# Rapid Aero Modeling of a Lift+Cruise UAM Configuration for Stability & Control Using Overset Grid CFD

*Pieter G. Buning, Benjamin M. Simmons, and Patrick C. Murphy (ret)*

*NASA Langley Research Center*

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# Talk Outline

- Background: Lift+Cruise vehicle, RAM process
- CFD grid and modeling considerations
- Converting input conditions to CFD simulations
- Parallel processing and convergence assessment
- Results
- Conclusions and lessons learned

# NASA Revolutionary Vertical Lift Technologies (RVLT) Urban Air Mobility (UAM) Lift+Cruise Reference Vehicle

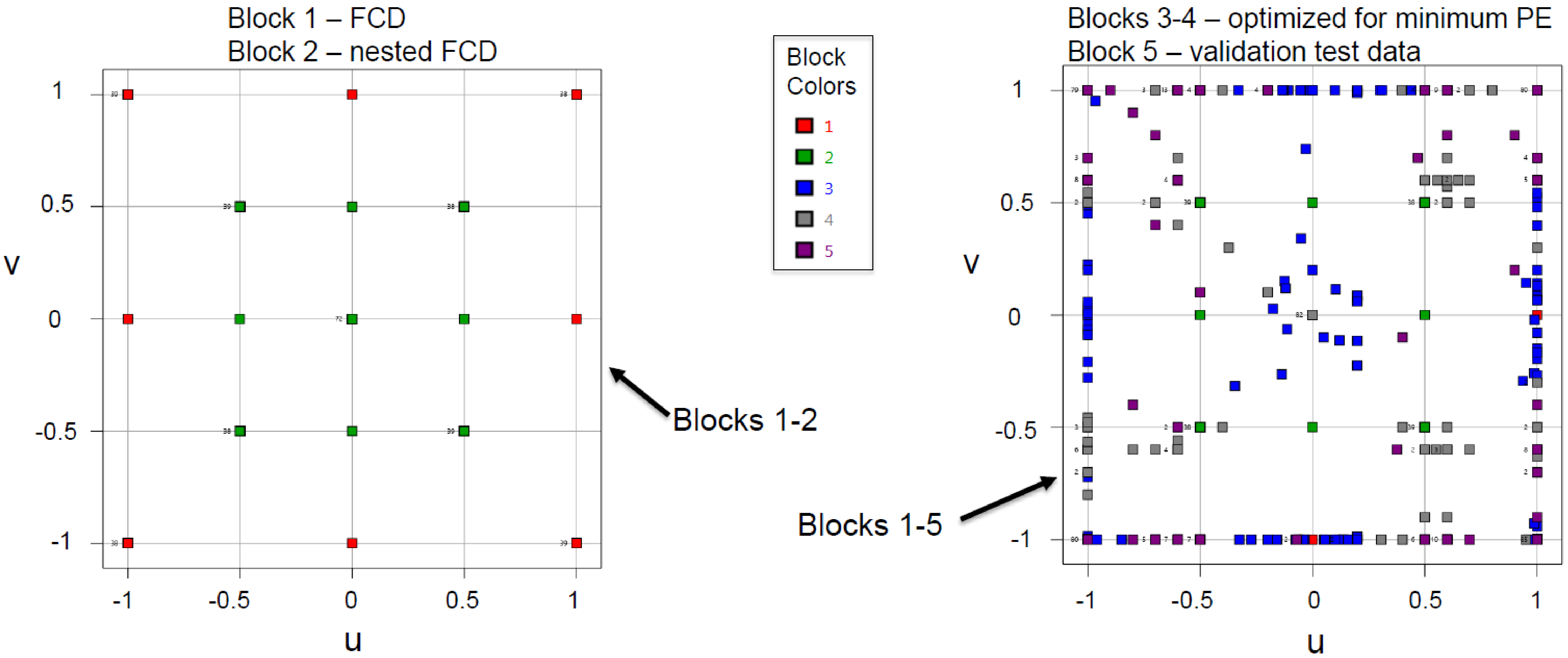
- 6-passenger VTOL, 5000 lb design GW
- Here we treat rotors as fixed-pitch, variable RPM
- Ref: C. Silva, W. Johnson, K.R. Antcliff, and M.D. Patterson, “VTOL Urban Air Mobility Concept Vehicles for Technology Development,” AIAA-2018-3847, June 2018.
- Image ref: https://sacd.larc.nasa.gov/uam-refs (OpenVSP and NDARC models available)

# Rapid Aero Modeling (RAM) Process

- Combination of Modern Design of Experiments (MDOE) and response surface modeling, coupled with process error estimation
- Can be applied with test or computational data as input (RAM-T or RAM-C)
- Refs:
  - P.C. Murphy, P.G. Buning, and B.M. Simmons, “Rapid Aero Modeling for Urban Air Mobility Aircraft in Computational Experiments,” AIAA-2021-1002, Jan. 2021.
  - B.M. Simmons, P.G. Buning, and P.C. Murphy, “Full-Envelope Aero-Propulsive Model Identification for Lift+Cruise Aircraft Using Computational Experiments,” AIAA-2021-3170, Aug. 2021.

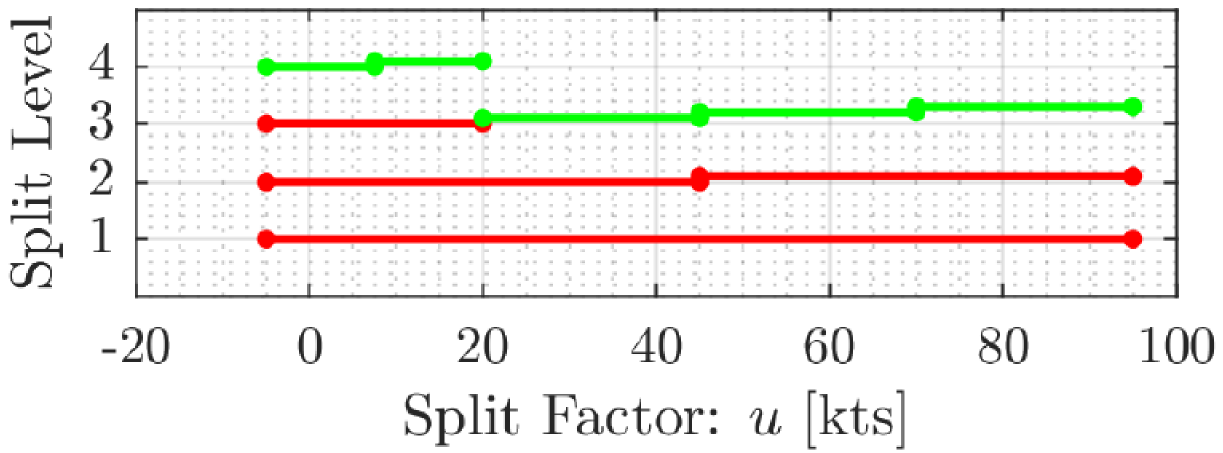
# RAM Design for L+C, 17-factor Test

- 17 Factors: 3 velocity components, 5 control deflections, 8 lift fan RPMs, 1 prop RPM
- 5 Blocks (factors are scaled to +/-1), 858 test points



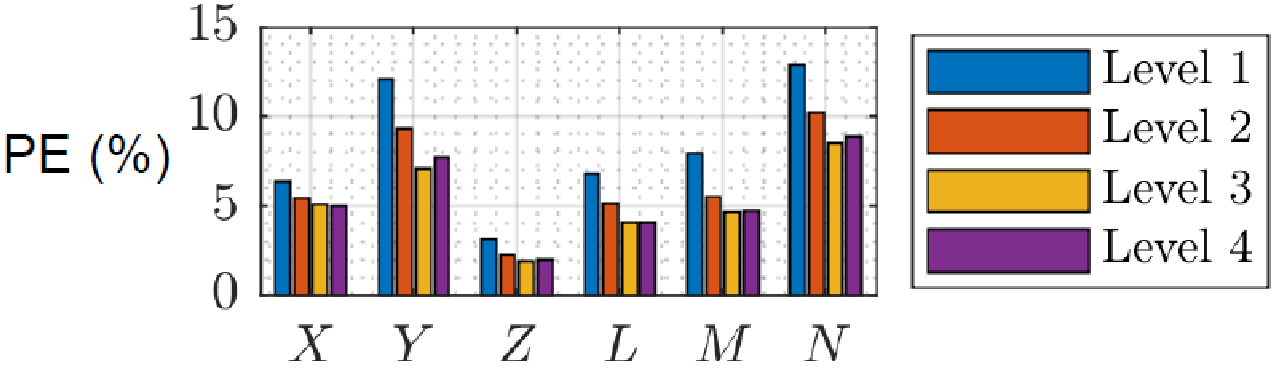
# Speed-Regime Splits & PE Metric for L+C Study

- Test regions are split when models fail prediction goals.
  - Satisfactory model – green bars.
  - Unsatisfactory model – red bars.



