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

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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

Goals

S&C Goal:

- To quickly produce static and dynamic aero databases for S&C researchers to work with
    - Accuracy is less important (+/-10%), as vehicle will never be built

CFD Goals:

- Experiment with rotor disk model for UAM configuration
- Try new options in OVERFLOW (2.3, 2.4) to accelerate convergence (static and time-accurate)

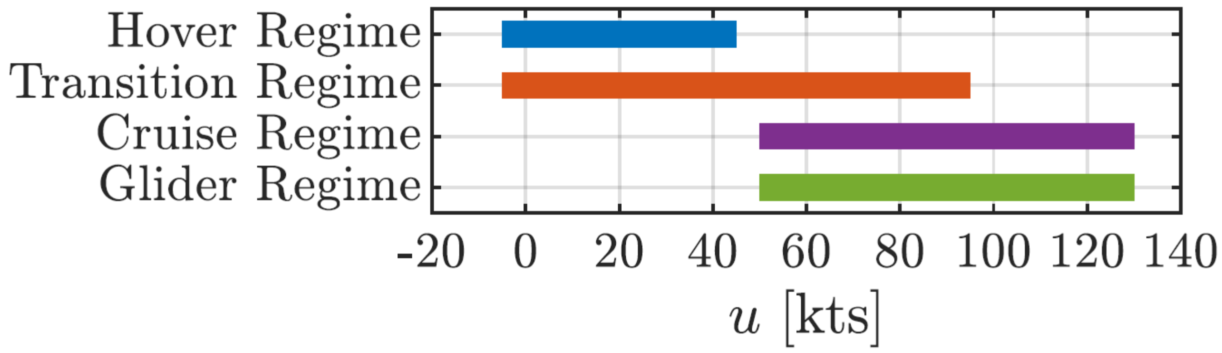
NASA Revolutionary Vertical Lift Technologies (RVLT) Urban Air Mobility (UAM) Lift+Cruise Reference Vehicle

- 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)

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

Rapid Aero Modeling (RAM) Process

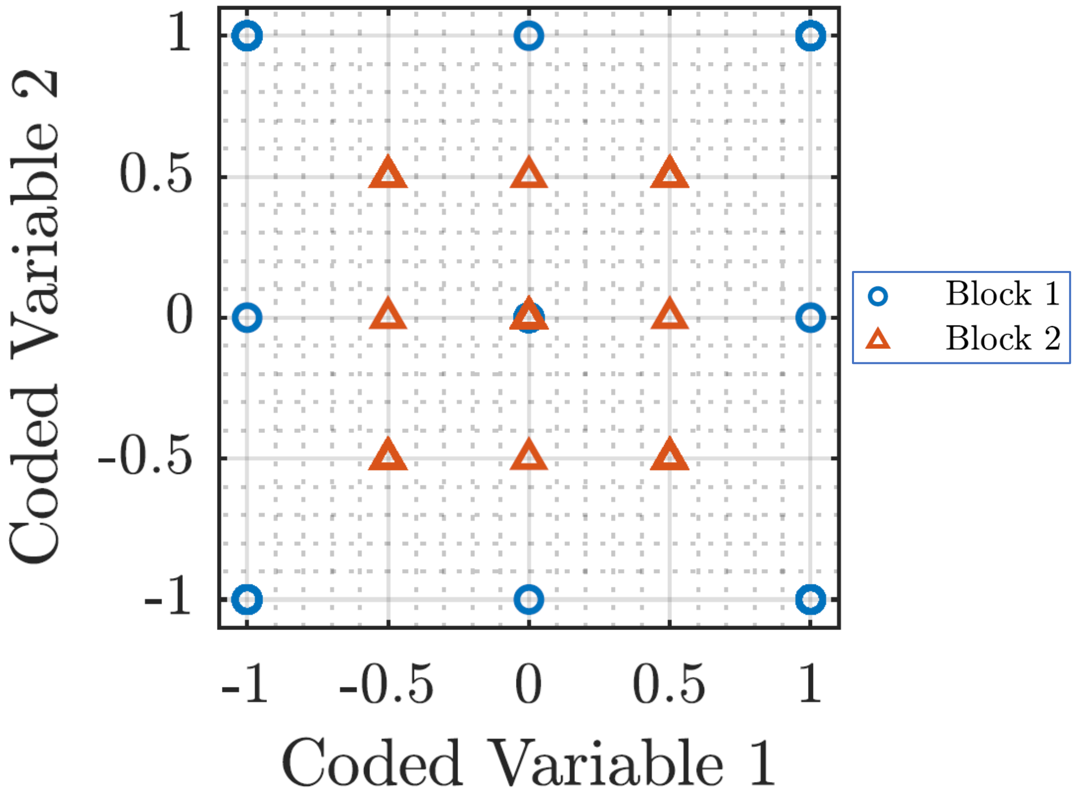
- Combination of Design of Experiments (DOE) and response surface modeling, coupled with process error estimation

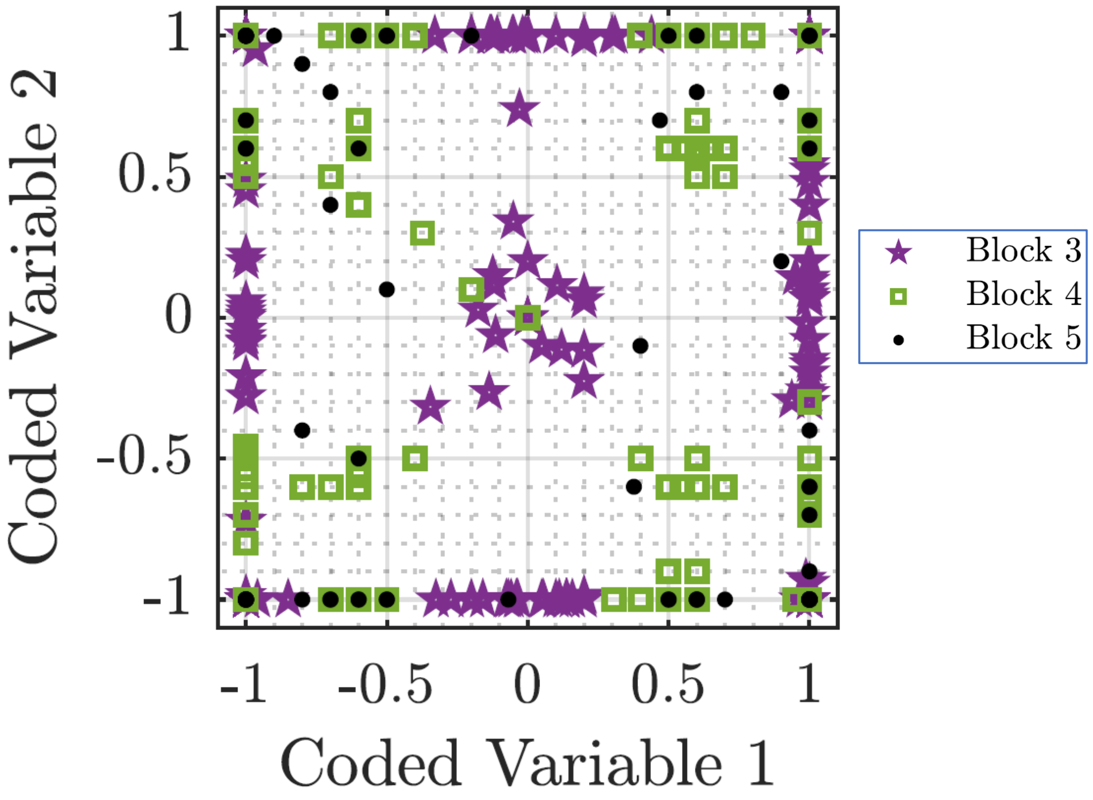
- Can be applied with test or computational data as input (RAM-T or RAM-C)

