

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

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Time-accurate computational fluid dynamics (CFD) simulations using overset meshes can enable reduced computational cost compared to a rigid, monolithic mesh for blunt-body atmospheric entry vehicles. If the vehicle has a significant change in attitude, the high-density region of the overset mesh designed for resolving the subsonic wake can be kept in position as the wake orientation changes relative to the body. Current simulations generally keep the wake mesh fixed in attitude while the body rotates, assuming the wake orientation remains relatively constant. However, changes in the relative velocity over a long-duration simulation or effects of the body geometry can invalidate this assumption. This work presents a method for calculating the desired mesh orientation to resolve a blunt body wake using the atmosphere-relative velocity of the vehicle. A motion driver using these calculations is implemented in a CFD-in-the-loop flight model bridging the FUN3D flow solver and POST2 trajectory propagator. Overset meshing is performed using the Yoga extension for FUN3D. Results are presented for simulations with both overset and monolithic meshes under large changes in relative velocity (and therefore wake orientation). The results demonstrate that the motion driver successfully orients an overset wake mesh to capture the subsonic wake with sufficient resolution despite variable body rotation and body-relative freestream velocity.

Nomenclature

d	Vehicle diameter
$\hat{p}$	Unit pointing vector
R_{JI}	Rotation matrix defining rotation between I and J reference frames
$\bar{r}_{dx}$	Displacement vector
$\bar{r}_{rot}$	Rotation point vector
$\bar{v}$	Velocity vector
$\bar{v}_{rel}$	Body-relative velocity vector
$\hat{x}, \hat{y}, \hat{z}$	Unit vectors in the x -, y -, and z -directions
α	Angle of attack
α_T	Total angle of attack
ϕ, θ, ψ	Roll, pitch, and yaw Euler angles
$\theta_{T, wake}$	Wake angle
Subscripts:	
$body$	Body grid
cg	Center of gravity
F	Body grid reference frame
G	Wake grid reference frame
O	Freestream frame
$wake$	Wake grid
x, y, z	Component in the x -, y -, and z -directions
∞	Freestream

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I. Introduction

PREDICTION of the dynamic behavior of blunt-body atmospheric entry vehicles is an ongoing field of study. This class of vehicle is generally known to be dynamically unstable in the range of low supersonic to transonic Mach numbers, and achieving similitude in flight conditions with physical experiments can be difficult, especially for vehicles designed for entry, descent, and landing (EDL) on other planets.

Numerical models using Computational Fluid Dynamics/Rigid Body Dynamics (CFD-RBD) can be used in instances where physical experiments are infeasible. In these models, a motion driver calculates the position and orientation of the vehicle (and thereby the CFD grid) based on the 6 degree of freedom (6DOF) rigid body equations of motion. The flow solver calculates the aerodynamic loads using the time-accurate fluid dynamics governing equations, and these loads are used as inputs to the 6DOF equations of motion, whereupon the cycle repeats. This allows CFD-RBD models to capture unsteady, accelerating flow. Current literature demonstrates the ability of CFD-RBD to augment physical experiments, such as ballistic range tests, to identify the dynamic behavior of a vehicle [1–3].

Correctly resolving the wake in these numerical simulations is critical to measuring the dynamic behavior of entry vehicles [4]. At supersonic and transonic Mach numbers, the subsonic wake can extend for many diameters away from the vehicle surface. Since this flow is subsonic, it can communicate back to the vehicle surface and affect the aerodynamic loads. Resolving the wake requires a high-resolution mesh and is therefore a significant contributor to the the computation time of a simulation.

As the vehicle changes attitude, the orientation of the subsonic wake changes relative to the body axes of the vehicle (i.e., relative to a fixed mesh) as demonstrated in Fig. 1. As these vehicles fly through large oscillations in attitude, using a single monolithic grid requires a large volume with high mesh density to be swept out behind the body anticipating any orientation of the wake. This large volume is inefficient since only a fraction of the grid nodes are required to resolve the wake at any given moment, while the larger portion of the grid is in relatively simpler flow. Resolution of other flow features like the bow shock can be similarly affected by the grid motion.

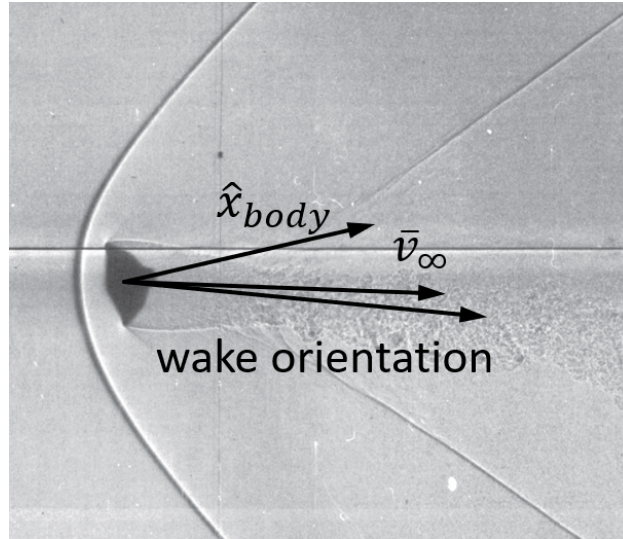


Fig. 1 Schlieren shadowgraph demonstrating the orientation of the subsonic wake relative to the freestream velocity and body reference frame for a blunt body (adapted from Schoenenberger et al. [5]).

As an alternative to using a rigid, monolithic grid, overset grids can be used to move the vehicle nearfield separately from the surrounding volume. Overset or "Chimera" grids are a collection of rigid grids that are allowed to overlap [6]. A flow solver must perform hole cutting and flow variable interpolation across the interacting boundaries of these grids to form a seamless flow field, which incurs some computational overhead. However, a complex flow field can be modeled using multiple simple grids which can be designed for high cell quality and desired mesh density. For an entry vehicle, the body nearfield can be modeled in one grid, with the wake modeled in a separate grid (possibly with a third, static background grid). This allows the body and nearfield to rotate without changing the orientation of the wake grid. Murman [7] used overset meshes in the OVERFLOW solver to model multiple entry vehicles at supersonic Mach numbers, achieving good agreement with experimental results. This capability has subsequently been used to model the

Mars Science Laboratory (MSL) ballistic range tests [2].

