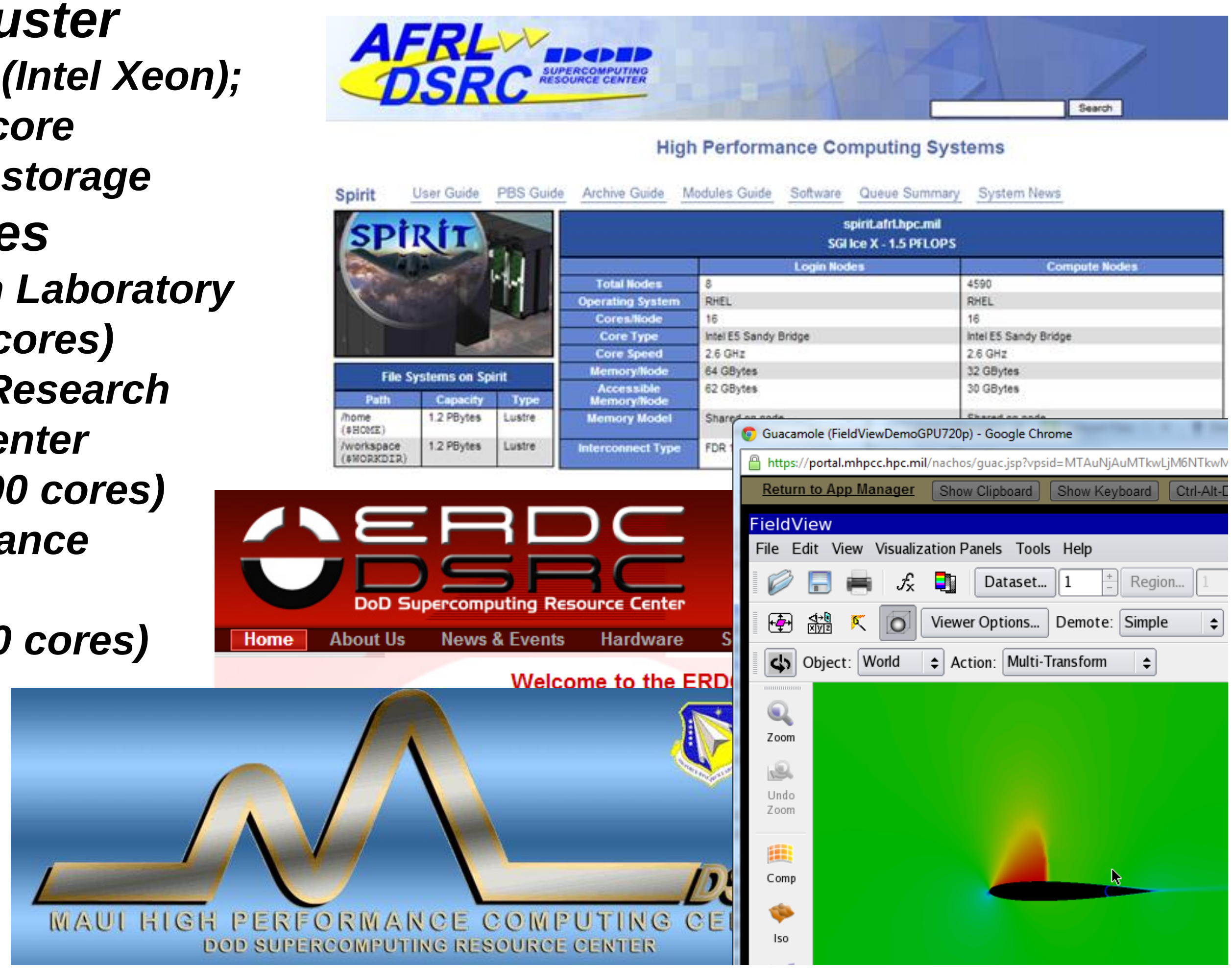


M&SRC: **Provides the computational foundation in expertise, equipment, and personnel to facilitate M&S and HPC research at USAFA**

Payoff: **Enriched cadet experience. Well prepared graduates in M&S and HPC who immediately contribute to AFRL and other AF organizations missions**

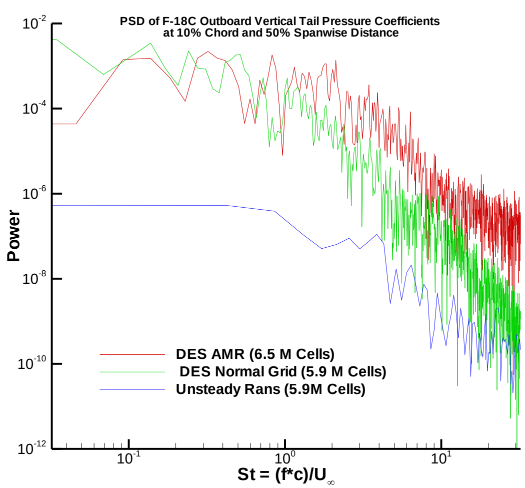
MSRC/HPC Resources

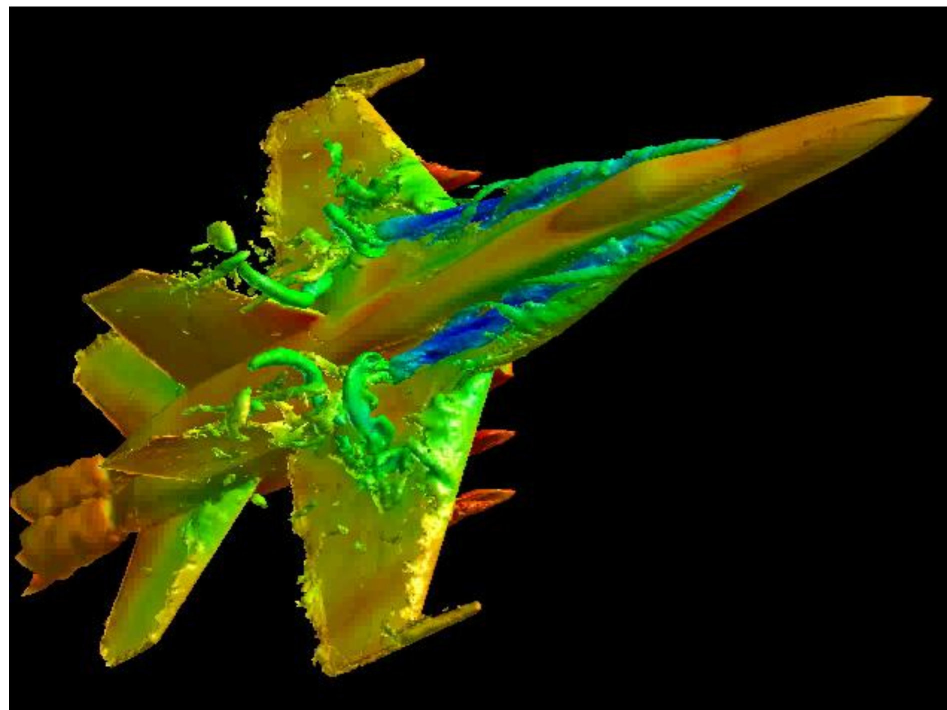
- ***Cadet academic cluster***
  - ***•144 compute cores (Intel Xeon); 2GB RAM/compute core***
  - ***•6TB common RAID storage***
- ***DoD HPC Resources***
  - ***Air Force Research Laboratory***
    - ***Spirit (73,000 cores)***
  - ***•Army Engineering Research and Development Center***
    - ***Garnet (150,000 cores)***
  - ***Maui High Performance Computing Center***
    - ***Riptide (12,000 cores)***
  - ***HPC Portal***
  - ***Utility Servers***
- ***•Local workstations***



F-18 High Alpha Research Vehicle

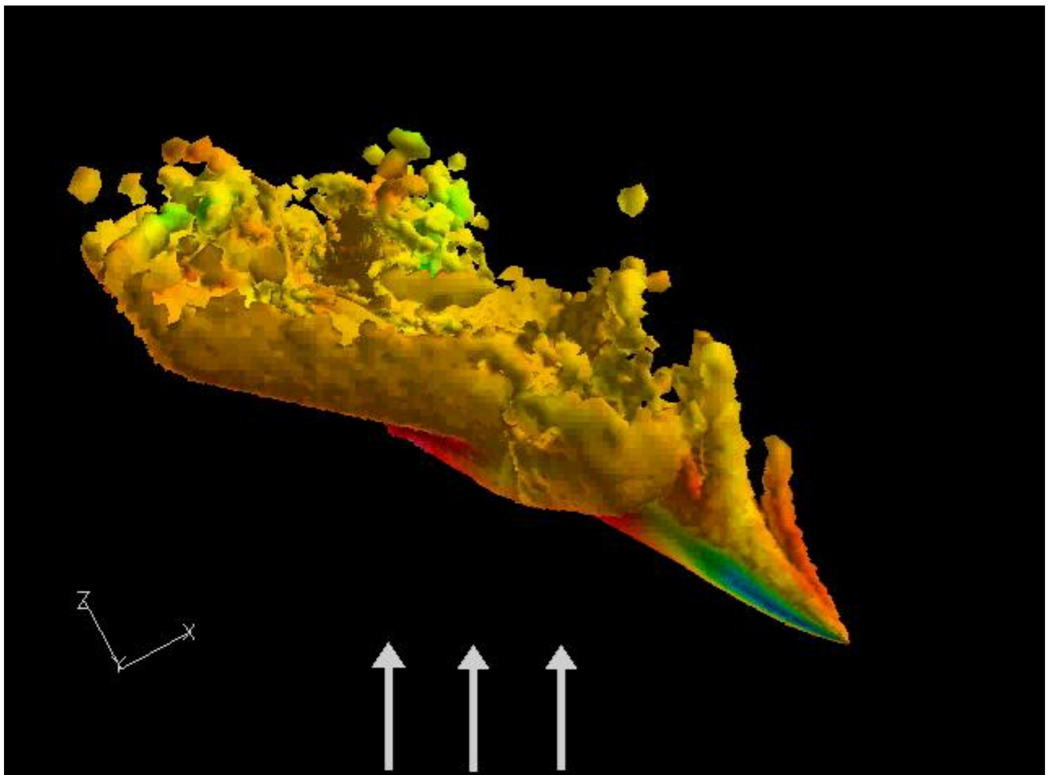
- 15,000 Time Steps (7.5 sec)
- 2nd Order Accurate in Time
- 2nd Order Accurate in Space
- SA-DES Turbulence Model
- M=0.2755, alpha=30^{o}, h=20k ft
- Re=13 Million based on MAC



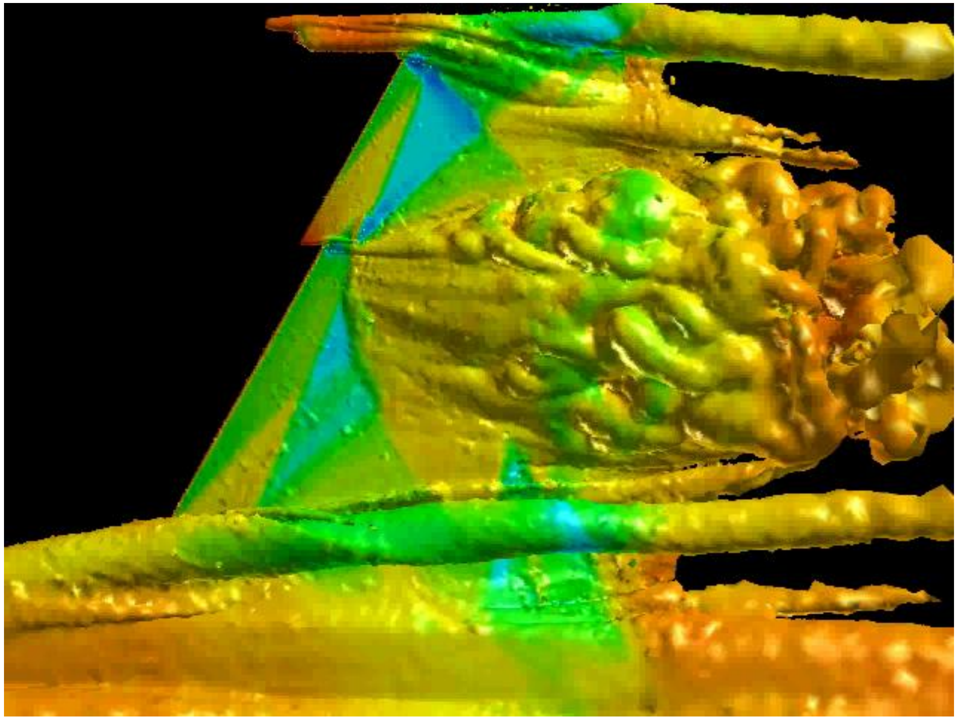


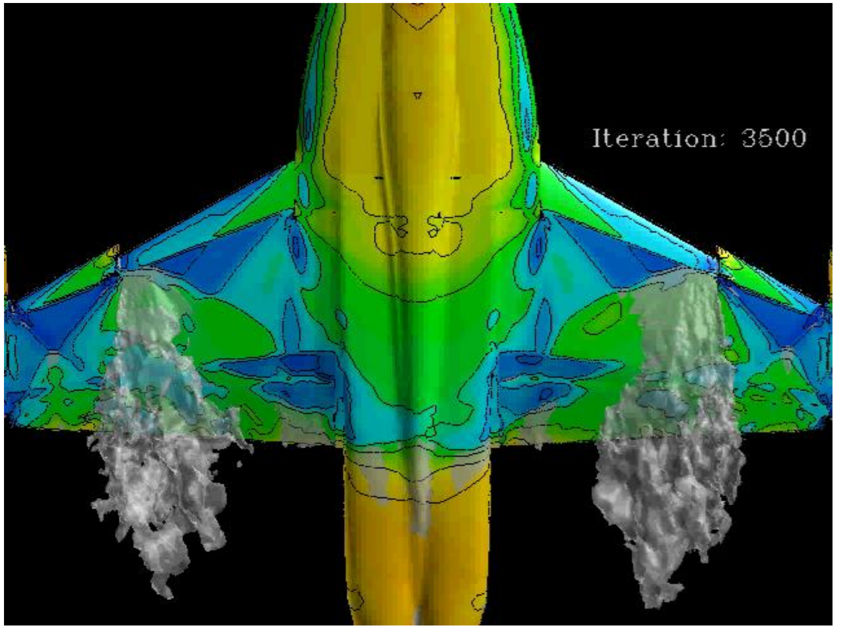
F-15E Entering Spin

- **CFD captured:** **Mean AOA, descent rate, spin rate**



F-18 Abrupt Wing Stall

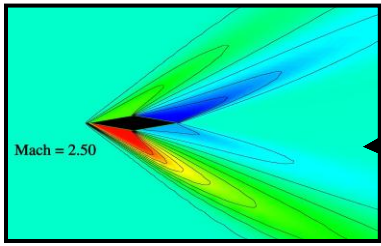


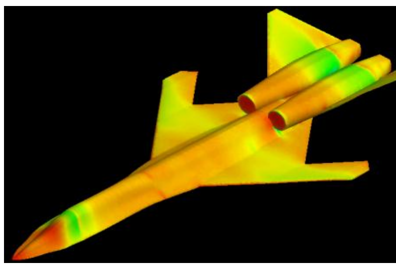


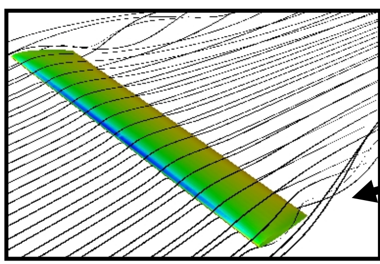
- CFD captured:
  - Unsteady shock oscillation frequency
  - min, max and average Cp

Computational Aerodynamics across the Aeronautics Curriculum

Application





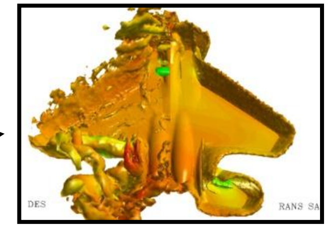


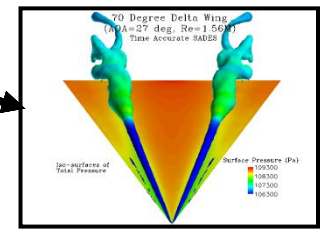
AE 442
AE 472
AE 481/2
AE 499

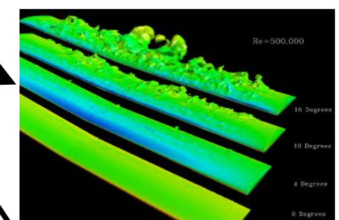
AE 341 (Aeronautical fluid mechanics)

AE 342 (computational aerodynamics)

AE 315 SO
(core Aero)







Demonstration

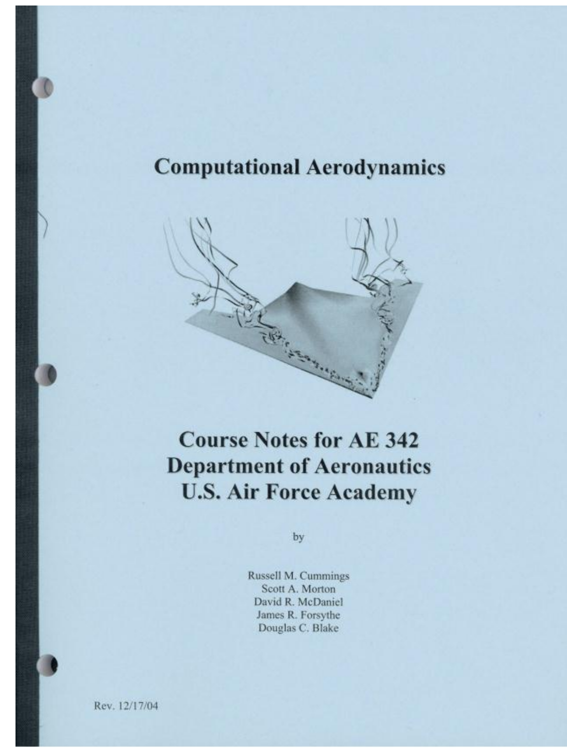
<u>Note</u>: AE 442 (Adv Aerodynamics), AE 482 (Aircraft Design), AE 499 (Cadet Research), AE 472 (Adv CFD)

