Aftbody Shape Effects on Dynamic Stability using Free-Flight CFD

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Genesis Sample Return Mission

- Dynamic stability is typically characterized by experiments
  - Forced-Oscillation Testing, Free-Oscillation Testing, Free-Flight Wind-Tunnel Testing, and **Ballistic Range Testing**
  - Flight parameters are not always completely represented
- Dynamic stability of the Genesis capsule were characterized by BR campaign in 1999
  - Experiment suggested capsule stability above Mach 2.0 for all angles
  - Due to a failure of drogue parachute deployment, capsule decelerated through dynamic unstable regime and saw unbounded growth in total angle of attack

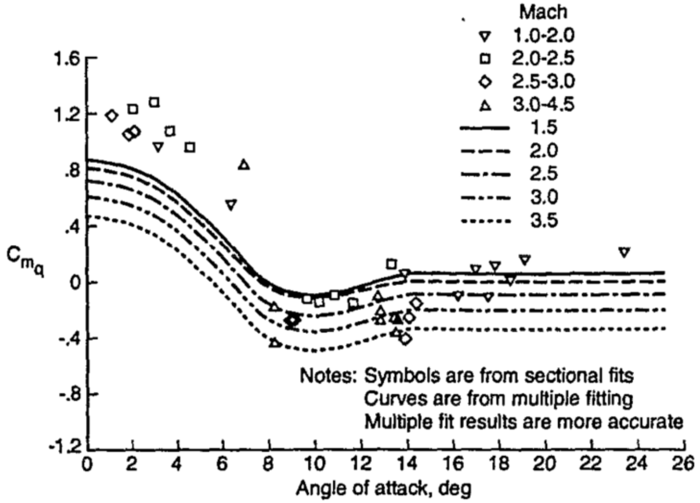
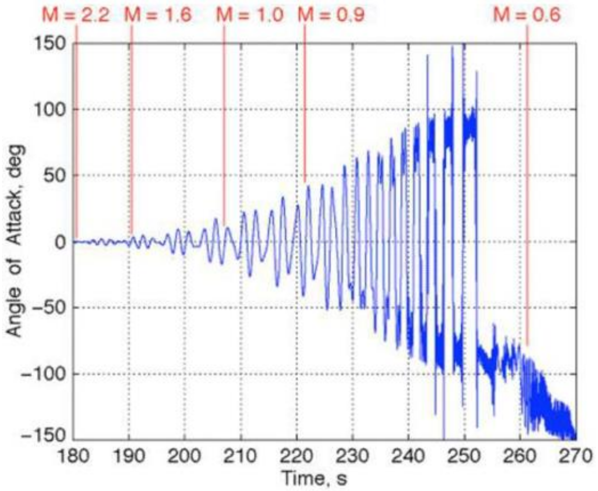
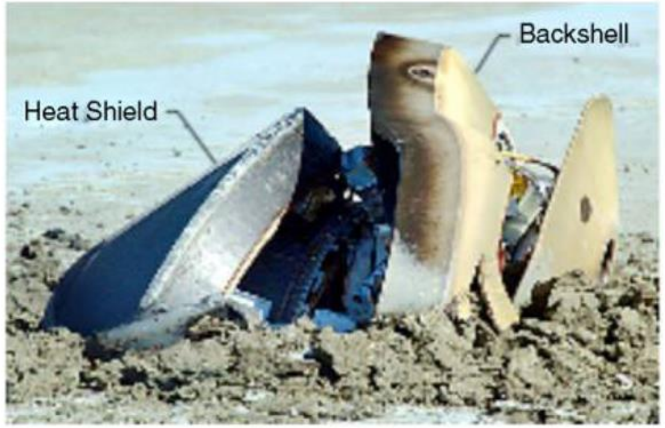


Figure 10. Pitch Damping Moment Coefficient vs. Mach Number.

Genesis Sample Return Capsule ([1]Desai, 2008)

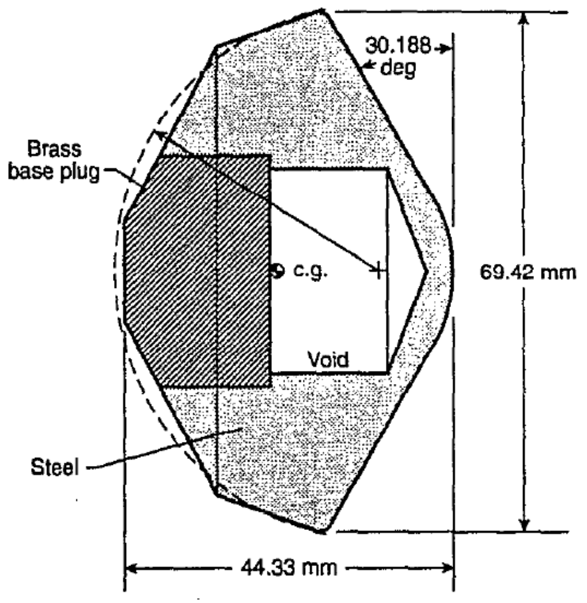




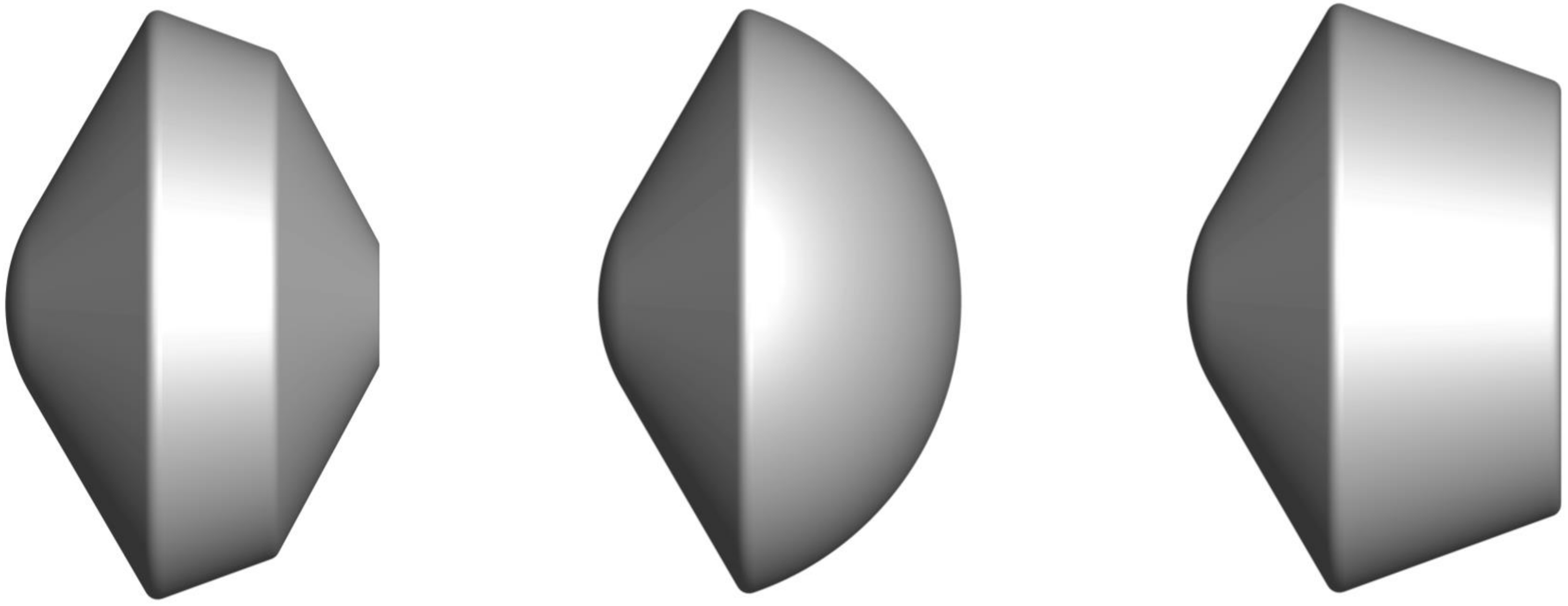
Cheatwood, F., et al. "Dynamic stability testing of the Genesis sample return capsule." *38th Aerospace Sciences Meeting and Exhibit*. 2000.

