



An Overset Grid Motion Driver for Resolving Entry Vehicle CFD Simulations with Large Changes in Wake Orientation



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Outline:

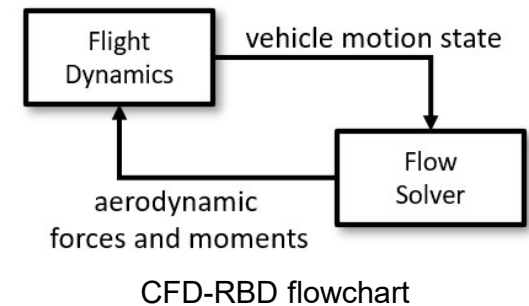
- Motivation
- Wake grid motion driver
- Integrating driver into a free-flight CFD model
- Demonstration in free-flight simulations
- Conclusions



Predicting Blunt Body Dynamics



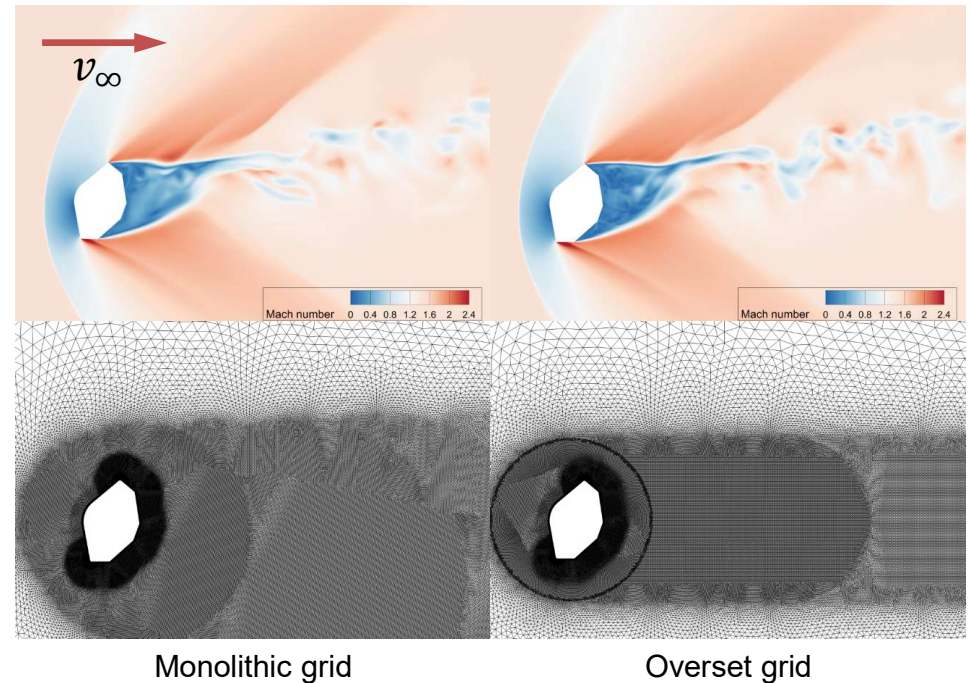
- Prediction of blunt-body dynamic behavior is a difficult and ongoing field of study
- Currently relies on physical experiments (e.g. ballistic range tests)
- Starting to be augmented by computational experiments
 - Forced-motion CFD simulations
 - Multi-degree-of-freedom CFD/rigid body dynamics (CFD-RBD) simulations [1-3]
- Flow time history is preserved, therefore unsteady flight can be modeled



1. Stern, E., Brock, J., McKown, Q., and Kazemba, C., "A Method for Deriving Capsule Pitch Damping Coefficients from Free-Flight CFD Data," AIAA Journal (not yet published), 2022.
2. Stern, E., Schwing, A., Brock, J. M., and Schoenenberger, M., "Dynamic CFD Simulations of the MEADS II Ballistic Range Test Model," AIAA Atmospheric Flight Mechanics Conference, 2016. <https://doi.org/10.2514/6.2016-3243>.
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Resolving the Wake

- Accurate prediction of blunt body dynamic characteristics relies on correctly resolving the wake[4]
- Blunt bodies go through large changes in attitude
- Wake changes orientation relative to the body
- A monolithic grid must have a large, high-density region to anticipate this motion
- Overset meshing can reduce the computational cost

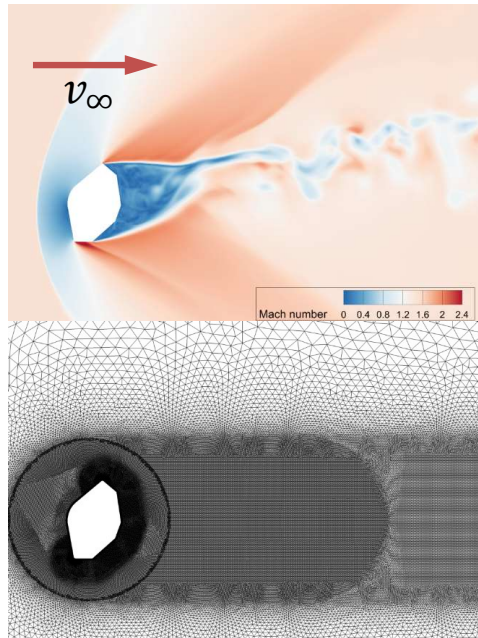


Genesis capsule Mach flow field at 20° angle of attack and Mach 1.5

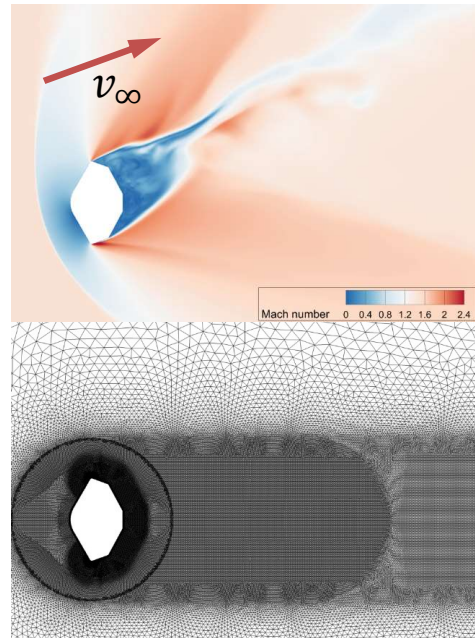
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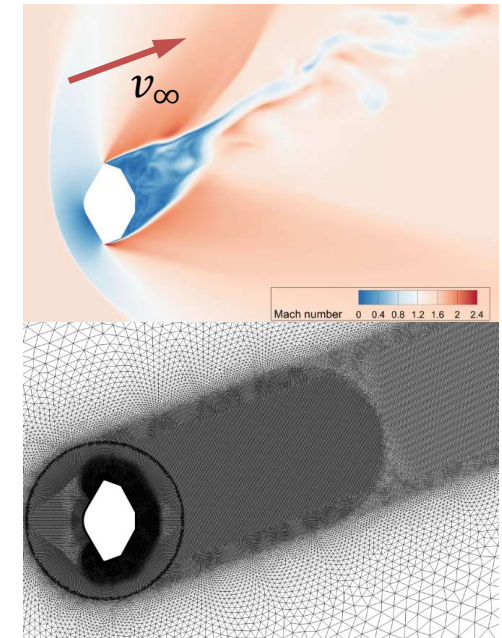
Overset Mesh Wake Resolution