Integrity - Service - Excellence

AE 342 Computational Aerodynamics: Undergraduate CFD

- Goal: educate "intelligent users" of CFD
  - Not code developers

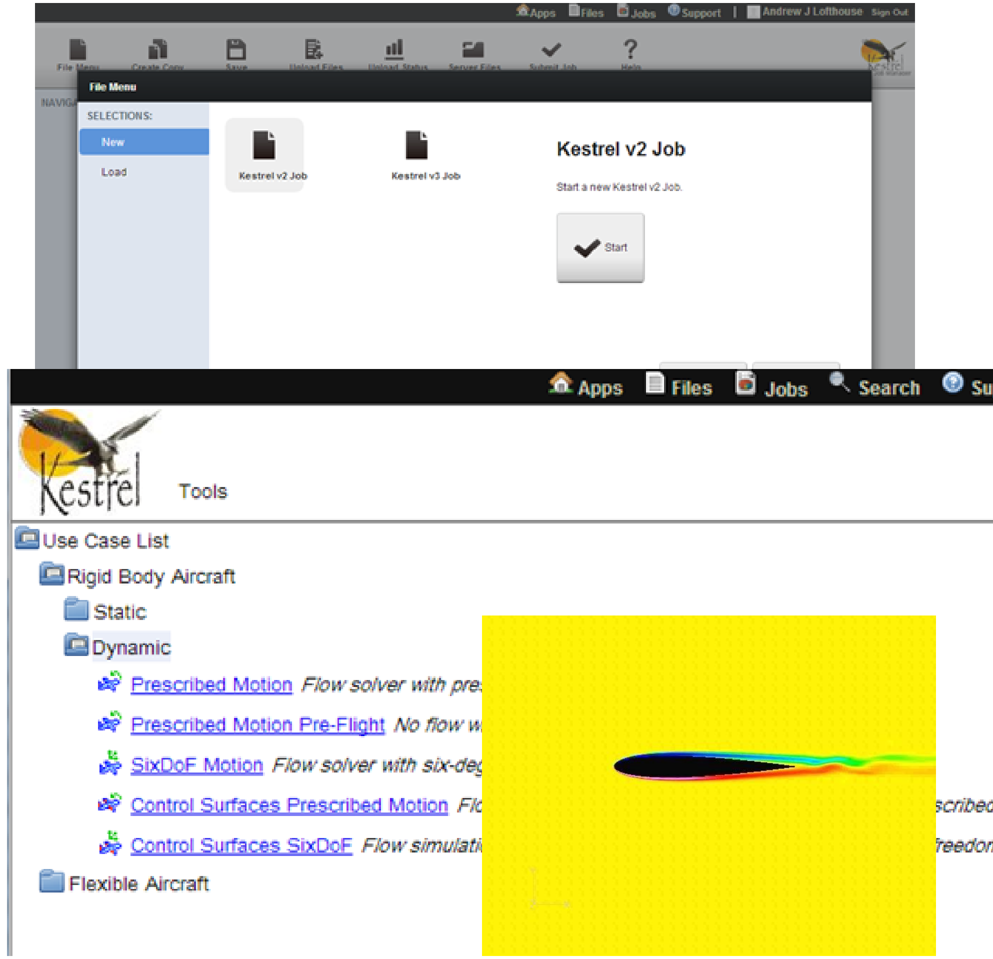
- Familiarization with computational techniques
  - Some computer programming
- In depth, practical and hands on experience with industry standard software
  - Grid Generation (Pointwise)
  - Flow Field Solver (Kestrel)
  - Data Post Processing (Fieldview)
- Final projects:
  - Viscous flow over a 2-D airfoil
  - Inviscid flow over a 3-D wing



1st Under Grad CFD text

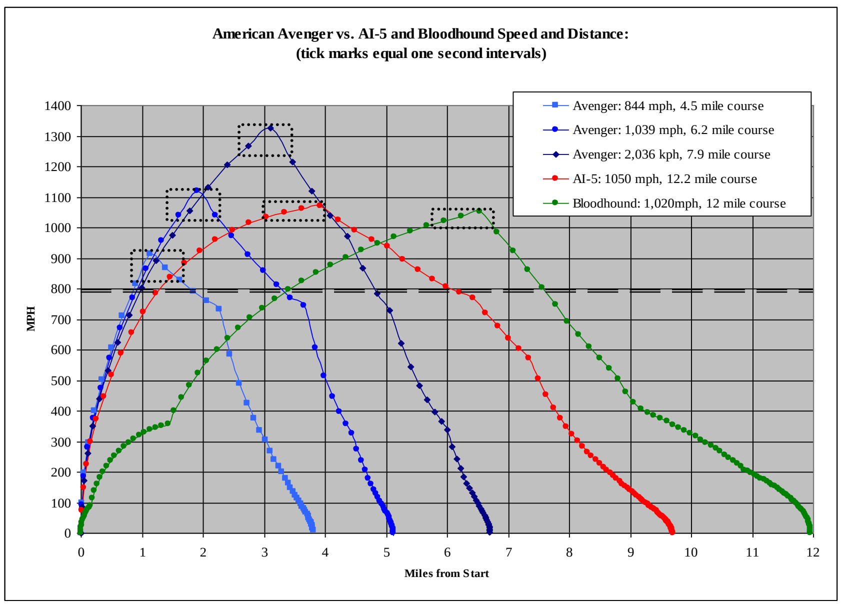
Kestrel

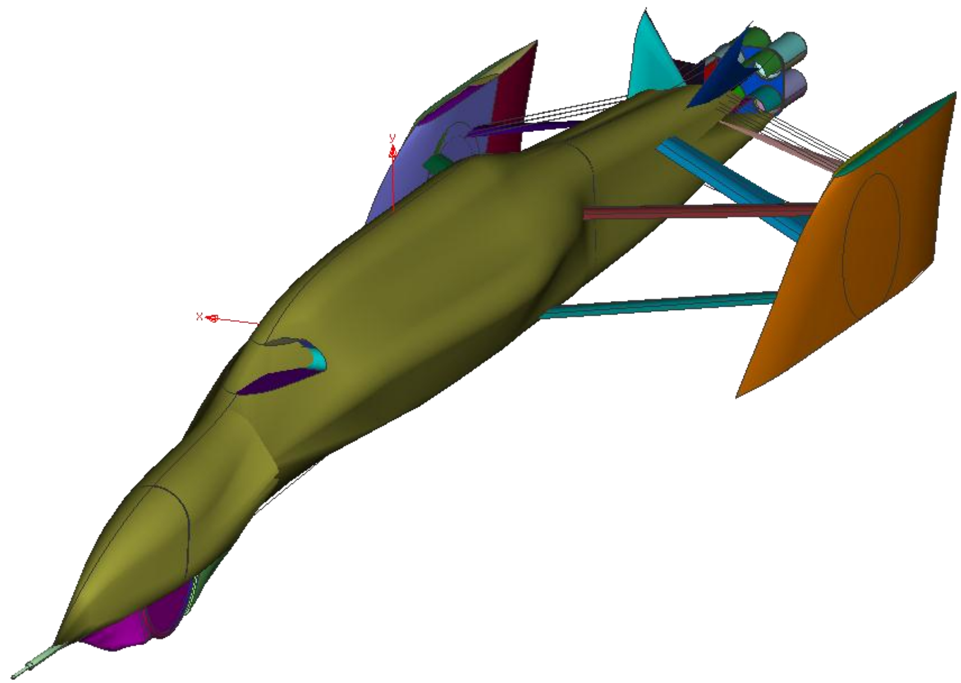
- Computational Research and Engineering Acquisition Tools and Environments (CREATE)
  - FY2008 for 12 years
  - Scalable, multi-disciplinary, physics-based computational engineering software
  - Annual release cycle
- Kestrel v4 (2013)
  - 2D / 3D unstructured solver ($Cobalt_{60}$, AVUS heritage)
  - RANS, DES turbulence models
  - 6-DOF, prescribed motion
  - Control surface deflection
  - Overset mesh for relative motion
  - Engine / structural models



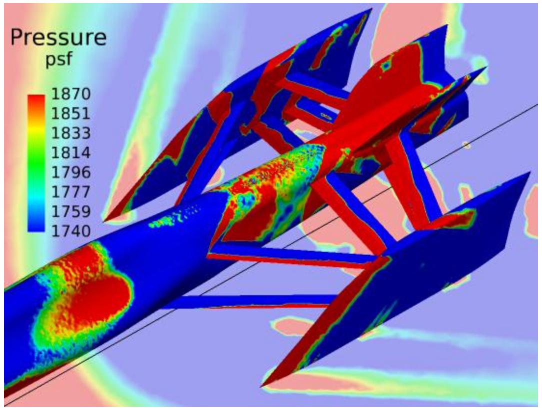
Land Speed Record Car
(C1C Ben Kramer)

- **Objective: Preliminary design analysis for drag and pitch stability**

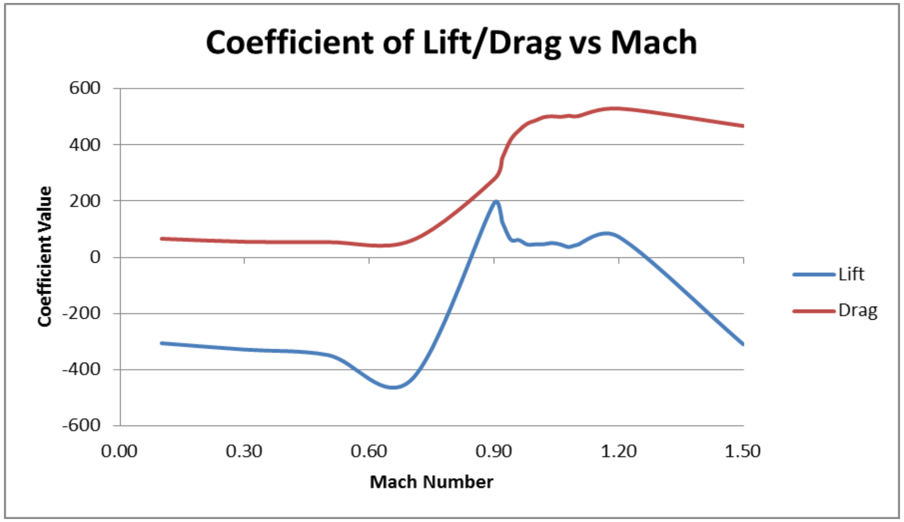


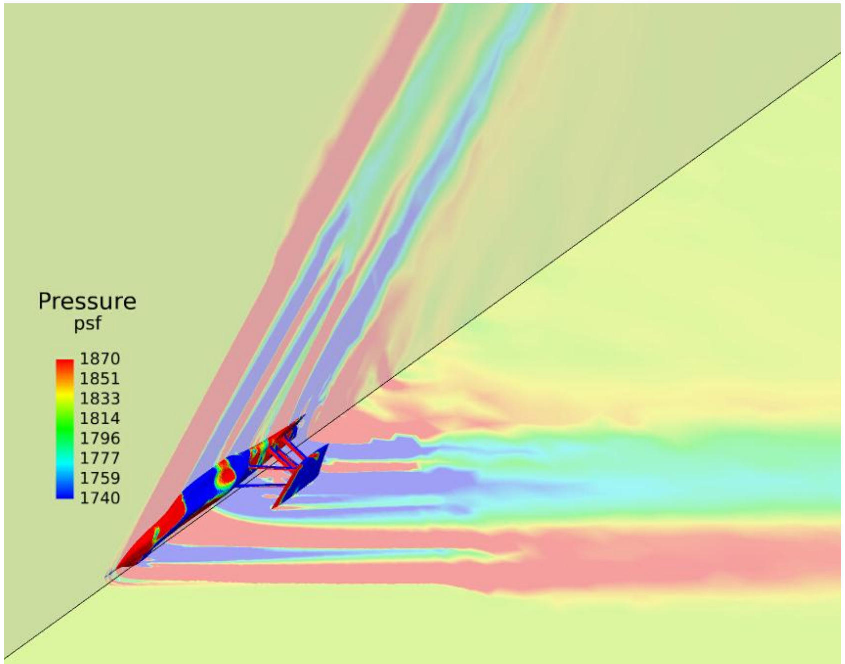


LSR Area Ruling



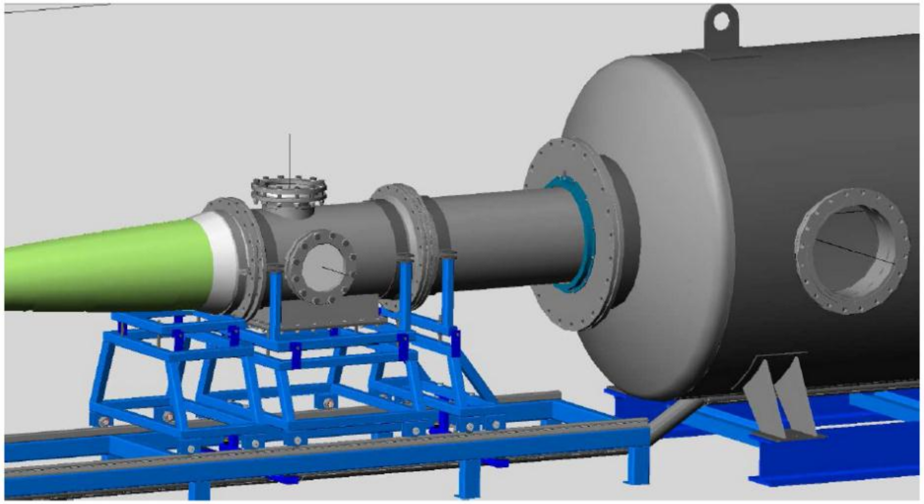
- Euler solution
- Mach sweep to 1.5

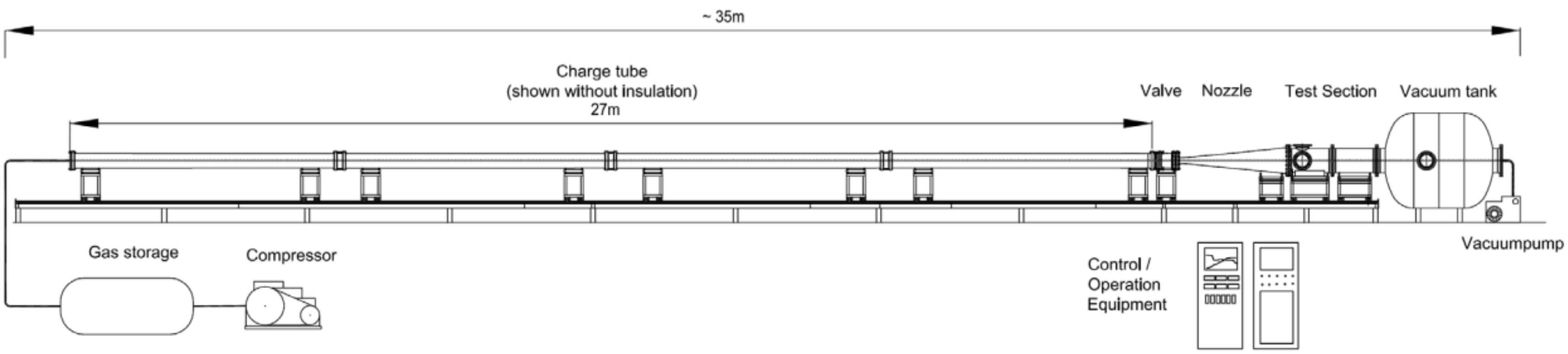




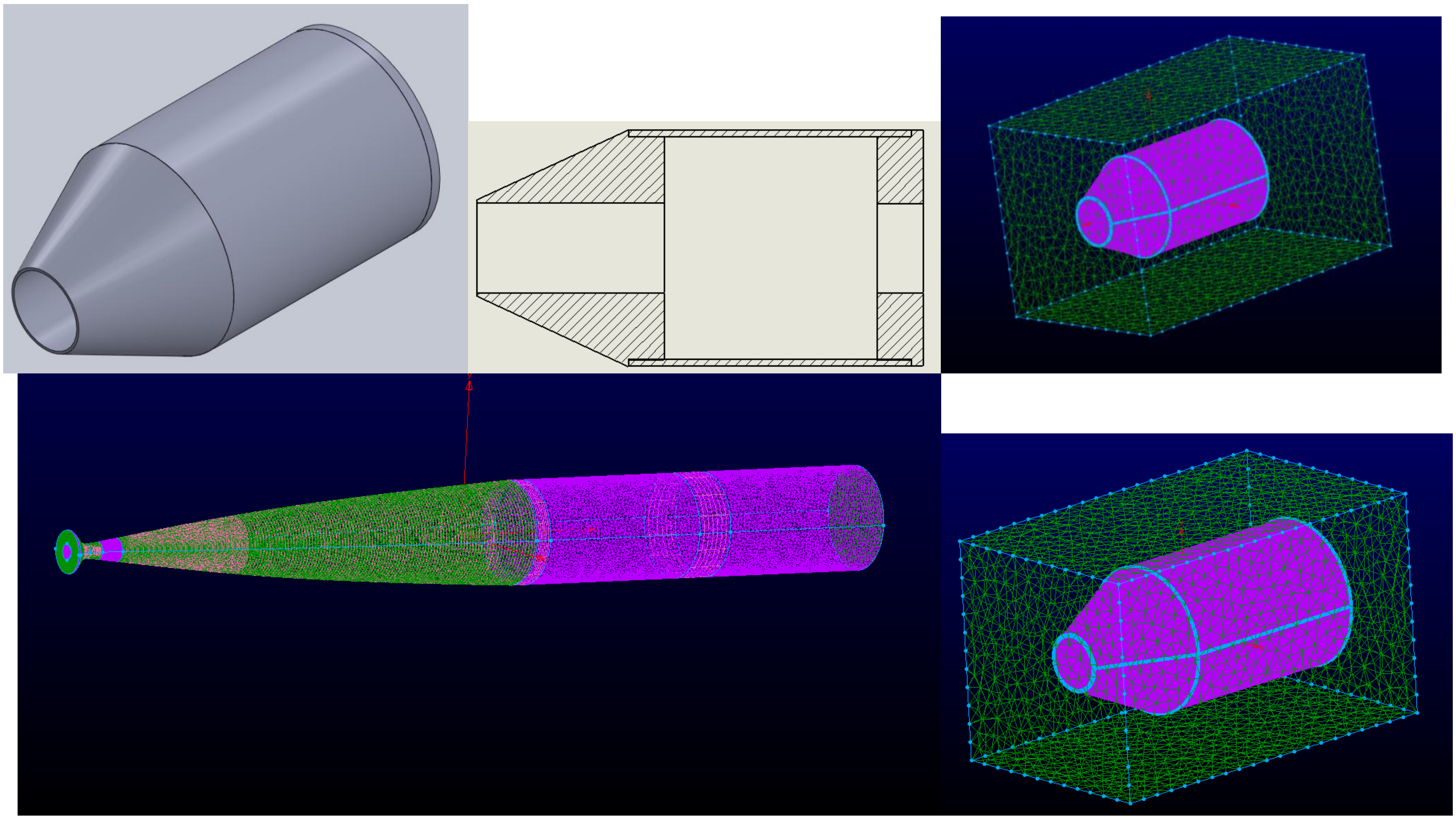
M6 Ludwieg Tube
(C1C Rivey)