Free-Flight Modeling Motivation

- Unsteady wake flow is believed to be a key contributor to vehicle dynamic instability
- Leveraging the Free-Flight CFD (FFCFD) capability within US3D, the goal is to perform 1 Degree of Freedom (DoF) simulations of the Genesis geometry for;
  - Mach and initial pitch amplitudes
  - Several aftbody outer mold line (OML) shapes



[2]Cheatwood et al. 2000



BS1 BS2 BS3

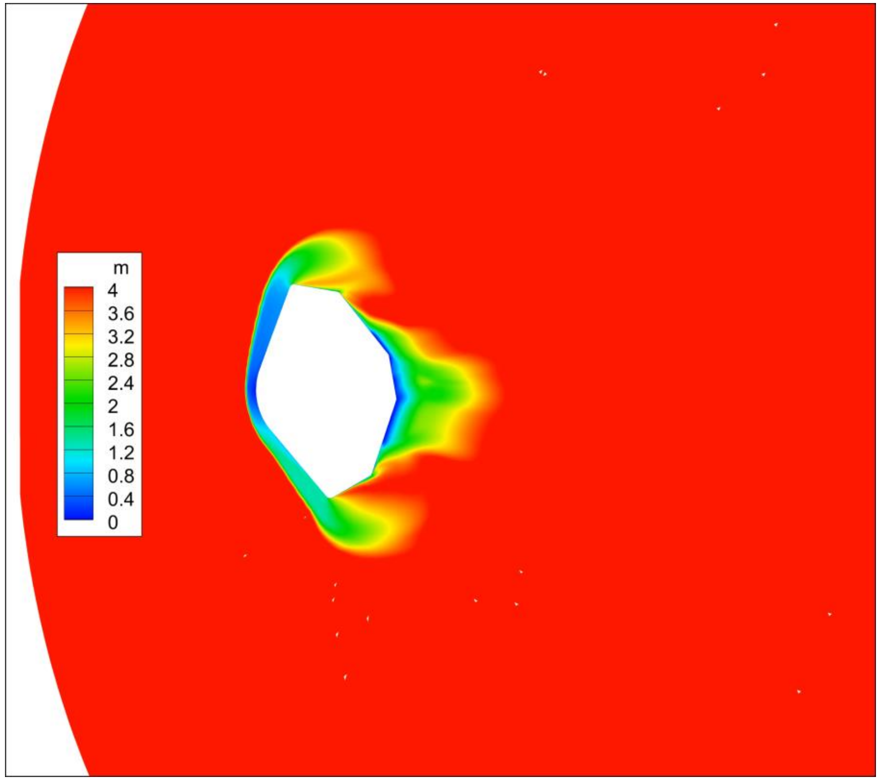
US3D Free-Flight Solver

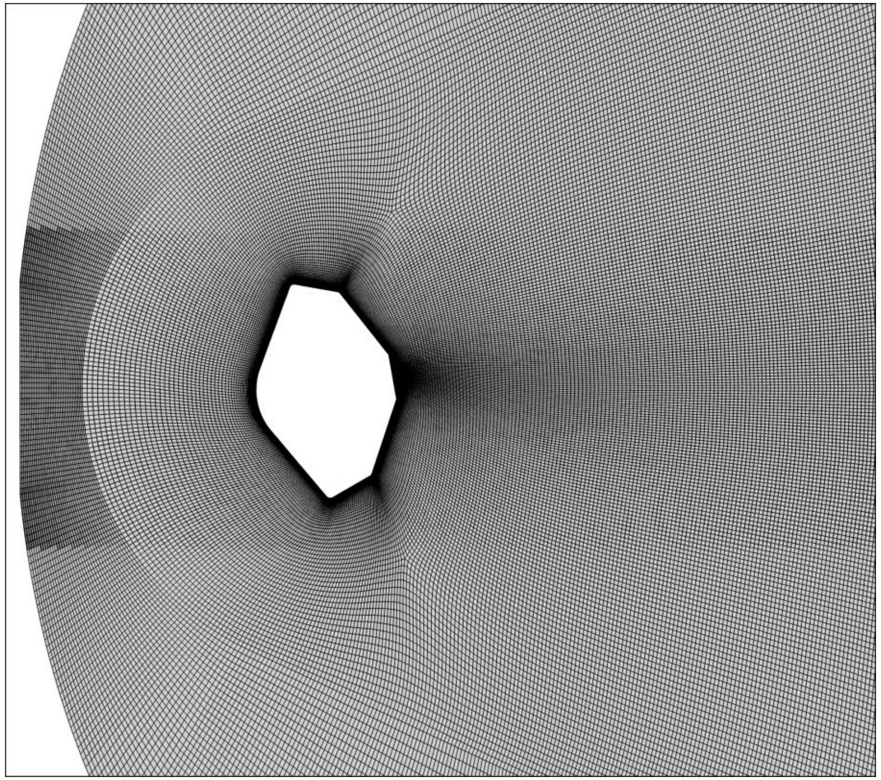
Free-flight Solver Loop:

- US3D computes the forces and moments
- Moments are integrated to obtain rigid body rotation
- Rigid body dynamics determine the grid deformation
- Lift and drag are integrated to determine frame velocity

Mesh Deformation:

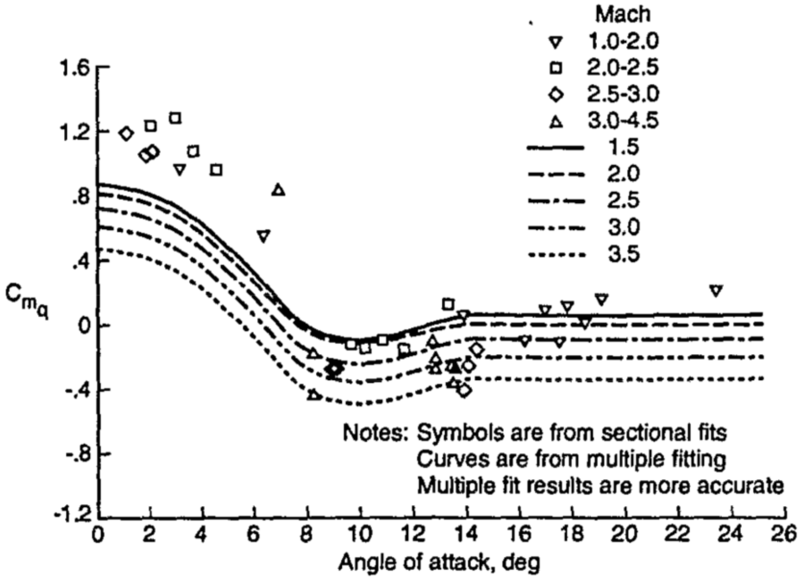
- Inner region rotates in response to moments imparted to the aftbody
- Intermediate region linearly interpolates node displacements between the inner and outer regions
- Outer region remains static



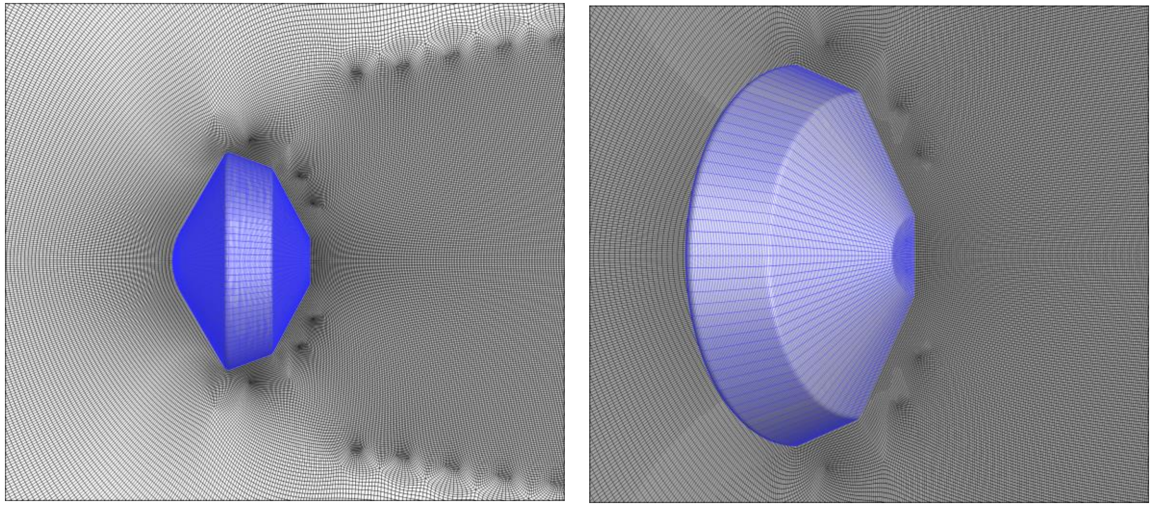


Simulation Parameters

- Reduce the number of effective parameters on free-flight dynamics
  - Initial position, velocity, and rotation rates set to zero
  - 1 DoF – rotation about z-axis
- **4 cases for each configuration:**
  - Initial attitudes of 2° and 15°
  - Freestream Mach number of 1.5 and 2.5
  - Simulation at least 5 periods in pitch oscillations
    - To provide a large enough data set to observe dynamic stability behavior