Current simulations assume the wake orientation remains close to parallel to the freestream velocity vector



If the flight path angle changes (such as over a long duration), the wake may drift out of the highly-resolved region



The wake grid should be transformed to keep the wake within the highly-resolved region



Objectives



- Develop an overset wake grid motion driver to keep the wake resolved even with large changes in flight path angle
- Incorporate the motion driver into an existing CFD-RBD model
- Demonstrate the motion driver for a vehicle that undergoes a large change in flight path angle

- Assumptions:
 - Two-part overset mesh with rigid wake and body grids
 - Body and wake grid are axisymmetric about the x -axis
 - The wake remains close to parallel to the vehicle-relative freestream velocity vector (given no known behavior)
- The wake grid points along the vehicle-relative freestream velocity vector:

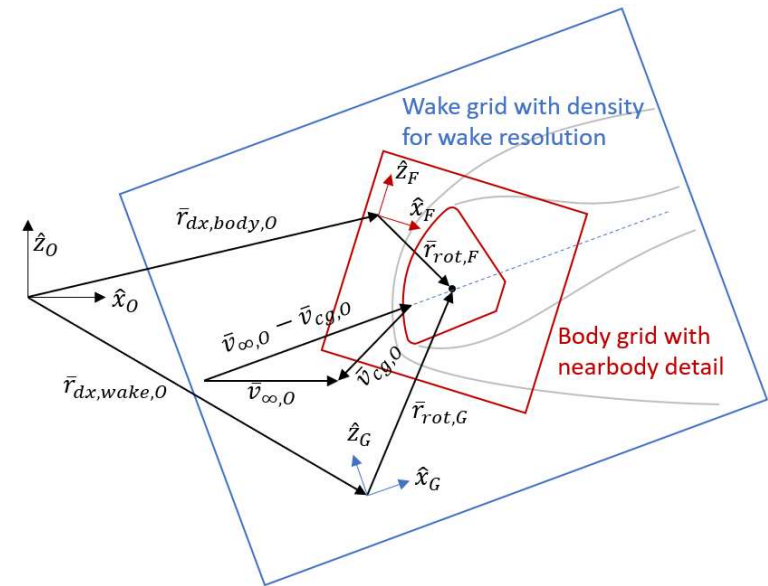
$$\bar{v}_{rel,0} = \bar{v}_{\infty,0} - \bar{v}_{cg,0}$$

$$\theta_{wake} = -\arcsin \frac{v_{rel,z,0}}{|\bar{v}_{rel,0}|}, \quad \psi_{wake} = \arctan \frac{v_{rel,y,0}}{v_{rel,x,0}}$$

$$R_{OG} = \begin{bmatrix} \cos \psi_{wake} \cos \theta_{wake} & -\sin \psi_{wake} \cos \psi_{wake} \sin \theta_{wake} \\ \cos \theta_{wake} \sin \psi_{wake} & \cos \psi_{wake} \sin \psi_{wake} \sin \theta_{wake} \\ -\sin \theta_{wake} & 0 \cos \theta_{wake} \end{bmatrix}$$

- The wake grid translates to stay fixed to the body grid at a given rotation point:

$$\bar{r}_{dx,wake,0} = \bar{r}_{dx,body,0} + R_{OF}\bar{r}_{rot,F} - R_{OG}\bar{r}_{rot,G}$$



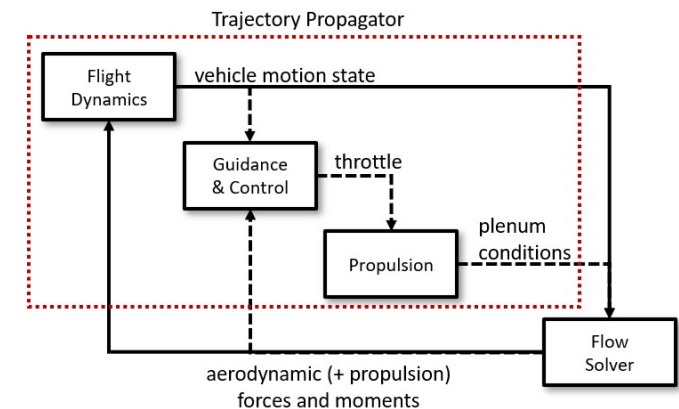
Atmosphere-fixed, body grid, and wake grid reference frames