- **Objective: Characterize expansion wave pattern for various diffusers / models**



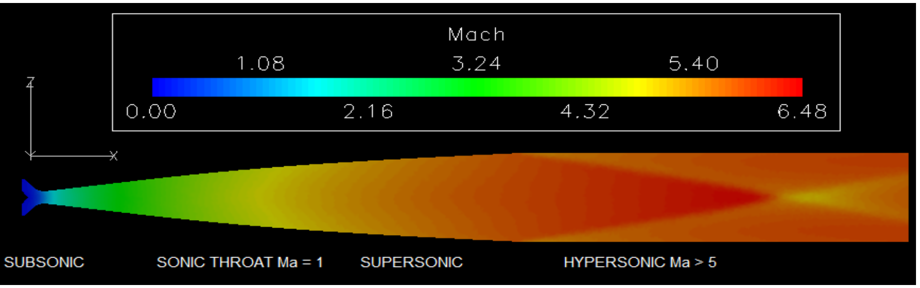


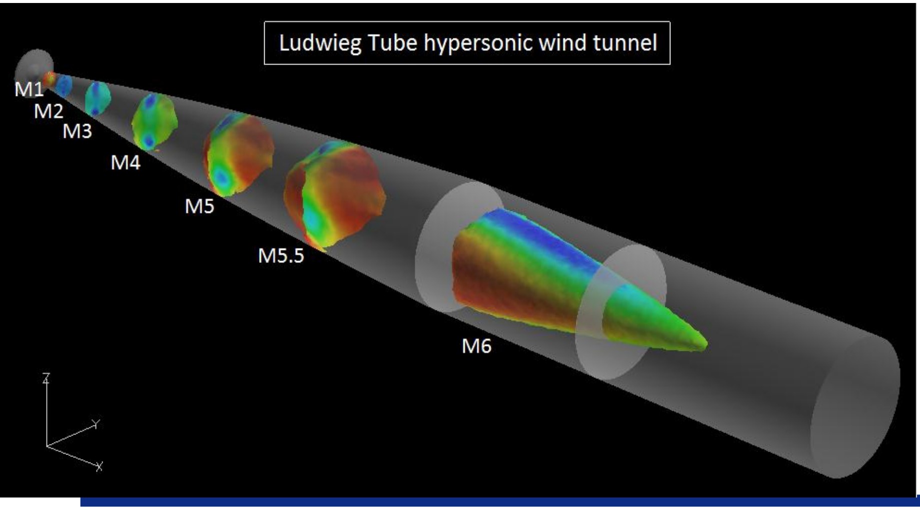
Diffuser Plug Design



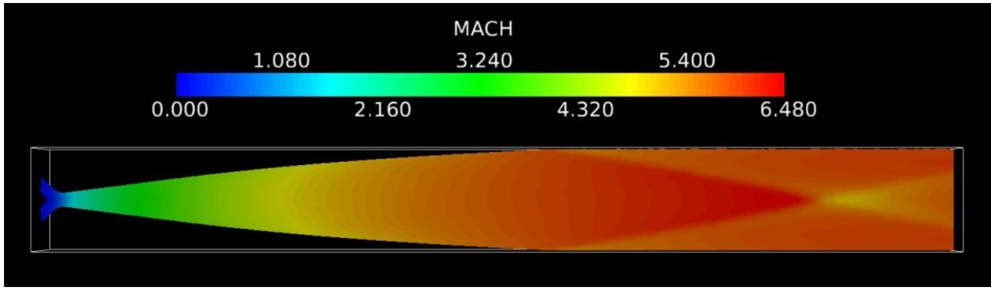
Ludwieg Tube

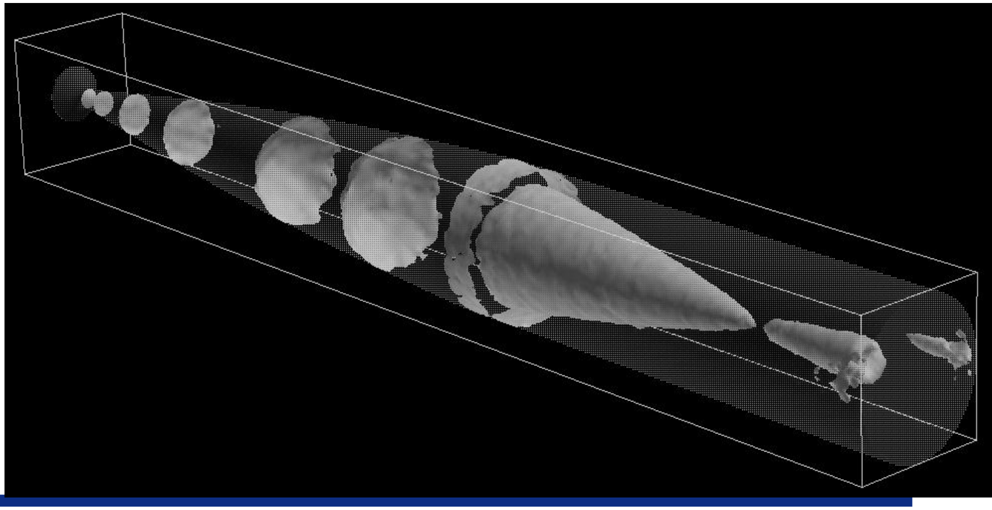
Cobalt Results





Kestrel Results





High AOA S&C

(Drs. Russ Cummings & Mehdi Ghoreyshi)

Discovery and rectification of undesirable aircraft behaviors during High Angle-of-Attack testing of High Performance Aircraft is not only the 'Norm', but those behaviors needing rectification/mitigation are usually complex, sometimes bizarre, and often 'spectacular'.

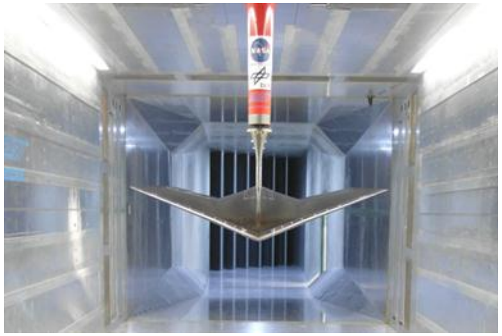
http://elementsofpower.blogspot.com/2012_09_01_archive.html

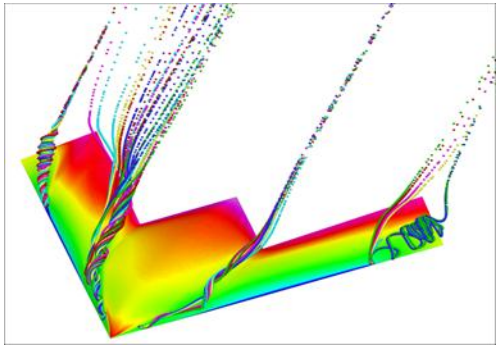
Motivation

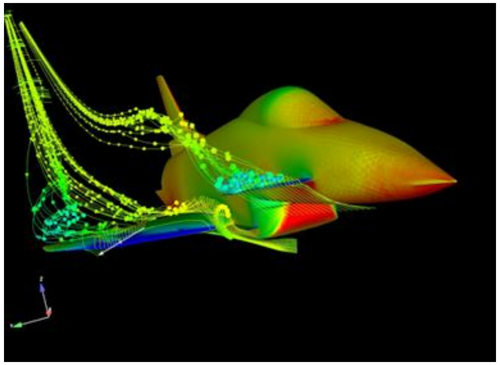
- **Traditional approaches are expensive / limited**
  - **Flight test**
  - **Wind tunnel**
  - **Semi-empirical methods**
- **Non-traditional configurations complicate the process – complex vortex-dominated flow fields**
  - **Non linear aerodynamics**
  - **Unsteady aerodynamics**
  - **Highly sensitive behavior with asymmetric flow conditions**
- **Led to creation of multiple NATO RTO/STO Applied Vehicle Technology (AVT) Task Groups**

Objective

- Validation data (static and dynamic)
- Predict aerodynamic behavior
- Assess prediction methods for S&C characteristics
- Medium-to-high AOA
- Two vehicle configurations:
  - Generic UCAV (SACCON)
  - X-31



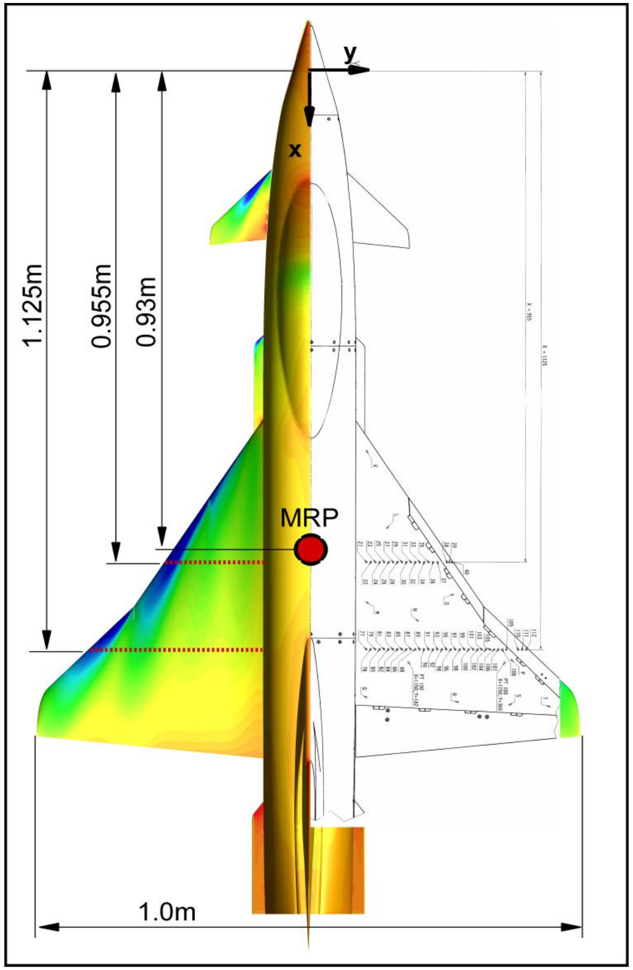


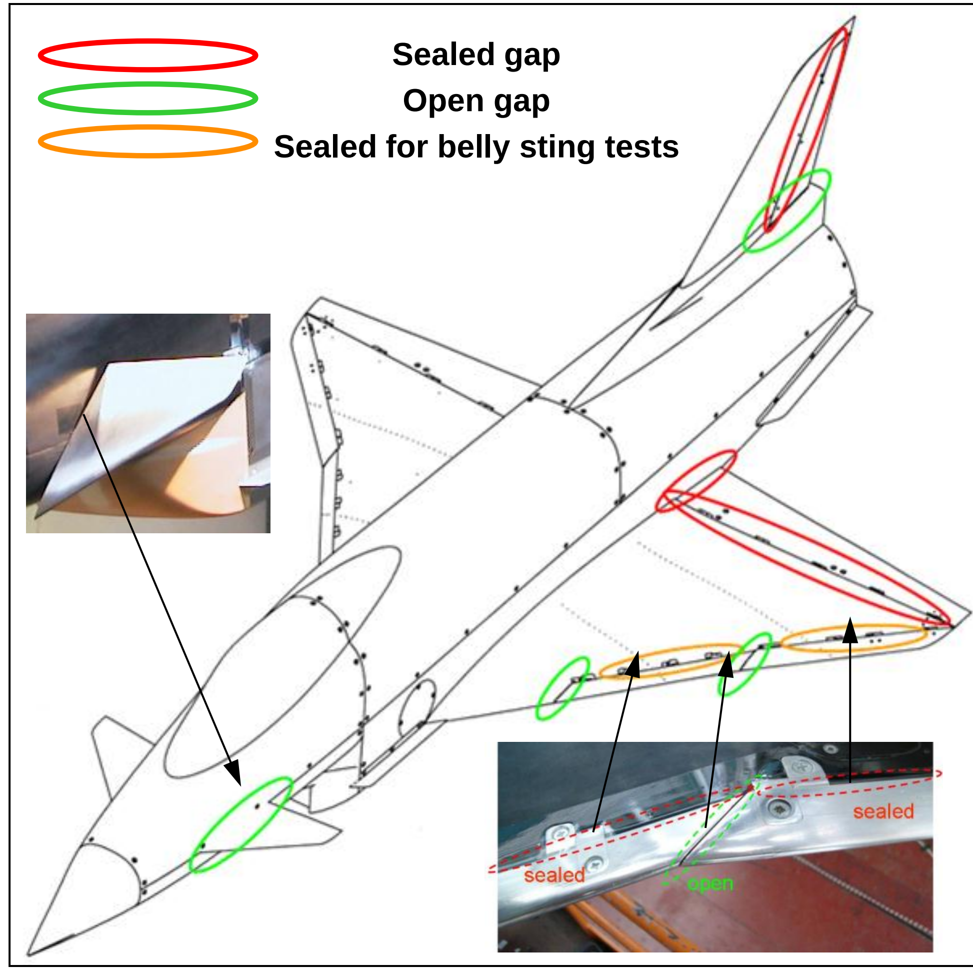


Cooperative Approach

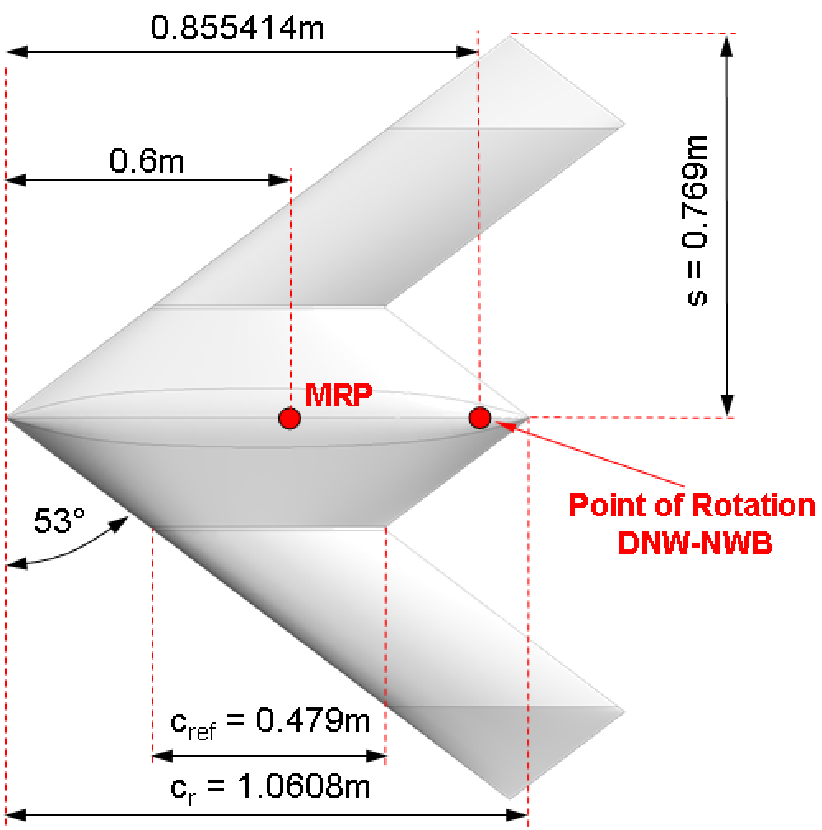
AVT-161 had 46 active participants from 12 NATO Nations plus Sweden and Australia