[2]Cheatwood et al. 2000



7.1 million elements (clustering not shown)

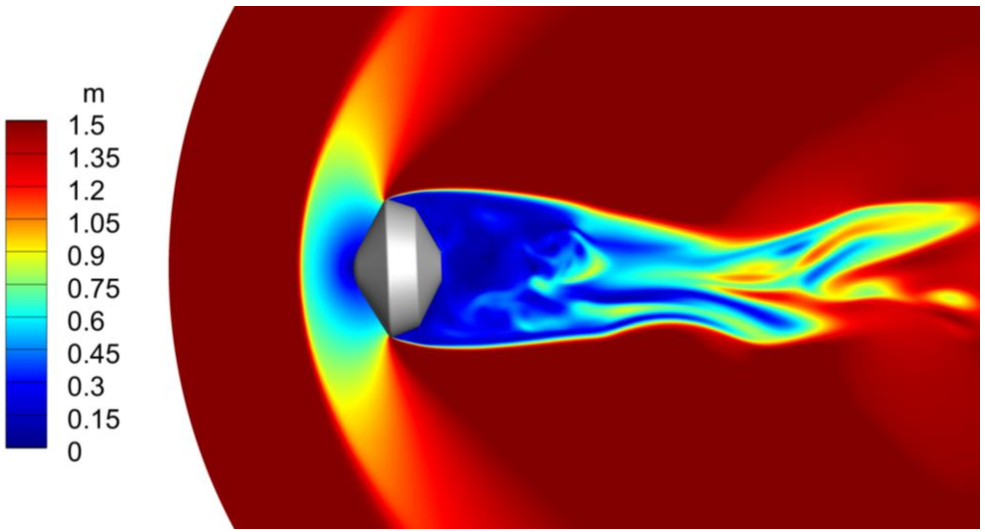
Flow Conditions (subscale)

M_∞	U_∞ (m/s)	rho_∞ (kg/m^3)	T_∞ (K)
1.5	514.6	1.2149	292.94
2.5	857.6	1.2149	292.94

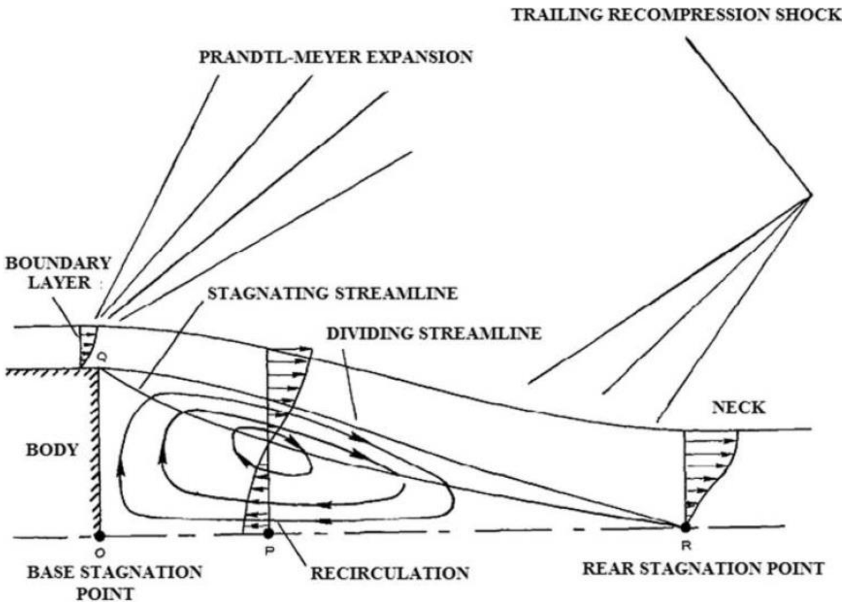
- Modified Steger-Warming flux evaluation scheme
- Time integration uses 2nd Order Implicit Euler
- Detached eddy simulation
  - Subscale grid modeled using the Spalart-Allmaras[3] turbulence model
- 1000 cores, Walltime ~41.3 hrs, physical time ~0.3 sec