Another alternative to rigid monolithic grids is the use of mesh deformation, where different parts of a single grid are moved non-rigidly. Stern et al. [8] developed a method for deforming the mesh of an entry vehicle driven by the 6DOF equations of motion. This method rigidly rotates an inner, spherical portion of the grid containing the vehicle nearfield. An intermediate region is deformed to transition between the inner region and a fixed outer region. Originally this transition used a linear deformation [8], but recent work has used radial basis functions [1]. This capability has been used to model multiple entry vehicles in the US3D flow solver with validation against physical experiments [1, 2, 9]. It was noted that this method performs well for deformations that do not exceed an attitude of $\pm 90^\circ$ away from the nominal attitude [8].

While both alternatives are suitable for reducing the mesh size, the literature only describes cases where the nearfield is moved or deformed. Contemporary simulation methodologies place the high-mesh-density volume parallel to the initial freestream velocity vector specified in the flow solver and keep it fixed for the duration of the simulation. These methodologies assume that a) the orientation of the vehicle velocity relative to the local atmosphere is a good approximation of the orientation of the wake, and b) that this velocity remains close to parallel to the freestream velocity as input in the flow solver inertial frame. The first part of that assumption is sensitive to the vehicle geometry, as flow separation and attachment can cause significant displacement of the wake. The second part of the assumption is valid for simulations where the lateral motion of the vehicle relative to the inertial frame is not significant (e.g., for a lifting body). If either statement is invalid, the wake can drift out of the region of high mesh density, leading to poor resolution of the subsonic portion.

This work documents the development of a motion driver that works with an existing overset meshing capability to reorient the wake grid as the vehicle velocity changes over time. This maintains the subsonic wake resolution even if the lateral velocity of the vehicle becomes significant. Section II presents a detailed description of the motion driver methodology and its implementation in a 6DOF CFD-in-the-loop flight model. Section III demonstrates the capability using the Genesis entry vehicle, comparing simulations using an overset mesh with a rigid, monolithic mesh. Section IV presents an alternative motion driver constructed using information gained about the vehicle through free-flight simulations. Finally, conclusions are presented in Section V.

II. Technical Approach

A. CFD-in-the-Loop Flight Model

This work extends the capability of an existing CFD-RBD model: a bridging code that links a state-of-the-art flow solver and trajectory propagator to perform 6DOF CFD-in-the-loop flight simulation. The flow solver is the Fully Unstructured 3D (FUN3D), a node-based, finite-volume, unstructured-grid solver developed at NASA Langley Research Center [10]. This flow solver can model inviscid or viscous flows, at steady-state or with time accuracy, for a perfect or a generic multi-species gas. FUN3D is commonly used for modeling atmospheric entry vehicles [11–13]. The Program to Optimize Simulated Trajectories II (POST2), also developed at NASA Langley Research Center, is used as the trajectory propagator [14]. POST2 not only performs the RBD calculations but also hosts other disciplinary models that extend the bridging code beyond a simple CFD-RBD model. POST2 is capable of integrating and facilitating communication with multiple custom disciplinary models such as guidance, propulsion, atmosphere, etc. As such, POST2 is commonly used as the focal point for end-to-end atmospheric entry vehicle simulations [15].

The bridging code linking FUN3D and POST2 has undergone a series of spiral developments since its initial capability, including time step interpolation [16] and the ability to control propulsion elements [17]. The model has also previously been validated for an entry vehicle in the low supersonic regime [18].

Figure 2 shows a flowchart of the bridging code architecture [16]. Independent POST2 and FUN3D processes are executed in a client/server relationship communicating over network sockets. At each time step, the POST2 module sends state information to the server, which then uses the FUN3D Python extension module to update and execute the flow solver. The resulting force and moment loads are sent back to POST2, which updates the equations of motion. Further detail of the bridging code is documented in Ref. [16].

The overset mesh motion driver is implemented in this bridging code. The calculations are performed during the course of the "vehicle state interpolation" shown in Fig. 2.

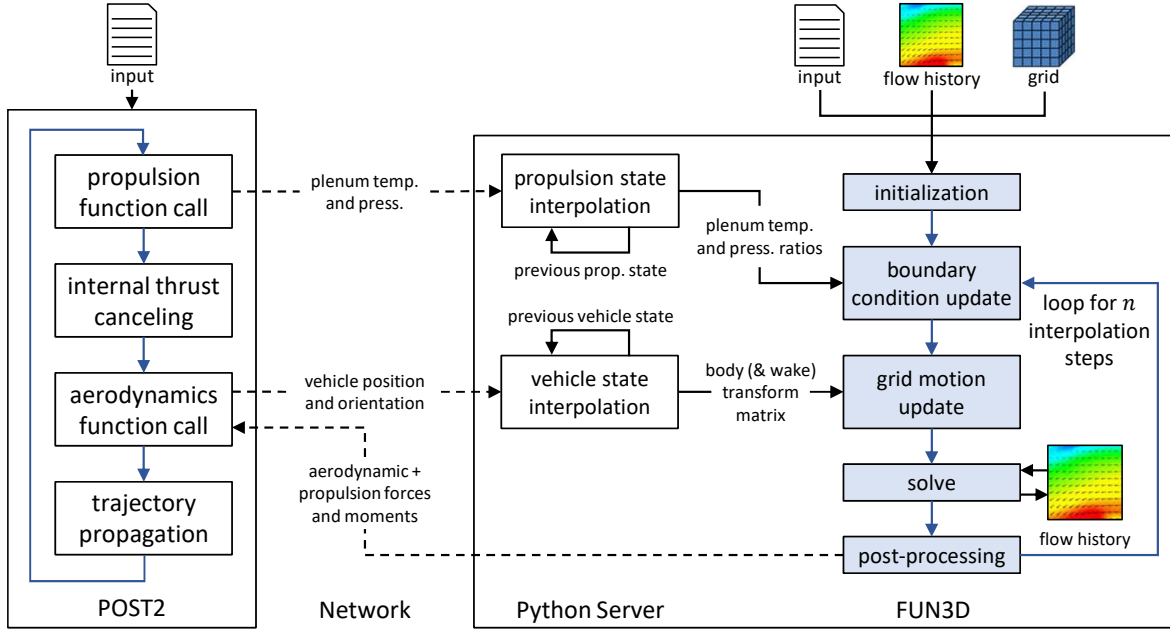


Fig. 2 Bridging code architecture.