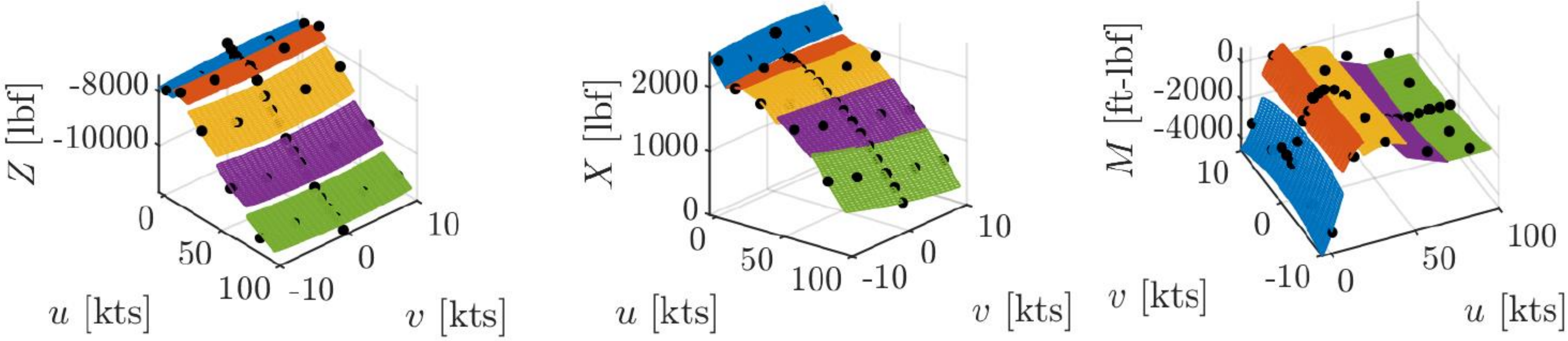

- Regions are halved to improve data density & model fidelity.

- In final analysis for L+C study, 4 split levels were required, resulting in 5 separate modeling regions.



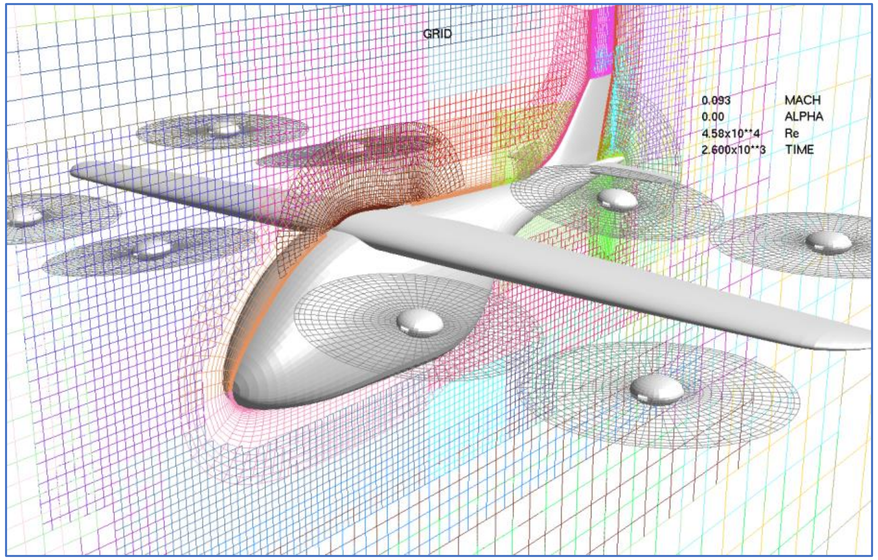
# Split-Region Models

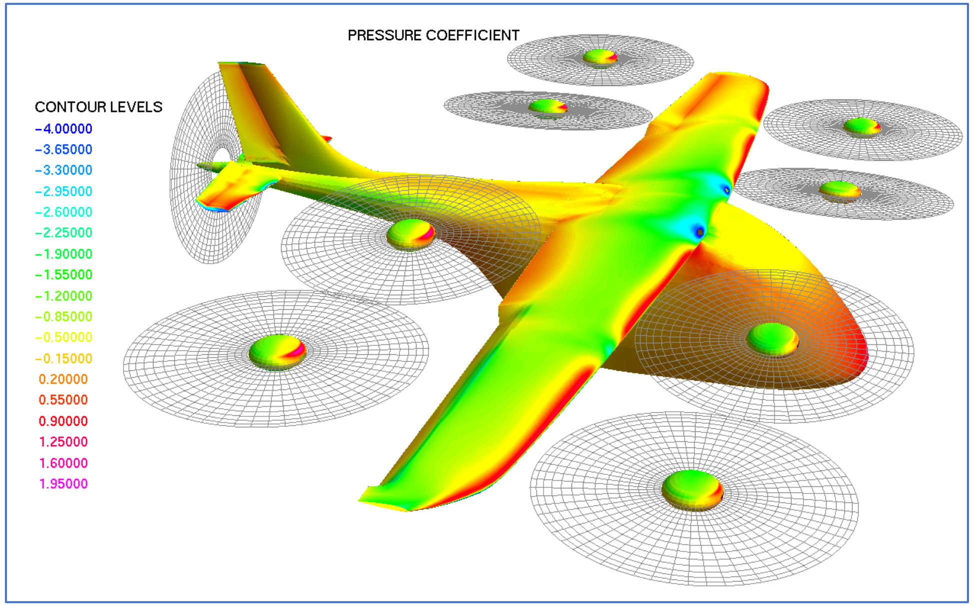
- L+C Longitudinal response models for separate regions as functions of (u, v).