[3]Spalart & Allmaras 1992

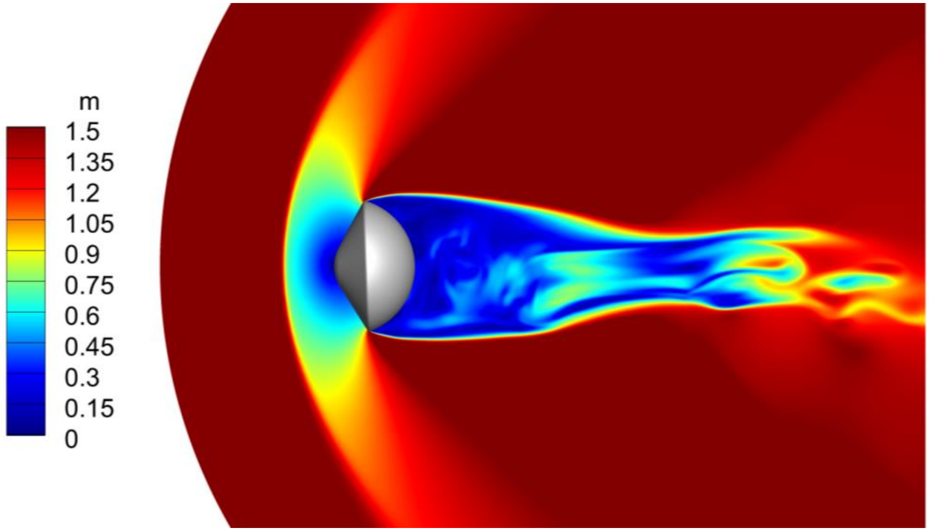
Wake Structures



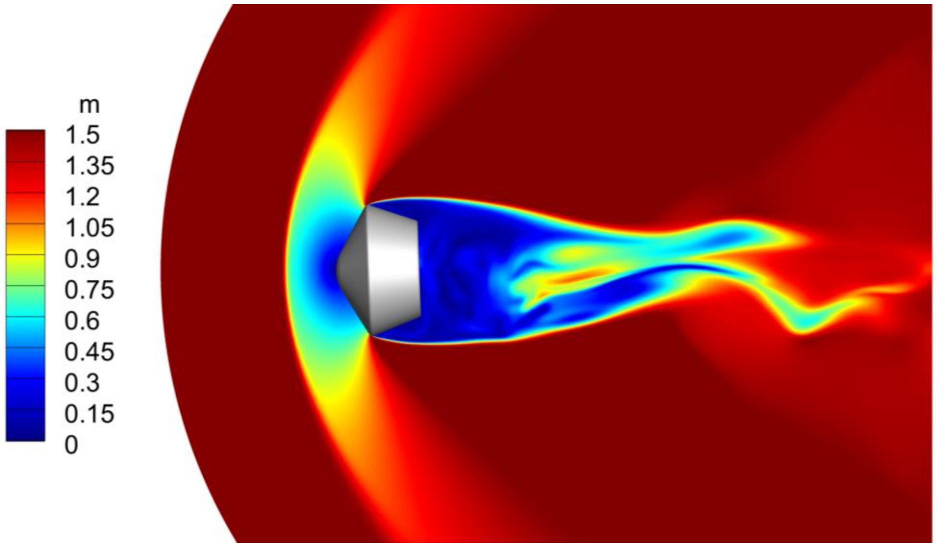
BS1: M=1.5, θ=2°



[4]Jaremenko et al. 1967

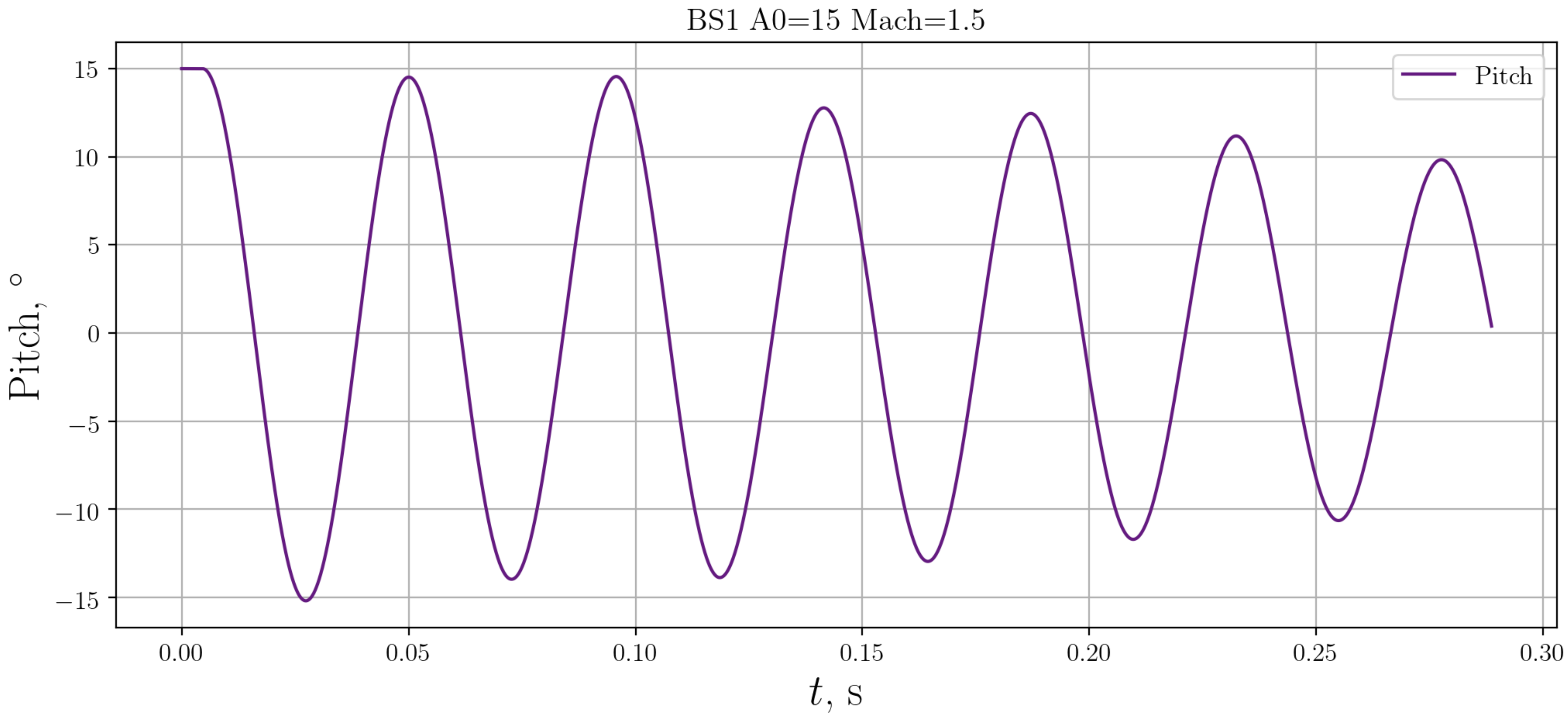


BS2: M=1.5, θ=2°

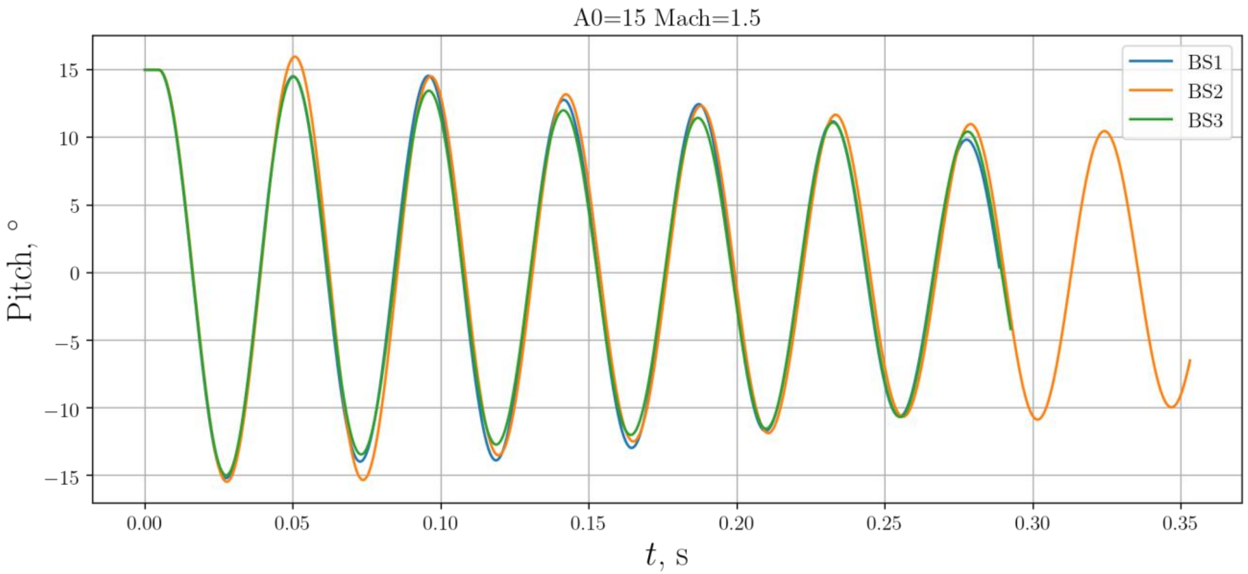


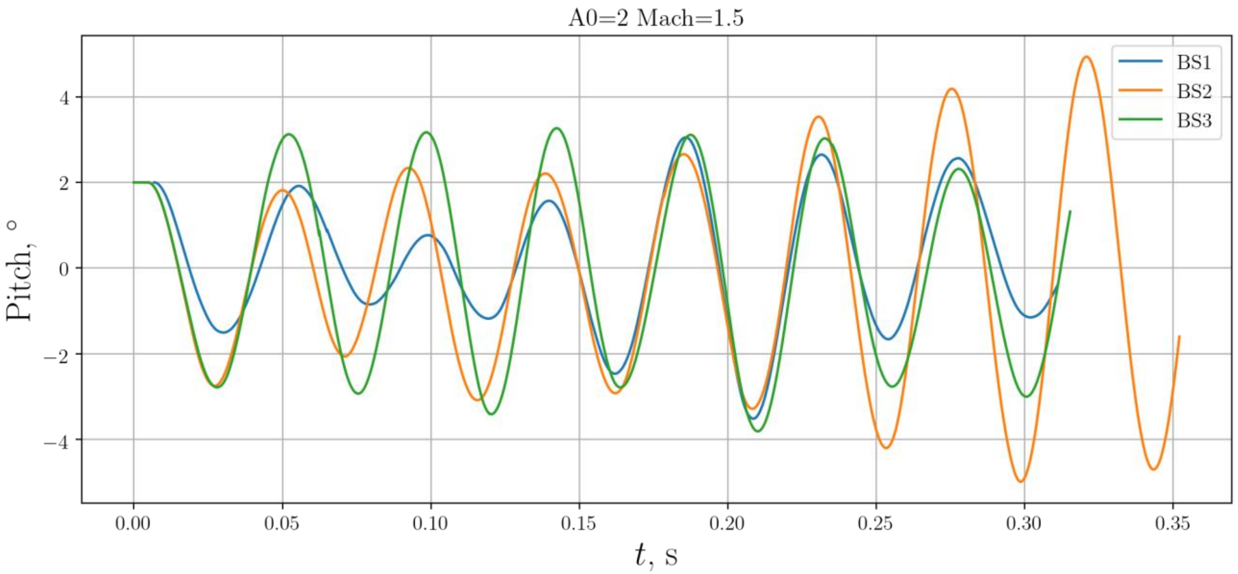
BS3: M=1.5, θ=2°

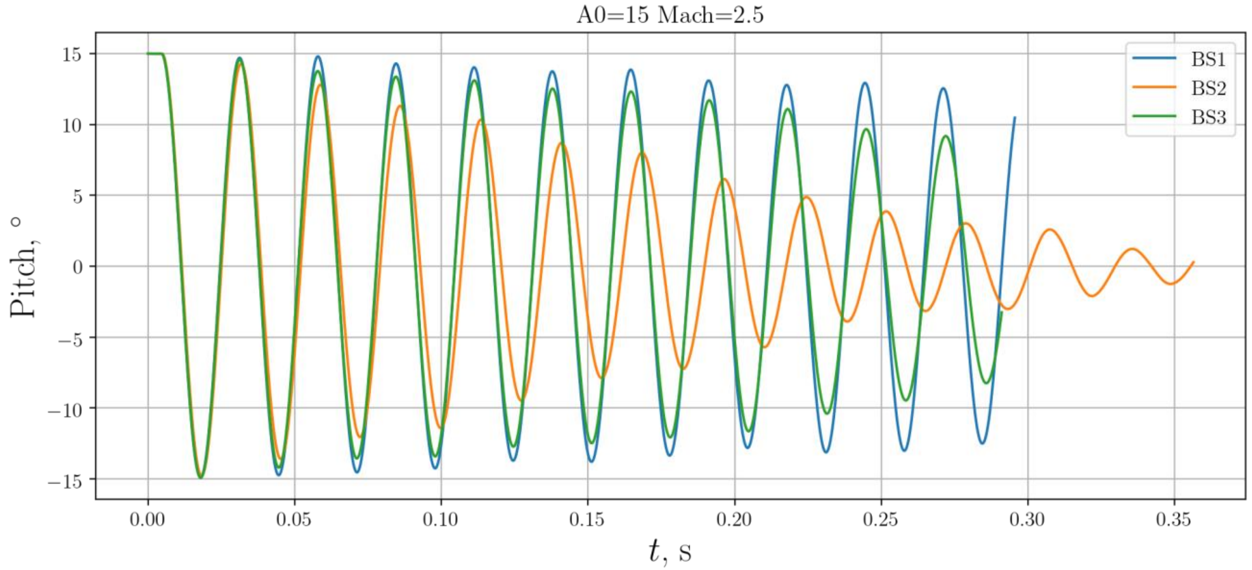
FFCFD Dynamic Data

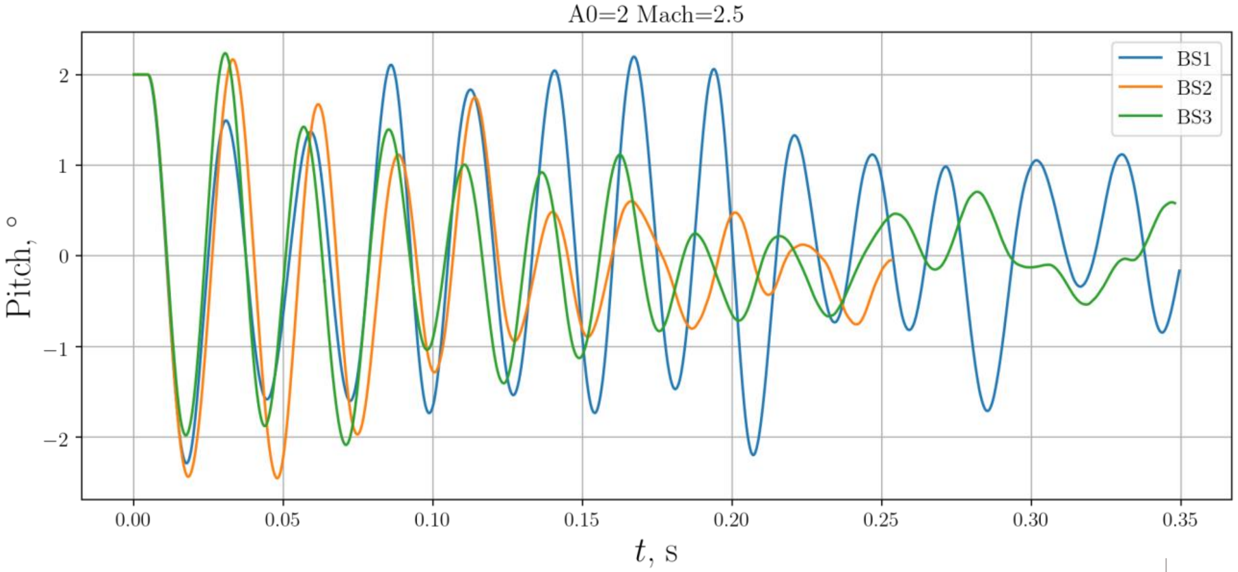


Pitch vs. Time





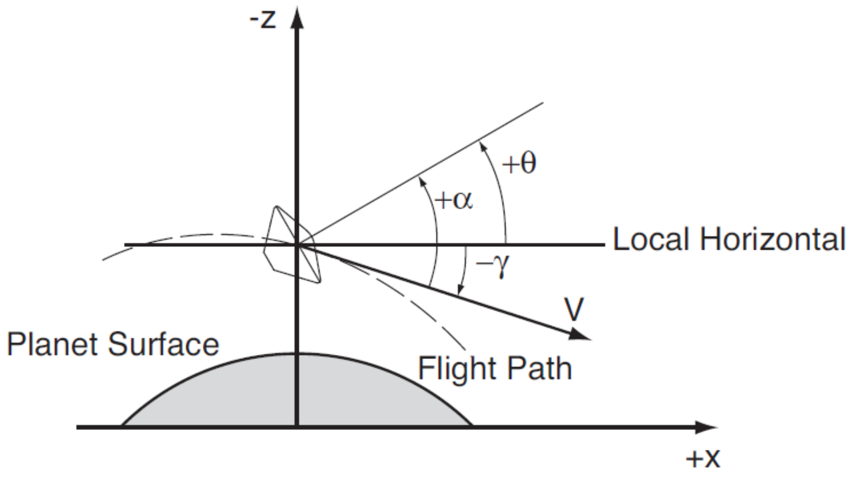




Pitch Damping Coefficient (C_{mq}+ $C_{m\alpha\_dot}$)

- Simplified relevant EOM based off Schoenenberger & Queen[5] 2008