B. Overset Meshing

Overset meshing is performed with Yoga, a parallel-domain overset grid assembler developed for use with FUN3D [19]. Yoga is designed to minimize calculation overhead by efficiently using all processor ranks through dynamic load processing. This assembler code has been validated against SUGGAR++, an existing overset capability compatible with FUN3D [20].

The methodology developed in this work uses two meshes for an entry vehicle. First is the "body" grid which contains the wall boundaries for the vehicle outer mold line (OML) and the high mesh density region required for resolving the nearfield and boundary layer. The second is the "wake" grid which contains the farfield boundaries and the high mesh density region for resolving the wake. It is assumed that the wake grid has a tailored mesh density for a wake with the bulk of the behavior acting along the wake grid x -axis. It is also assumed that the density of the mesh is axisymmetric about the x -axis.

C. Transformations

Figure 3 shows the relevant reference frames and the quantities that must be calculated to determine the motion of the wake grid (motion of the body grid is determined as described in Ref. [16]). The freestream frame O has a fixed orientation relative to the freestream reference velocity. The F and G frames are the grid reference frames for the body and wake grids, respectively. Both frames can have arbitrary origins relative to the vehicle OML.

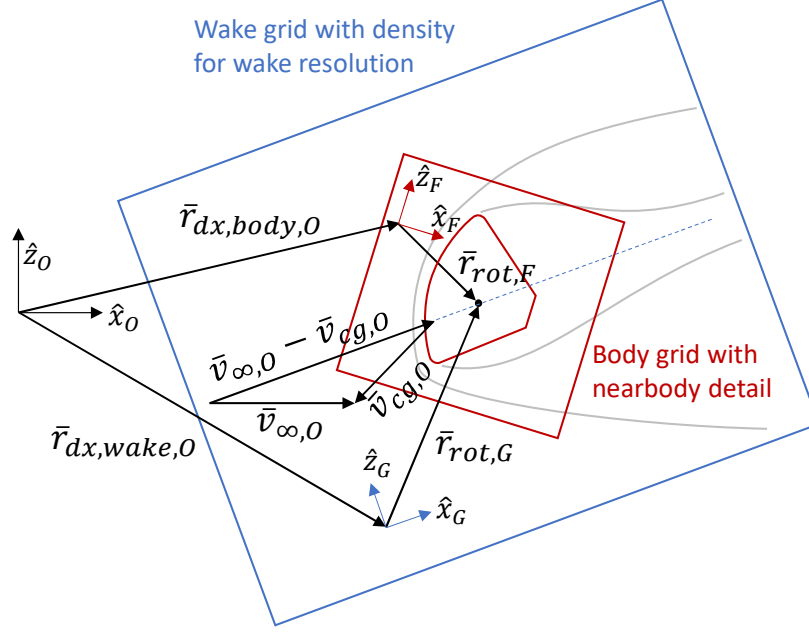


Fig. 3 State determination for a wake grid.

Setting the orientation of the wake grid requires calculating R_{OG} , the direction cosine matrix (DCM) defining the orientation of the G frame with respect to the O frame. For good wake resolution, R_{OG} should be set based on the wake orientation. Figure 4 defines the relationship between the wake orientation, body orientation, and freestream velocity. The total angle of attack α_T is the angle between the body-relative freestream velocity vector $\bar{v}_{rel,O}$ and the body reference frame unit x vector $\hat{x}_F$. $\hat{p}_{wake}$ is the pointing vector from the vehicle center of gravity (CG) to an average "center" of the wake at some distance from the vehicle (determined graphically in this work). The wake angle $\theta_{T,wake}$ is the included angle between $\hat{p}_{wake}$ and $\hat{x}_F$.

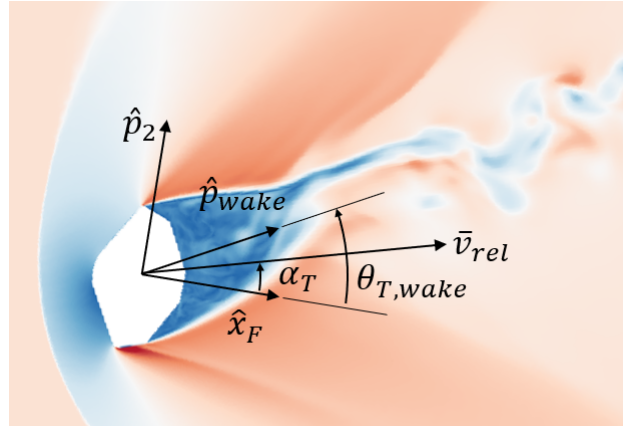


Fig. 4 Wake pointing vector definition.

Without *a priori* information about the behavior of the wake, the assumption is made that $\hat{p}_{wake}$ is parallel to $\bar{v}_{rel,O}$, which is calculated as:

$$\bar{v}_{rel,O} = \bar{v}_{\infty,O} - \bar{v}_{cg,O} \quad (1)$$

where $\bar{v}_{\infty,O}$ is the freestream velocity, and $\bar{v}_{cg,O}$ is the velocity of the vehicle CG, both in the O frame. $\bar{v}_{\infty,O}$ is a known input to FUN3D, and $\bar{v}_{cg,O}$ is calculated by the existing bridging code [16]. Thus the orientation of the wake grid, R_{OG} ,

is calculated as:

$$R_{OG} = \begin{bmatrix} \cos \psi_{wake} \cos \theta_{wake} & -\sin \psi_{wake} & \cos \psi_{wake} \sin \theta_{wake} \\ \cos \theta_{wake} \sin \psi_{wake} & \cos \psi_{wake} & \sin \psi_{wake} \sin \theta_{wake} \\ -\sin \theta_{wake} & 0 & \cos \theta_{wake} \end{bmatrix} \quad (2)$$

R_{OG} is a 3-2 Euler angle DCM where the desired pitch and yaw of the wake grid, θ_{wake} and ψ_{wake} respectively, are calculated as:

$$\theta_{wake} = -\arcsin \frac{v_{rel,z,O}}{|\bar{v}_{rel,O}|}, \quad \psi_{wake} = \arctan \frac{v_{rel,y,O}}{v_{rel,x,O}}, \quad (3)$$

The roll angle of the wake grid is defaulted to zero since the mesh density is assumed to be axisymmetric.