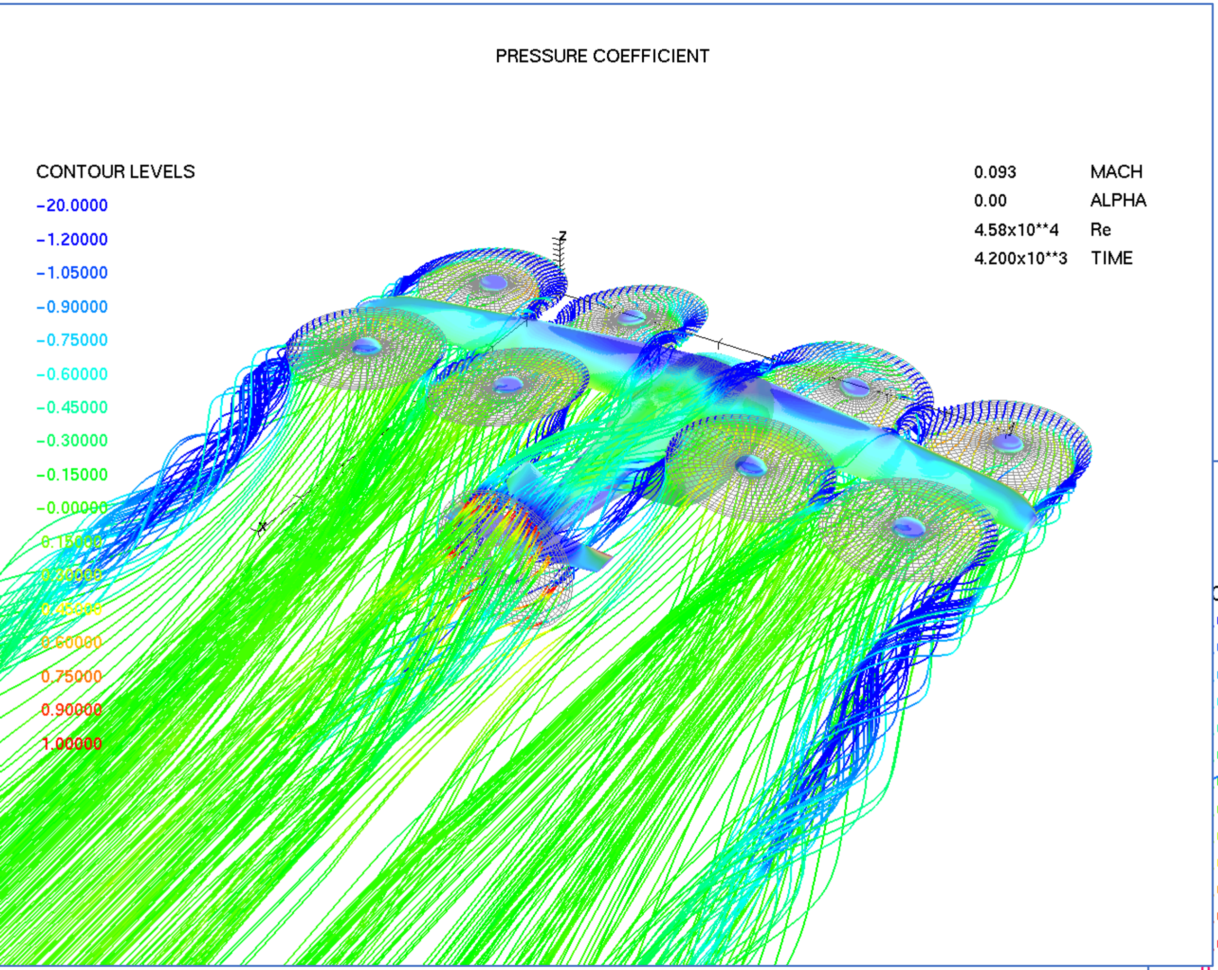
# CFD Grid and Modeling Approaches

- Use coarse grids (e.g., x points around airfoil)
- Old-style gridding techniques: axis singularities, collapsed grid at wing and tail tips
- Rotor disk model (rough effect of rotors, steady-state)
- Deform wing and tail surfaces for deflected ailerons, rudder and elevator
- Ignore some geometry (no pylons, no landing gear)
- Steady-state simulations (not time-accurate)
- No DES turbulence model (even with separated flow)
- **Resulting grid system is ~4 Mpts, typical run is 4200 iterations**

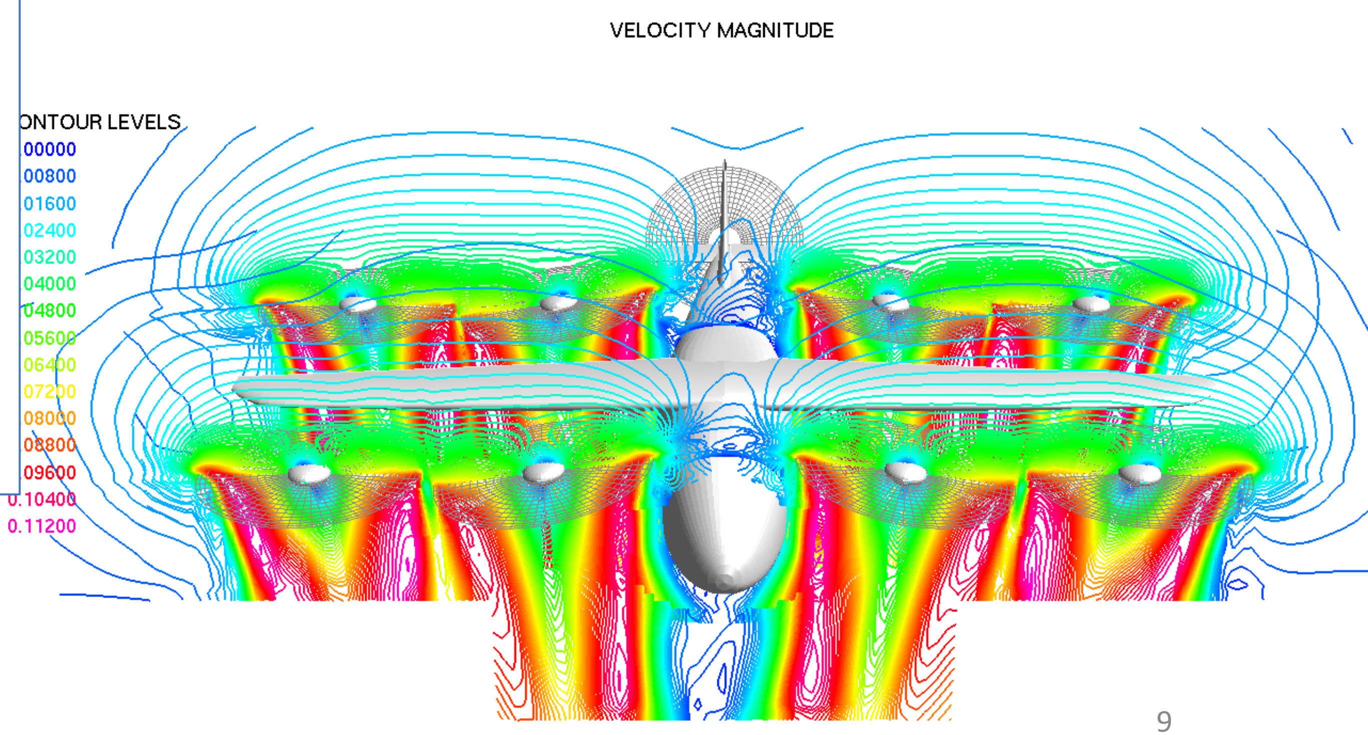


# CFD Grid and Modeling Approaches




Hover case: lift fans running, no propeller. Velocity magnitude contour slices through forward and aft lift fans



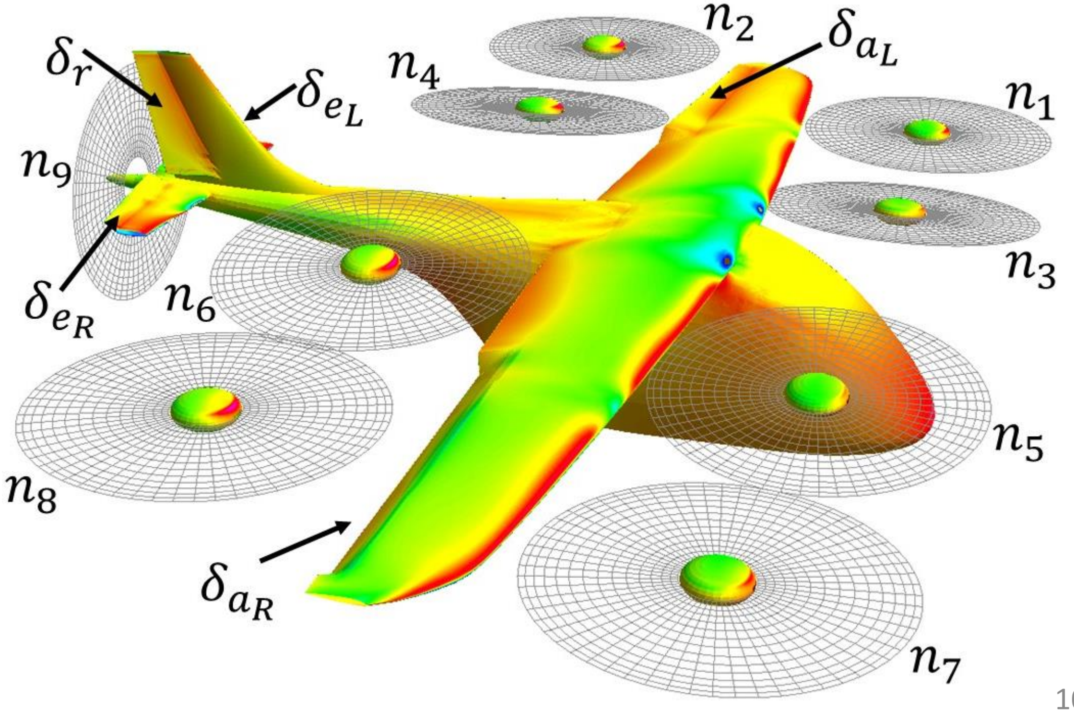

Transition case: forward flight with lift fans and propeller running. Particle traces colored by $C_p$, released at lift fan tips

# Operational Process

- Flight conditions specified as (Mach,alpha,beta), or (u,v,w)?
- Output as force and moment coefficients, or dimensional values?
- 17-factor input conditions given in Excel spreadsheet, converted to text file
- Script system converts
  - (u,v,w) into (Mach,alpha,beta) in OVERFLOW input file
  - Rotor and propeller RPMs into rotor disk input tip Mach numbers
  - Control surface deflections into grid generation script input