X-31 Configuration



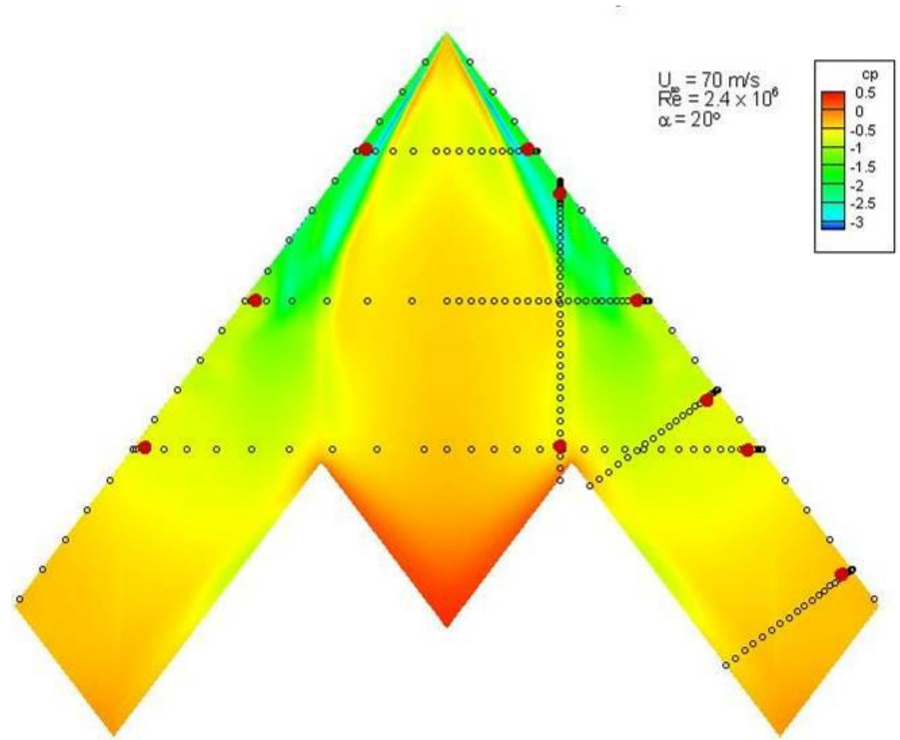


SACCON Configuration



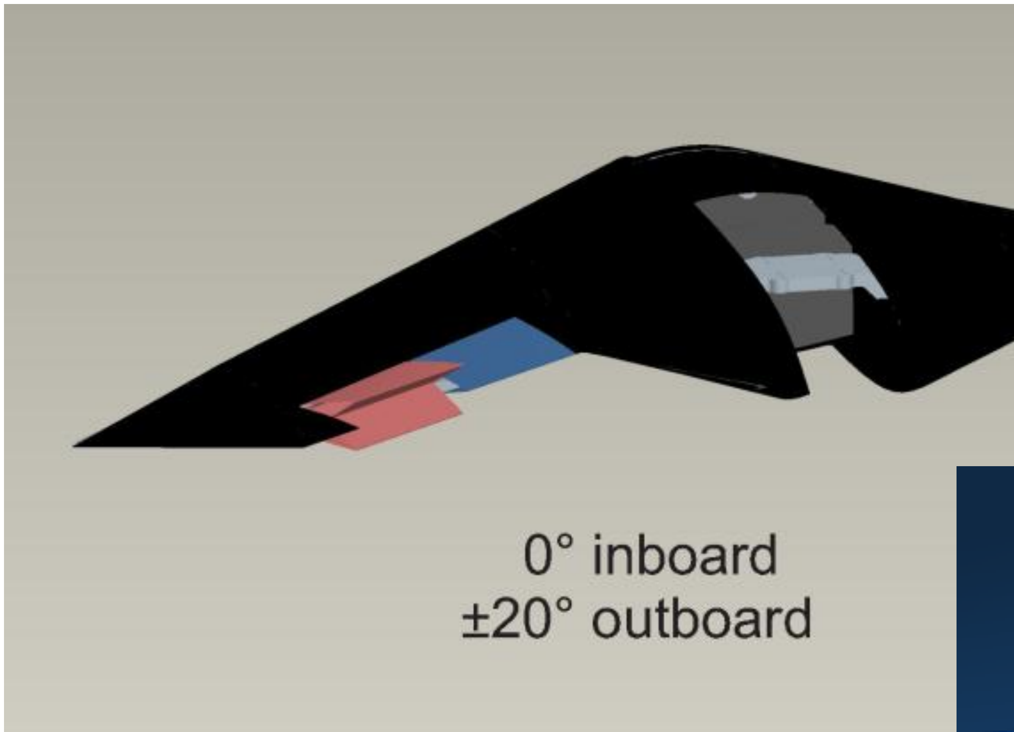
c_{ref} : Reference length for Re, moments and red. freq.

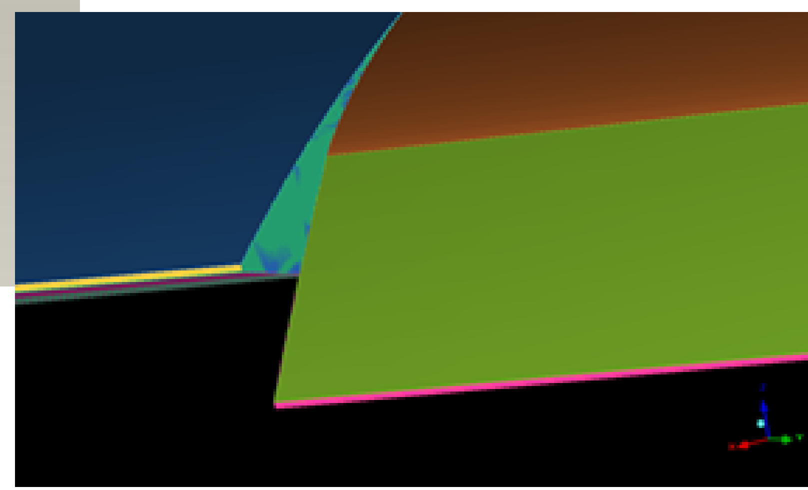
c_r : inner root chord



285 Pressure ports
202 top – 10 Kulites
83 bottom

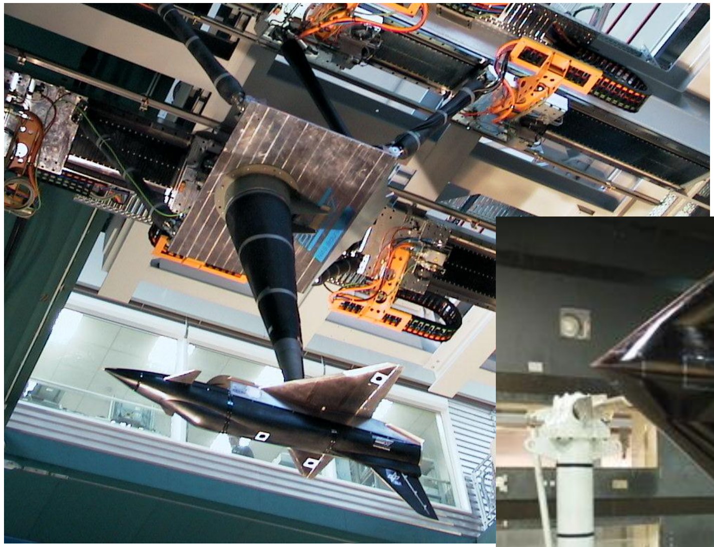
SACCON Configuration





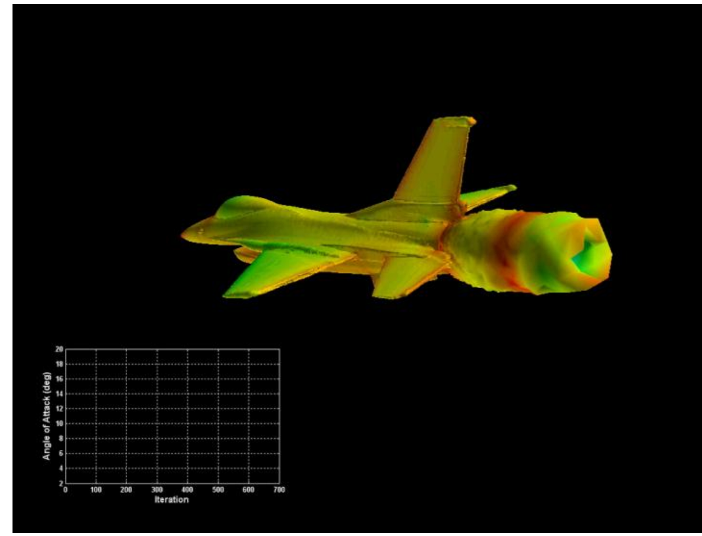
Experimental Approach

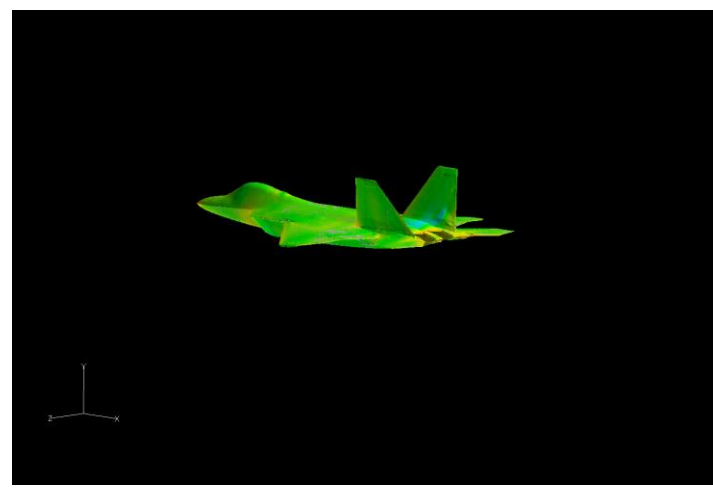
- X-31: 2x Wind Tunnel @ DLR
  - Static / Dynamic
  - Forces / Moments
  - Surface Pressure
- SACCON: 5x Wind Tunnel @ DLR / NASA
  - Static / Dynamic
  - Forces / Moments
  - Surface Pressure
  - Transition (IR)
  - PIV



S&C Prediction Approaches

- Semi-empirical
  - Use historical data
  - Traditional configurations
  - Linear aerodynamics
- Full-order modeling
  - 30 AOAs, 10-20 Mach, 5 sideslip, control surface deflections
  - 15,000 – 20,000 CFD runs
- CFD and modeling
  - 100’s of simulations (training maneuvers)
  - Interpolation schemes
  - System ID / Reduced Order Models





SID and ROM Approaches

- **SIDPAC (NASA Langley)**
  - **Least square approximation of functional relationship**
  - **Gram-Schmidt orthogonalization**
- **Volterra Functions**
- **Radial Basis Functions**

Linear Range

Non-Linear Range

Give models in terms of primary variables:

$$C_l(\beta, p, \dot{p}, r, \dot{r}) = C_1 p + C_2 \dot{p}p^2 + C_3 r + C_4 p^4 + C_5 \dot{p}^2 p^2 + C_6 \dot{p}^3 + C_7 \dot{r}\dot{p}^2$$

Indicial Functions

$$C_L(t) = C_{L_0} + \frac{d}{dt}\left[\int_0^t C_{L_\alpha}(t-\tau)\alpha(\tau)d\tau\right] + \frac{d}{dt}\left[\int_0^t C_{L_q}(t-\tau)q(\tau)d\tau\right]$$

$$C_m(t) = C_{m_0} + \frac{d}{dt}\left[\int_0^t C_{m_\alpha}(t-\tau)\alpha(\tau)d\tau\right] + \frac{d}{dt}\left[\int_0^t C_{m_q}(t-\tau)q(\tau)d\tau\right]$$

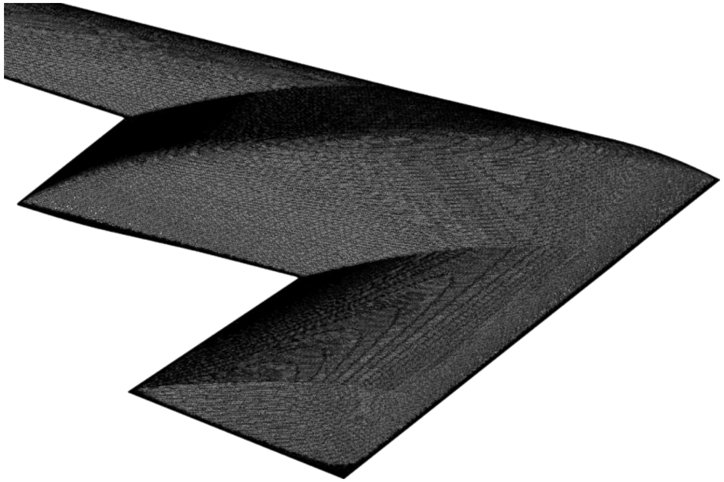
- **Requires system response to unit step impulse in AOA / q**
- **Results in model similar to "textbook" approaches (stability derivatives can also be nonlinear)**

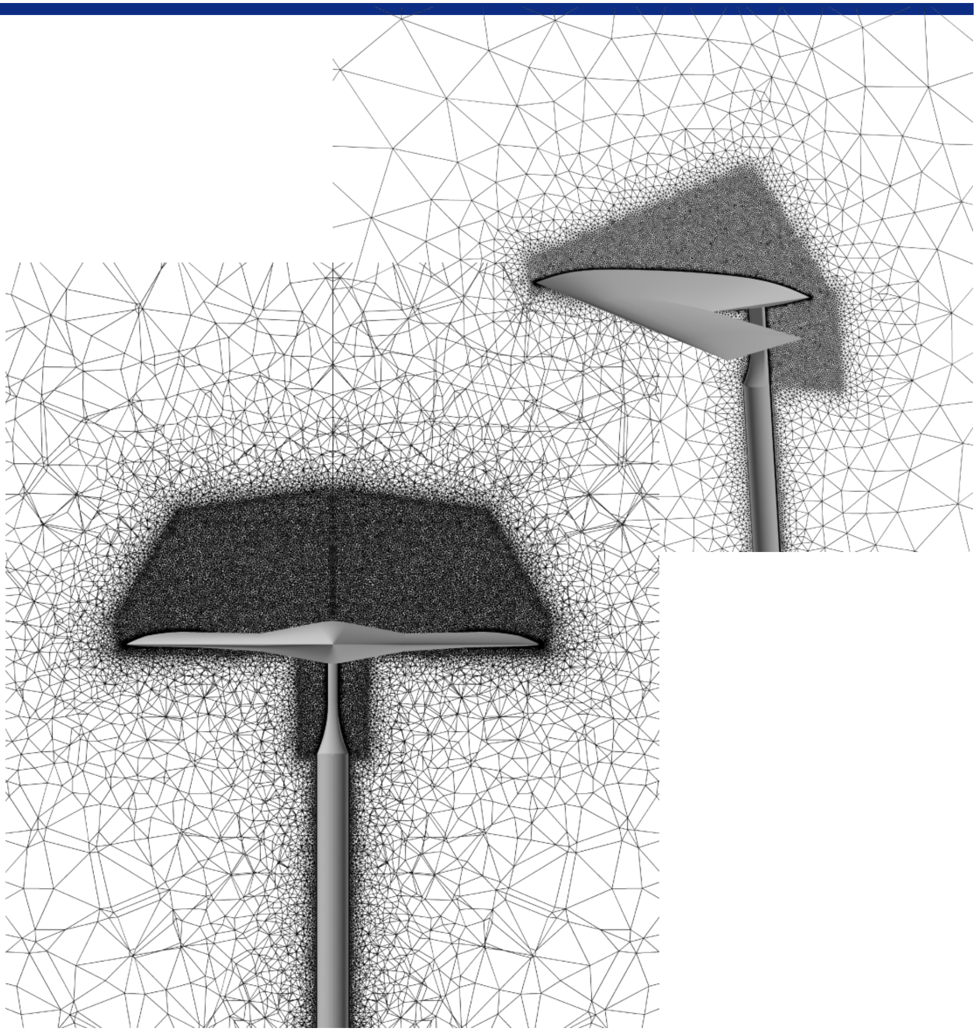
$$C_l(\beta, p, \dot{p}, r, \dot{r}) = C_{l_0} + C_{l_\beta}\beta + C_{l_p}p + C_{l_r}r + C_{l_{\dot{\beta}}}\dot{\beta} + C_{l_{\dot{p}}}\dot{p} + C_{l_{\dot{r}}}\dot{r}$$

- **Requires large number of step functions across AOA / Mach / etc space**
- **Once response determined, model used for different maneuvers**

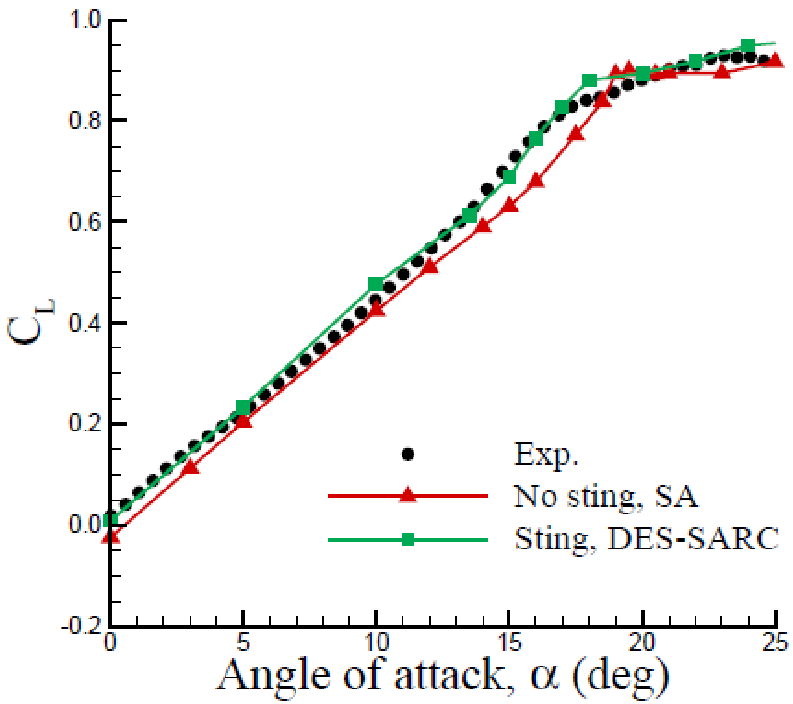
UCAV-SACCON Meshes

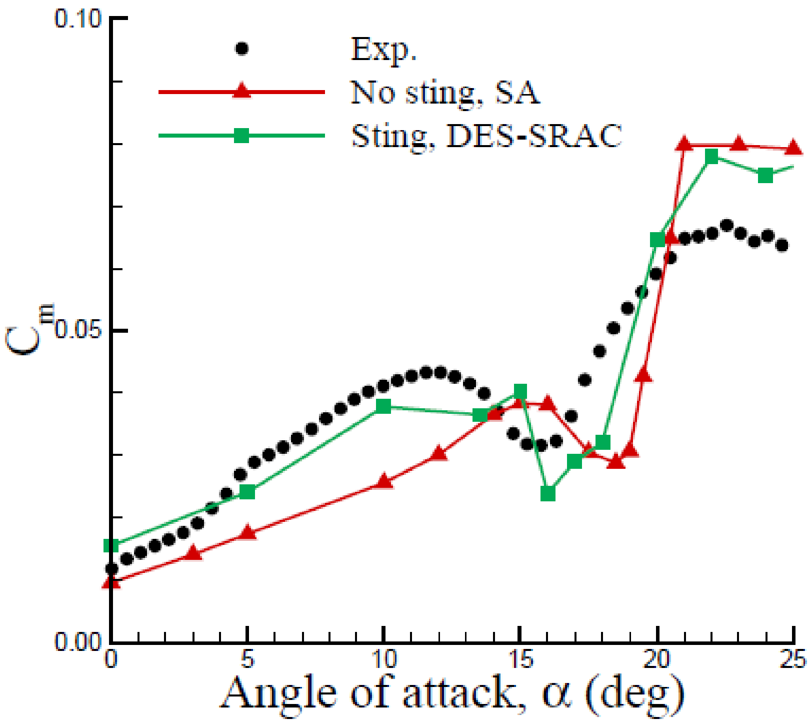
- Unstructured mesh
  - 16 prism layers
  - 26-30 million cells