POST2-FUN3D Bridging Code



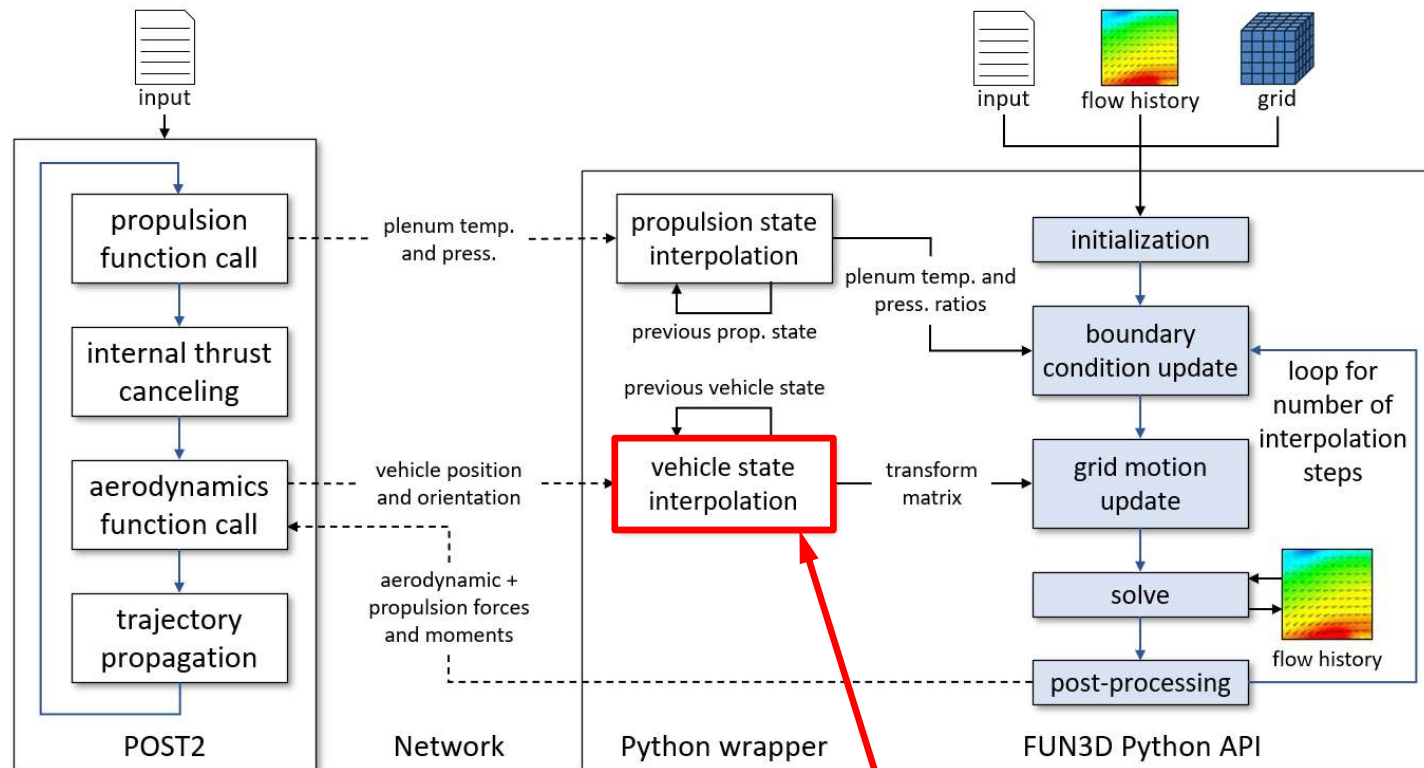
- An existing CFD-RBD bridging code has been developed using FUN3D as the flow solver and POST2 as the trajectory propagator [16-18]
- Both software have been extensively used for modeling entry vehicles
- Incorporating disciplinary models in POST2 allows for full CFD-in-the-loop flight simulation
- Overset grid assembly performed with Yoga [19]



- Ernst, Z., Drosendahl, M., Robertson, B. E., and Mavris, D. N., "Development of a Trajectory-Centric CFD-RBD Framework for Advanced Multidisciplinary/Multiphysics Simulation," AIAA SCITECH 2022 Forum, 2022. <https://doi.org/10.2514/6.2022-1793>.
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POST2-FUN3D Bridging Code



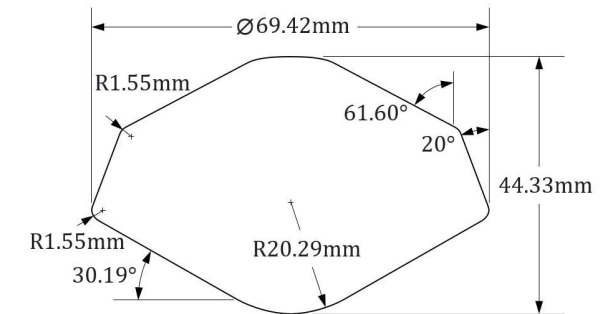
Wake grid motion driver calculations implemented here



Experiment



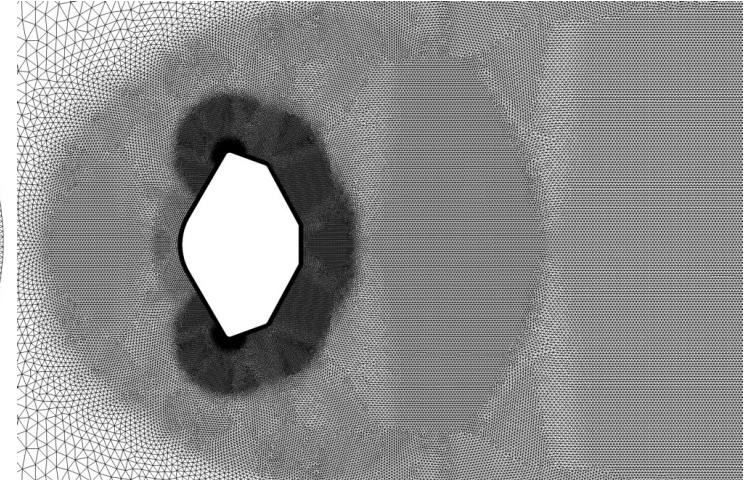
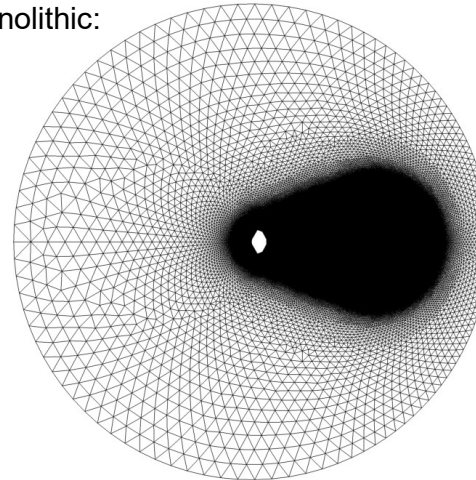
- The Genesis ballistic range model is used as the demonstrator vehicle
- Developed both a monolithic and overset meshes
- Executed time-accurate, fixed-attitude simulations to verify wake behavior in different regions of the meshes
- Ran free-flight simulations of the overset mesh to verify operation of the wake grid motion driver