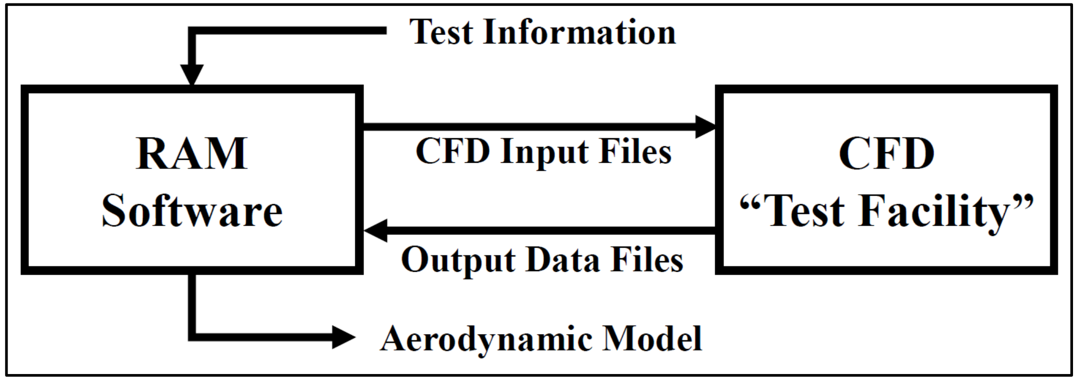
14 available control effectors

- Lifting rotors $(n_1, n_2, \ldots, n_8)$
- Pusher propeller $(n_9)$
- Ailerons $(\delta_{a_L}, \delta_{a_R})$
- Elevators $(\delta_{e_L}, \delta_{e_R})$
- Rudder $(\delta_r)$

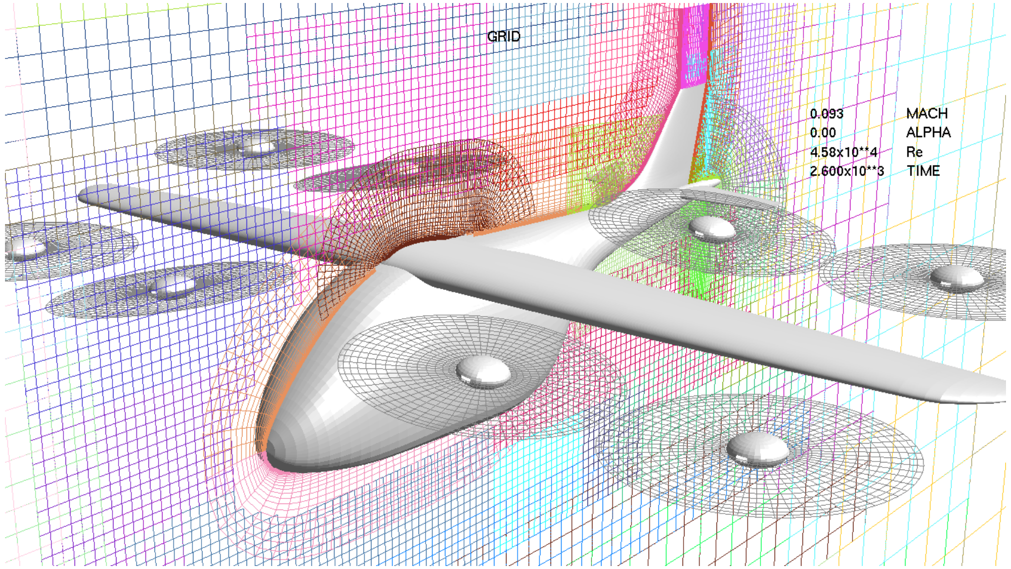


# RAM Applied to Computational Experiments

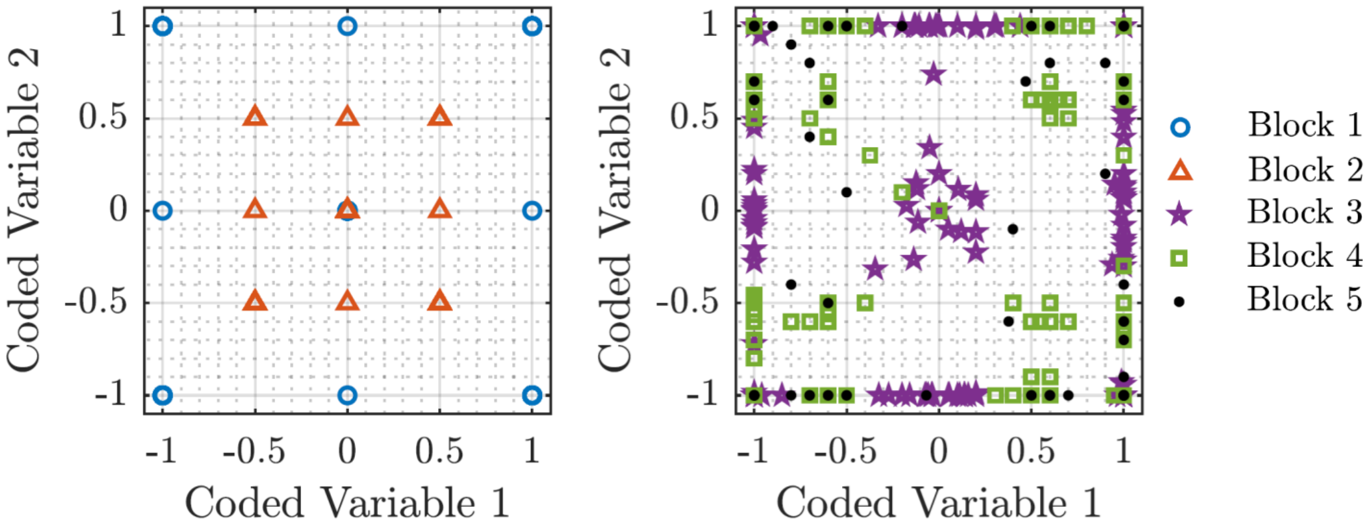
- Rapid Aero Modeling (RAM) software utilized for Lift+Cruise aero-propulsive modeling
  - Statistically rigorous, efficient, and automated testing process for computational experiments (as well as wind tunnel testing)
  - Factor space partitioning and blending logic enables modeling complex aerodynamic phenomena over a large range of flight conditions
  - More details are in AIAA Papers 2021-1002 and 2021-1644
- NASA OVERFLOW CFD code used as a RAM "test facility"




**RAM/CFD modeling process overview.**




**CFD overset grid system for Lift+Cruise.**

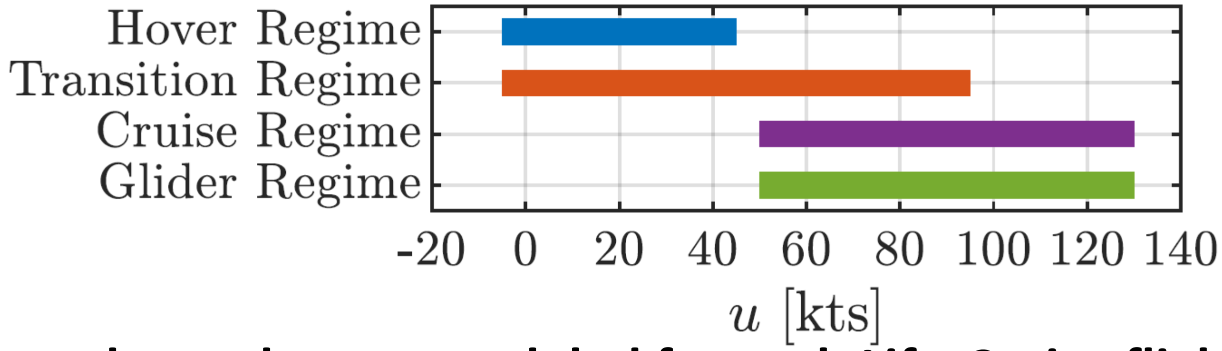



**2D slice of 17-factor RAM DOE test blocks.**

# Lift+Cruise Flight Regimes Used for Modeling

Lift+Cruise full-envelope model development was performed in distinct flight regimes based on which propulsors are active.

- **Hover Regime:** low-speed rotorcraft/multirotor-like flight (lifting rotors enabled and pusher propeller disabled)
- **Transition Regime:** low- and high-speed flight transitioning from rotorcraft-like flight to airplane-like flight (lifting rotors enabled and pusher propeller enabled)
- **Cruise Regime:** high-speed airplane-like operation (lifting rotors disabled and pusher propeller enabled)
- **Glider Regime:** high-speed airplane-like operation without any propulsion




**Forward speed range modeled for each Lift+Cruise flight regime.**

# Operational Process (2)

Parallel processing:

- Typical batch run has 50 nodes, 20 cpus/node, 2 hr wall time
- Each node runs one case
- Mid-range compute system can run 4 batch runs simultaneously
- Typical 17-factor, 5-block set has 858 cases: 10-20 hr wall time total, depending on availability

Convergence evaluation:

- Given fairly rapid turnaround, use simple checks to judge convergence of a large set of runs
- Over last 20% of force history, compute standard deviation of (all) force & moment coefficients
- Compute average slope of force & moment coefficient histories, normalized to 1000 steps
- Compare both to % of estimated “full-scale” coefficient values
  - What is a “full-scale” value?
  - Level of convergence can vary greatly between hover and forward flight