- References:
  - 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 Lift+Cruise, 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
  - Block 1: Face-Centered Design (FCD), Block 2: Nested FCD
  - Blocks 3-4: Optimized for minimum Prediction Error (PE)
  - Block 5: Validation

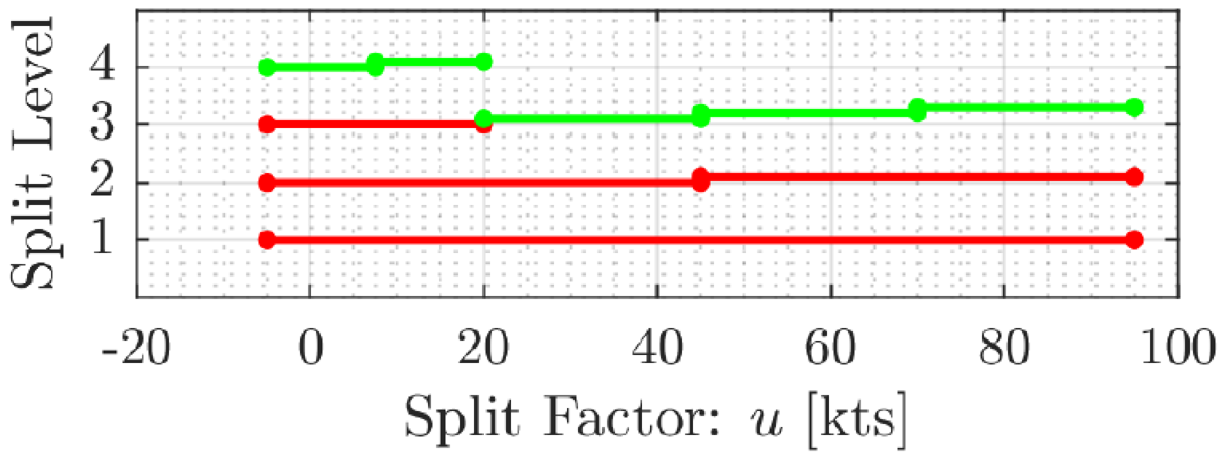




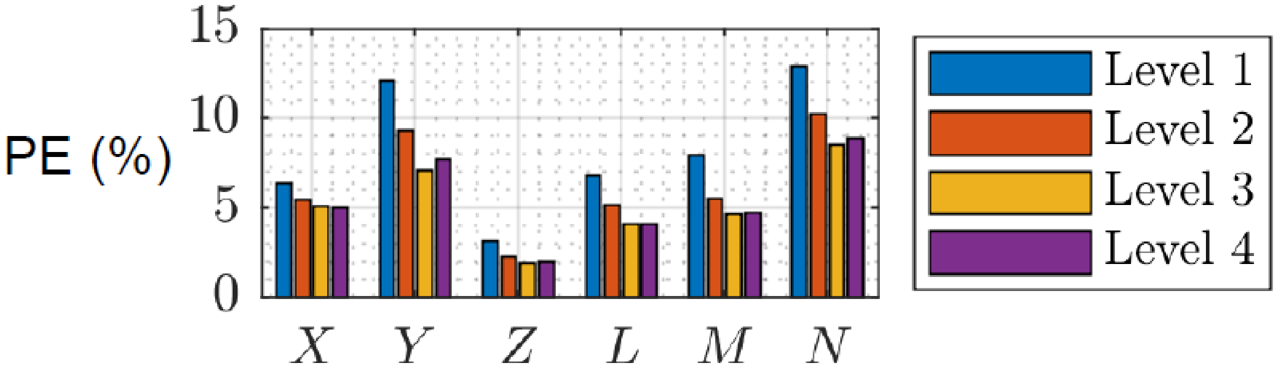
2D slice of 17-factor RAM DOE test blocks

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.



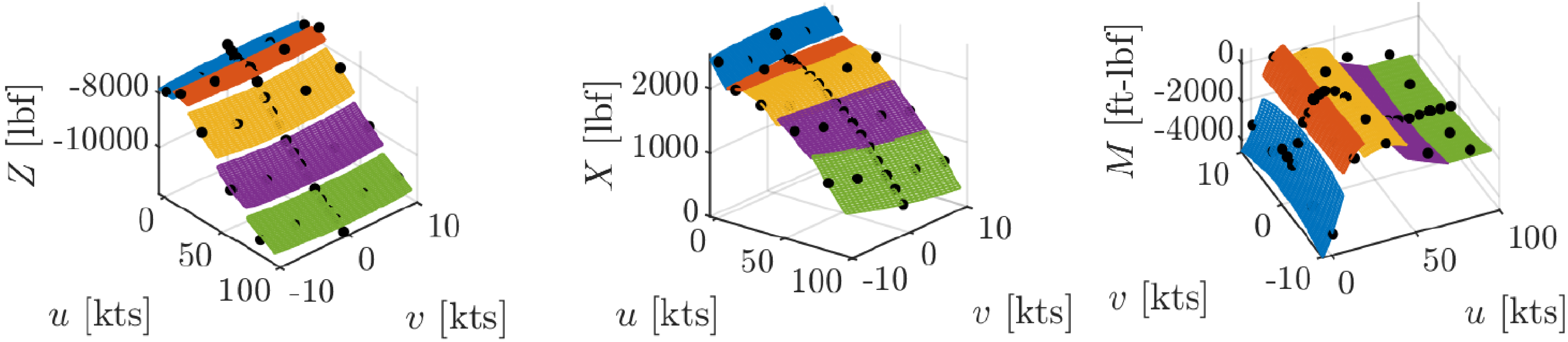
- Regions are halved to improve data density & model fidelity.



- 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).