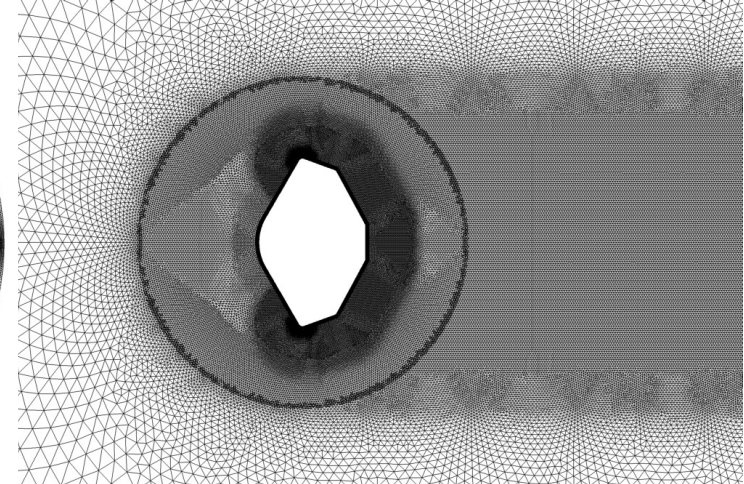
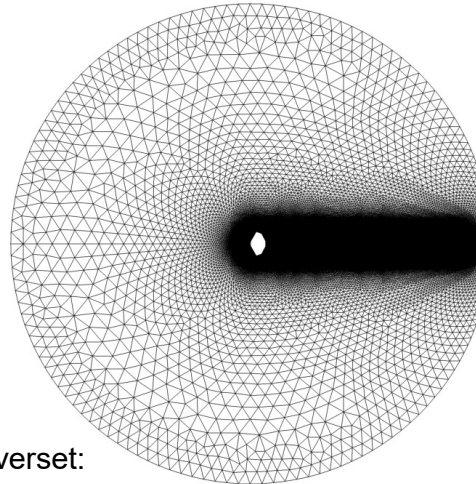
Genesis ballistic range model dimensions

- Grids developed in HeldenMesh 4.14
- Identical surface element sizing to achieve $y^+ < 1$ at the wall
- Identical element sizing in the nearbody and wake

Monolithic:



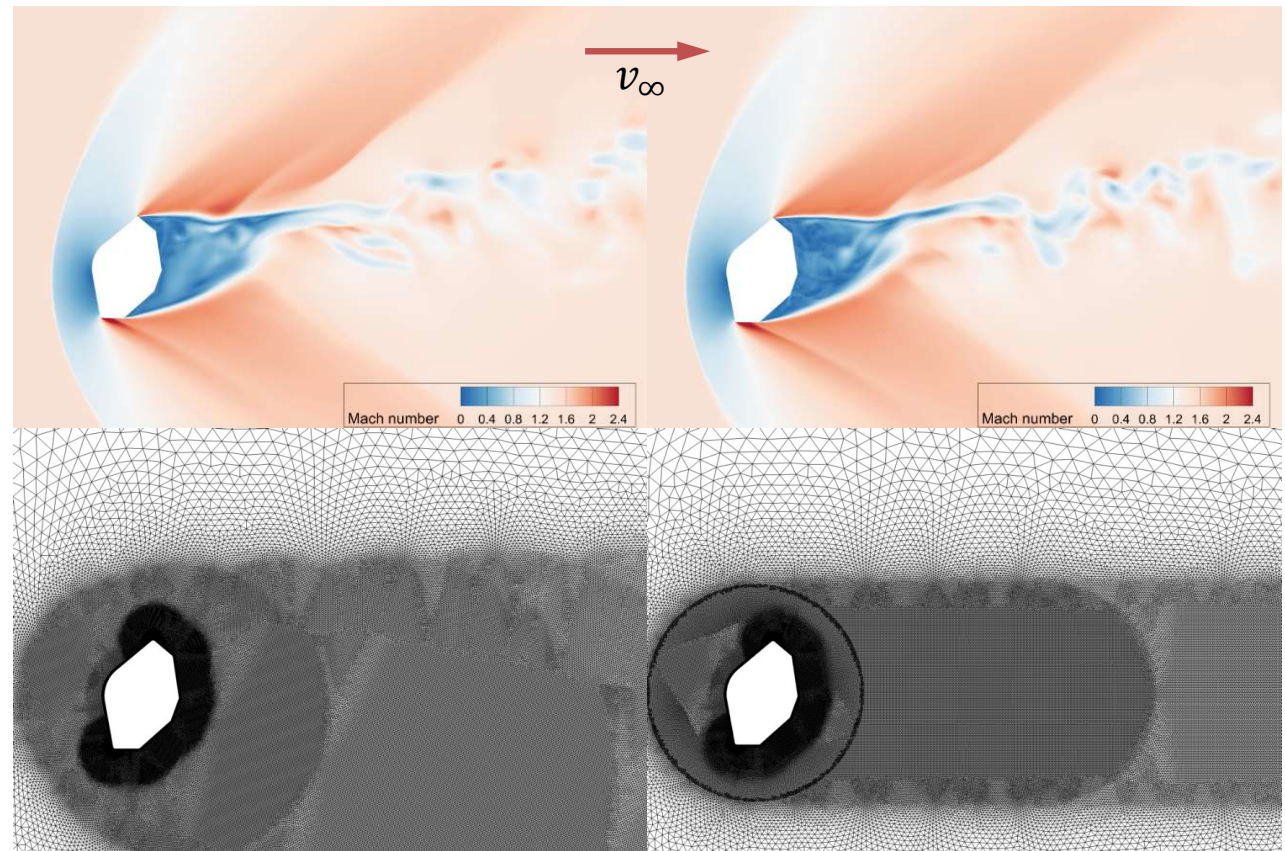
Overset:



Grid	Node	Count (10^6)	
		Tet cell	Hex cell
Monolithic	38.3	213	5.65
Overset	19.6	100	5.67