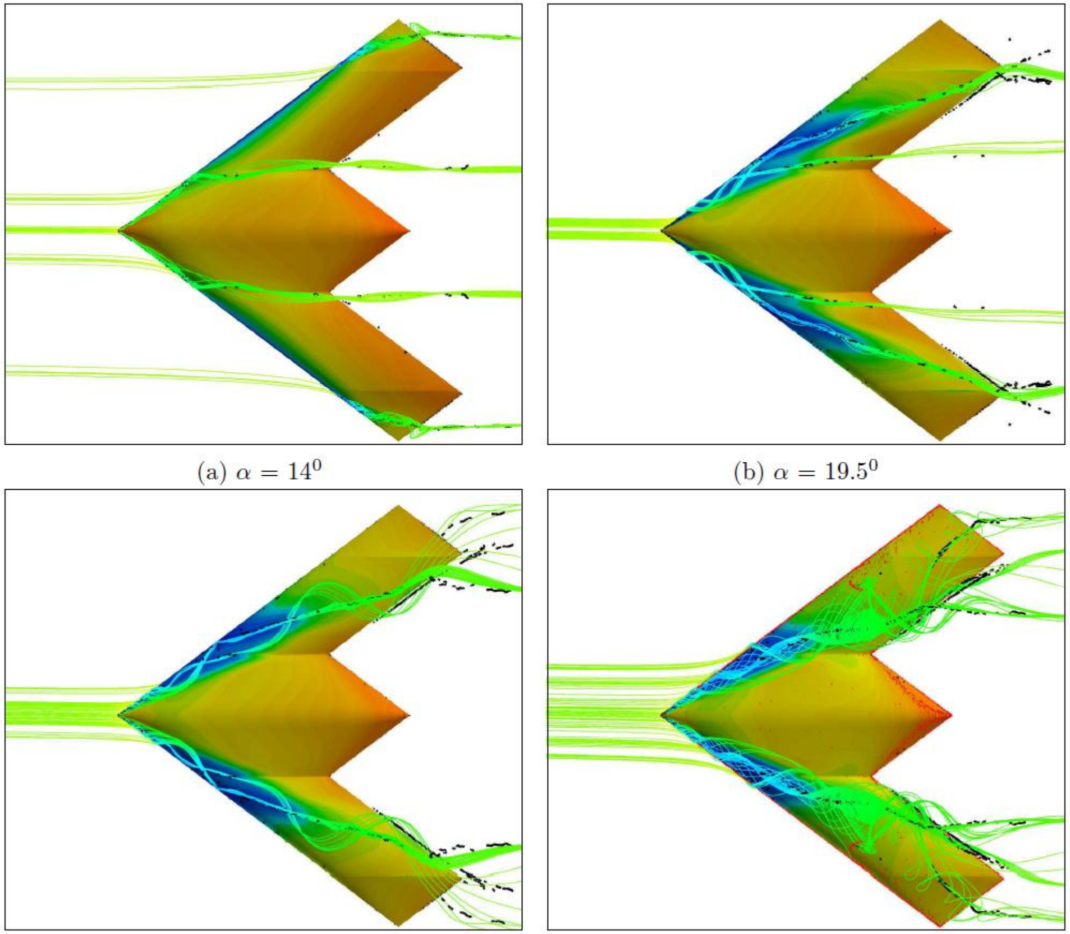


Sting vs No Sting





SACCON Solutions



(a) $\alpha = 14^0$ (b) $\alpha = 19.5^0$

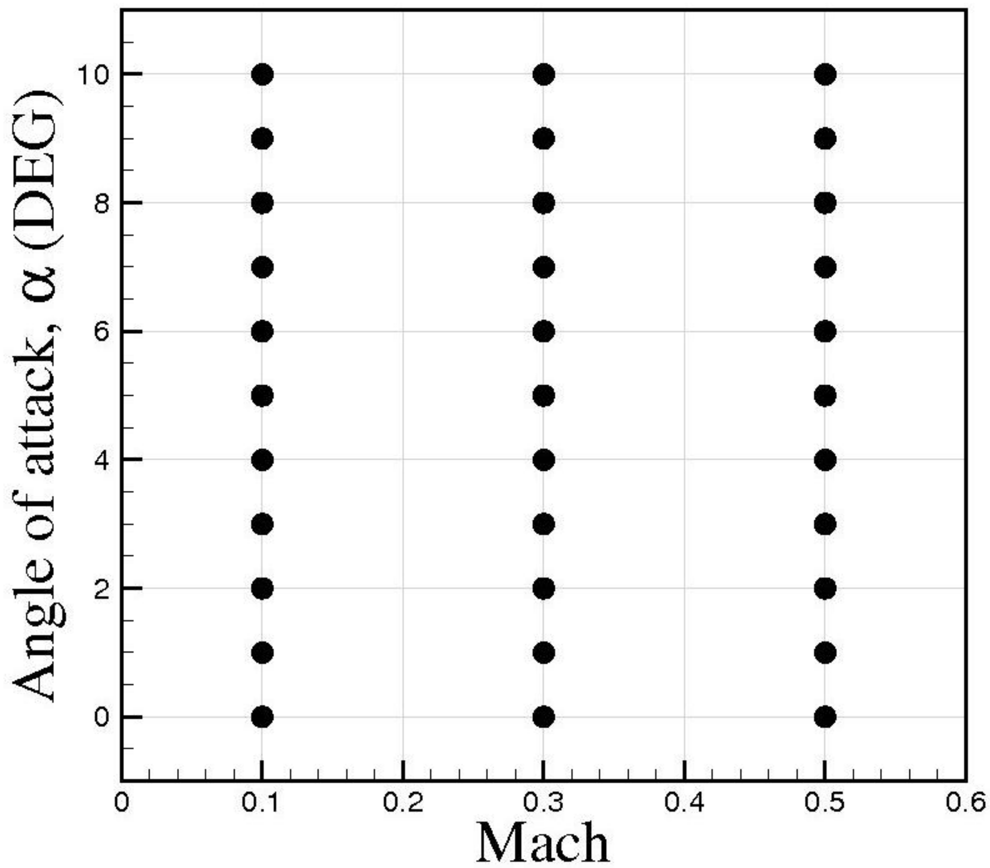
(c) $\alpha = 20.5^0$ (d) $\alpha = 23^0$

SACCON Design Space

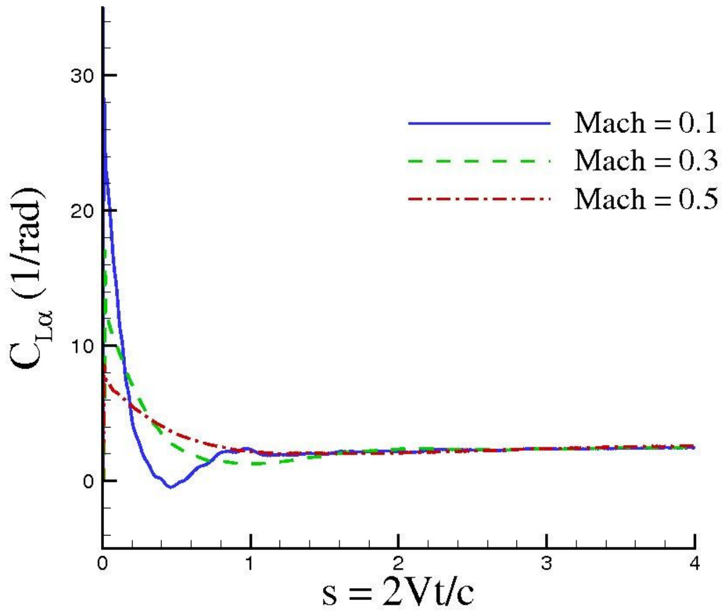
Maneuver constraints

-10 < α <   10
0.1 < M < 0.5

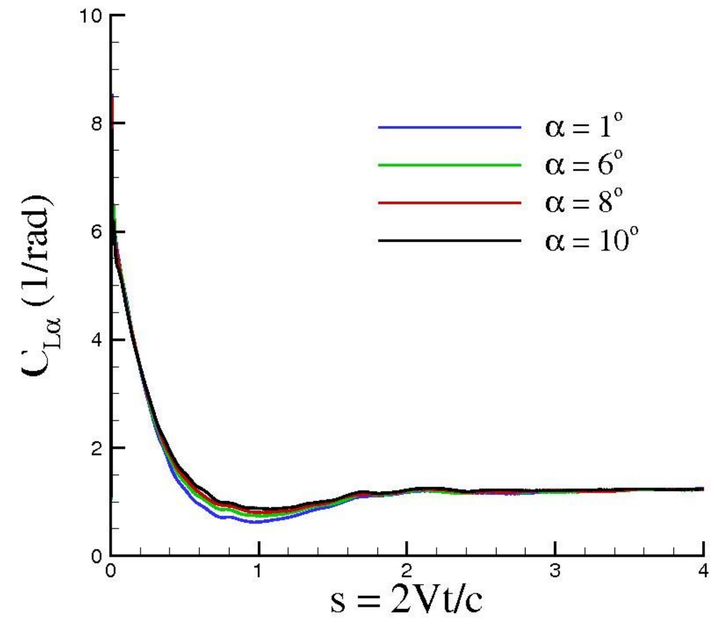
We assume forces and moments are symmetric about α =0 and therefore only positive angles were simulated



SACCON Indicial Functions



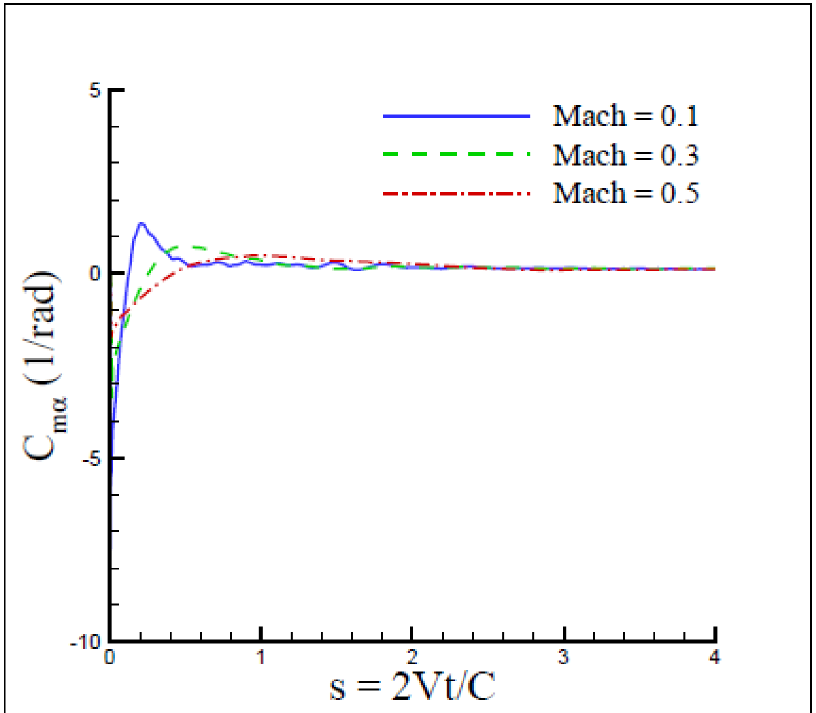
The initial peak decrease with increasing Mach number

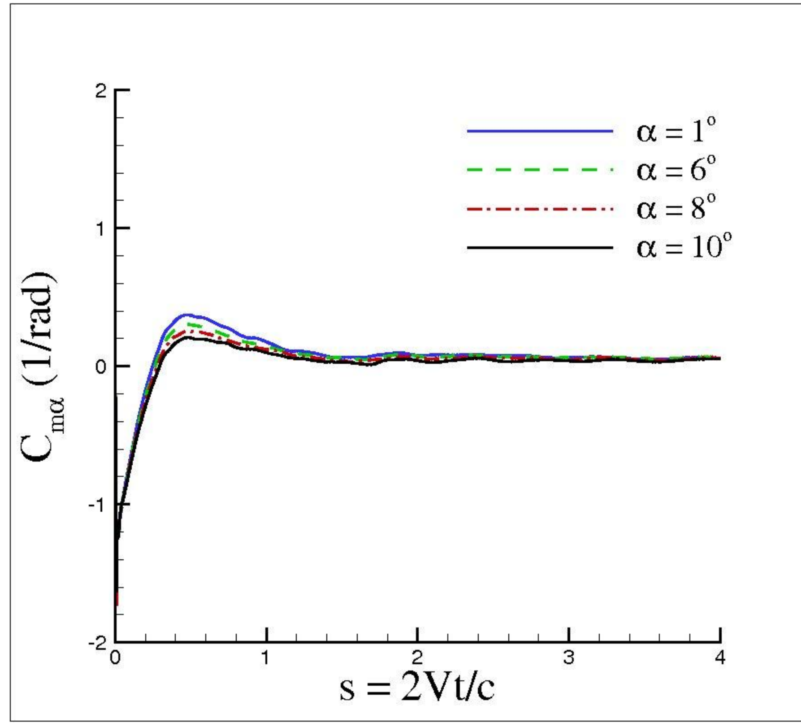


The final values are similar in the linear regime.