The displacement of the wake grid in the O frame, $\bar{r}_{dx,wake,O}$, must also be calculated to define the wake grid motion. This vector is calculated as:

$$\bar{r}_{dx,wake,O} = \bar{r}_{dx,body,O} + R_{OF}\bar{r}_{rot,F} - R_{OG}\bar{r}_{rot,G} \quad (4)$$

where $\bar{r}_{dx,body,O}$ and R_{OF} are the displacement vector and DCM, respectively, of the body grid relative to the freestream frame O . Both variables are calculated in the existing bridging code [16]. $\bar{r}_{rot,G}$ and $\bar{r}_{rot,F}$ define the rotation point of the wake grid about the body grid in the wake and body reference frames, respectively; both variables are inputs to the model.

Whereas the FUN3D Python extension was previously called to update the motion for only one body, these functions will be called twice: once each for the nearbody and wake grids. Since the wake grid contains no solid surfaces for which forces and moments must be integrated, the overset mesh requires no changes to the transformation of the loads for communication back to POST2. Furthermore, this motion driver is compatible with both Yoga and SUGGAR++, although only results using Yoga are presented in this work.

III. Comparison of Overset and Monolithic Grids

The wake grid motion driver capability is demonstrated by comparing simulations of an entry vehicle using overset and monolithic grids.

A. Grid Construction

The Genesis entry vehicle ballistic range model is used as a vehicle of interest [21]. The dimensions of this model are shown in Fig. 5. Since the capsule has a shallow angle on the first aftbody segment, it can exhibit significant separation and attachment behavior that can affect the wake orientation.

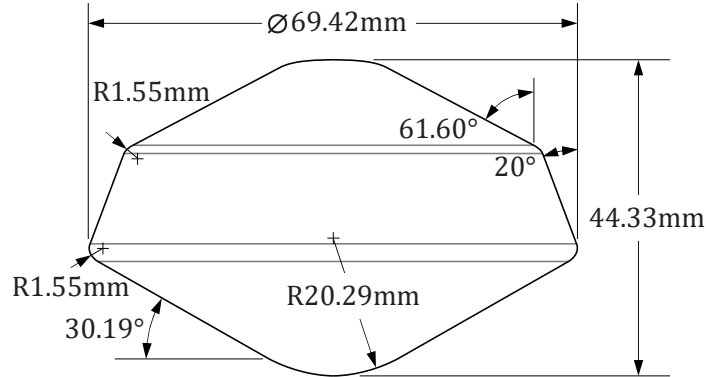


Fig. 5 Genesis ballistic range model (adapted from [21])

Two mixed-element meshes are constructed for the ballistic range model. Each grid has a spherical farfield with a radius of $10d$, where d is the diameter of the vehicle. The nearfield of each grid is constructed using a spherical volume source with a diameter of $2d$. The center of the sphere is chosen to coincide with the center of gravity of the vehicle, i.e., the point about which the body will tend to rotate. In addition, the shoulder and aftbody surface sizing is extended as a volume source for a radius of $d/4$. Each grid has the same hexahedral boundary layer structure grown from the vehicle surface, achieving a y^+ equal to one at the wall. The remaining volume uses tetrahedral cells.

Each grid has a different design for resolving the wake. The first is a rigid, monolithic grid designed to resolve the wake within a range of α_T values. This is achieved using a conical volume source with spherical dome ends. The cylinder has a diameter of $2d$ at the vehicle, an included angle of 40° , and a length of $8d$. This source has the same density at the small end as the nearfield, with decreasing density as it reaches the farfield. A cross-section of this grid is shown in Fig. 6.

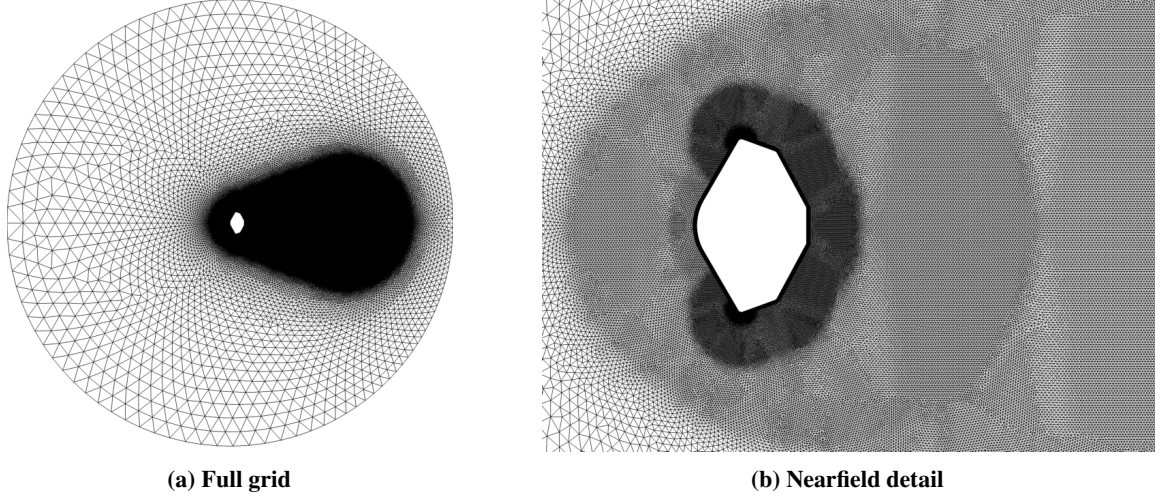


Fig. 6 Rigid, monolithic grid with conical wake refinement.

The second grid is an overset mesh with separate nearfield and wake grids. The nearfield grid has a spherical outer boundary of $2d$ diameter, with the same nearfield sources and boundary layer described above. The wake grid uses a cylindrical volume source with a diameter of $2d$ and a length of $8d$. This source has the same change in mesh density with distance as the source used in the monolithic mesh. The spherical nearfield source is duplicated in the wake grid so that the mesh density at the interface of both grids will be similar. For this overset mesh, the point of rotation in the nearbody and wake grids are chosen to be identical and coincident to the center of gravity of the vehicle. A cross-section of the overset grid is shown (with hole-cutting applied) in Fig. 7. The interface between the nearfield and wake grids is visible from the overlap in cells.