  - Assuming constant velocity, free-to-Oscillate, no-heave:

$$\ddot{\alpha} - \frac{\rho V_\infty S d^2}{4I}\left(C_{m_q} + C_{m_{\dot{\alpha}}}\right)\dot{\alpha} - \frac{\rho V_\infty^2 S d}{2I} C_{m_\alpha}\alpha = 0$$



- Constant coefficients gives solution for simple harmonic oscillator with damping:

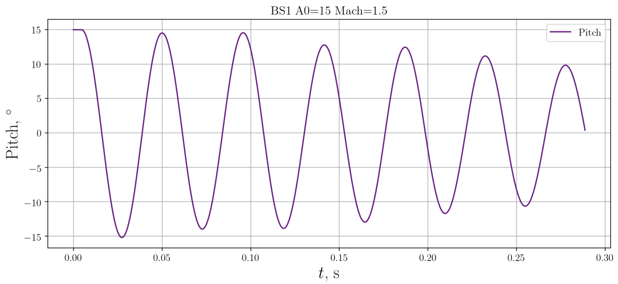
$$\alpha = Ae^{\xi_1 t}\cos(\omega t + \delta)$$ where, $$\xi_1 = \frac{\rho V S d^2}{8I}\left(C_{m_q} + C_{m_{\dot{\alpha}}}\right)$$

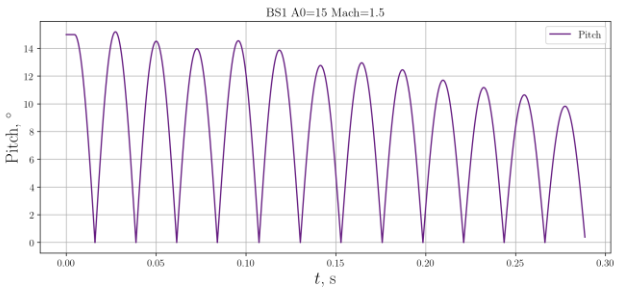
Initial pitch amplitude (A)

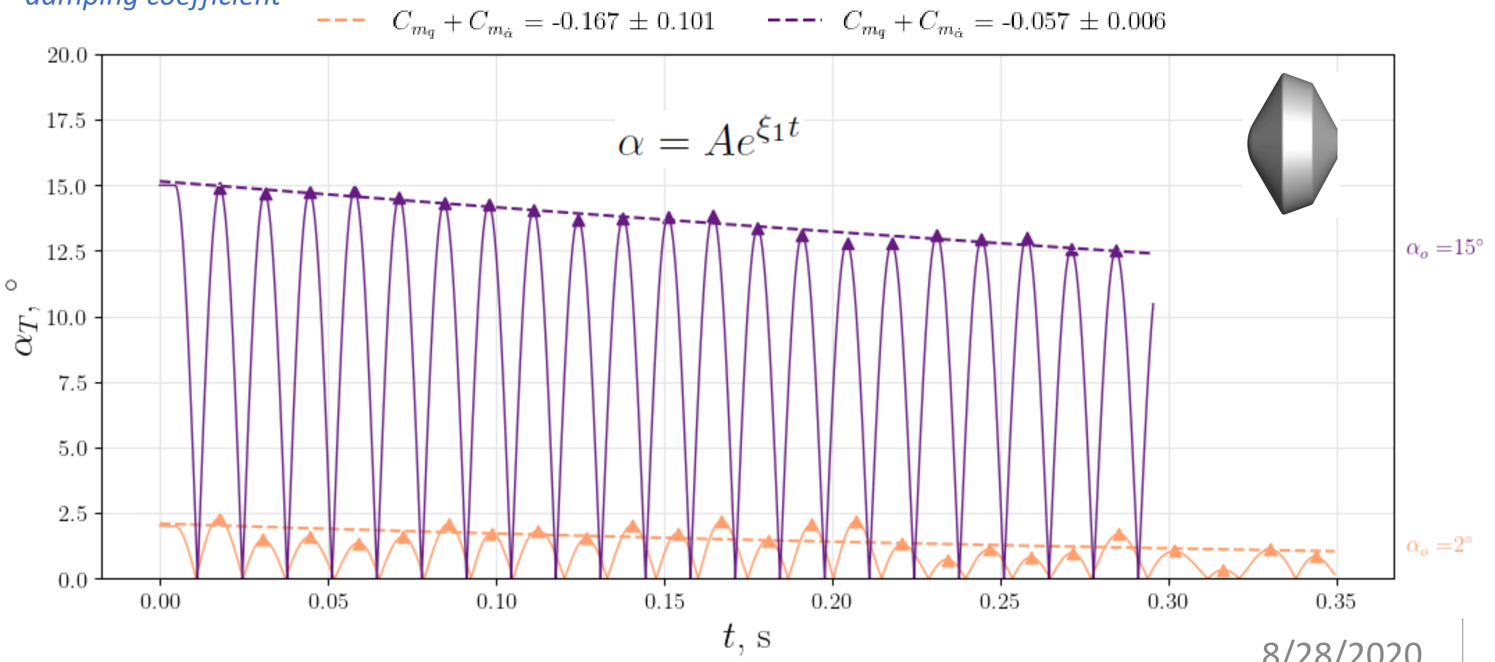
Oscillation frequency (ω)