# Convergence Evaluation

Convergence for sample case (u,v,w)=(2.5,-1,-5) kt, with lift fans and propeller

Statistics measured over 840.0000 steps, with 840 samples.

| Curve | Final | Average | Std Dev | Slope | Ratio | Ratio2 |
|---|---|---|---|---|---|---|
| CFz | 514.9 | 515.6 | 0.5748 | -0.2350E-02 | 0.002 | 0.005 |
| CFx | -148.7 | -149.0 | 0.1740 | -0.1690E-03 | 0.002 | 0.001 |
| CMy | -158.4 | -164.3 | 3.251 | 0.1329E-01 | 0.040 | 0.081 |
| CFy | 9.073 | 9.317 | 0.2350 | -0.9527E-03 | 0.050 | 0.102 |
| CMx | 22.80 | 22.42 | 0.1790 | 0.5042E-03 | 0.016 | 0.022 |
| CMz | -3.072 | -2.860 | 0.2187 | -0.8622E-03 | 0.153 | 0.301 |

**"Ratio"** is 2σ measure over sample period;
**"Ratio2"** is slope*1000 steps;
both normalized by average value or "normal" value

Convergence for sample case (u,v,w)=(-0.5,2.0,-10) kt, no lift fans, no propeller

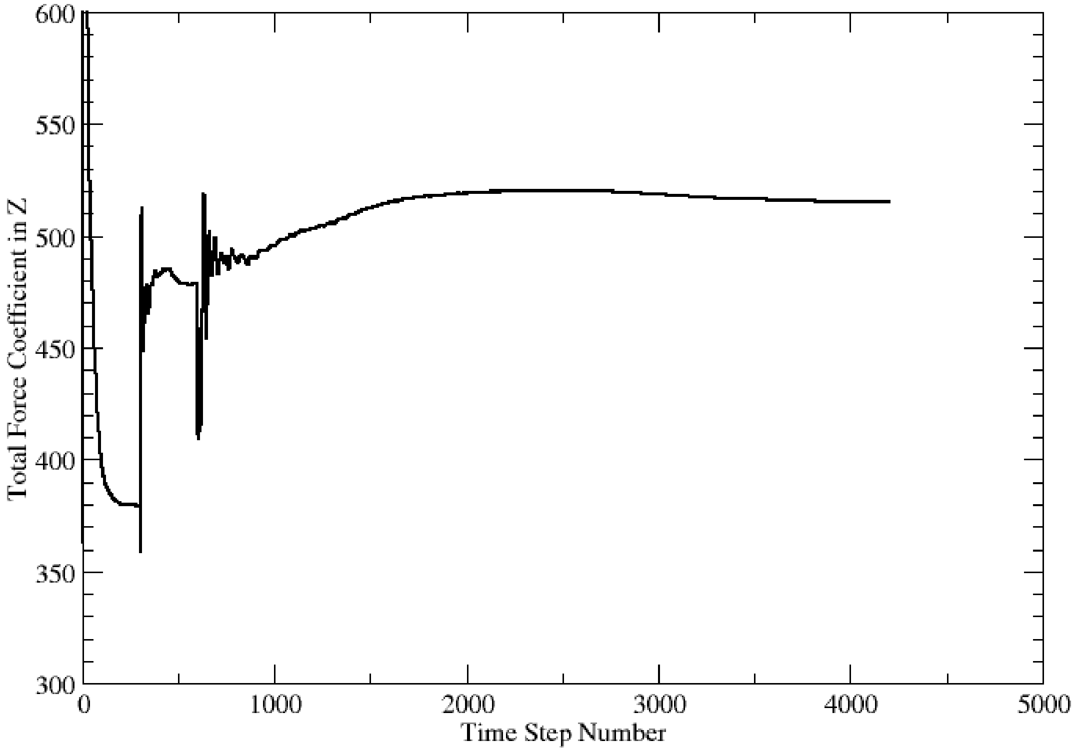
| Curve | Final | Average | Std Dev | Slope | Ratio | Ratio2 |
|---|---|---|---|---|---|---|
| CFz | -1.811 | -1.804 | 0.2412E-01 | 0.7514E-04 | 0.027 | 0.042 |
| CFx | -0.1534 | -0.1748 | 0.1520E-01 | 0.6118E-04 | 0.030 | 0.061 |
| CMy | 1.282 | 1.248 | 0.2965E-01 | 0.1179E-03 | 0.030 | 0.059 |
| CFy | -0.4627E-02 | -0.5365E-01 | 0.3286E-01 | 0.1341E-03 | 0.657 | 1.341 |
| CMx | -0.9176E-01 | -0.9983E-01 | 0.3326E-02 | 0.2769E-05 | 0.067 | 0.028 |
| CMz | -0.2905E-01 | -0.2277E-01 | 0.3116E-02 | -0.3507E-05 | 0.062 | 0.035 |

# Convergence Evaluation

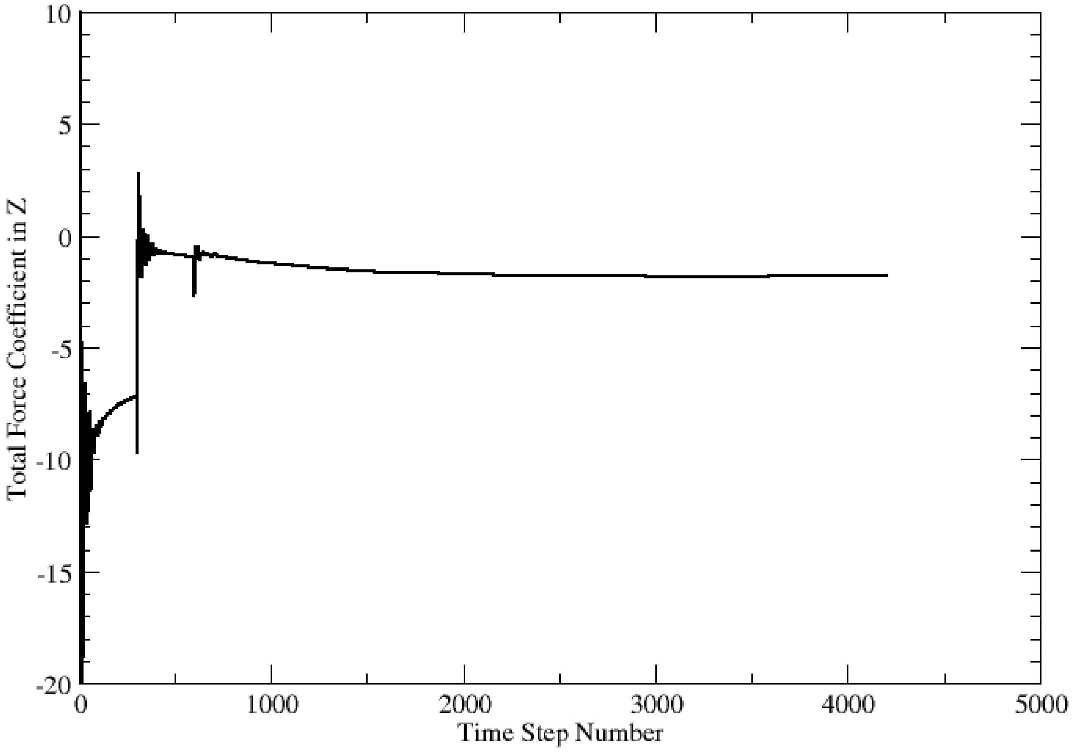
Comparison of sample cases with and without lift fans (both roughly hover)

- 250x difference in magnitudes
- Reasonable convergence for this force coefficient