$$C_{L\alpha}(t - \tau, \alpha, M)$$

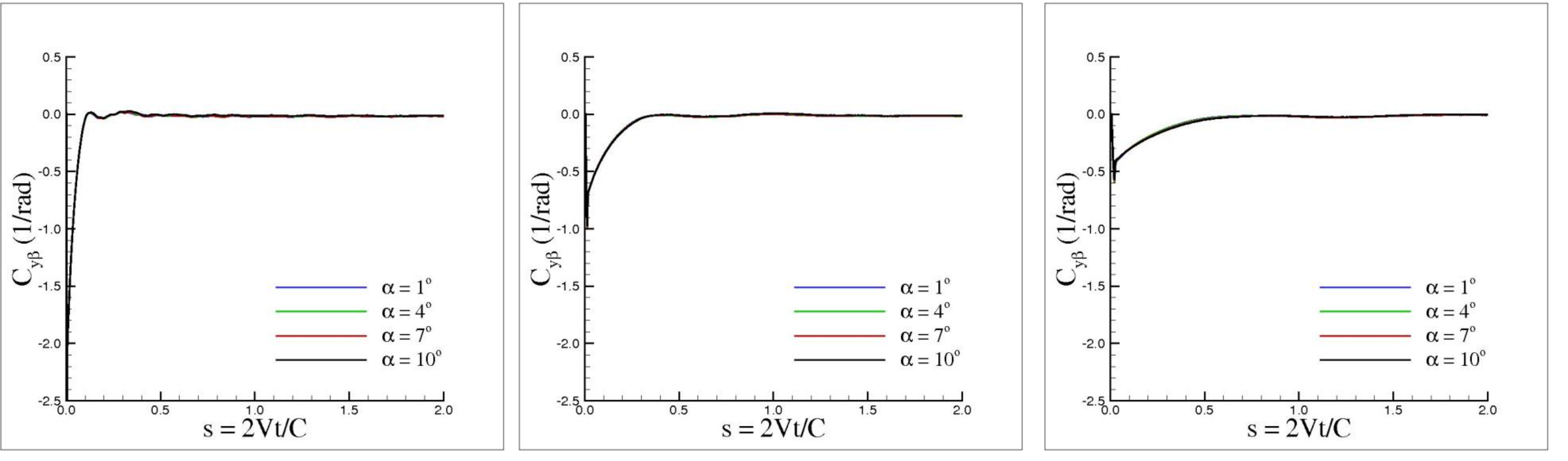
SACCON Indicial Functions





$$C_{m\alpha}(t-\tau, \alpha, M)$$

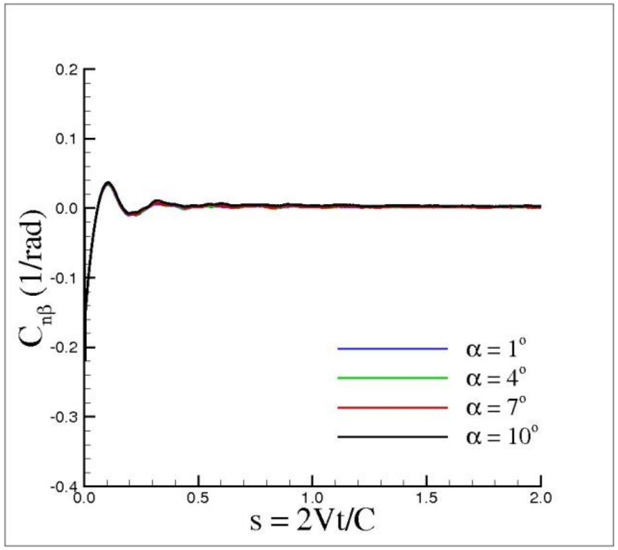
SACCON Indicial Functions

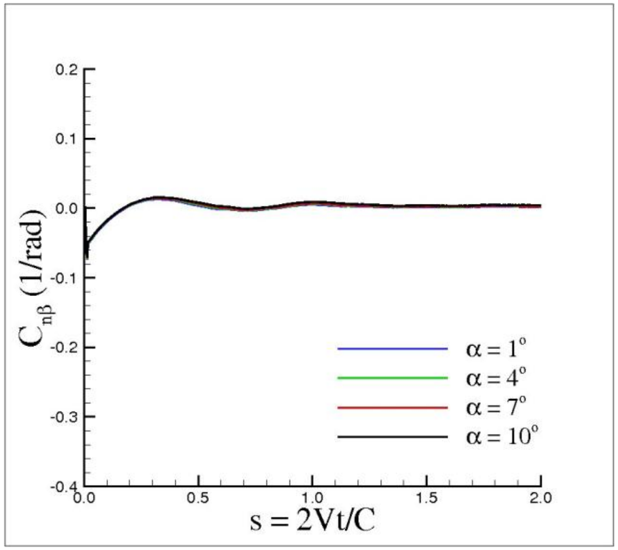


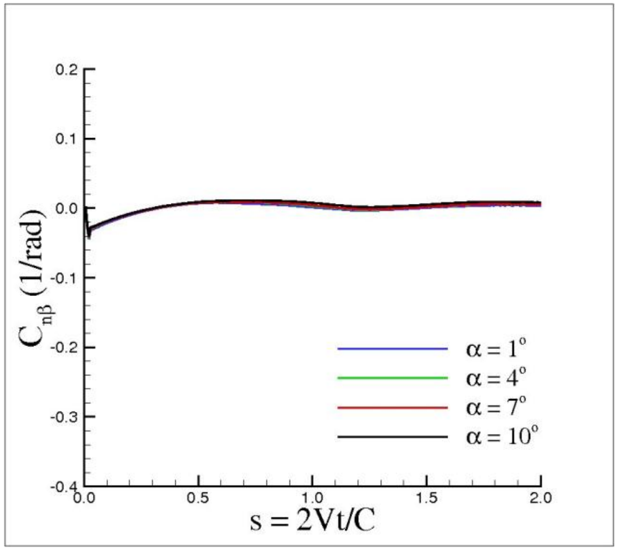
M= 0.1 M= 0.3 M= 0.5

$$C_{Y\beta}(t-\tau, \alpha, M)$$

SACCON Indicial Functions







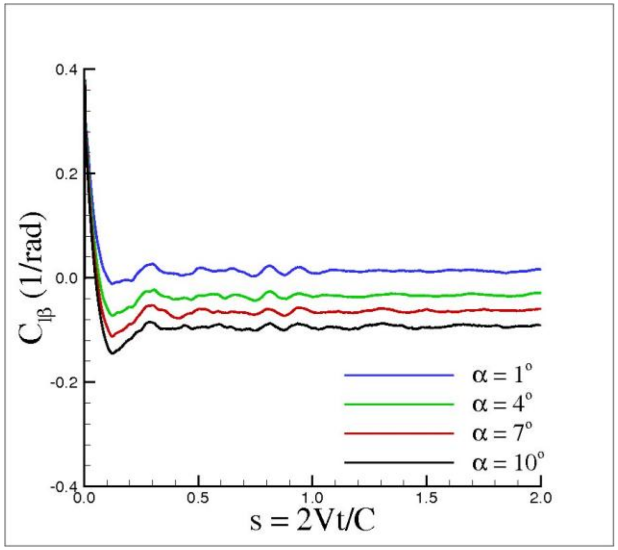
M= 0.1

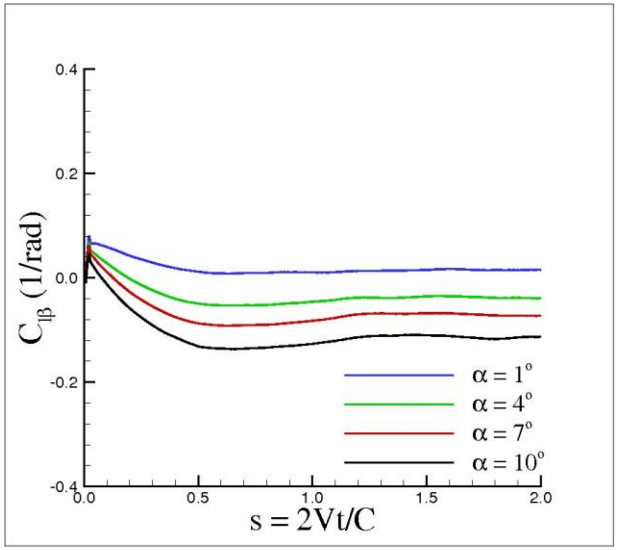
M= 0.3

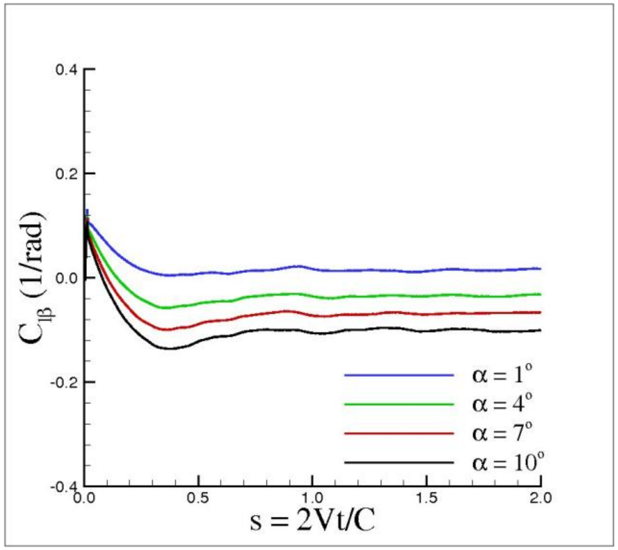
M= 0.5

$$C_{n\beta}(t-\tau, \alpha, M)$$

SACCON Indicial Functions







$$C_{l\beta}(t-\tau,\alpha,M)$$

The roll moment is very nonlinear vs angle of attack and Mach number

Generation of Manuevers

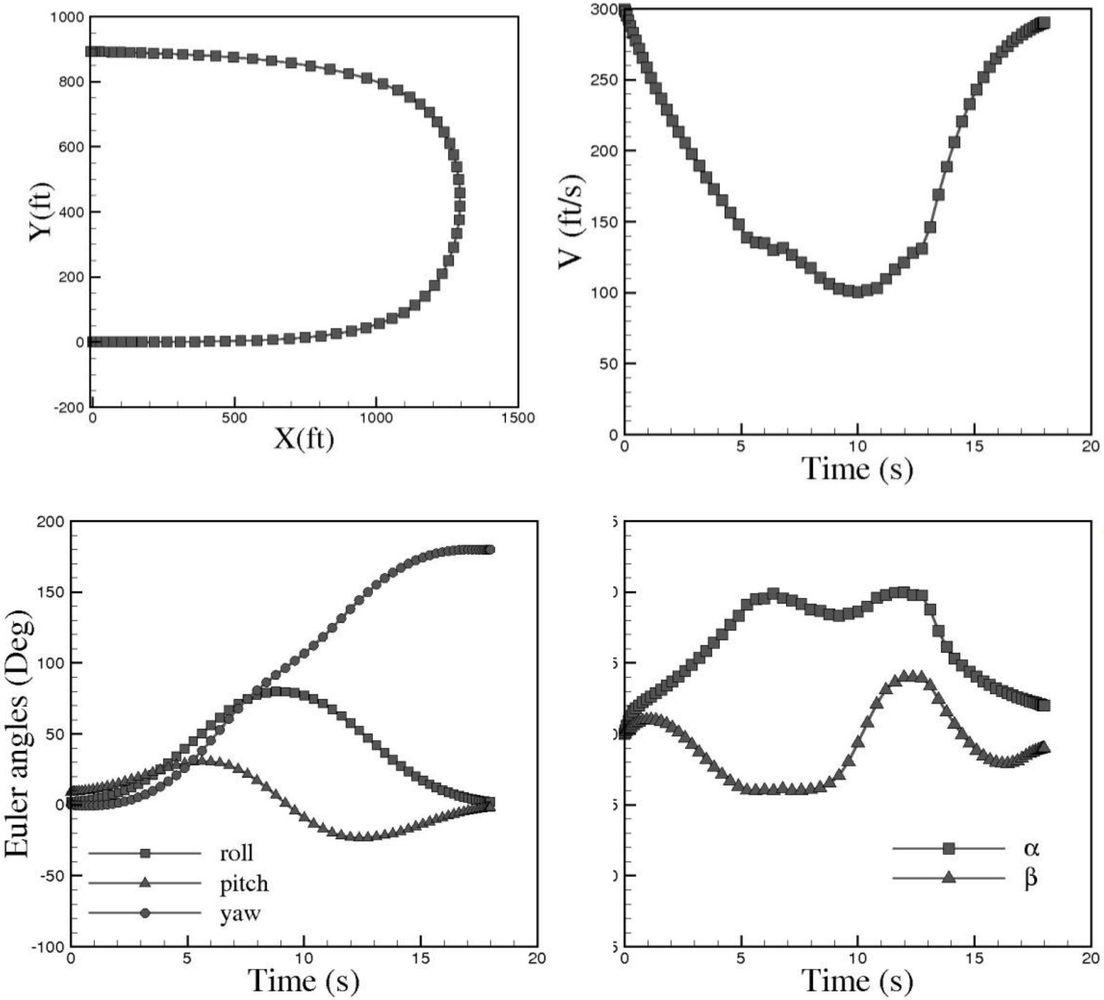
- **Indicial Functions ▸ Derivative-Based Model ▸ Aircraft Equations of motion**
  $C_L(t) = C_{L0} + C_{L\alpha}(t=\infty,\alpha,M)\alpha + C_{Lq}(t=\infty,M)q + C_{L\delta}.\delta$

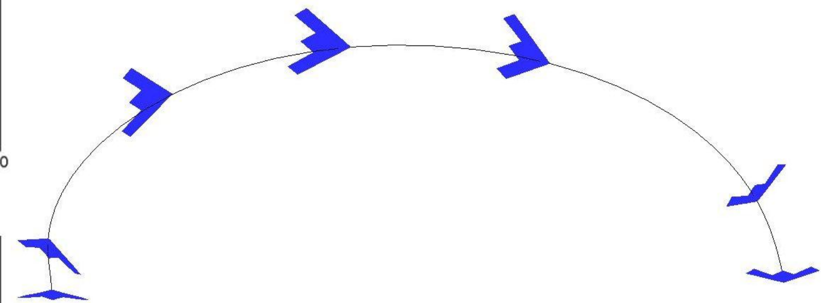
- **Validity of ROMs**
  Replay maneuvers through unsteady CFD calculation
  - **Compare forces/moments with ROM values**

Half Lazy Eight

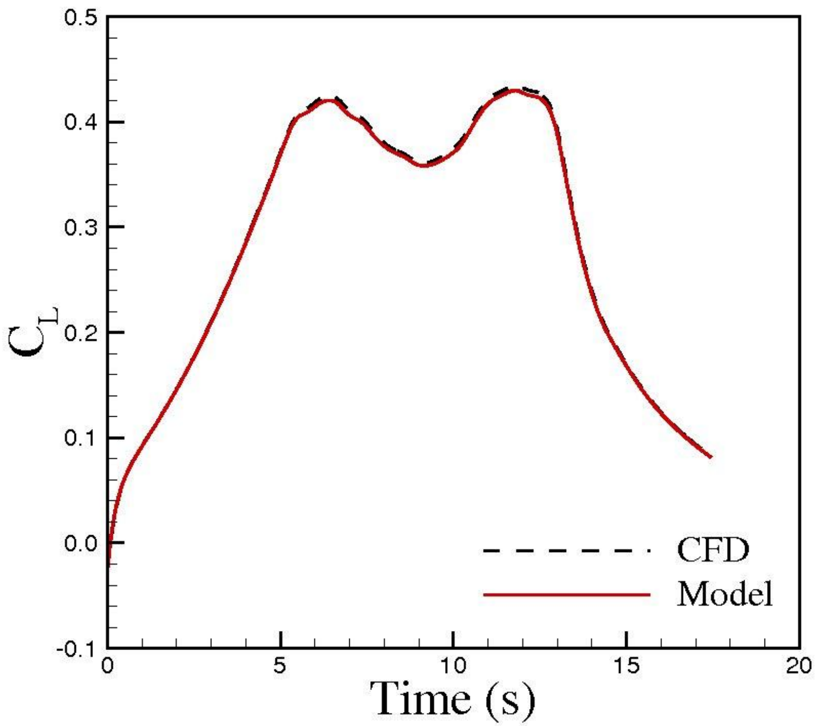
- **The aircraft performs a climbing and rolling followed by a diving turn until the final aircraft heading is 180^0 changed.**
  - **Initial Point: V=300 ft/sec, Alt= 10,000 ft, Yaw Angle = 0**
  - **Final Point: V=300 ft/sec, Alt= 10,000 ft, Yaw Angle = 180**
  - **Path constraints (maximum V, maximum AoA, rate of AoA, etc.) are defined.**