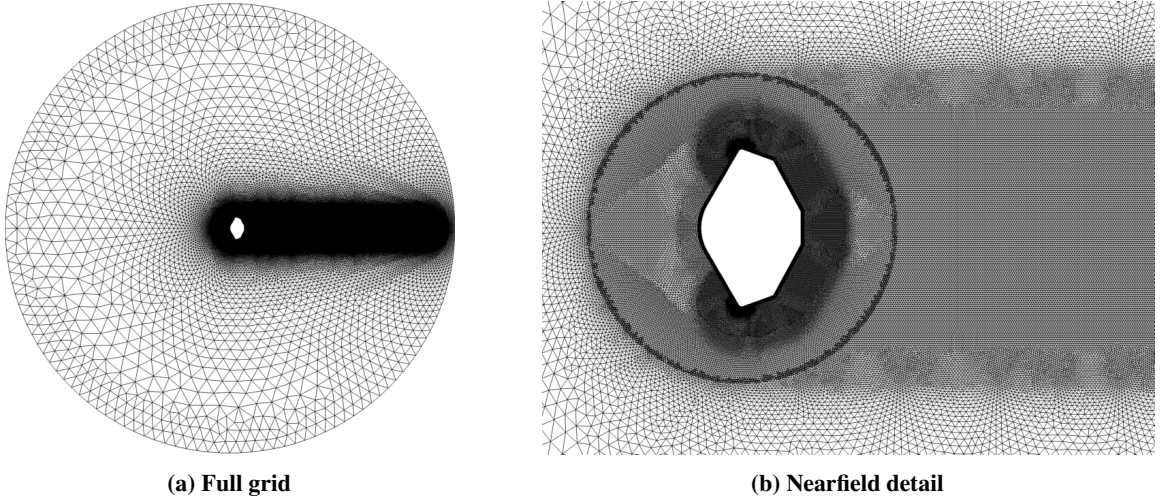


Fig. 7 Overset grid with cylindrical wake refinement.

The size of each grid is compared in Table 1. The monolithic grid with conical wake refinement has approximately 95% more nodes than the overset mesh.

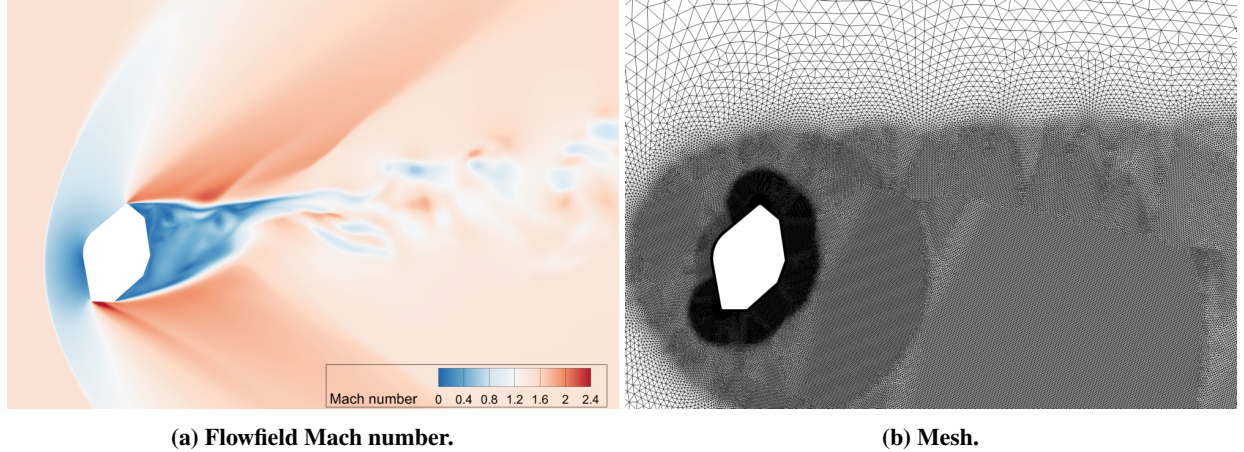
Table 1 Grid metrics

Grid	Nodes (10^6)	Tetrahedral cells (10^6)	Hexahedral cells (10^6)
Monolithic cone	38.3	213	5.65
Overset (average)	19.6	100	5.67

B. Time-Accurate Fixed-Attitude Simulations

Time-accurate, fixed-attitude simulations are executed in order to observe the differences in the wake due to the orientation of the grids. This will verify that the resolution of both grids is sufficient, and that the behavior of the grids with respect to attitude matches the behavior expected from the literature. The grids are simulated at standard sea-level atmospheric conditions with a freestream Mach number of 1.5. The vehicle is modeled in fully-turbulent flow with a Spalart-Allmaras-based detached eddy simulation (DES) model [22]. A stencil-based van Albada flux limiting scheme [23] was used with an L2Roe flux construction [24]. All simulations were executed on the K-Cluster at the Langley Research Center using the same number of Intel Skylake CPUs.

Both the monolithic and overset grids were simulated at a pitch angle of 20° and freestream velocity along the x -axis of the O frame (giving an angle of attack α of 20°). Figure 8 plots the results for the monolithic grid. The flowfield in Fig. 8a shows that the subsonic wake is contained within the area of high mesh density displayed in Fig. 8b. Large flow structures extend out $5d$ from the body, and the recompression shocks are also well defined. This demonstrates that for any orientation of the vehicle and freestream velocity vector, the monolithic grid will satisfactorily resolve the wake when α_T is less than 20° .

**Fig. 8 Monolithic grid flowfield in the x - z plane at 20° pitch angle.**

The overset grid was simulated at the same conditions. However, only the nearbody grid was transformed, with the wake grid kept horizontal. The result, plotted in Fig. 9, shows good agreement with the monolithic grid. This verifies that with overset meshing, the large high-density region and associated cost of the monolithic mesh is not needed. It can also be observed that the wake follows some nonzero angle relative to the freestream vector, similar to the model in Fig. 1. Figure 10 compares the scalar force coefficient responses from the monolithic and overset grids. Both the drag and lift coefficients are converged at similar values, providing further evidence that the grids are of similar quality when the wake is properly resolved.