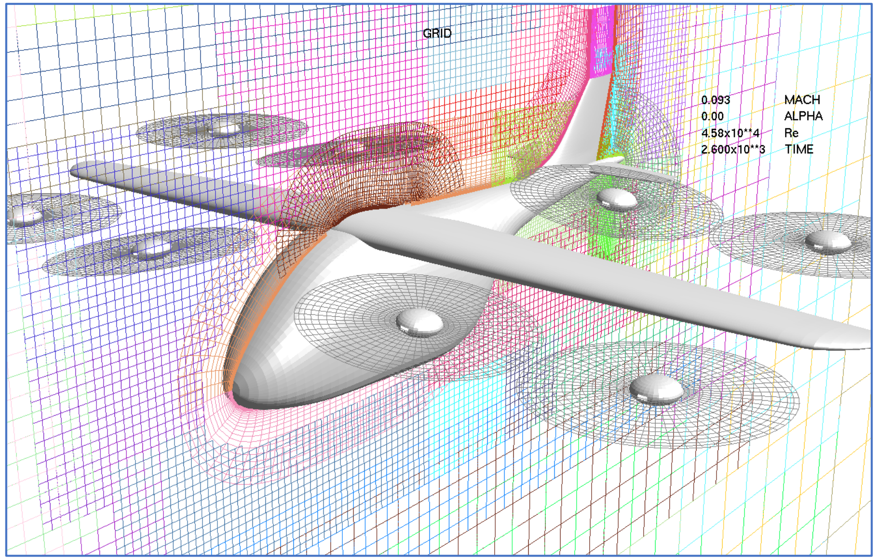


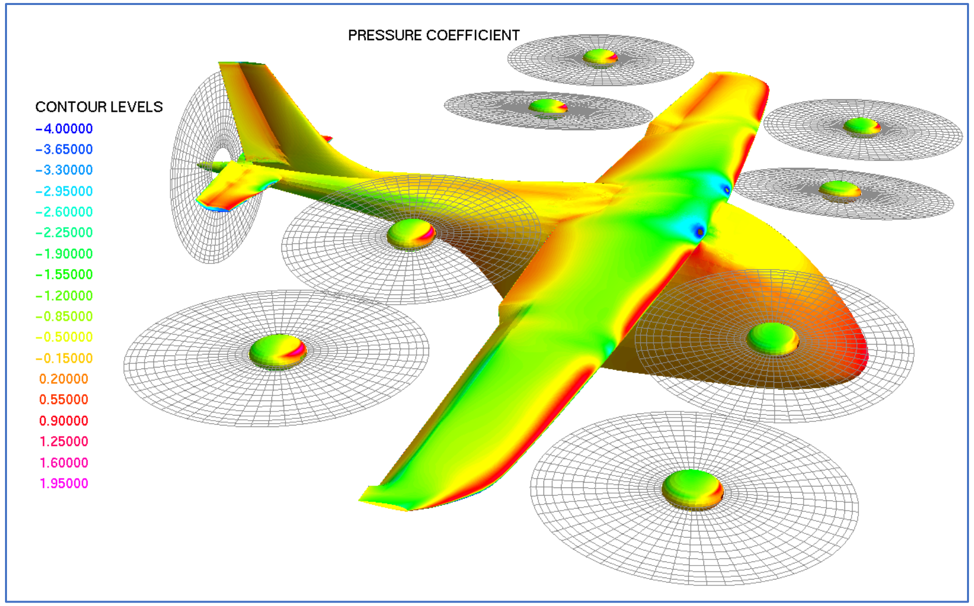
CFD Grid and Modeling Approaches

- Ignore some geometry (no pylons, no landing gear)
- Deform wing and tail surfaces for deflected ailerons, rudder and elevator
- Rotor disk model (rough effect of rotors, steady-state)
- Use coarse grids (e.g., 85 points around airfoil for tail surfaces)
- Old-style gridding techniques: axis singularities, collapsed grid at wing and tail tips

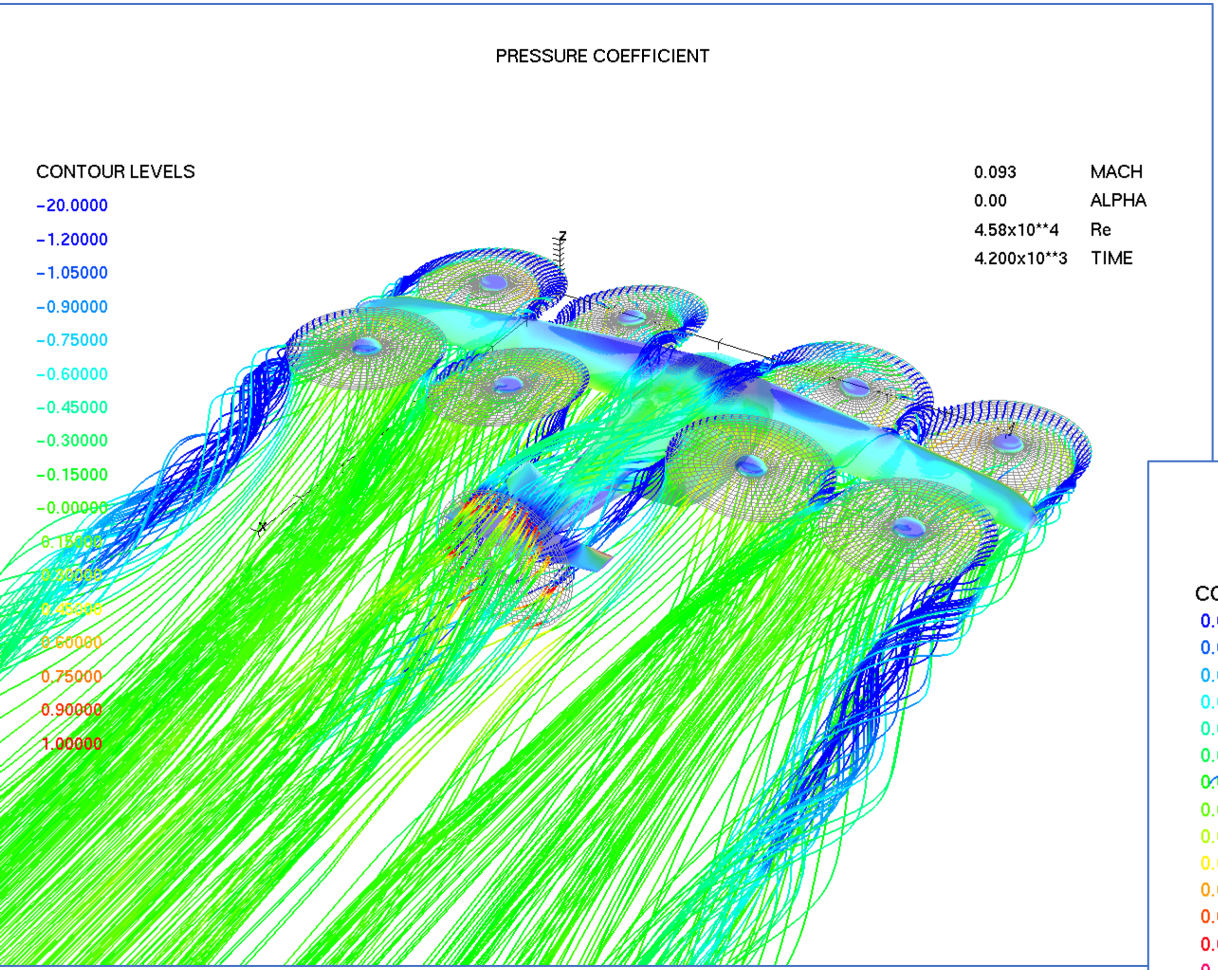
- Steady-state simulations (not time-accurate)
- No DES turbulence model (even with separated flow)