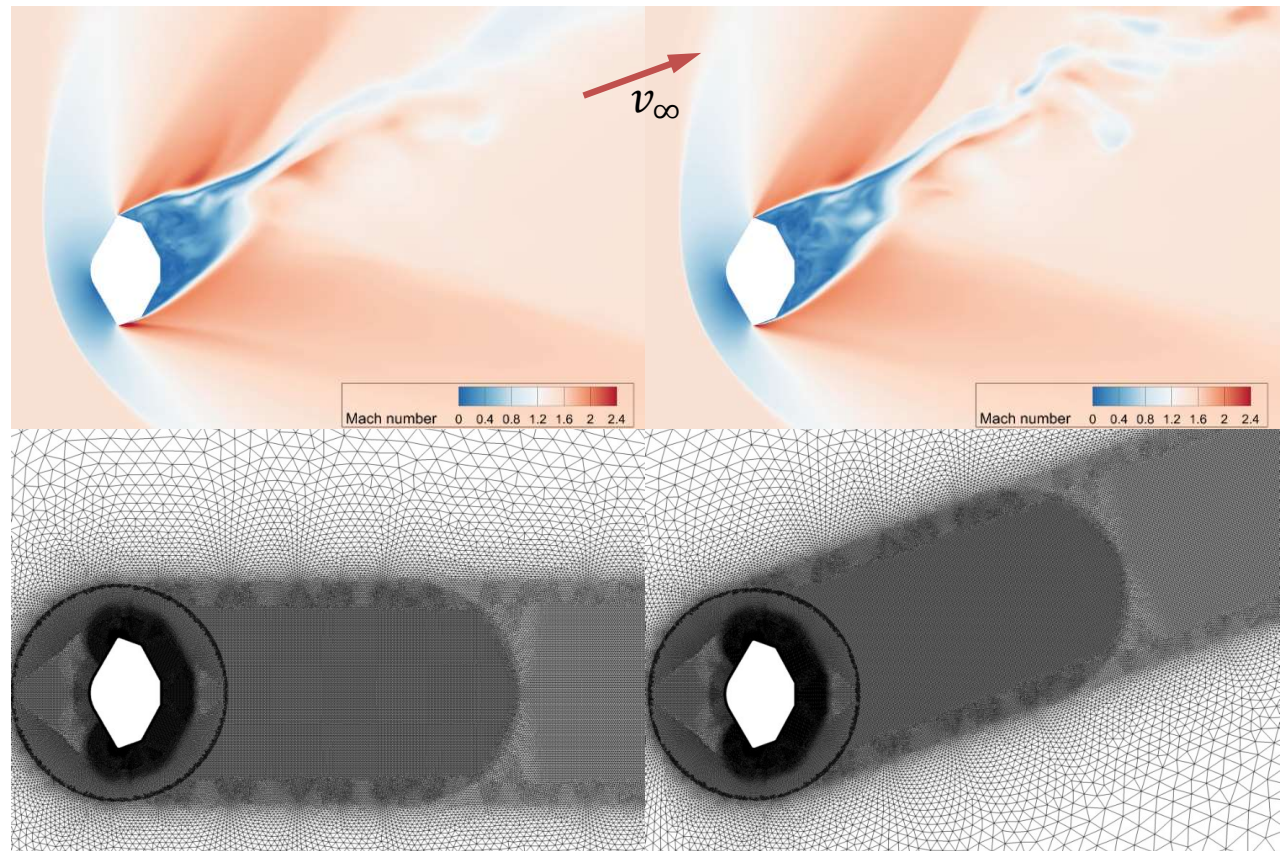
- Monolithic and overset meshes have similar qualitative and quantitative performance at $\alpha = 20^\circ$
- Wake flows at a nonzero angle to the relative freestream velocity
- Cost of the grid assembly is not significant

Grid	Normalized execution time
Monolithic	1.95
Overset	1.00



Monolithic grid Overset grid
Genesis capsule Mach flow field at 20° angle of attack and Mach 1.5

- Failing to move the wake grid results in lower resolution of the wake and recompression shocks
- Large-scale structures are no longer present



Overset, non-moving Overset, moving
Genesis capsule Mach flow field at 20° angle of attack and Mach 1.5



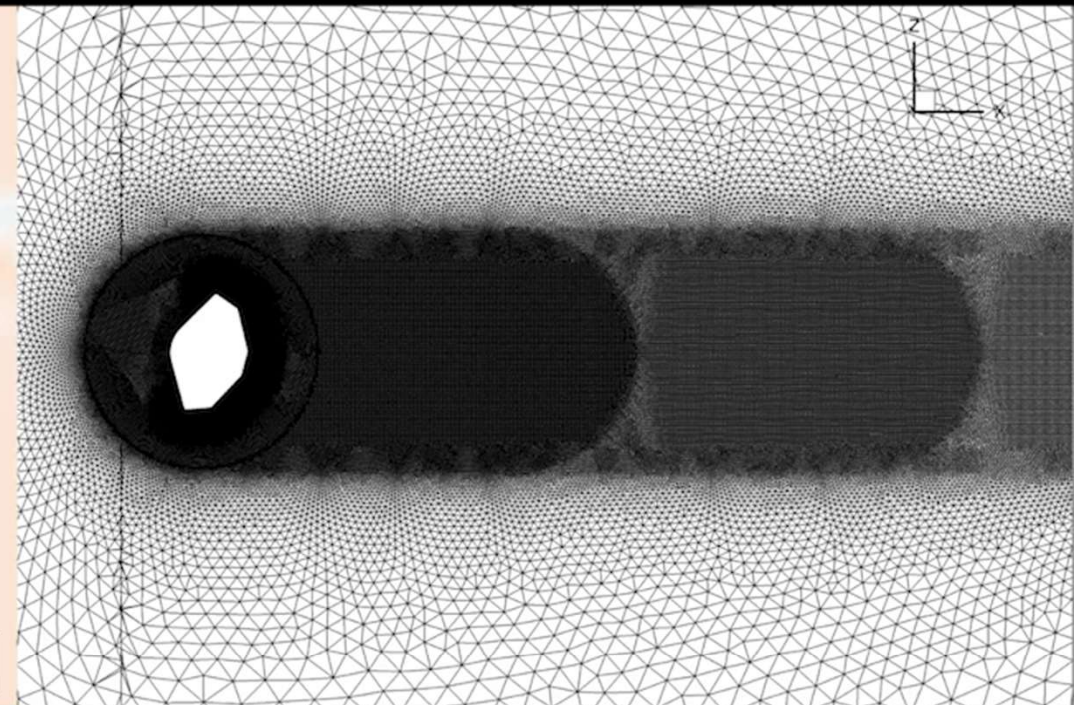
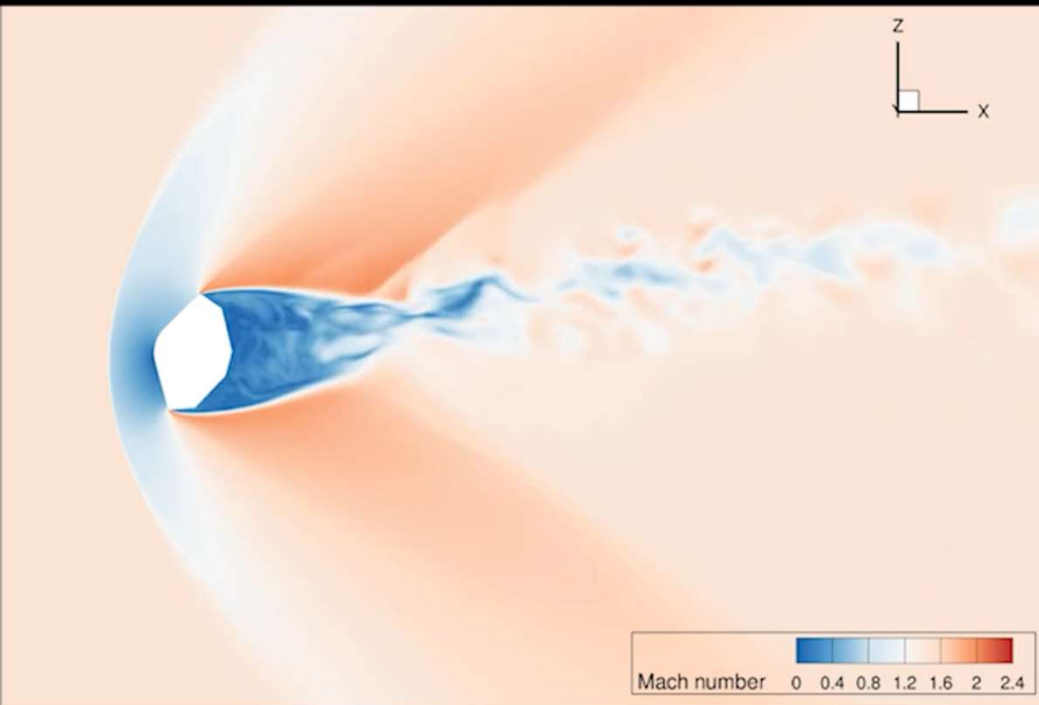
Free-Flight Simulations