Total Z-Force Coefficient
With Lift Fans




Total Z-Force Coefficient
Without Lift Fans

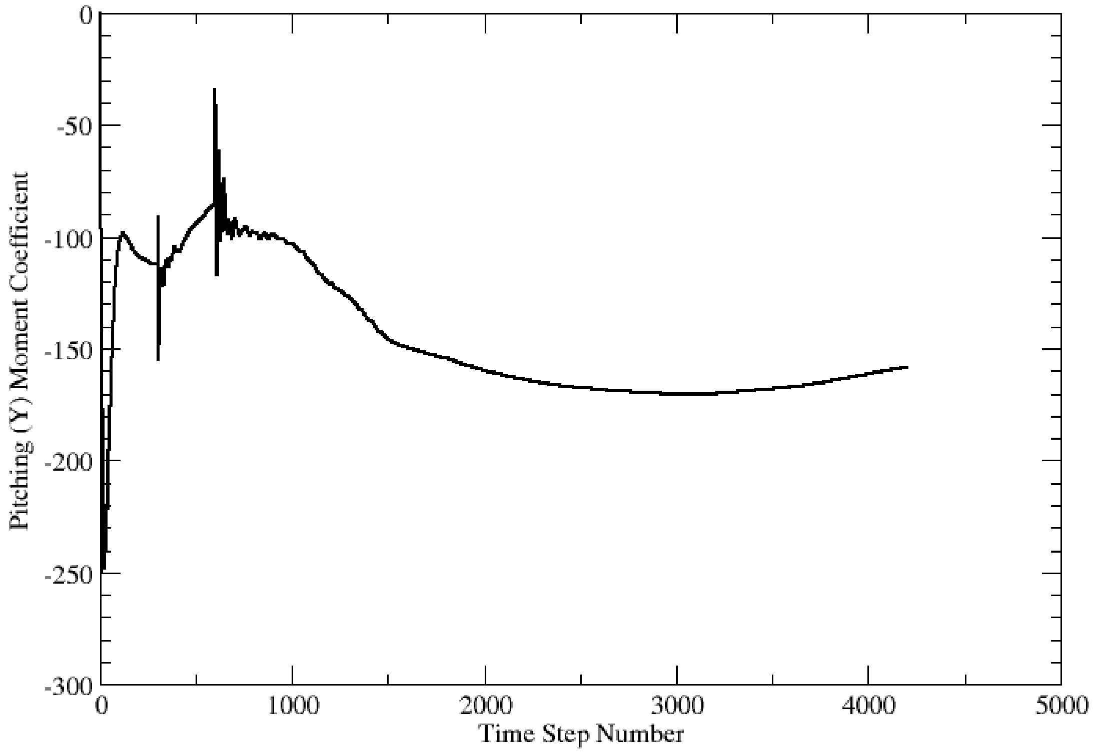


# Convergence Evaluation

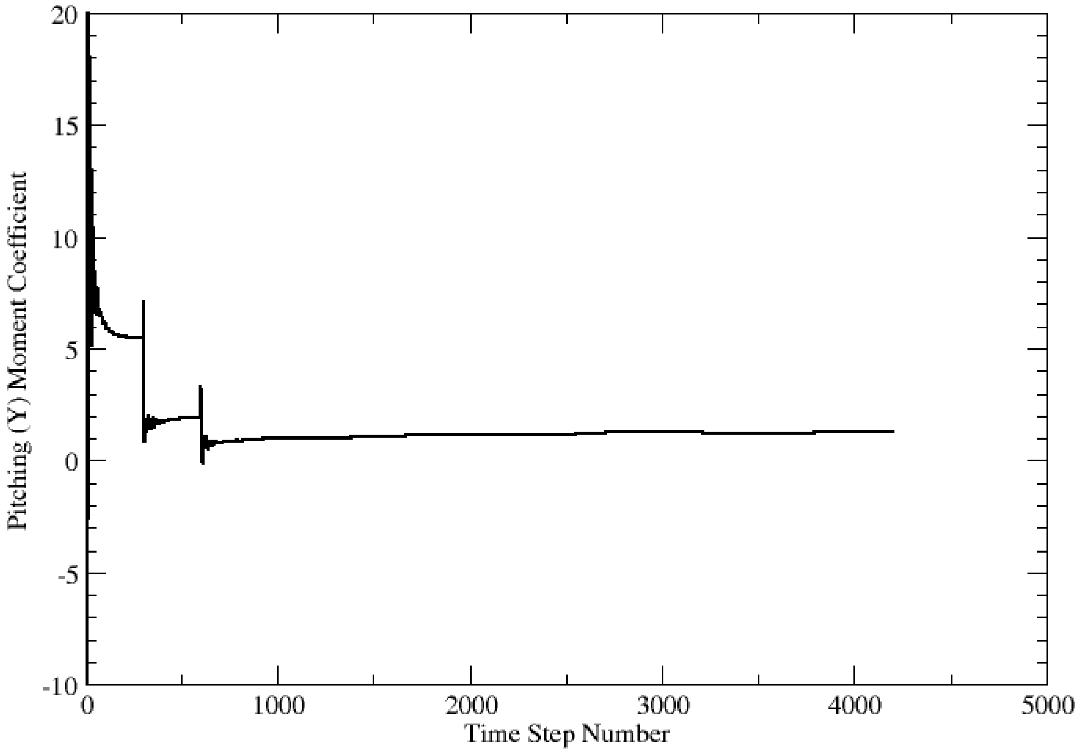
Comparison of sample cases with and without lift fans (both roughly hover)

- 150x difference in magnitudes
- Convergence is within tolerance

Total Pitching Moment Coefficient
With Lift Fans

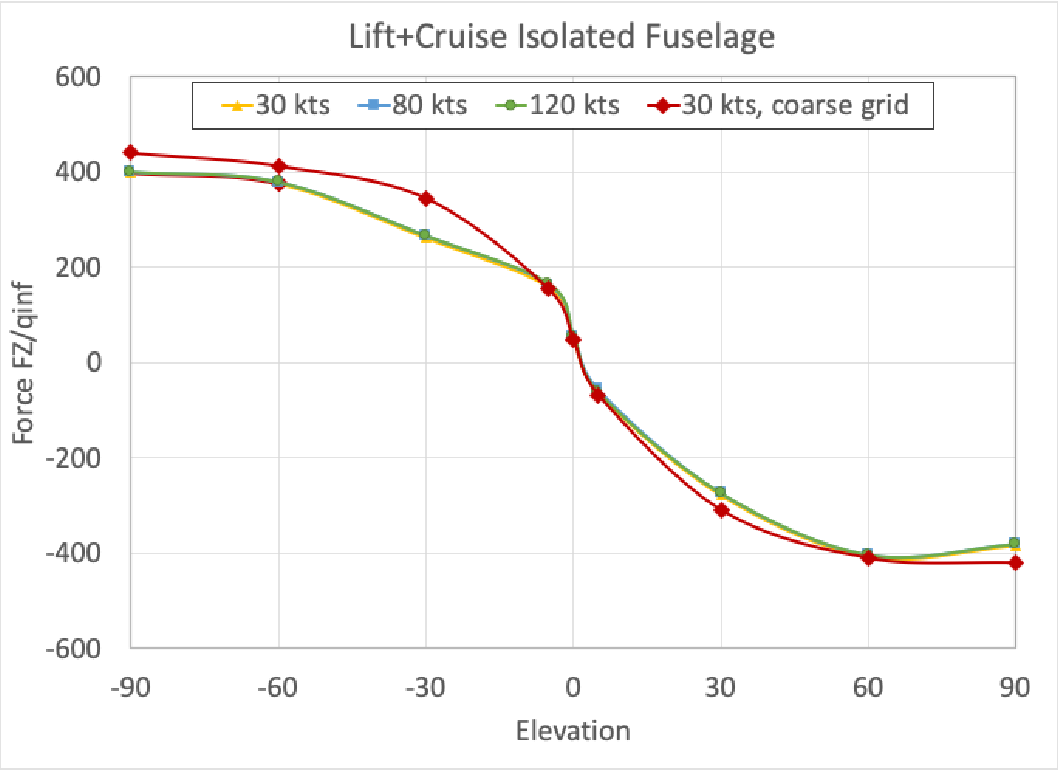



Total Pitching Moment Coefficient
Without Lift Fans

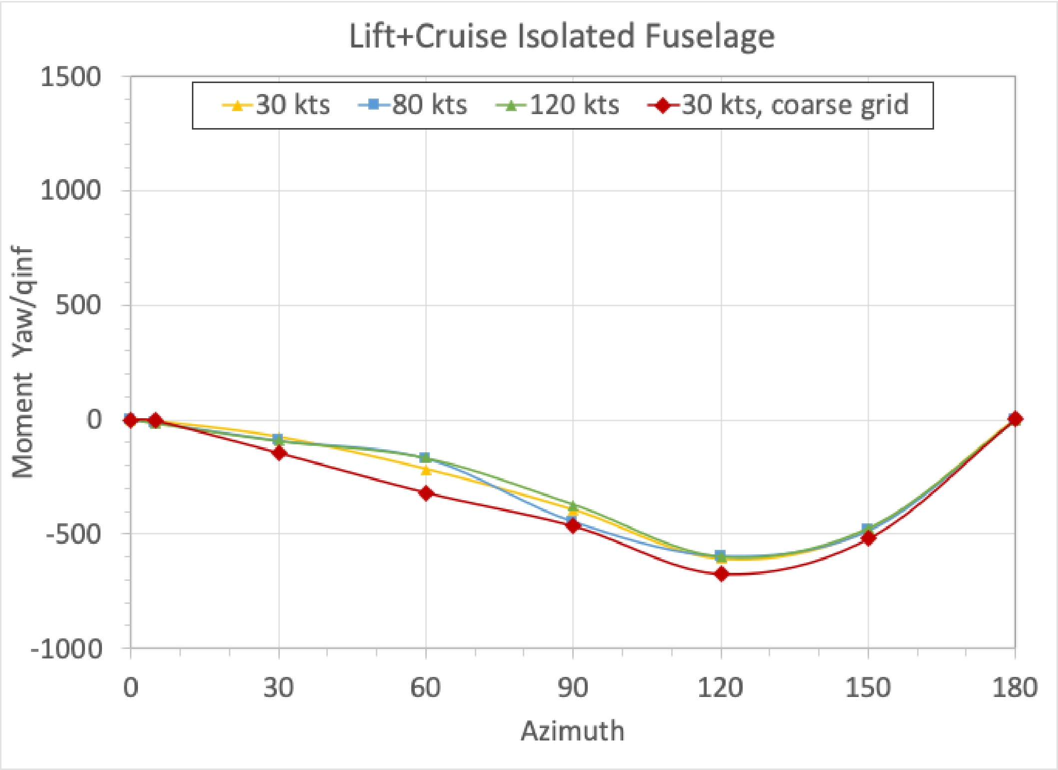


# Static Results

Comparison of fine grid and coarse grid forces and moments for Wing/Body/Tail configuration (unpowered)
Note most of these are extreme attitudes for airplane mode