Resulting grid system is ~4 Mpts, typical run is 4200 iterations



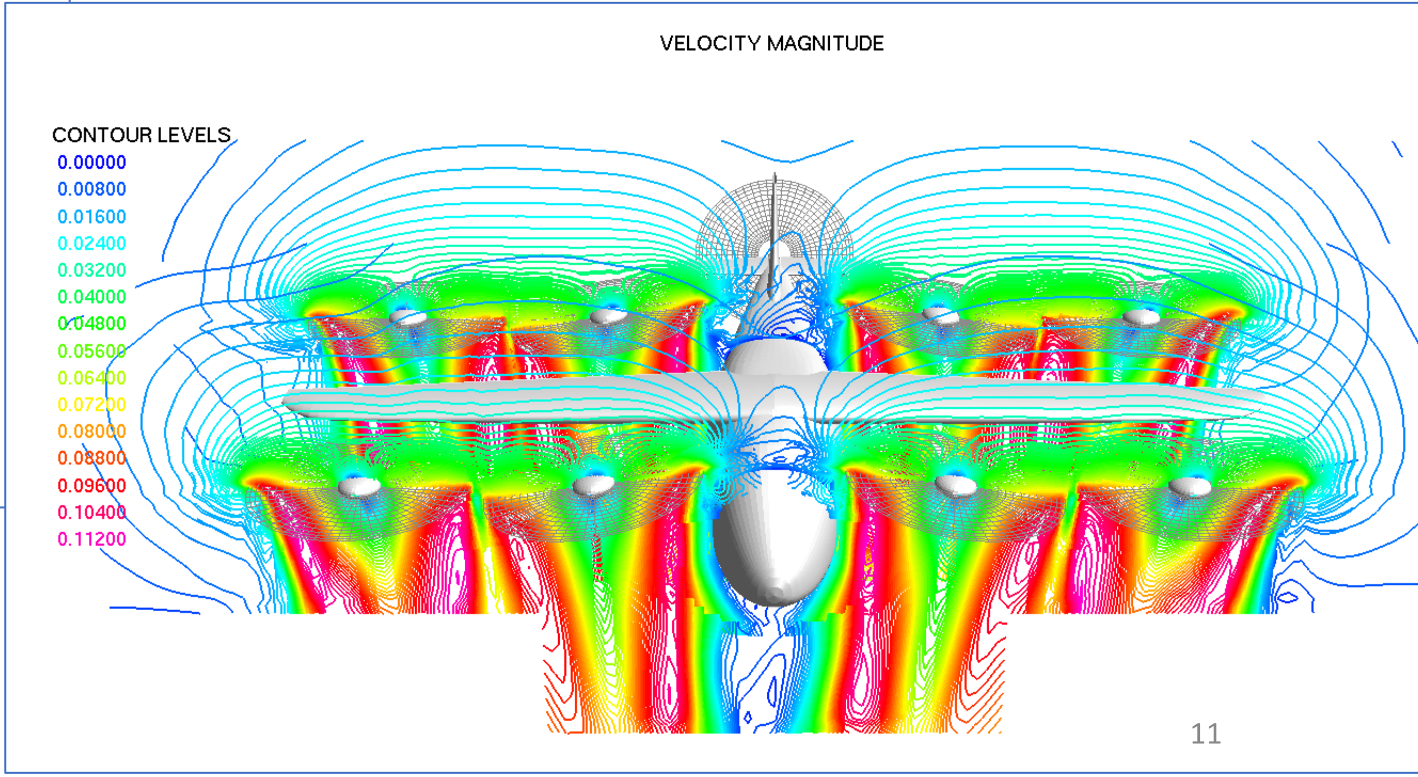


CFD Sample Cases



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

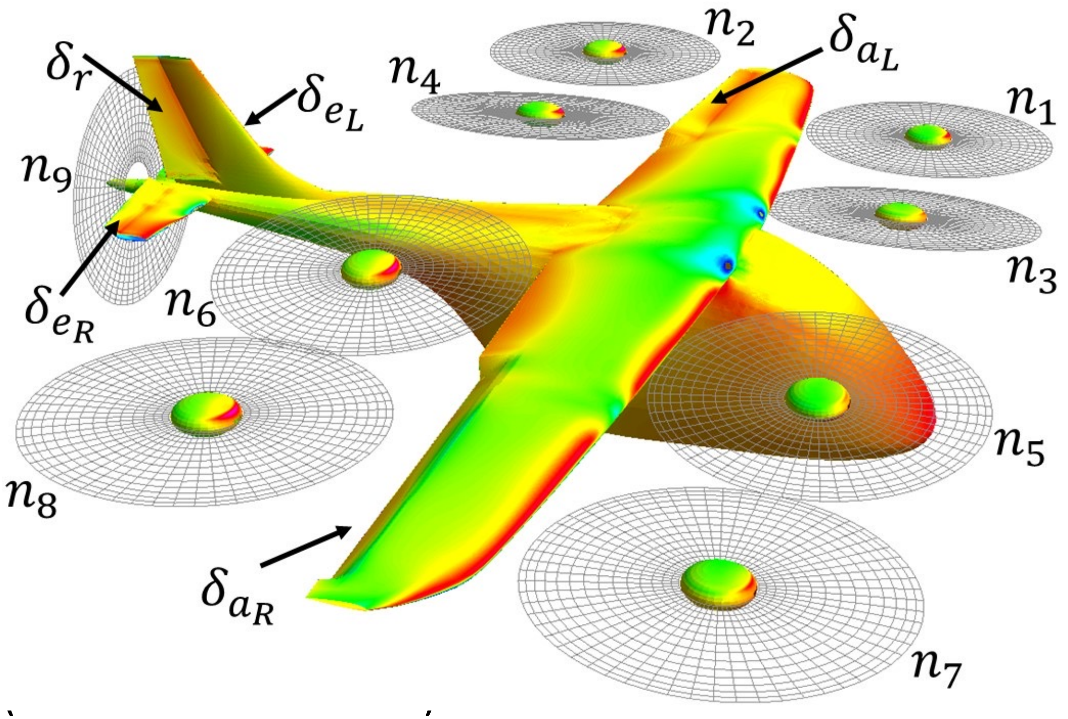
Hover case: lift fans running, no propeller. Velocity magnitude contour slices through forward and aft lift fans



Converting Input Conditions into CFD Simulations

14 available control effectors

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



Script system:

- 17-factor input conditions given in Excel spreadsheet
- Script 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

➢ Flight conditions specified as (Mach,alpha,beta), or (u,v,w)?