- Vehicle simulated at Mach 1.5 at standard sea level conditions
- Vehicle was given a center of gravity (CG) offset in the z -axis to produce a trim angle of attack
 - Combined with gravity, this helps increase the lateral velocity (and flight path angle)
- Drag was ignored to keep the vehicle close to the initial Mach number condition for a longer duration.



Free-Flight Simulations

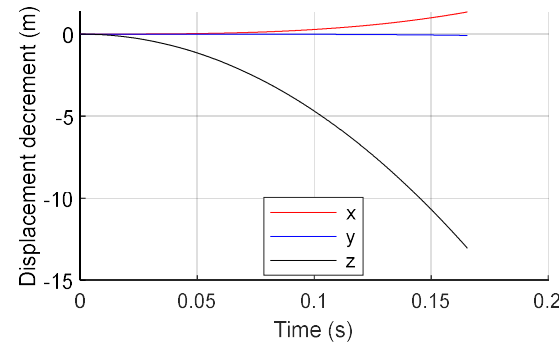




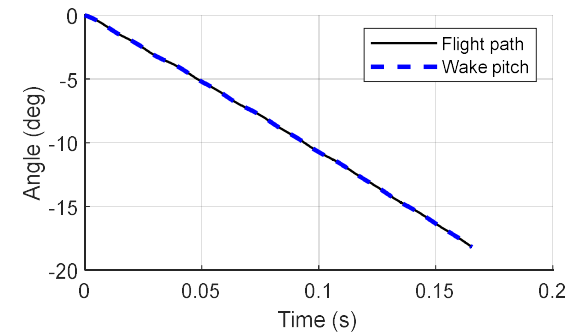
Free-Flight Simulations



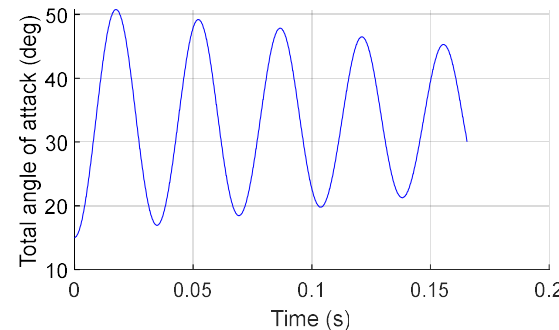
- The wake grid motion driver moved the grid as expected relative to the body grid
- The wake remained resolved even at large angles of attack and increasing flight path angle
- The overset mesh maintains a lower computational cost than the monolithic grid



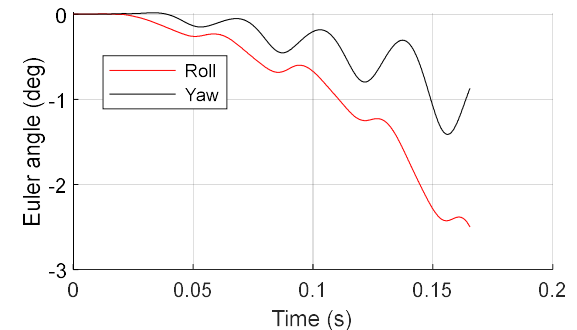
Body displacement decrement



Wake grid orientation



Body total angle of attack



Body roll and yaw Euler angles

Grid	Normalized execution time
Monolithic	1.18
Overset	1.00

Complex Wake Grid Pointing

- Wake grid pointing can be made more accurate with known wake behavior from previous data:

$$\Delta\theta_{T,wake} = 0.751\alpha_T - 0.0115\alpha_T^2$$

- Determine pointing vector of the wake as a function of total angle of attack and relative velocity:

$$\alpha_T = \arccos \frac{\hat{p}_{body,0} \cdot \bar{v}_{rel,0}}{|\bar{v}_{rel,0}|}$$