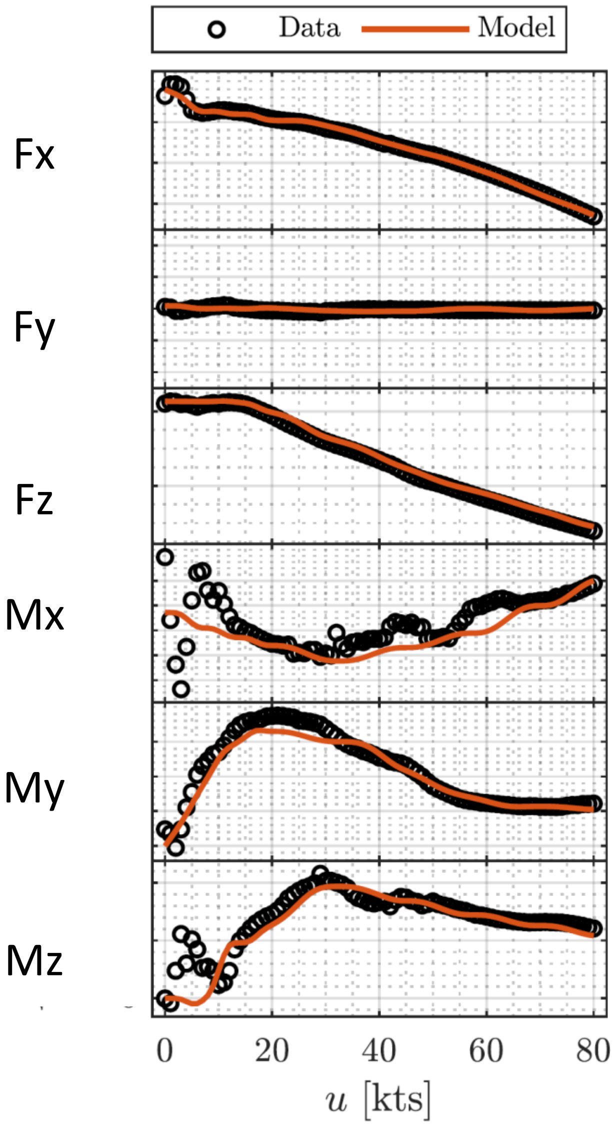



Normal force comparison for a pitch sweep at 0 deg sideslip

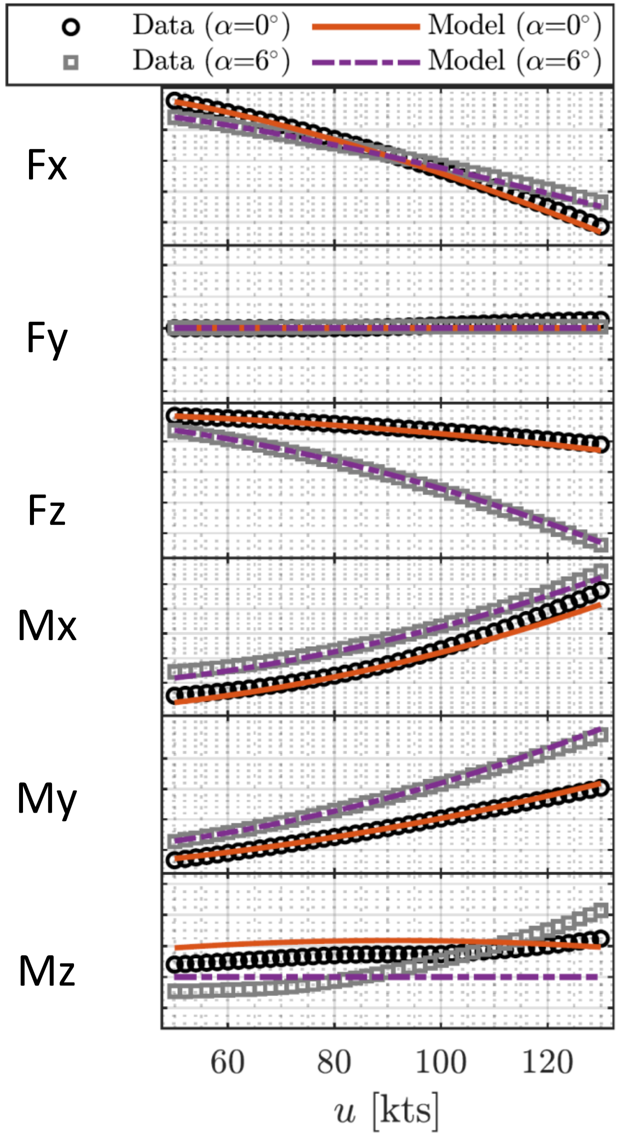



Yawing moment comparison for an azimuthal sweep at 0 deg pitch

# Comparison of CFD Data and Model Predictions




**Transition comparison**

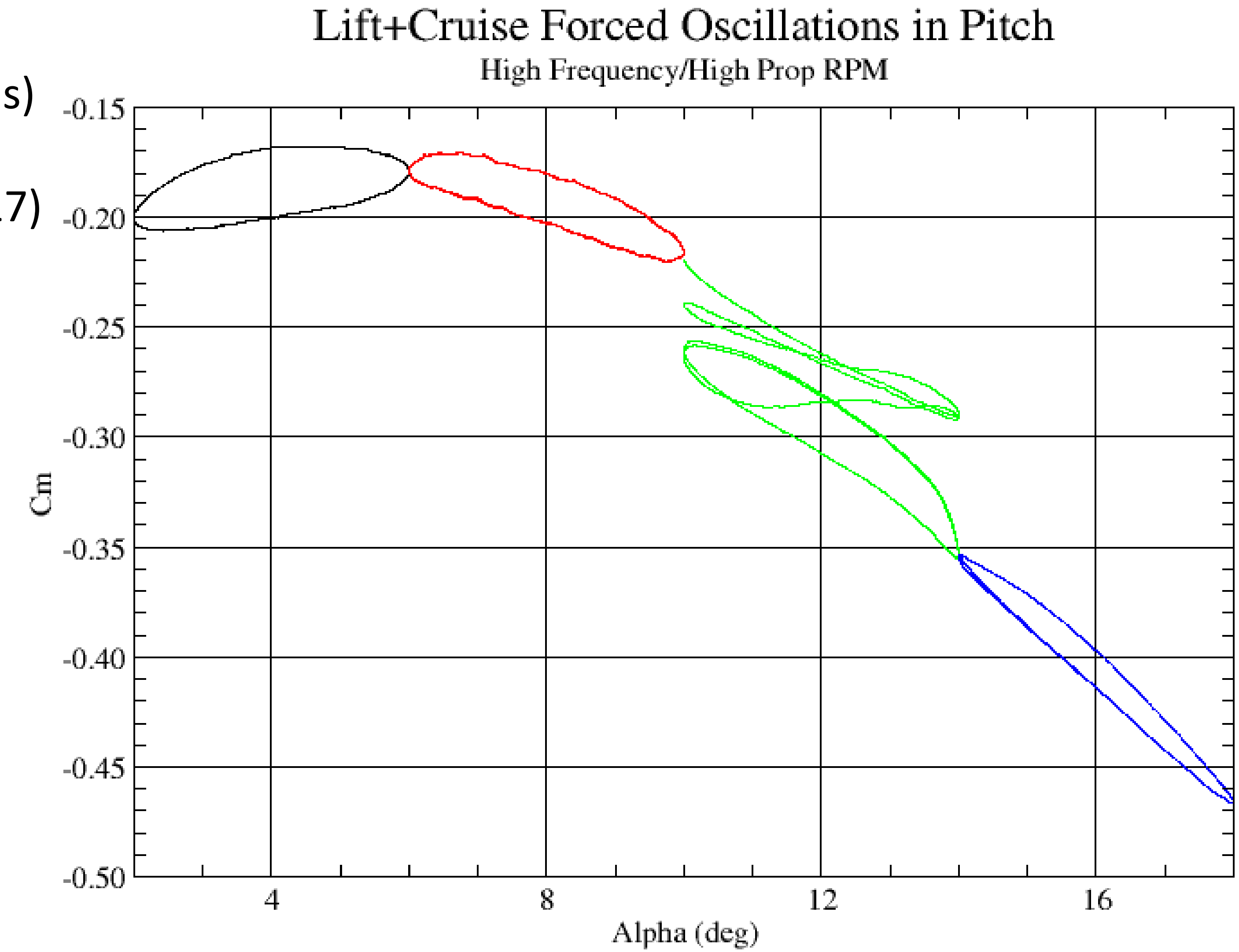



**Cruise comparison**

# Dynamic Results: Forced Oscillations

Pitch oscillations in Cruise configuration
(airplane mode, with propeller but not lift fans)