➢ Output as force and moment coefficients, or dimensional values?

Operational Process: Parallel Processing

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

Operational Process: Convergence Evaluation

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

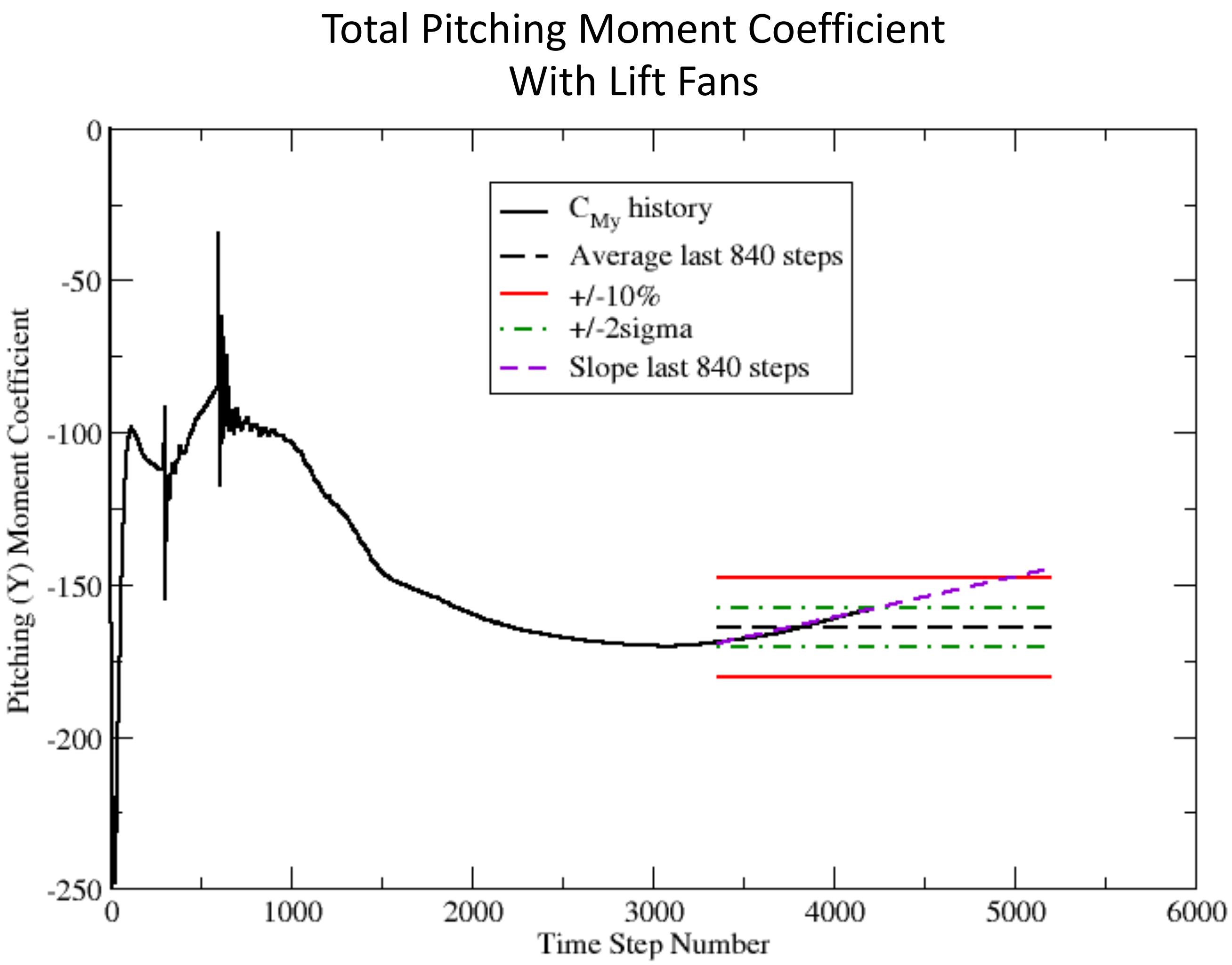
Convergence for sample case: (roughly) hover **with** lift fans and propeller

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

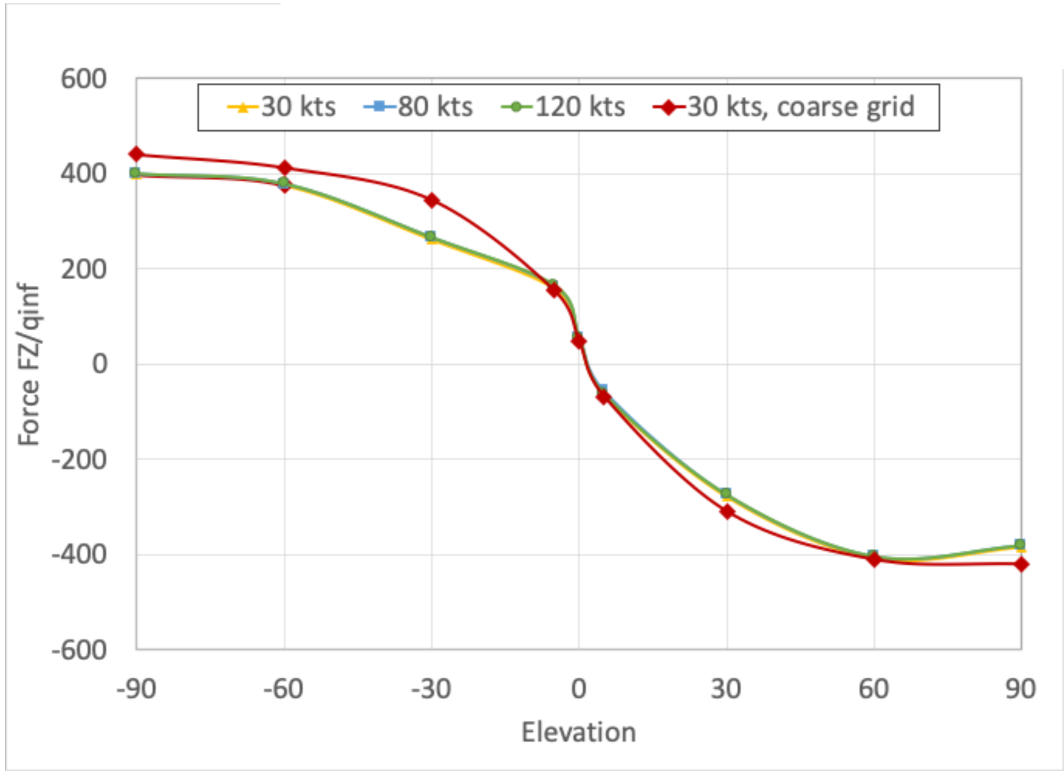
"Ratio" is 2σ measure over sample period; **"Ratio2"** is slope*1000 steps;
both normalized by average value or "normal" value