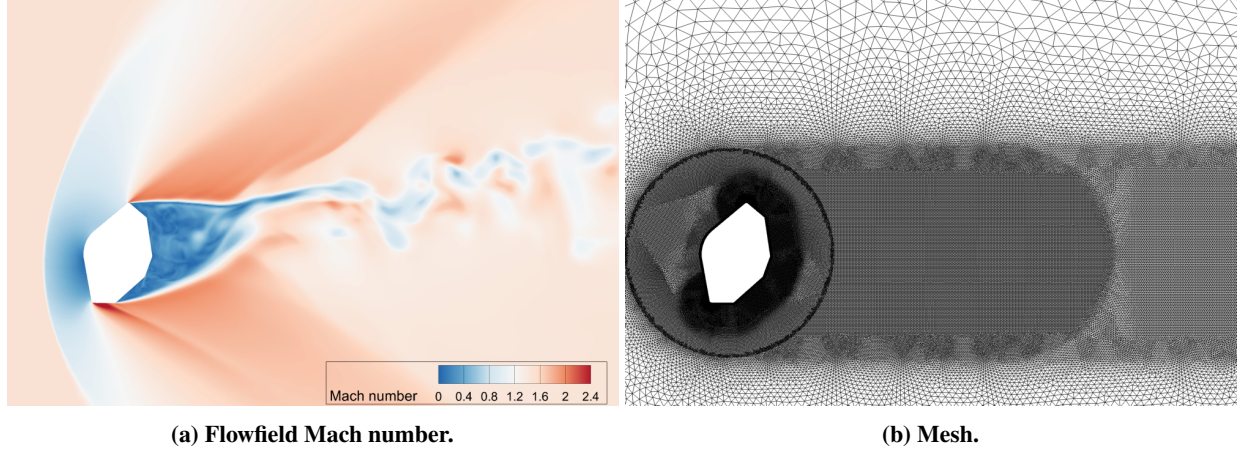


Fig. 9 Overset grid flowfield in the x - z plane at 20° pitch angle, with no wake grid transformation.

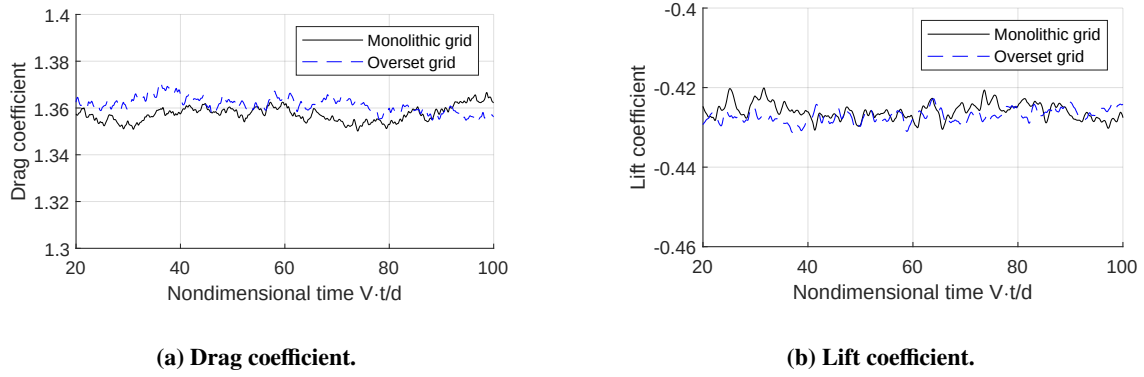


Fig. 10 Comparison of monolithic and overset grid force coefficient results at $\alpha = 20^\circ$.

Another set of fixed-attitude simulations was run on the overset mesh with the vehicle pitch at 0° and freestream velocity vector at an angle of 20° . This represents a state in a free-flight simulation where α_T is the same as for the previous simulations, at 20° , but the body-relative velocity vector has deviated relative to the freestream frame. Figure 11 shows the overset mesh with the wake grid remaining untransformed, as would be the case without the wake grid motion driver. The wake in Fig. 11a clearly exits the high-density region of the wake grid, resulting in the loss of the structures seen in Figs. 8 and 9. Figure 12 demonstrates that with the wake grid transformed according to the motion driver, the wake is once again resolved at an equivalent level to the results shown in Fig. 9.

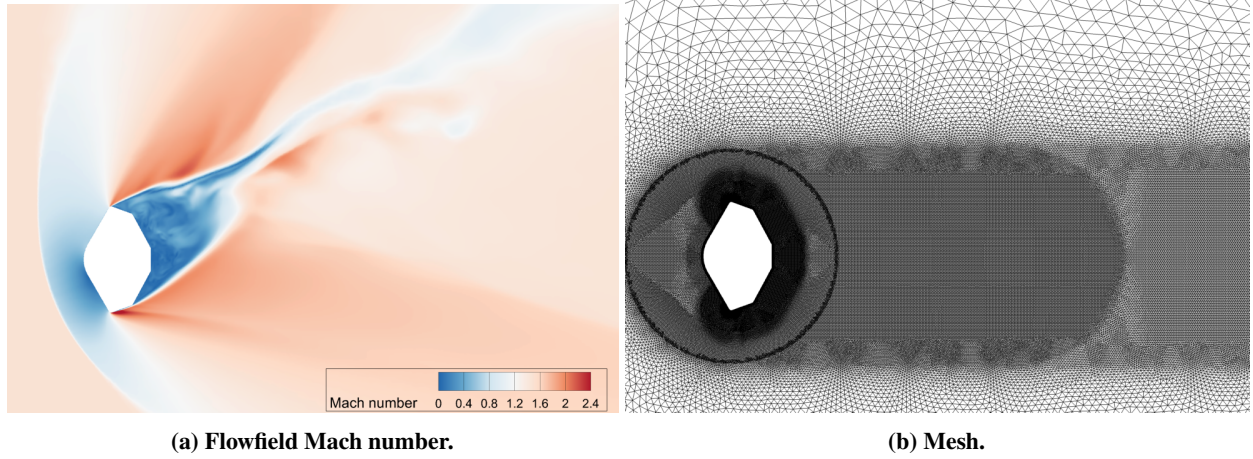


Fig. 11 Overset grid flowfield in the x - z plane at $\alpha = 20^\circ$ with no wake grid transformation.