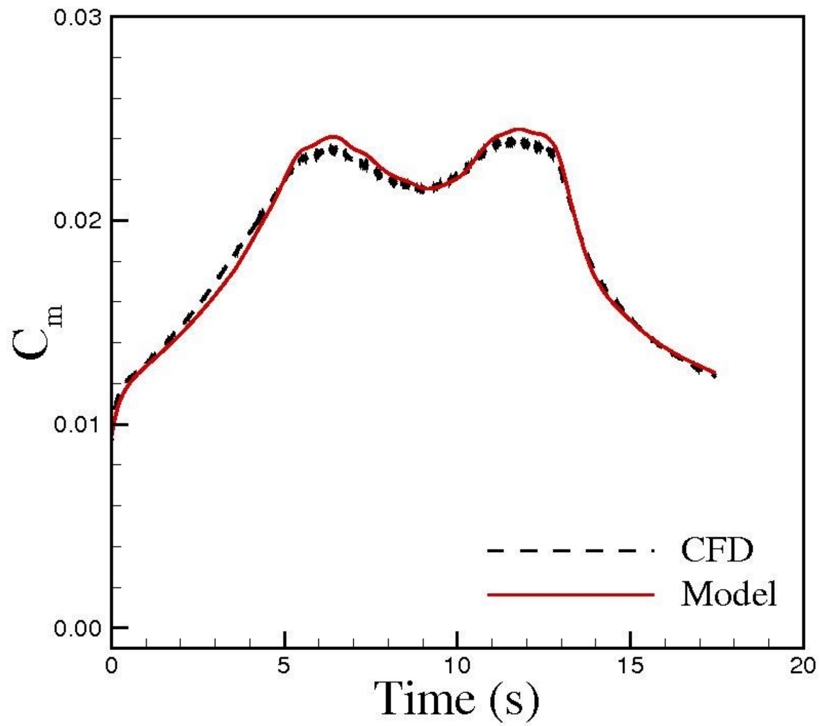
Half Lazy Eight



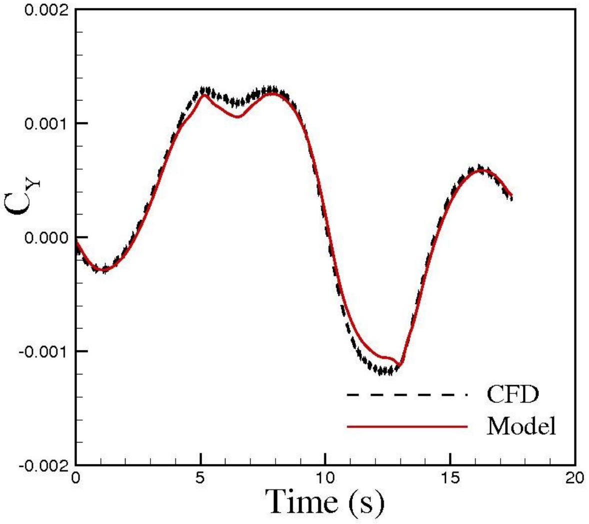


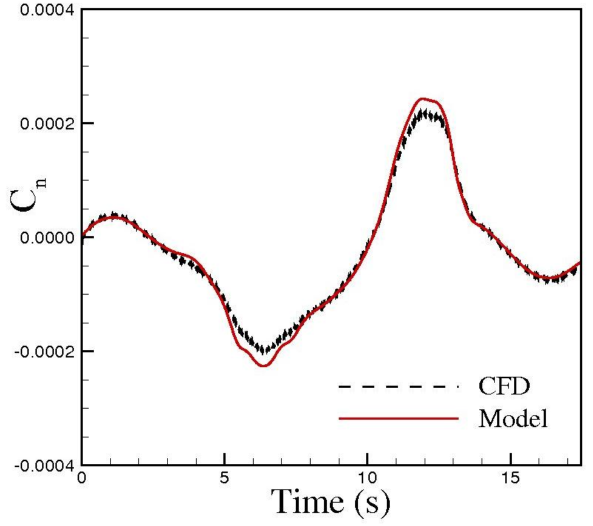
Half Lazy Eight

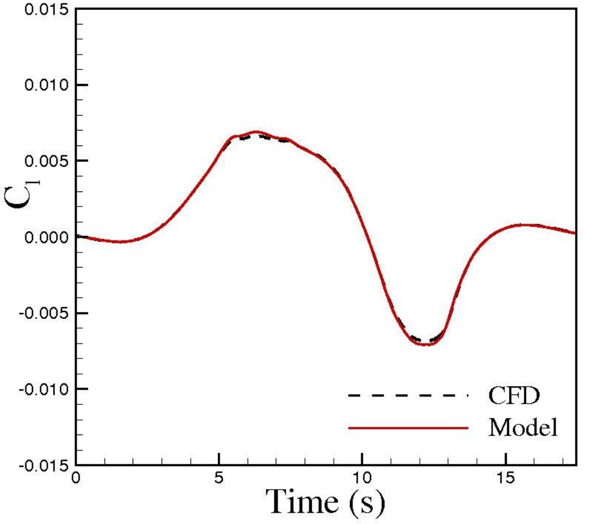




Half Lazy Eight







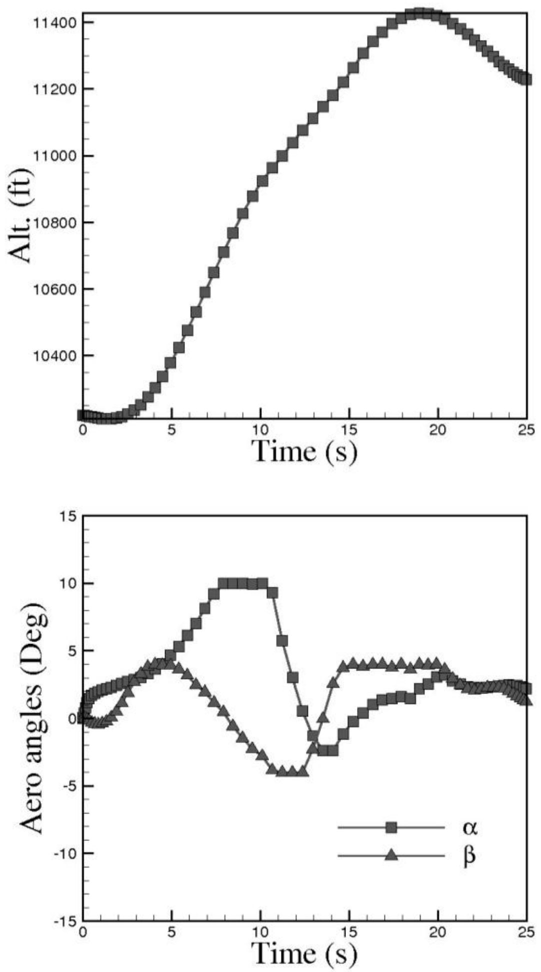
Full order model cost ~= 50,000 CPU Hrs

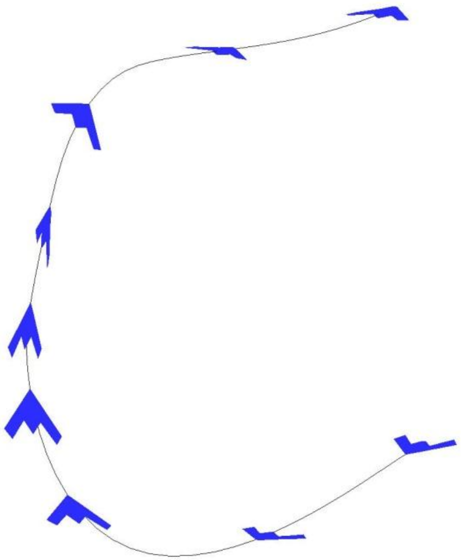
Immelman Turn

- Half loop with a half roll at end. Aircraft final path is exactly opposite of the initial path.

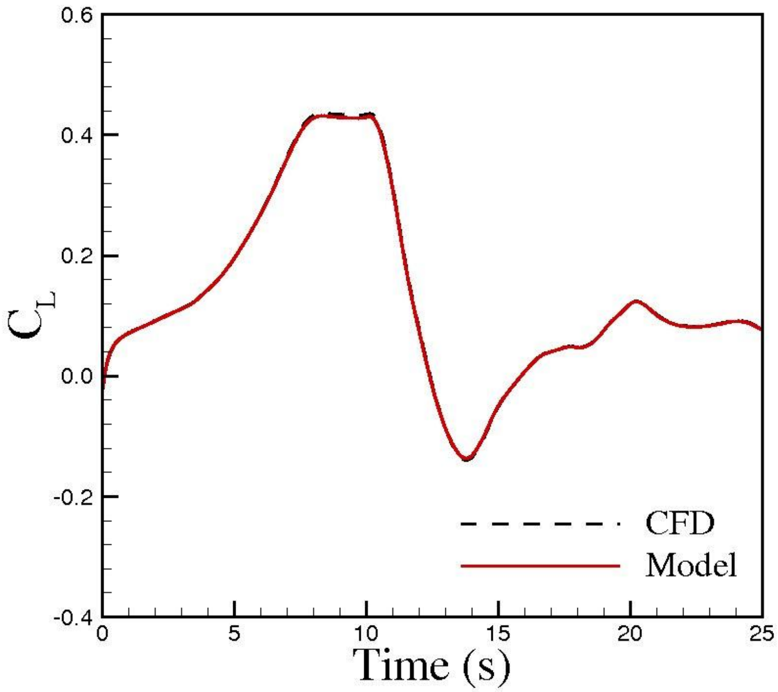
  - Initial Point: V=300 ft/sec, Alt= 10,000 ft, Yaw Angle = 0
  - Final Point: V=300 ft/sec, Alt= 11,000 ft, Yaw Angle = 180
  - Path constraints (latitude, maximum V, maximum AoA, rate of AoA, etc.) are defined.

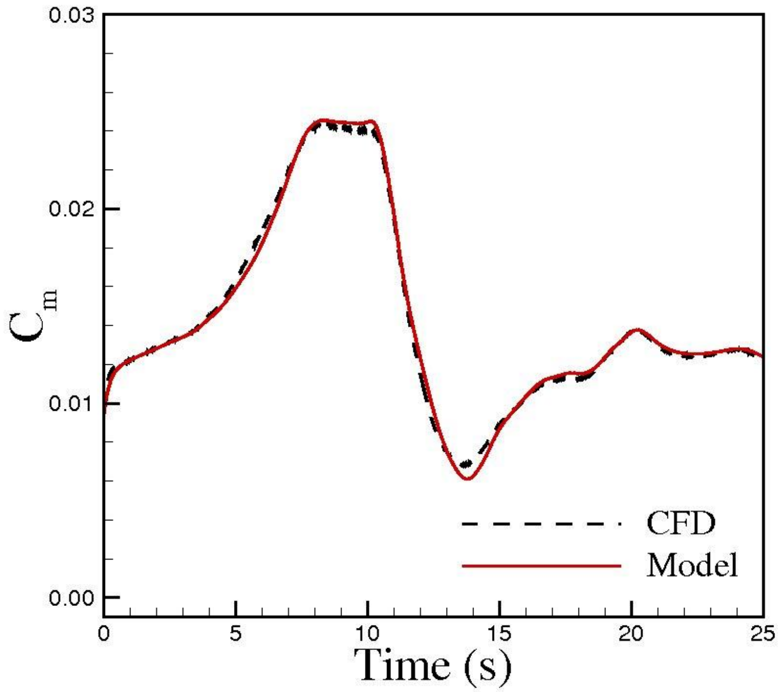
Immelman Turn



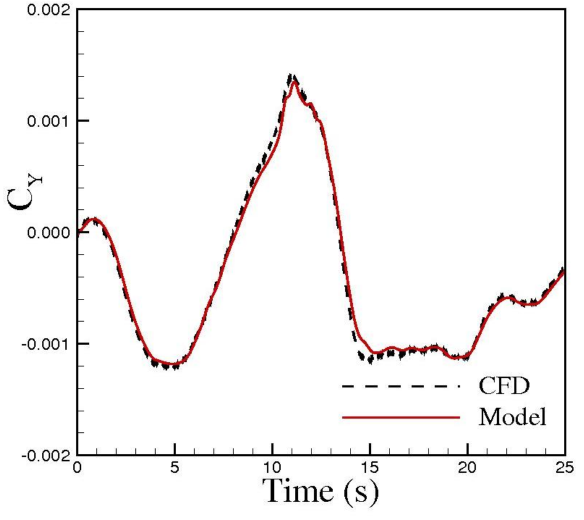


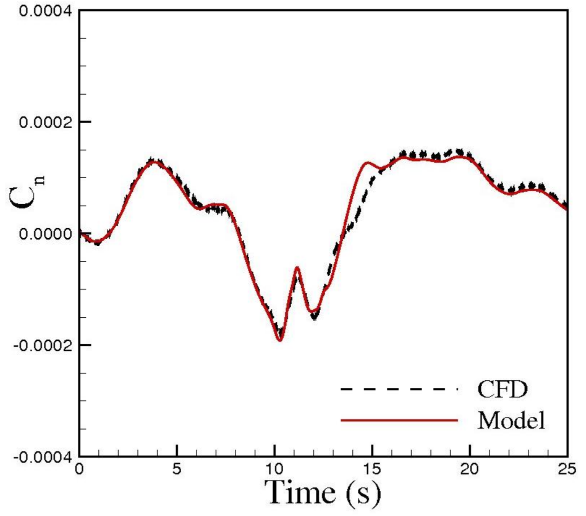
Immelman Turn

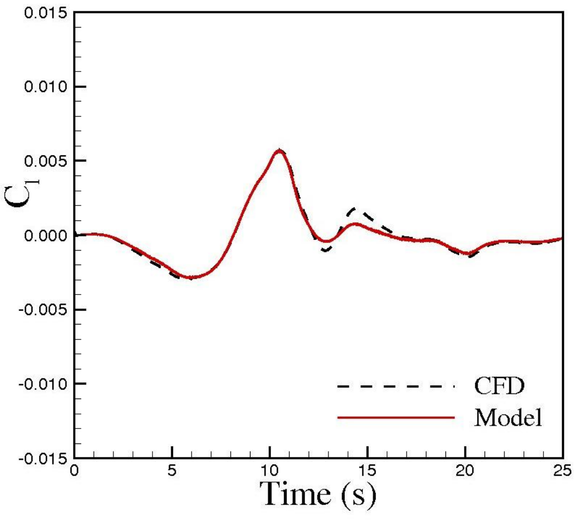




Immelman Turn



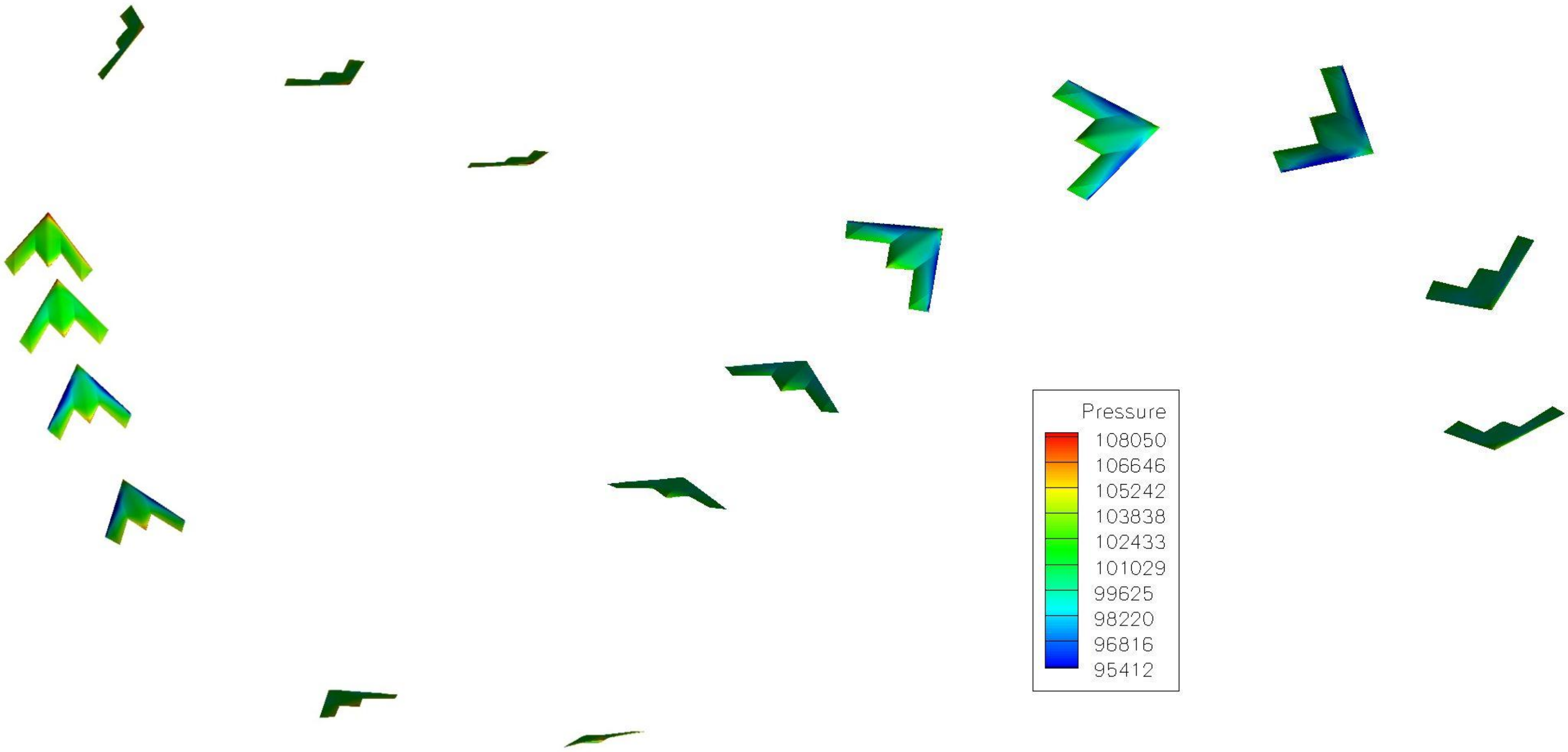




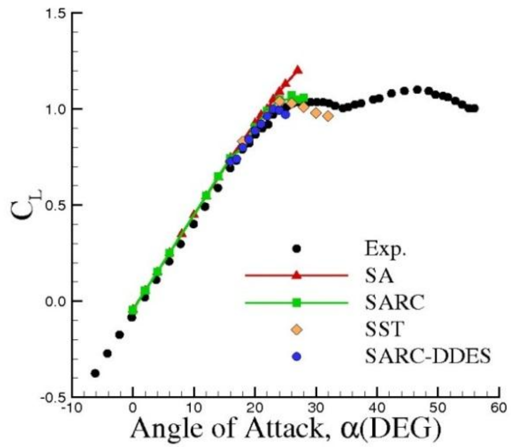
- **Discrepancies in roll / yaw moments (12s-16s)**
  - **Negative AOA – roll / yaw moments not symmetric about 0-deg AOA**

Full order model cost ~= 62,000 CPU Hrs

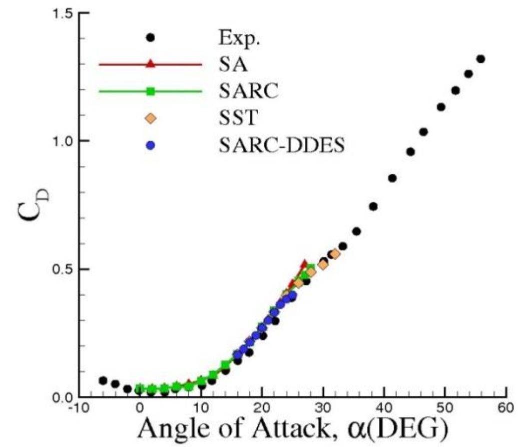
Immelman Turn



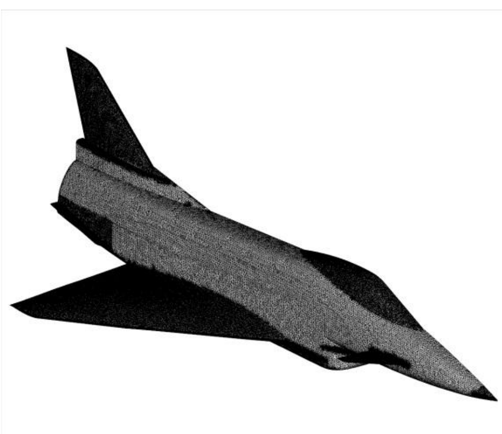
X-31

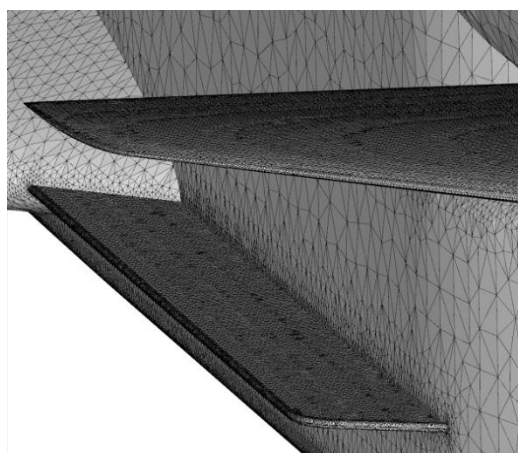


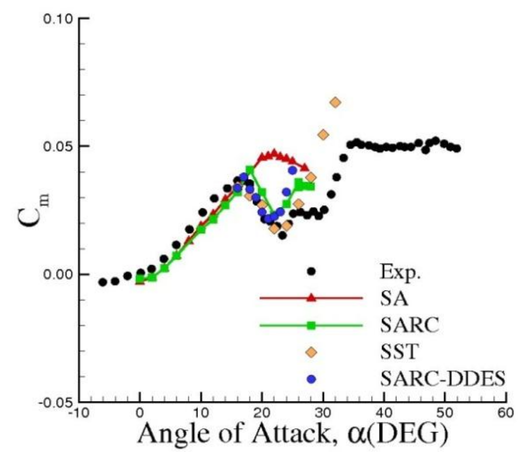
1.5
1.0
0.5
0.0
-0.5
C_L
-10
0
10
20
30
40
50
60
Angle of Attack, α(DEG)
Exp.
SA
SARC
SST
SARC-DDES



1.5
1.0
0.5
0.0
C_D
-10
0
10
20
30
40
50
60
Angle of Attack, α(DEG)
Exp.
SA
SARC
SST
SARC-DDES