Convergence Evaluation

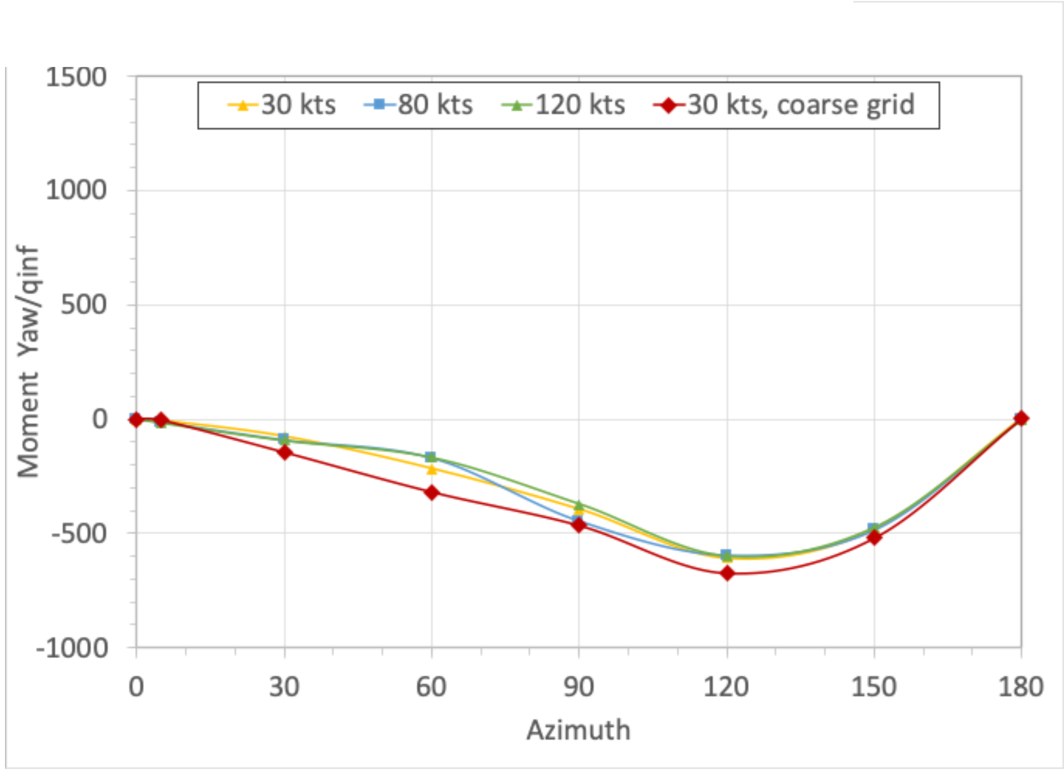


Static Results

Comparison of fine grid and coarse grid forces and moments for Glider mode (unpowered)
Note most of these are extreme attitudes for an airplane



Normal force comparison for a pitch sweep at 0 deg sideslip

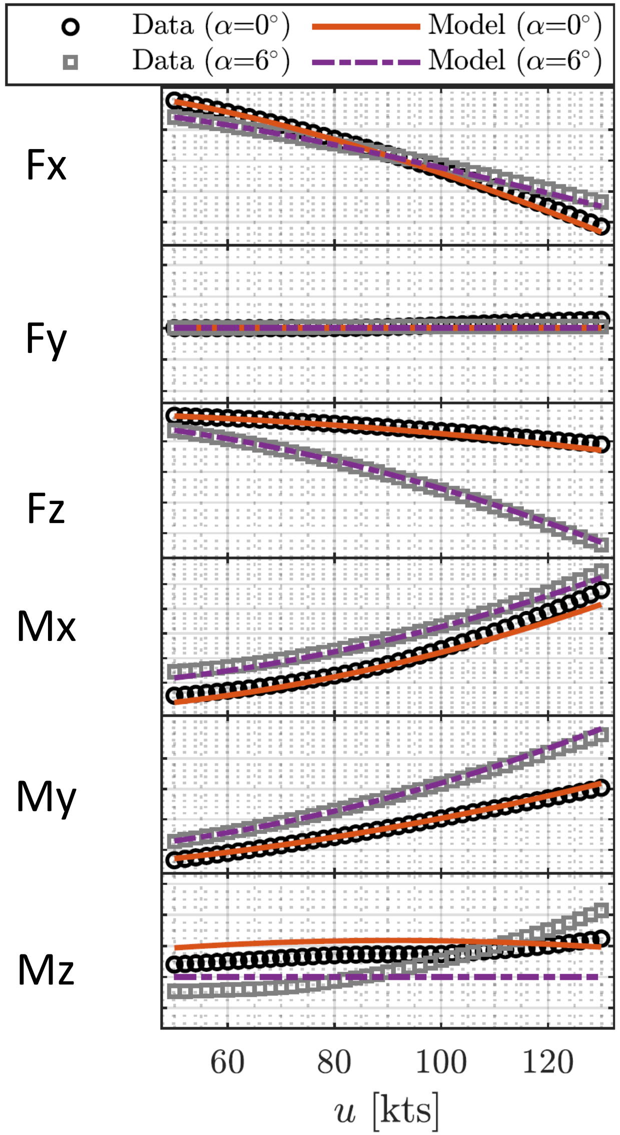


Yawing moment comparison for an azimuthal sweep at 0 deg pitch

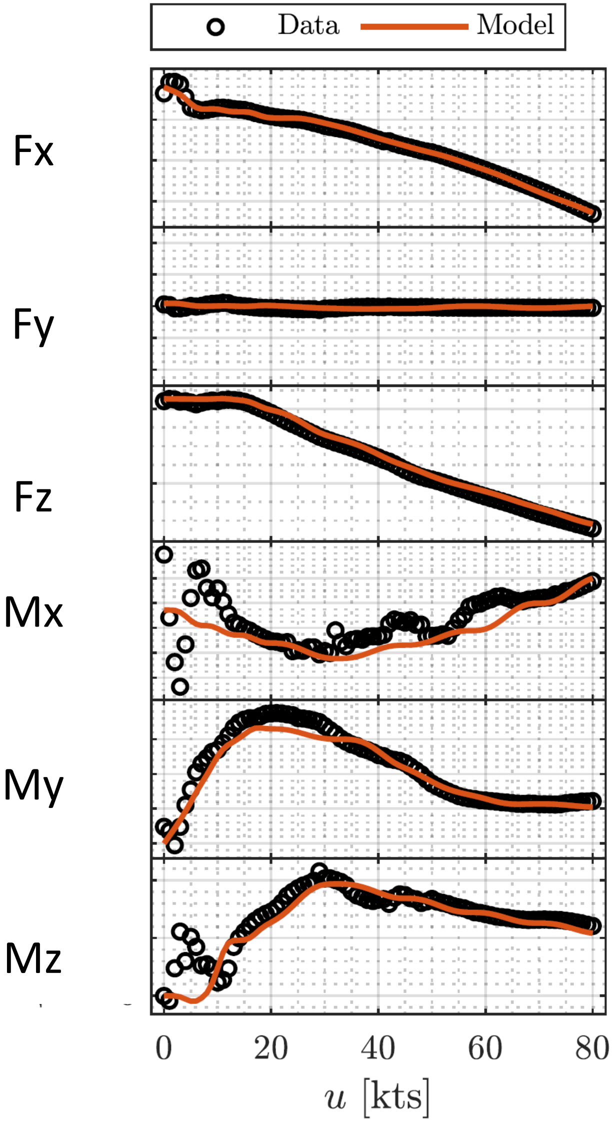
Fine grid results from Brian Allan (NASA Langley)