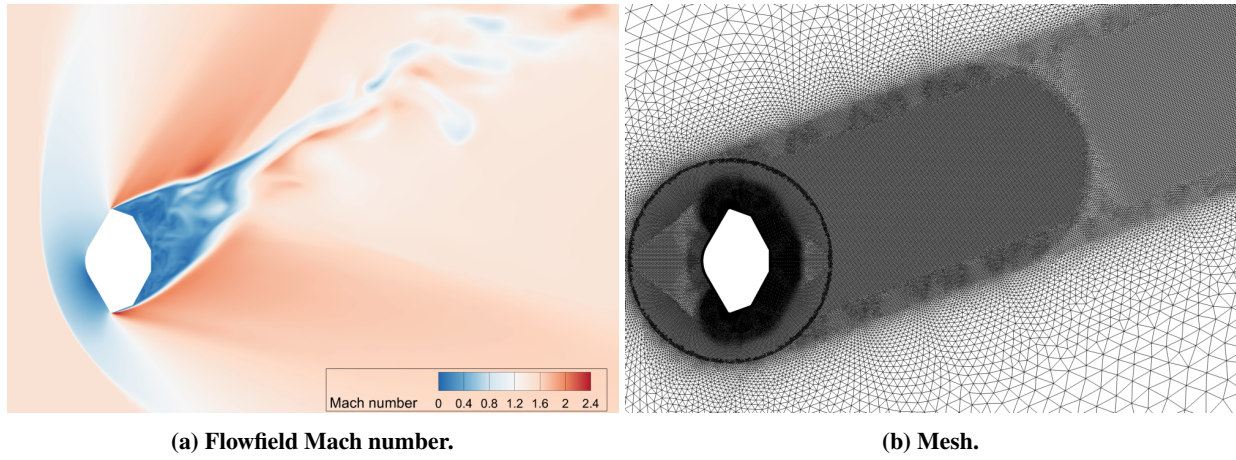


Fig. 12 Overset grid flowfield in the x - z plane at $\alpha = 20^\circ$ with wake grid transformation.

Table 2 Computational cost of time-accurate fixed-attitude simulations

Grid	Normalized execution time
Overset, rotating	1.00
Overset, non-rotating	1.01
Monolithic	1.95

The execution times for all the simulations are listed in Table 2, normalized by the execution time of the overset mesh. Although the monolithic grid with conical refinement does satisfactorily resolve the wake, this comes with nearly two times the computational expense. The overset mesh can provide the same satisfactory resolution but at a much lower cost than the conical refinement grid. The cost of the overset mesh shows a slight variation, which can be expected considering both the changing flow conditions and differences in the hole cutting process. Within these forced motion simulations, the calculations for the wake grid orientation have zero cost. When executed within a free-flight simulation, these calculations are expected to yield a negligible increase in overhead.

C. Free-Flight Simulations

Free-flight simulations of the vehicle were executed in order to exercise the motion driver for non-prescribed trajectories and observe the vehicle motion response. Simulations using both the overset and monolithic grids were executed using the same initial motion state, freestream conditions, and vehicle mass properties. Each simulation was initialized using a forced-motion simulation to move the pitch of the vehicle up to 15° and keep it there long enough to allow any transients to damp out. The flow solver settings are identical to those used for the fixed-attitude simulations. Therefore, the differences in the trajectory response will only be due to the grid resolution, the hole-cutting and interpolation process of the overset mesher, and the initial flow field.

The mass properties of the vehicle are presented in Table 3. An arbitrary z -axis CG offset was selected to ensure a high trim angle of attack. In addition, the z -axis moment of inertia was increased to limit the motion in yaw. This will allow the vehicle to develop significant lift and therefore a change in flight path angle as the simulation progresses. The drag force on the vehicle is ignored to allow it to fly at speeds closer to the initial Mach number for an extended duration. Along with negligible out-of-plane components of the initial conditions, this means the vehicle motion is effectively constrained to 2DOF motion: free-to-pitch, and free-to-heave.

Table 3 Vehicle mass properties

Parameter	Value
mass	316.5g
x -axis CG	18.0mm
y -axis CG	0.0mm
z -axis CG	-3.471mm
x -axis moment of inertia	$3.01 \times 10^{-4} \text{kg/m}^2$
y -axis moment of inertia	$1.99 \times 10^{-4} \text{kg/m}^2$
z -axis moment of inertia	$39.8 \times 10^{-4} \text{kg/m}^2$

Figure 13 plots the body orientation response for the overset grid simulation. The gross motion is in the pitch angle shown in Fig. 13a, while the roll and yaw angles in Fig. 13b increase over time but their magnitude remains less than 1° .

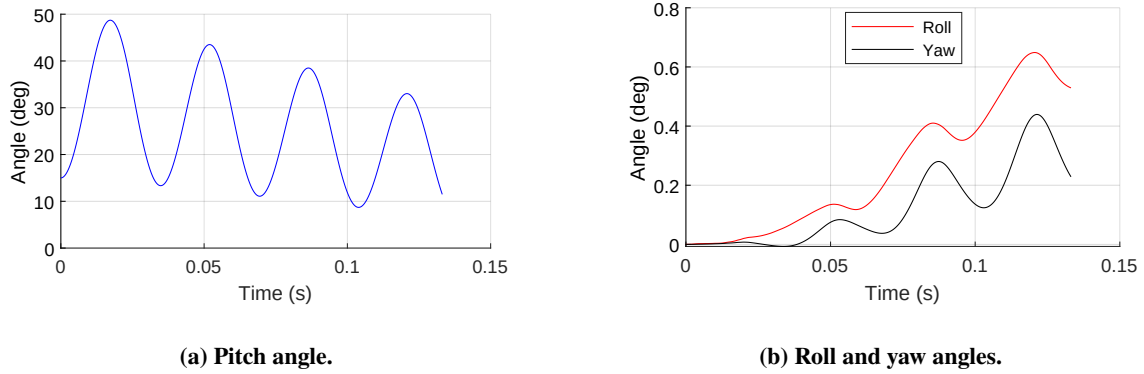


Fig. 13 Body orientation response for the overset grid in free flight with no drag.

The α response is plotted in Fig. 14. The response oscillates over a large amplitude with damping over time. The trim angle of attack of approximately 33° would already place the wake outside the high-density region of the monolithic mesh, let alone the peak α of 50° .