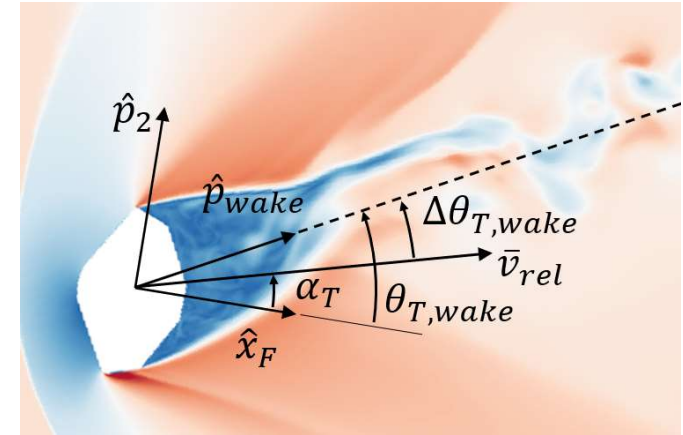
$$\hat{p}_{body,0} = R_{OF}\hat{x}_F$$

$$\theta_{T,wake} = \alpha_T + \Delta\theta_{T,wake}$$

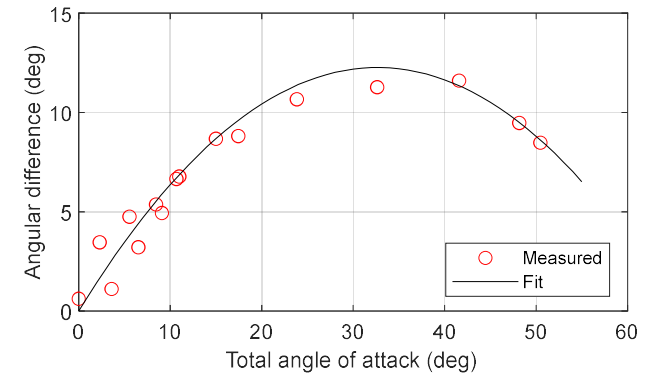
$$\hat{p}_{wake,0} = \hat{p}_{body,0} \cos \theta_{T,wake} + \hat{p}_2 \sin \theta_{T,wake}$$

$$\hat{p}_2 = \frac{(\hat{p}_{body,0} \times \bar{v}_{rel,0}) \times \hat{p}_{body,0}}{|(\hat{p}_{body,0} \times \bar{v}_{rel,0}) \times \hat{p}_{body,0}|}$$

- Pointing vector substituted for freestream velocity in the methodology



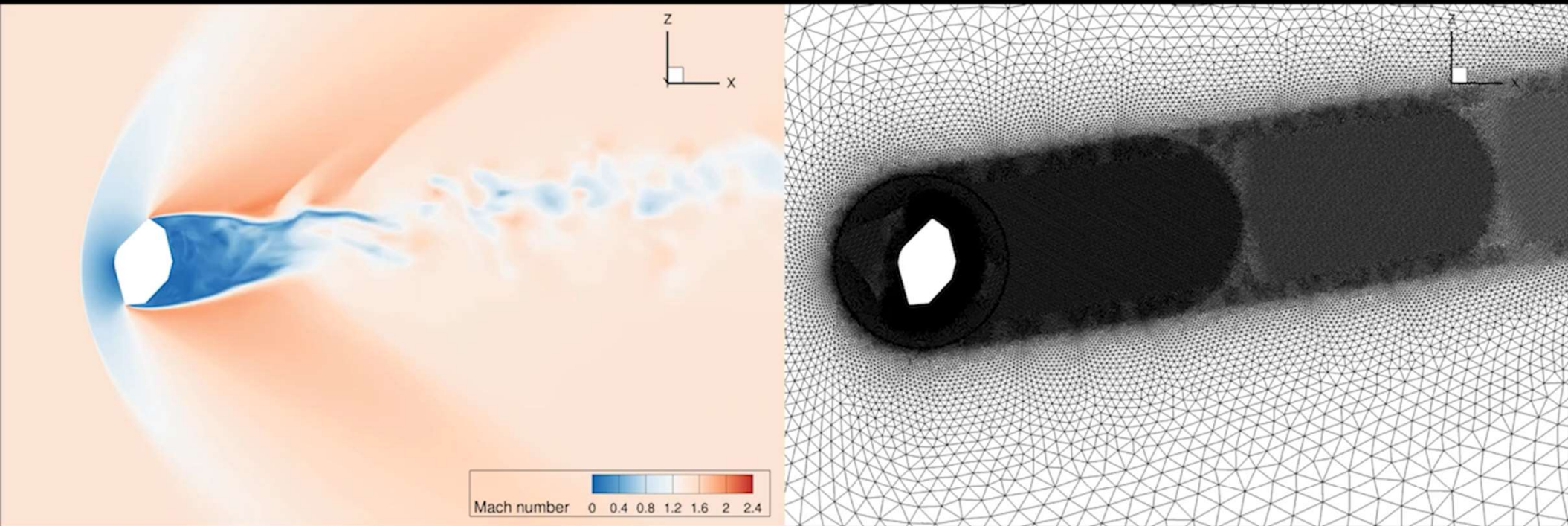
Wake pointing angle definition



Difference between the total angle of attack and wake pointing angle for Genesis ballistic range test vehicle



Complex Wake Grid Pointing

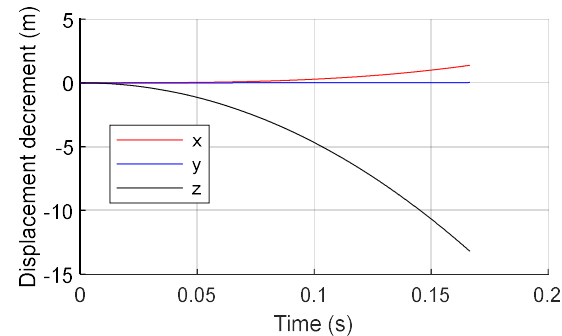




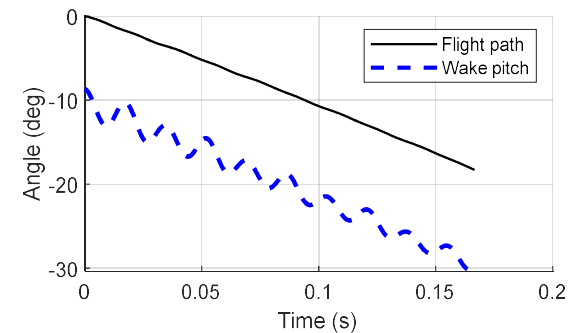
Complex Wake Grid Pointing



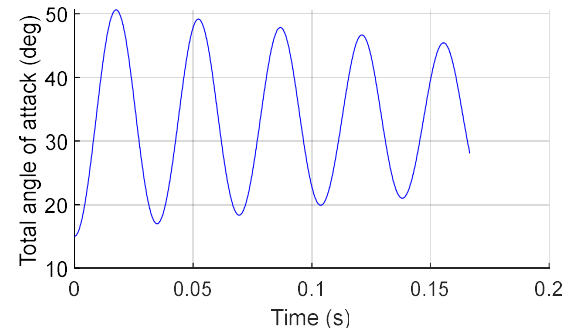
- Free-flight simulation run with wake grid orientation driven based on the known vehicle behavior
- The wake grid aligns closer to the large structures in the wake
- High-density region could be reduced, decreasing computational cost