Comparison of CFD Data and Model Predictions

"One-factor-at-a-time" (OFAT) Speed Sweeps



Cruise comparison



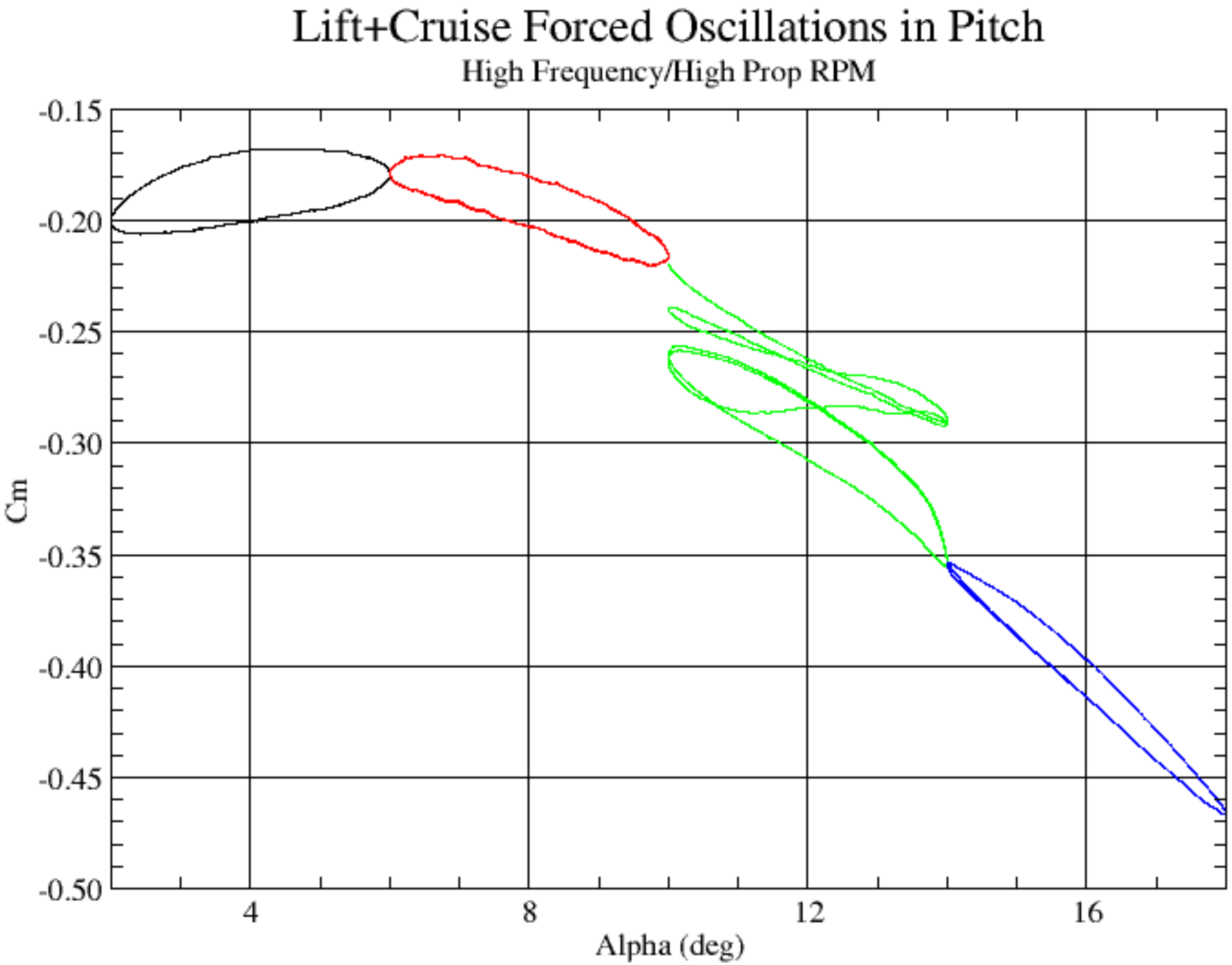
Transition comparison

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)
Alpha = [4,8,12,16^o] +/- 2^o
0.175 Hz oscillation

1800 steps/cycle, 5 subiterations/step, 4 cycles
11 hr wall time with 64 cores (4 nodes) per case



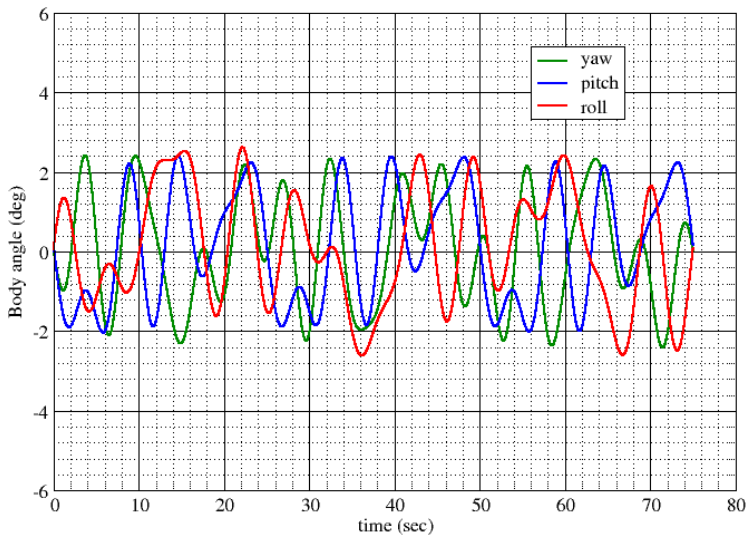
Dynamic Results: Multisine Maneuver

Multisine maneuver in Glider configuration
(airplane mode, no propeller or lift fans)

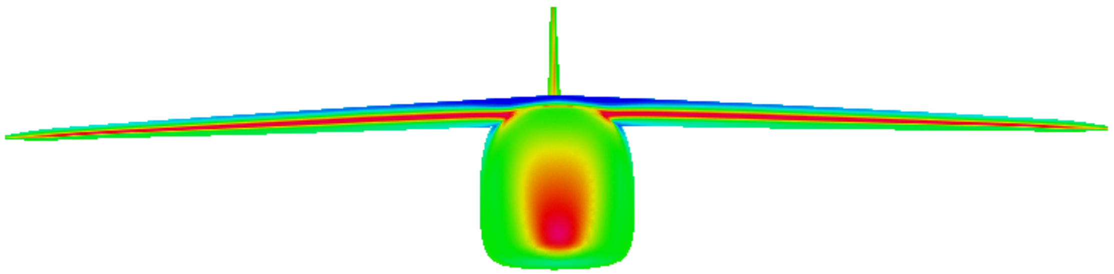
Flight conditions: 6000 ft alt, 110 kt (Mach 0.17)
Highest frequency = 0.213 Hz