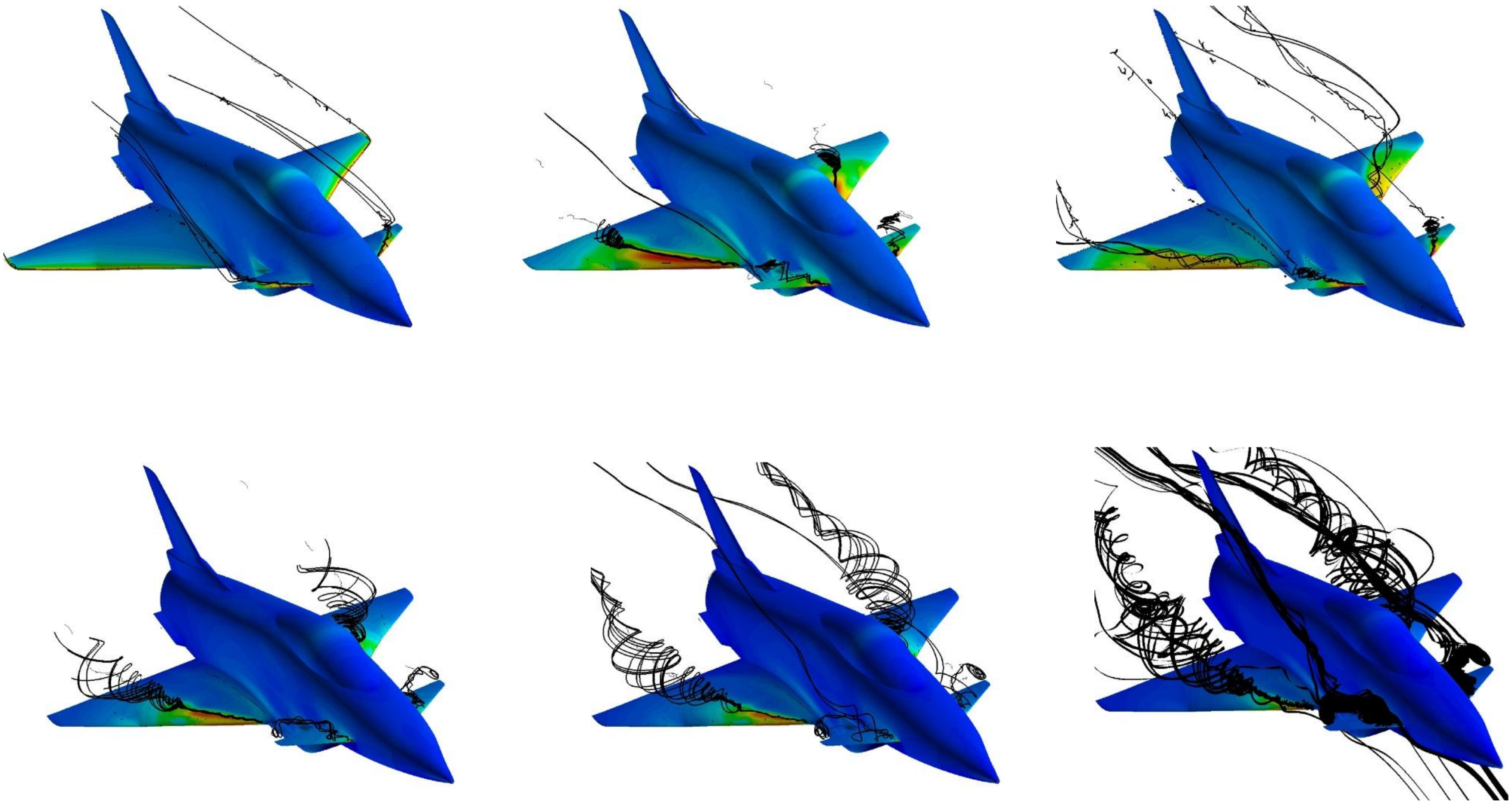






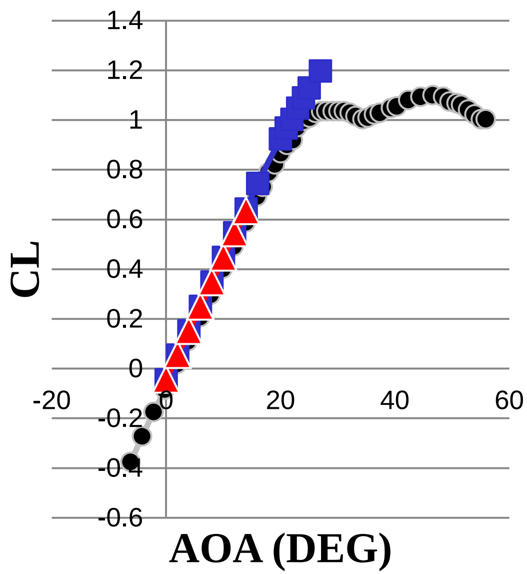
0.10
0.05
0.00
-0.05
C_m
-10
0
10
20
30
40
50
60
Angle of Attack, α(DEG)
Exp.
SA
SARC
SST
SARC-DDES

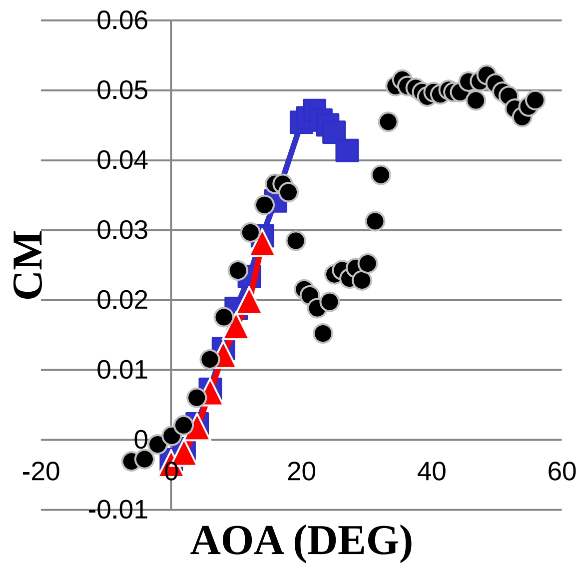
X-31

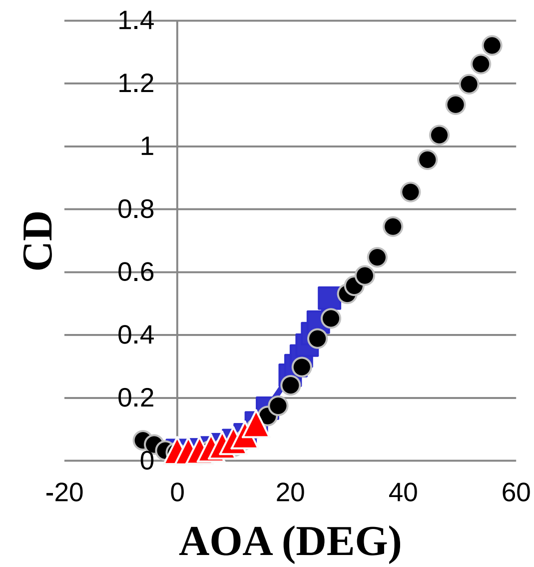


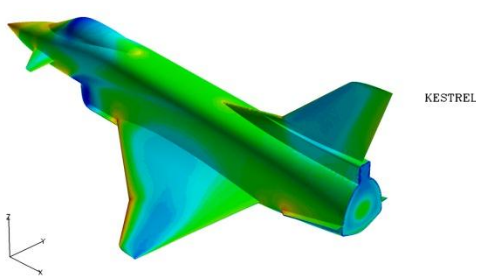
X-31: Kestrel vs Cobalt

(C1C Alex Kim)

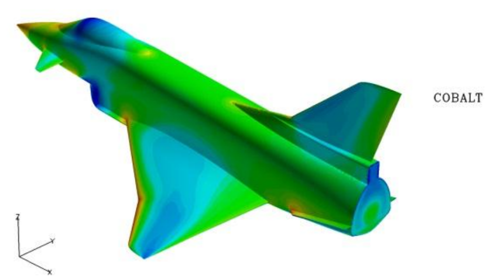






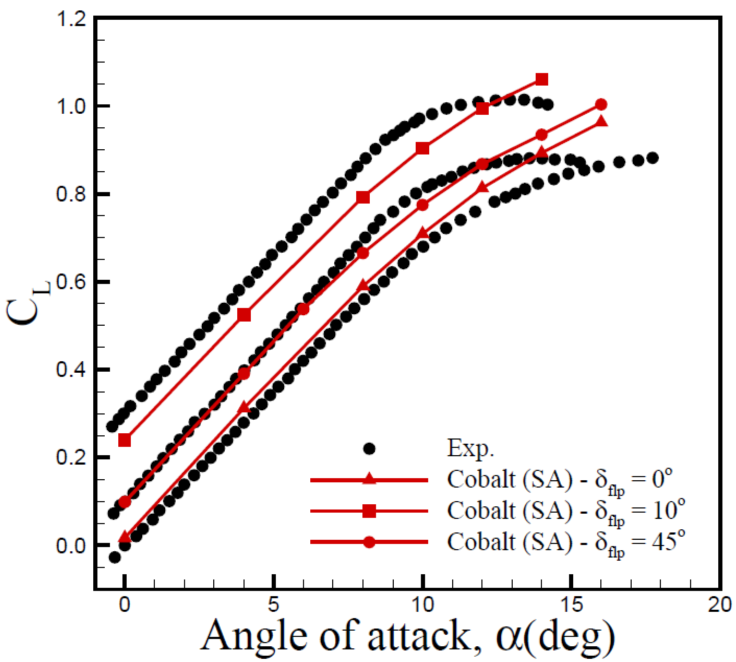


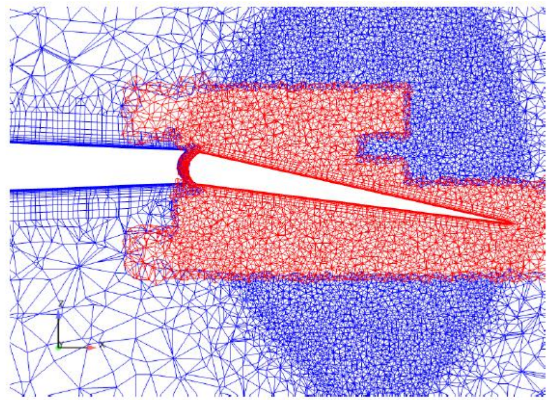
Exp
Cobalt SA
Kestrel SA



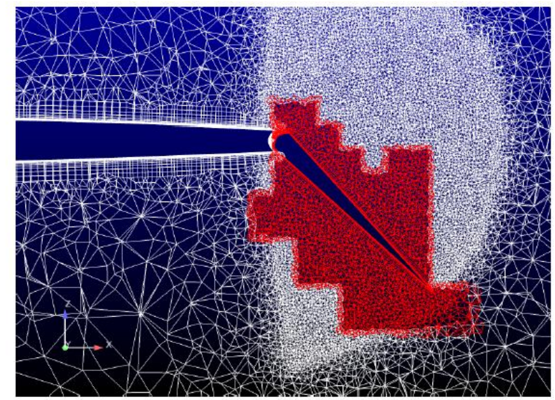
Integrity - Service - Excellence

Control Surfaces

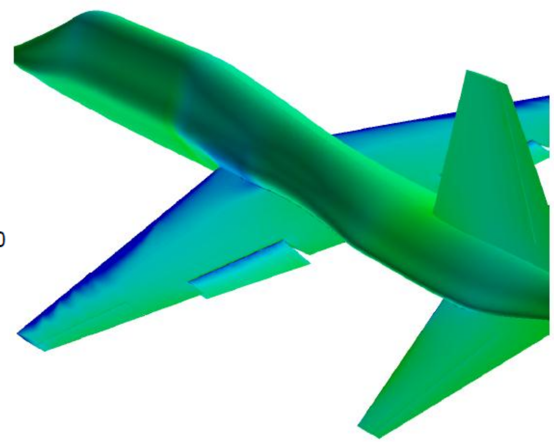


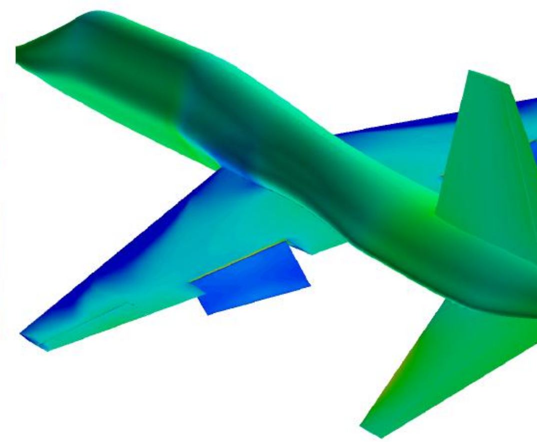


(a) Overset grid for $\delta = 10^o$

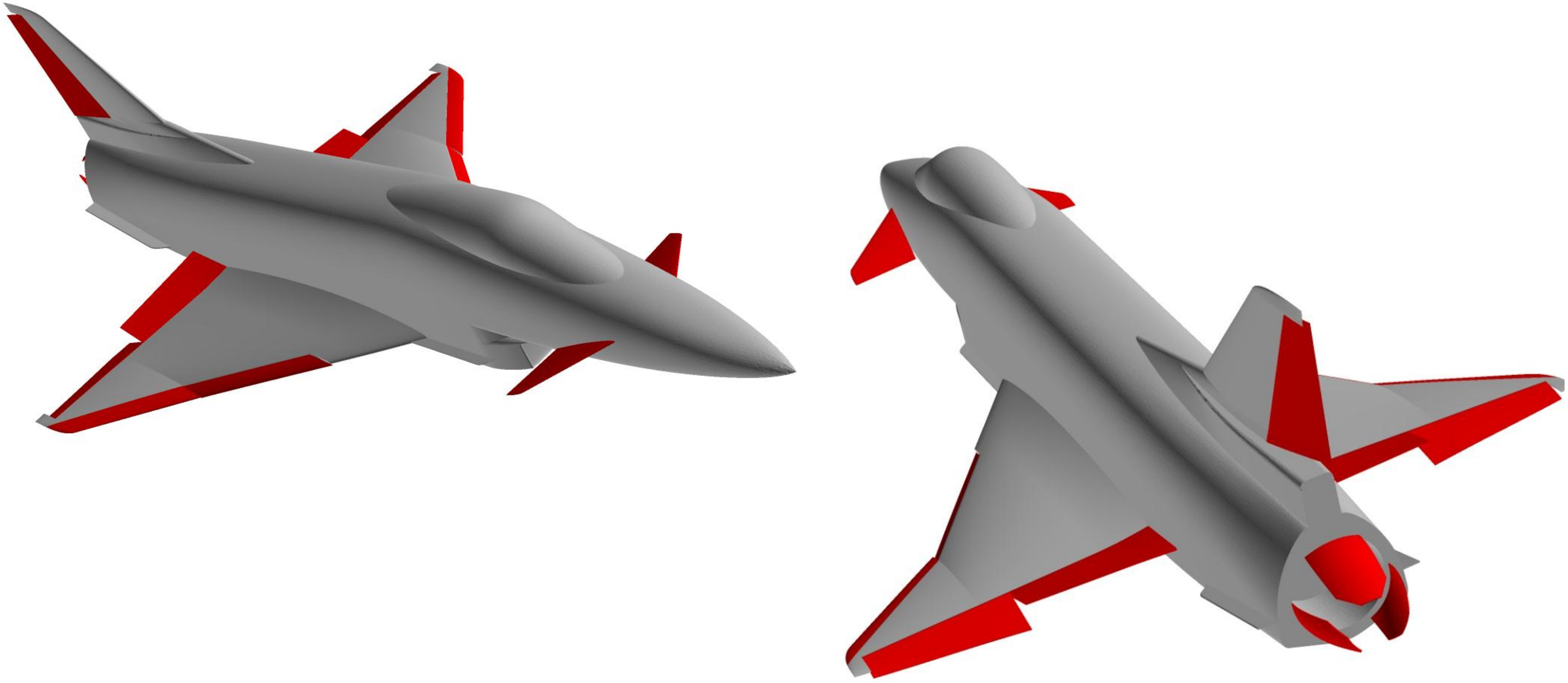


(b) Overset grid for $\delta = 45^o$



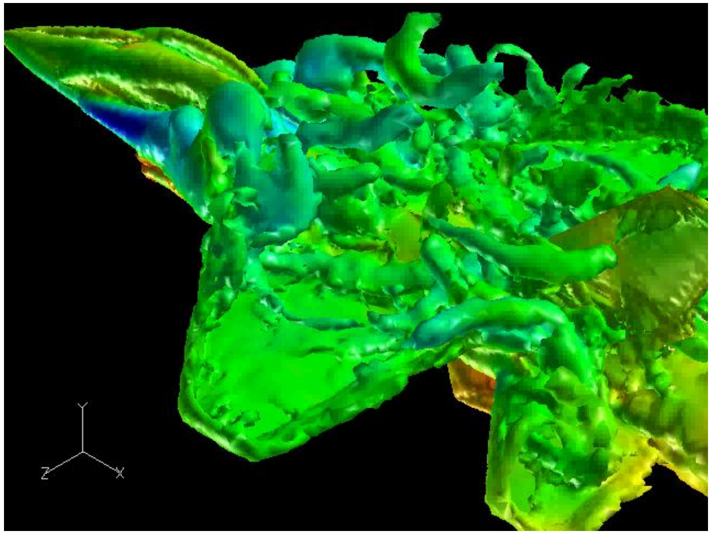


X-31 Control Surfaces



Summary

- Heritage
  - Full aircraft, 3D, unsteady
  - DoD HPC resources
  - Kestrel
- Computational across the curriculum
  - AE 342 (required)
  - AE 472 / 499 (cadet involvement in research)
- Stability & Control Estimation Methods
  - NATO STO Task Group



Acknowledgements

- Dr. Scott Morton (founding MSRC director, principle Kestrel developer)
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- Dr. David McDaniel (former MSRC researcher, principle Kestrel developer)
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- Dr. Mehdi Ghoreyshi (MSRC Researcher)
- C1C Ben Kramer
- C1C Alex Kim
- C1C Josh Rivey

Questions?