Phase shift constant (δ)

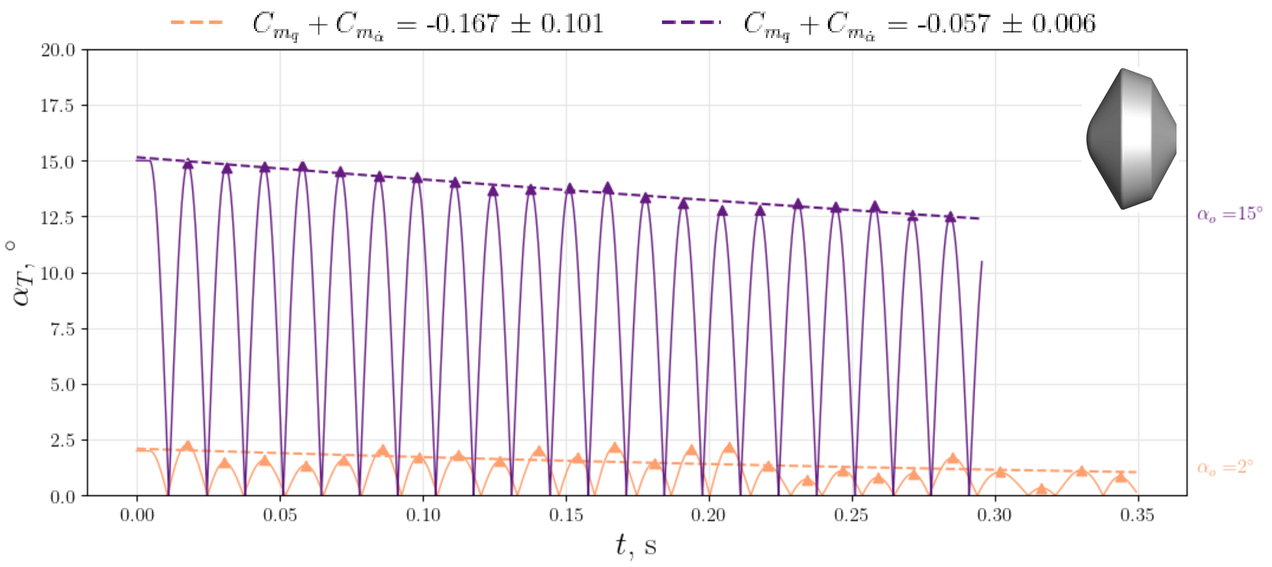
Constant velocity damping coefficient (ξ_1)

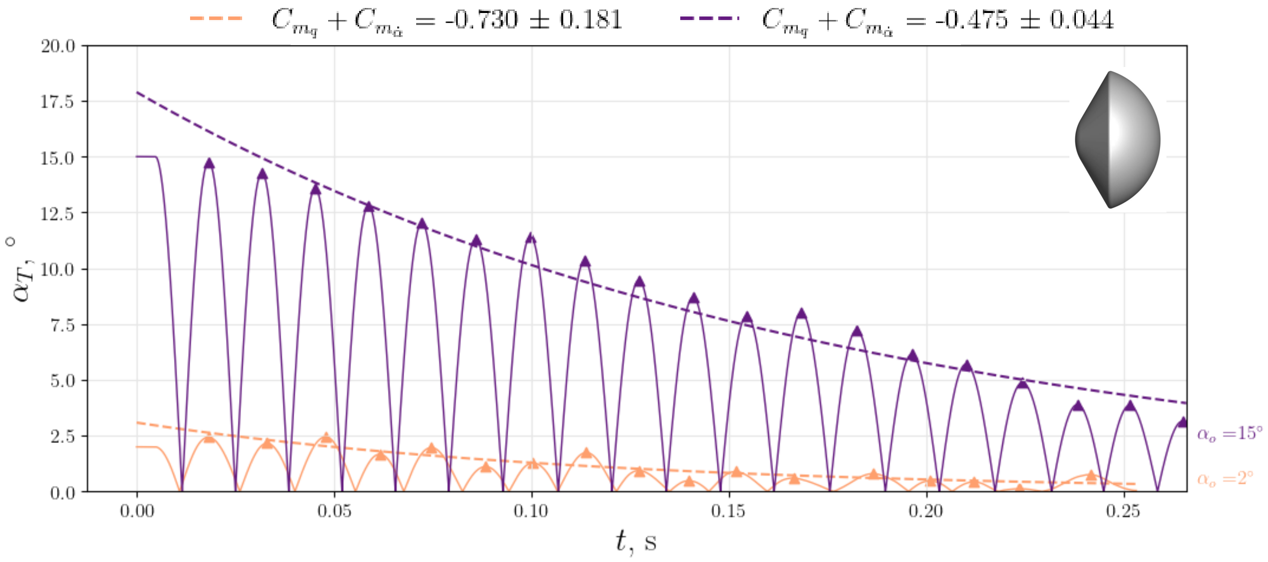






Pitch Damping Coefficient Mach 2.5



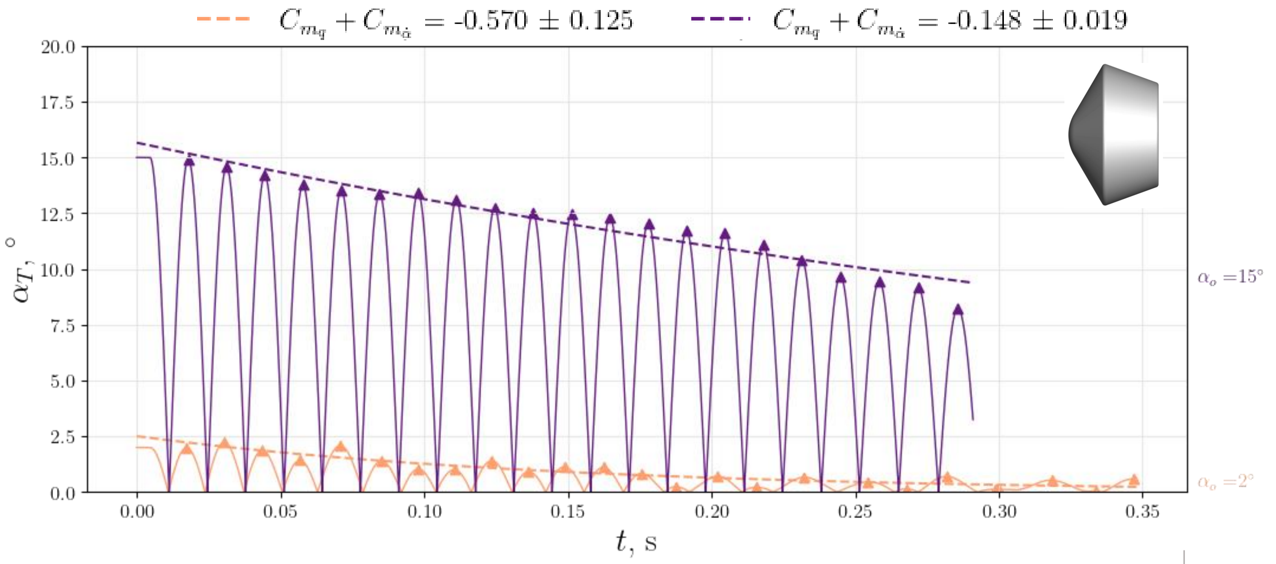


Dynamic stability summary:

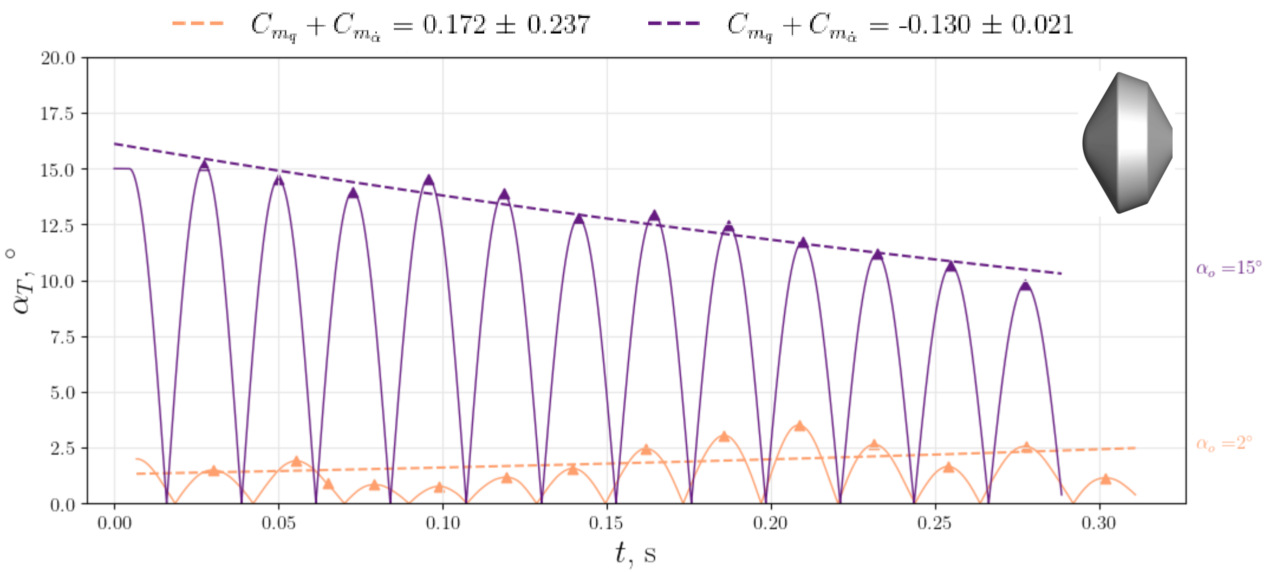
- Pitch oscillations decay for all cases

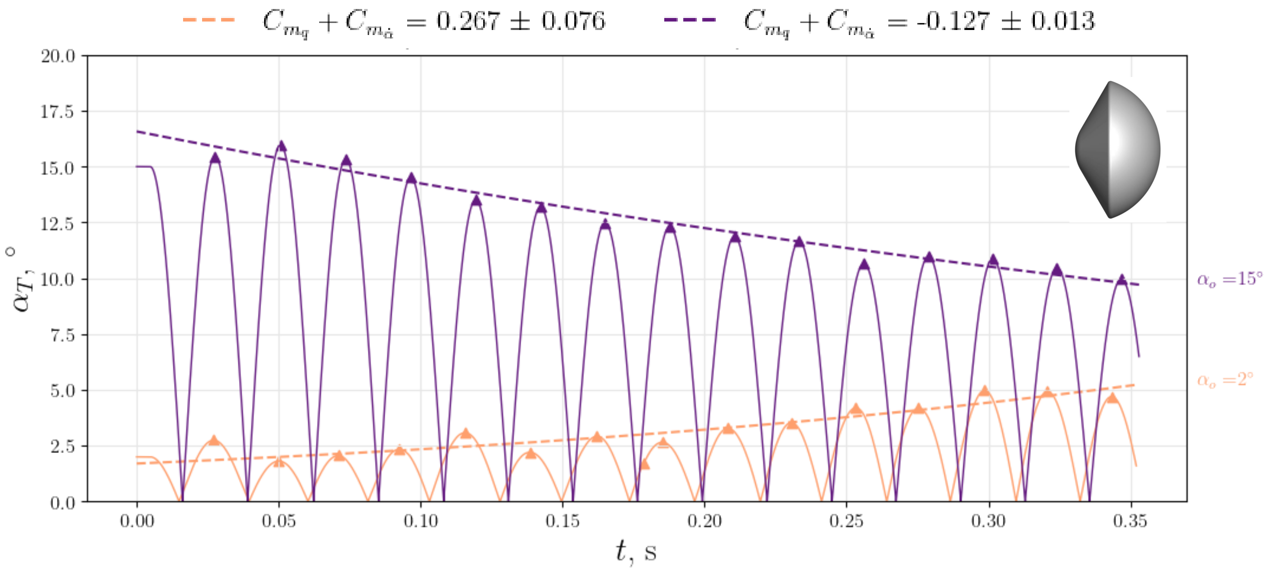
Pitch damping (in descending order)

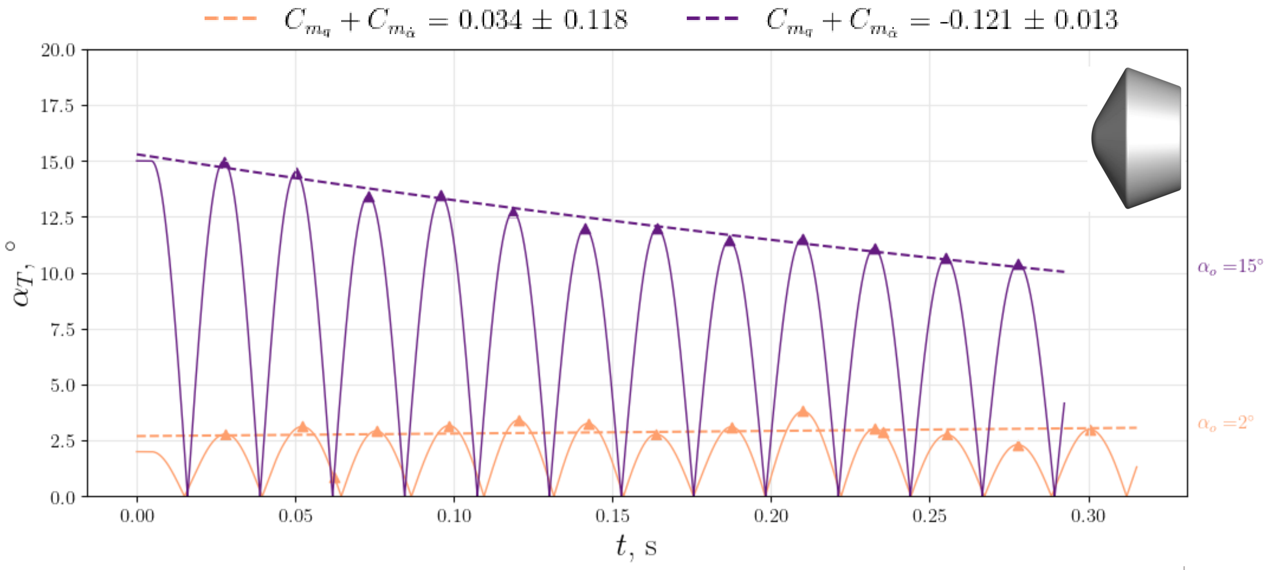
- 15° cases – BS2, BS3, BS1
- 2° cases – BS2, BS3, BS1



Pitch Damping Coefficient Mach 1.5







<u>Dynamic stability summary</u>

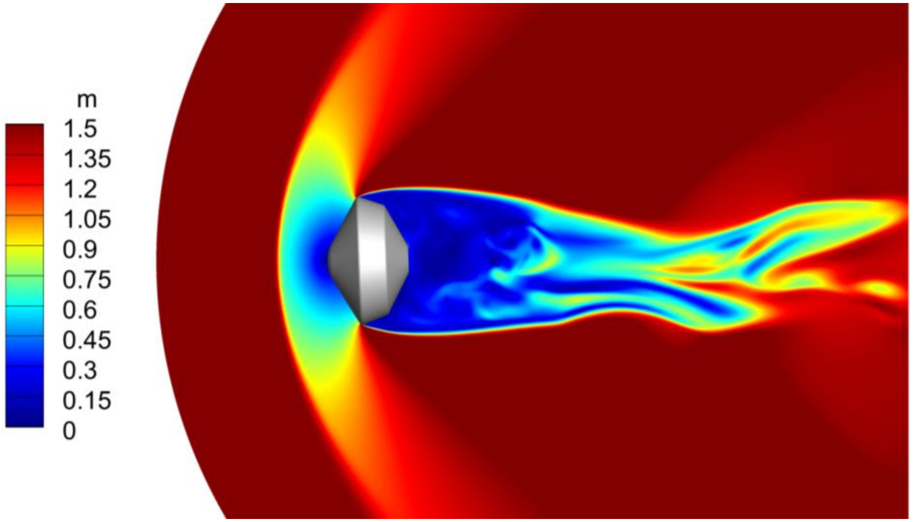
Pitch oscillation damping (BS1 more damping)