80 sec simulation time in 28,800 steps
32 hr wall time, 64 cores

Lift+Cruise Sample 5-Frequency Multisine Input



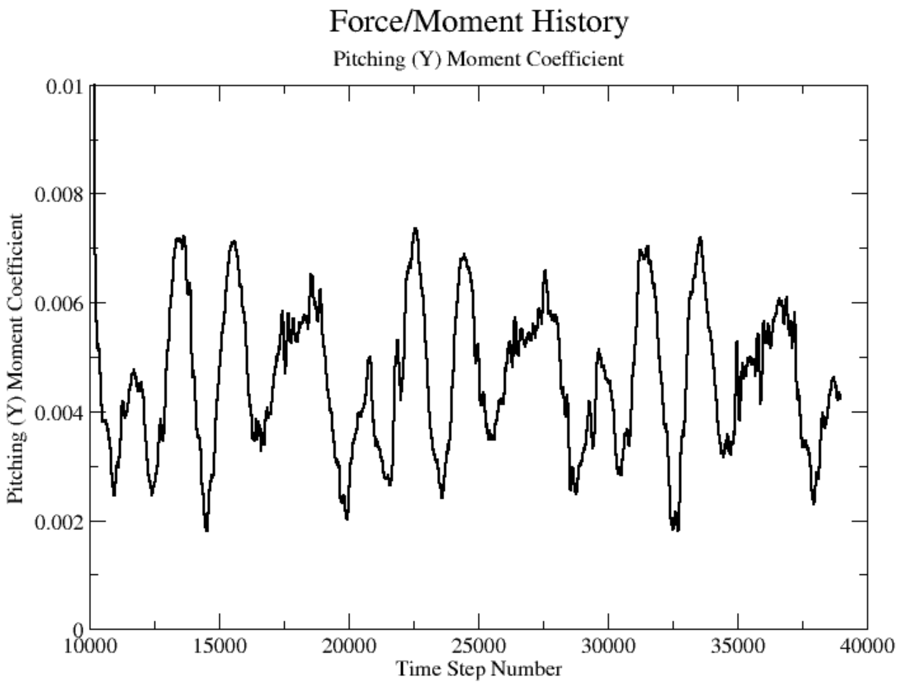
Surface pressure coefficient



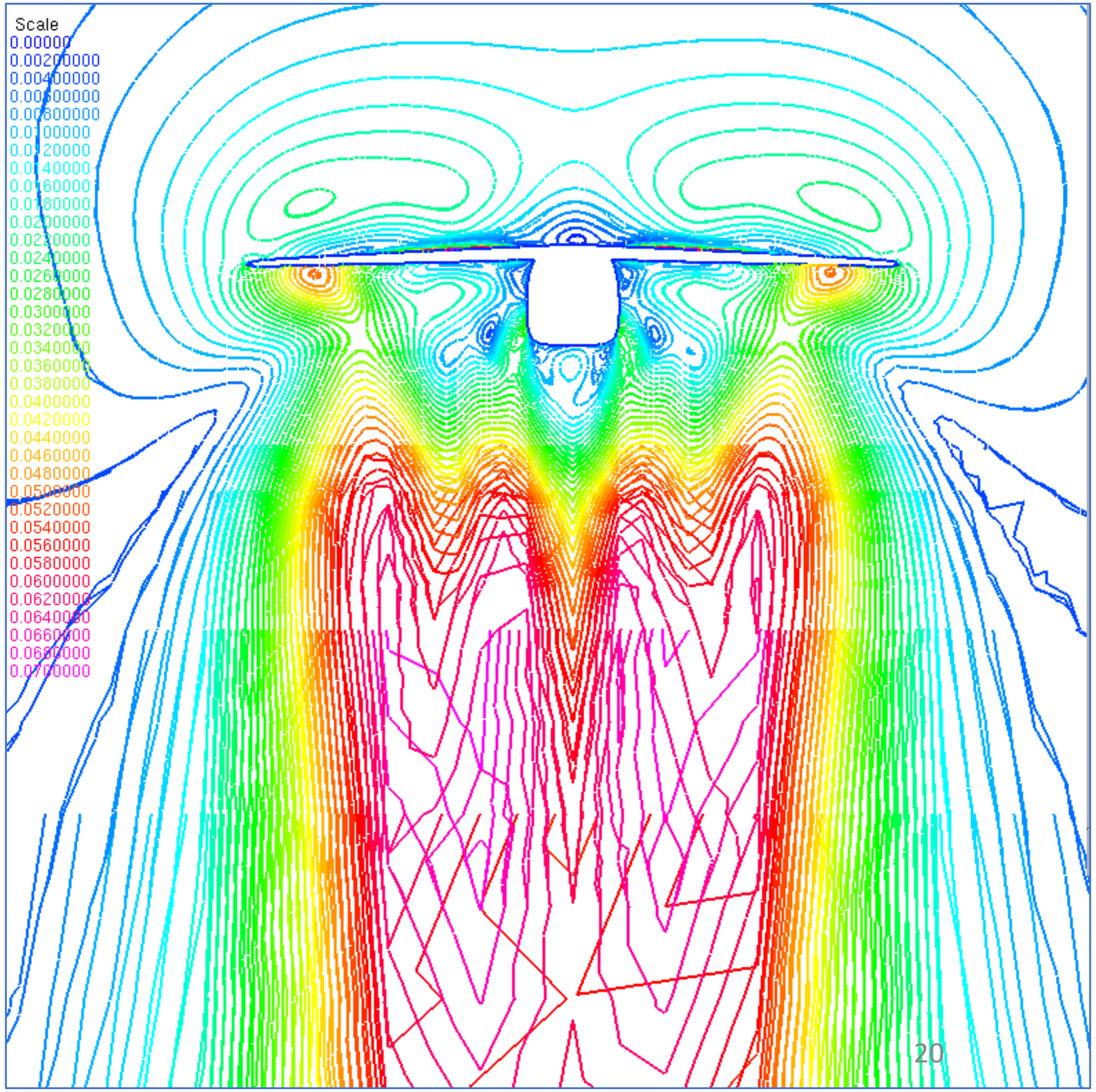
Dynamic Results: Multisine Maneuver

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)

Conclusions & Lessons Learned

How did we do on original goals?

- Scripting to set up process took a while (be careful of units, axes!)
- Very efficient for generating static data points
- Rotor disk model worked well

- Need to improve convergence evaluation
- Need to resolve multisine hover issues
- Revisit subiteration convergence with OVERFLOW 2.4

Acknowledgments

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