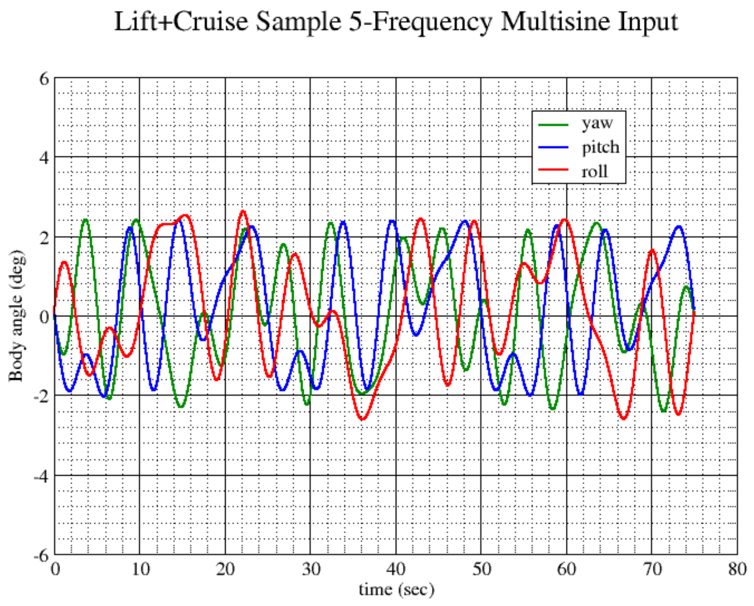
Flight conditions: 6000 ft alt, 110 kt (Mach 0.17)

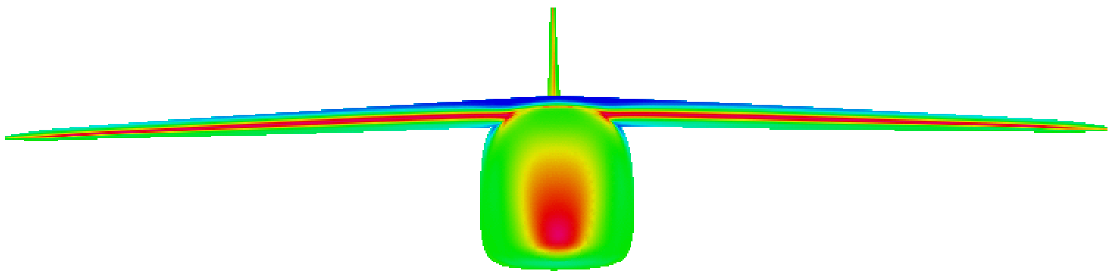


# Dynamic Results: Multisine Maneuver

Multisine maneuver in Cruise configuration
(airplane mode, with propeller but not lift fans)

Flight conditions: 6000 ft alt, 110 kt (Mach 0.17)

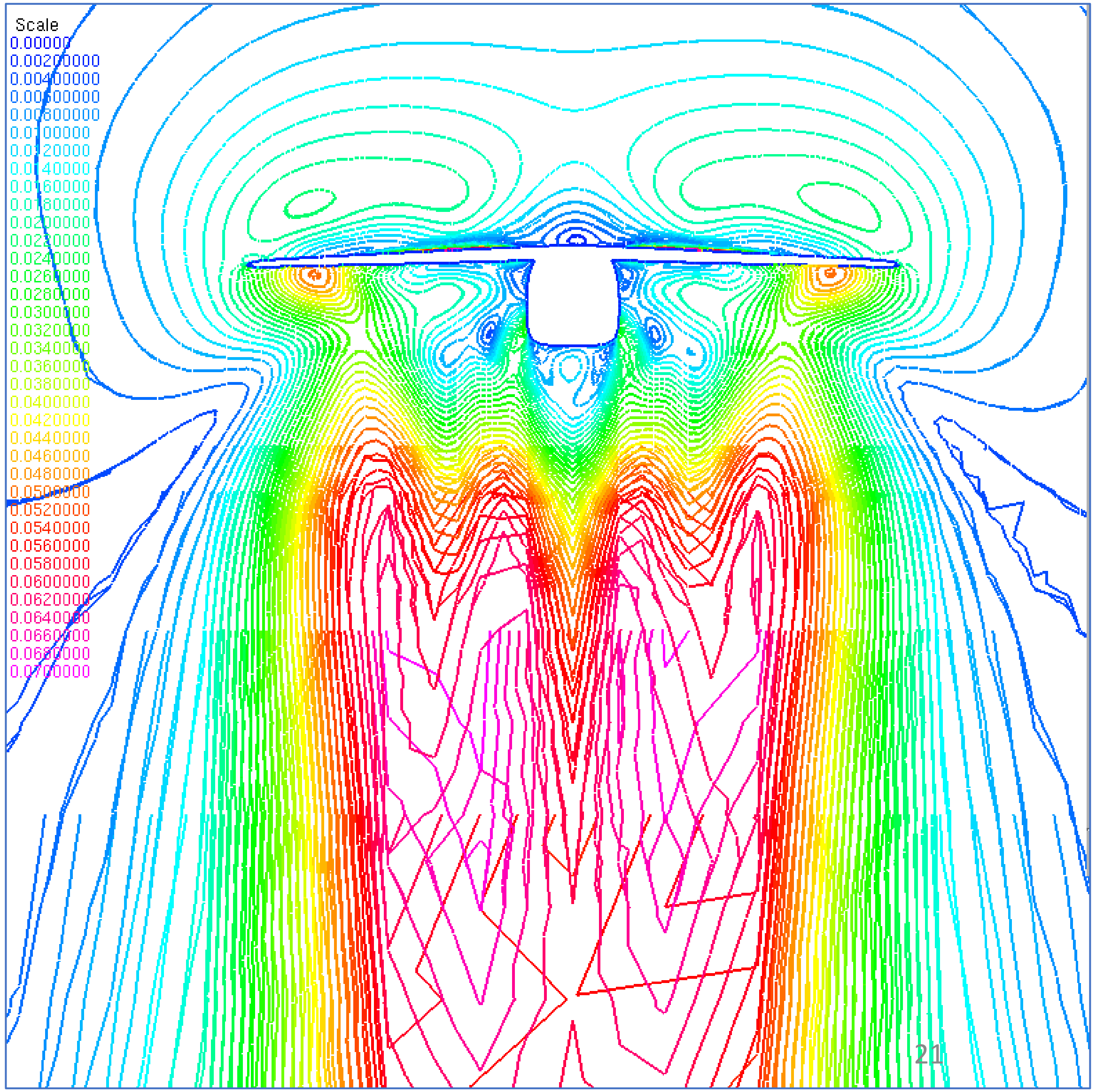


# Dynamic Results: Multisine Maneuver

Multisine maneuver in Hover configuration
(with lift fans but not propeller)

Flight conditions: 6000 ft alt, 0 kt




Velocity magnitude contours

# Conclusions & Lessons Learned

- Use of CFD for preliminary design stability & control:
  - RAM process is an efficient way to build S&C database
    - Input can come from CFD, WT or other methods
  - For CFD, need to understand tradeoff between accuracy and timeliness
    - CFD approximations and compute time
    - Lower fidelity alternatives
  - Response surface modeling choice of dependent and independent variables
    - Affects surface fit accuracy
    - Affects intuitive interpretation of results (are you an “airplane person” or a “helicopter person”?)
  - Yes, CFD gridding best practices matter (axis patches, tip caps)

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