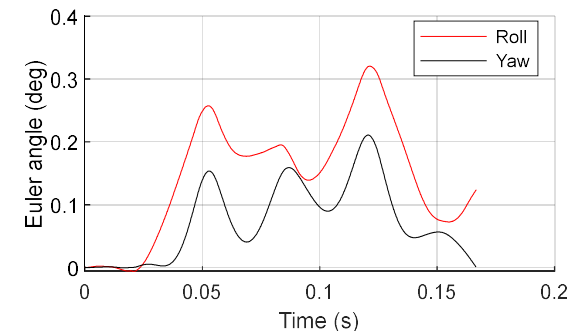
Body displacement decrement



Wake grid orientation



Body total angle of attack



Body roll and yaw Euler angles



Conclusions



- A wake grid motion driver was designed to maintain wake resolution with changing vehicle attitude and flight path angle
 - The grid motion driver methodology could also be applied for CFD-RBD models that use mesh deformation
- This motion driver was successfully implemented in a CFD-in-the-loop flight simulation and demonstrated using an entry vehicle
- Adaptation of the POST2-FUN3D bridging code for overset simulations was successful
- The motion of the wake grid can be tailored to the vehicle and flight conditions in order to further reduce computational cost



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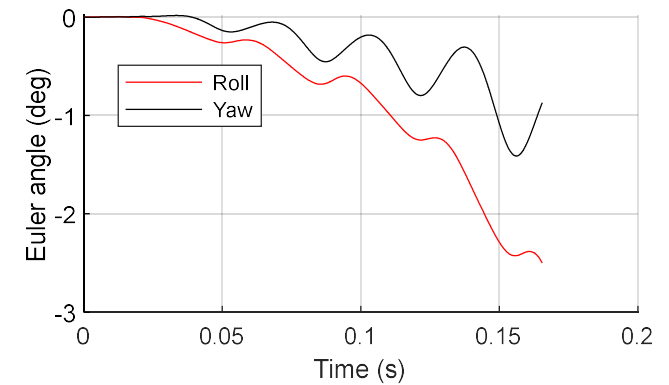
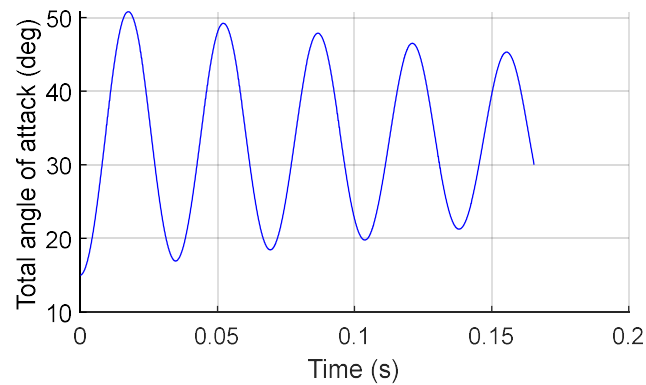
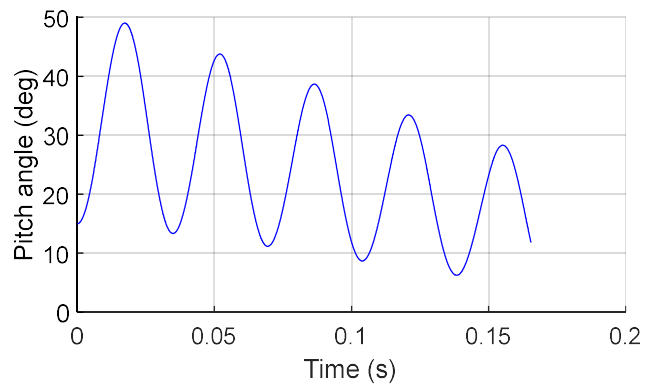
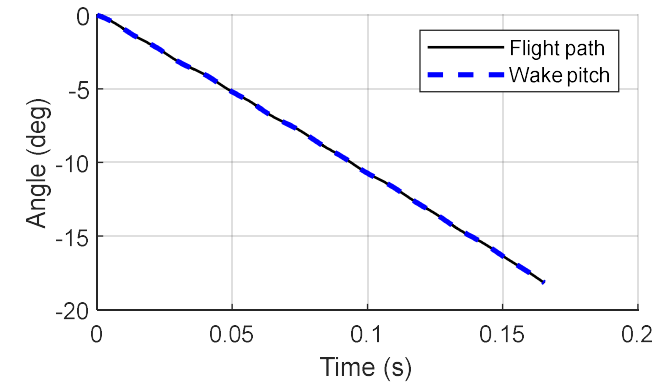
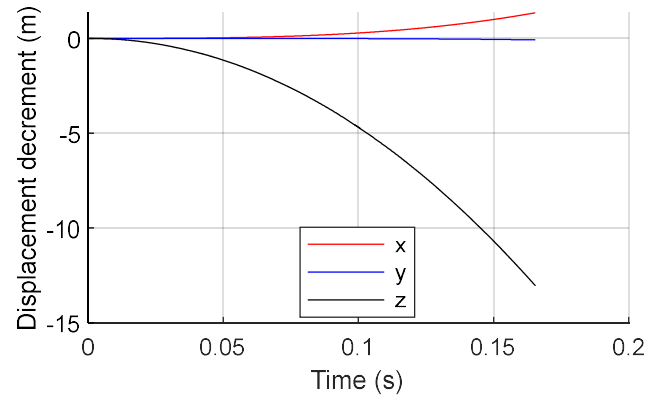
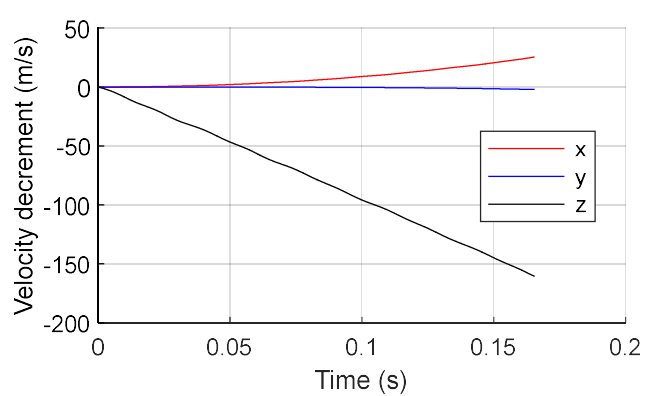
Flow Solver Settings



- SA-based detached eddy simulation [22]
- Stencil-based van Albada flux limiting [23]
- L2Roe flux construction [24]
- $Re_d = 3.4 \times 10^7$
- $\frac{V\Delta t}{D} = 0.0432$



Free-Flight, Overset, No Drag





Free Flight, Overset, Wake Pointing