- 15° cases – BS1, BS2, BS3

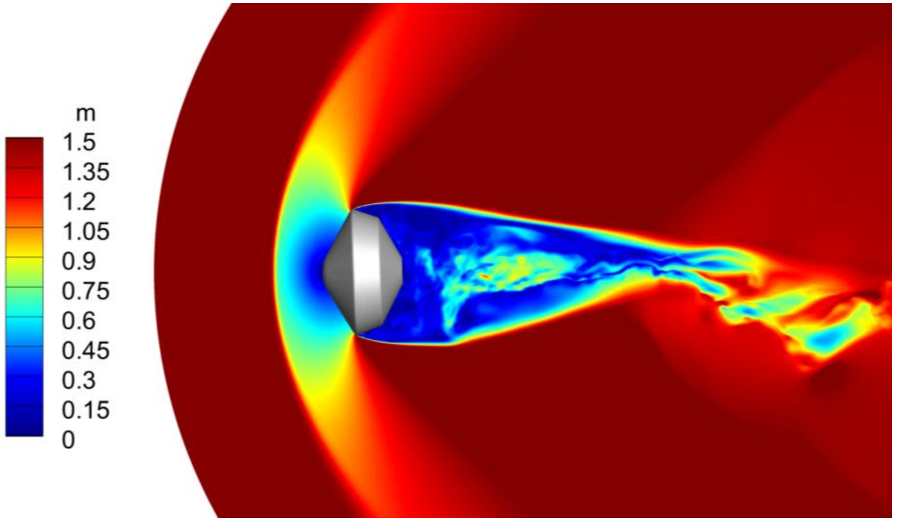
Pitch oscillation growth (BS2 more growth)

- 2° cases – BS2, BS1, BS3

Low dissipation flux evaluation

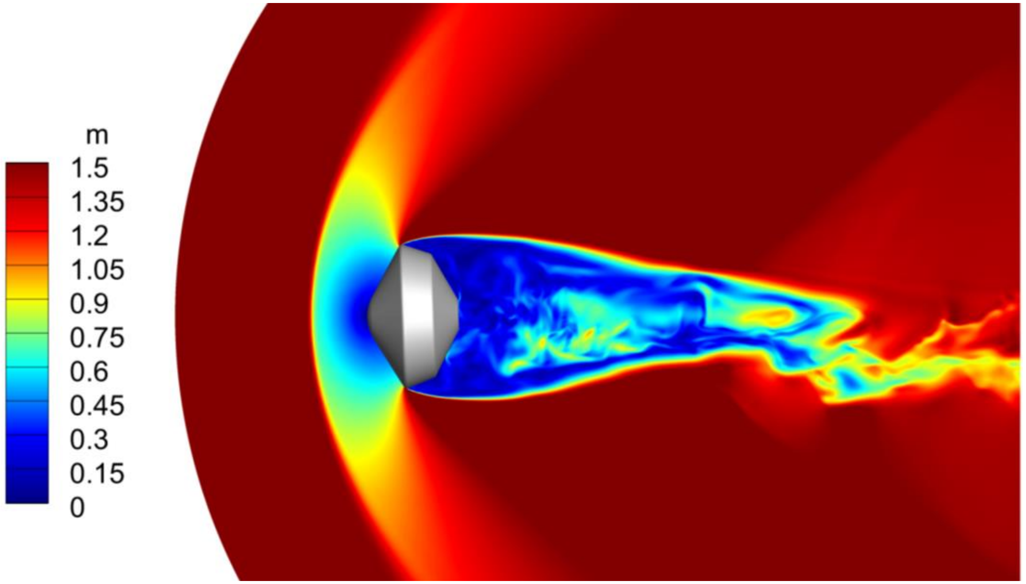


BS1(MSW): M=1.5, θ=2°



BS1(2nd Order KEC, Ducros Sensor): M=1.5, θ=2°

- 2nd Order gradient-based reconstruction[6] (KEC)
  - Larsson[7] sensor vs. modified Ducros[8] sensor
  - Computational cost comparison using 1000 cores:
    - MSW - 6710 cpu hours
    - KEC - 7550 cpu hours
    - Results in an 12.5% increase in computational cost

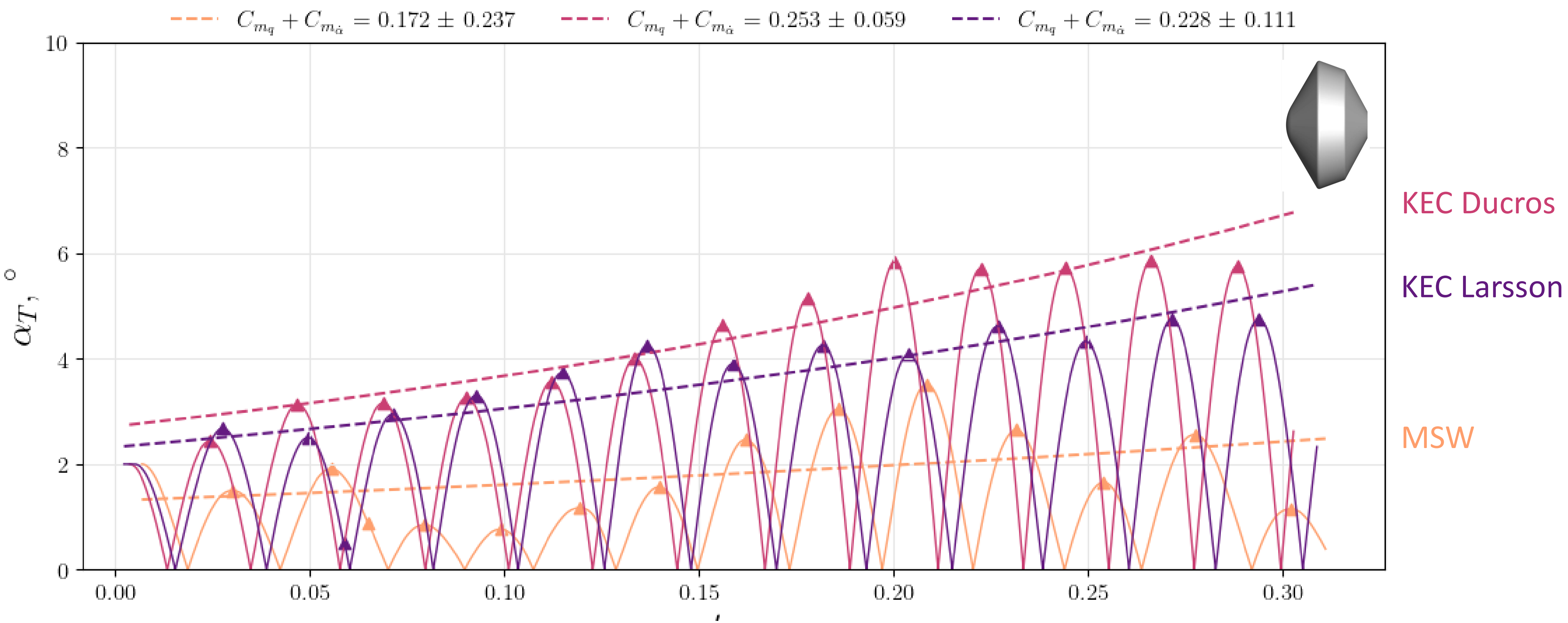


BS1(2nd Order KEC, Larsson Sensor): M=1.5, θ=2°

[6]Subbareddy et el. 2014, [7]Larsson et al. 2012, [8]Hendrickson et al. 2018

Pitch Damping Comparison: MSW vs. KEC

Mach 1.5, A_o=2° for BS1:



Suggestions for future work:

- Quantify resolved frequencies over a variety of test cases
- Vary timestep and grid resolution
- Make direct comparisons to experiments if possible

Summary

- Generated a Mach-Alpha database for 3 different backshell geometries
  - Observed dynamic instability for low initial pitch angles
  - Dynamic behavior remained stable for high pitch angles
  - Mach number saw similar trends but less sensitive than pitch angle
- Analyzed pitch damping for each configuration for 1 DoF
  - Pitch damping for Mach 2.5 at initial pitch of 2° and 15° (BS2 most damped)
  - M=1.5, 15° - nearly identical dynamic behavior
  - M=1.5, 2° - unstable regime, pitch oscillation growth for all cases
- Investigated effects of numerical flux schemes on individual results for BS1 at unstable conditions
  - Dynamic behavior is sensitive to the numerics
  - Numerical method becomes increasingly more important than the backshell shape when modeling small-scale features

Acknowledgements:

Joseph Brock, Dirk Ekelschot, Eric Stern, Jeff Hill, and Brett Cruden

Questions?