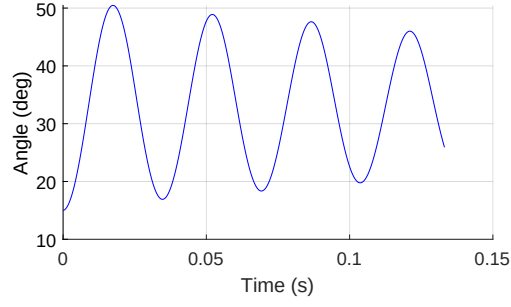


Fig. 14 Angle of attack response for the overset grid in free flight with no drag.

The flight path angle calculated by POST2 is plotted in Fig. 15. This is overlaid on the wake grid pitch angle calculated directly from FUN3D. This shows that the wake grid orientation is correctly specified in the grid motion. In a free-to-heave scenario, this vehicle achieves a change in flight path angle greater than 10° within three pitch oscillation periods. For an overset grid with fixed wake grid orientation, this change in angle would begin to affect the resolution of the wake. However, the wake grid motion driver can accommodate this change.

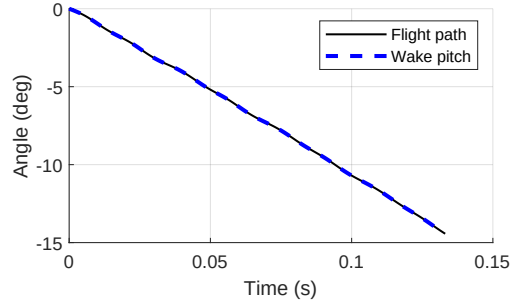
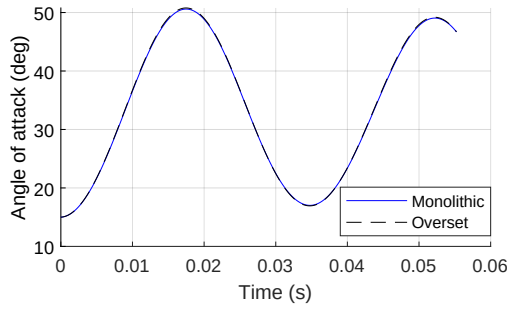
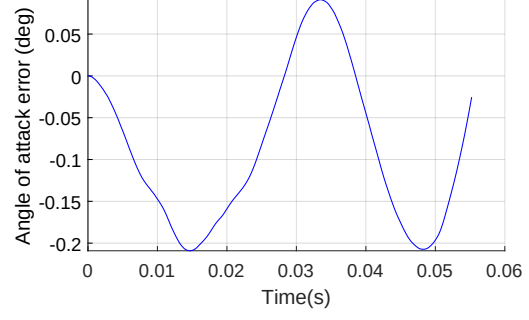


Fig. 15 Flight path and wake pitch angle response for the overset grid in free flight with no drag.

The α response of the monolithic grid is plotted in Fig. 16a and compared with the response from the overset grid. The large-scale trajectory response between the grids is very similar. However, the monolithic mesh exhibits slightly increased pitch damping than the overset grid. The plot of the error between the α response in Fig. 16b reveals that the error is at its highest magnitude when α is highest (i.e., where the wake in the monolithic grid is furthest from the high-density region of the mesh). While the actual magnitude of the error is small in this instance, the comparison of results demonstrate that a difference can be observed.



(a) Angle of attack.

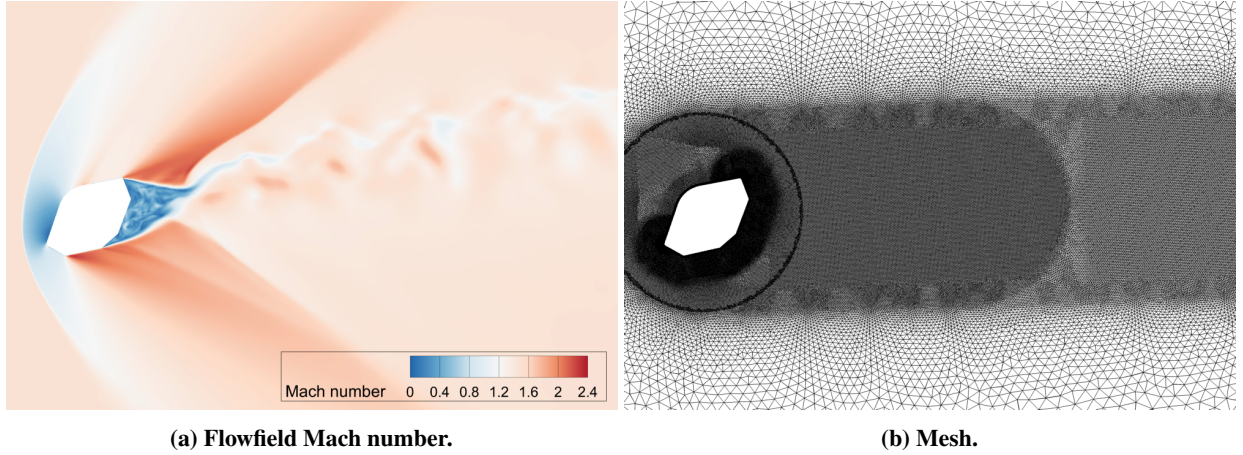


(b) Angle of attack error.

Fig. 16 Comparison of angle of attack response for monolithic and overset meshes in free flight with no drag.

The flowfield Mach number results are plotted for the overset and monolithic meshes in Figures 17 and 18, respectively, for the flow at $t = 18\text{ms}$, when the vehicle has an α of about 50° . The overset grid in Fig. 17a captures the eddy structures from the wake out to a much further distance than the monolithic grid in Fig. 18a due to the monolithic mesh rotation. Also note that the wake grid in Fig. 17b shows the change in angle from the horizontal as the flight path angle decreases. The overset grid also captures a distinct difference in the recompression shock behavior, once again due to the increased resolution in that area.

The free-flight simulation results demonstrate that the overset grid motion driver allowed the vehicle to be simulated at lower computational cost and better spatial resolution in the areas of interest than a monolithic grid.



(a) Flowfield Mach number.

(b) Mesh.

Fig. 17 Overset grid flowfield in the x - z plane at $\alpha = 50^\circ$

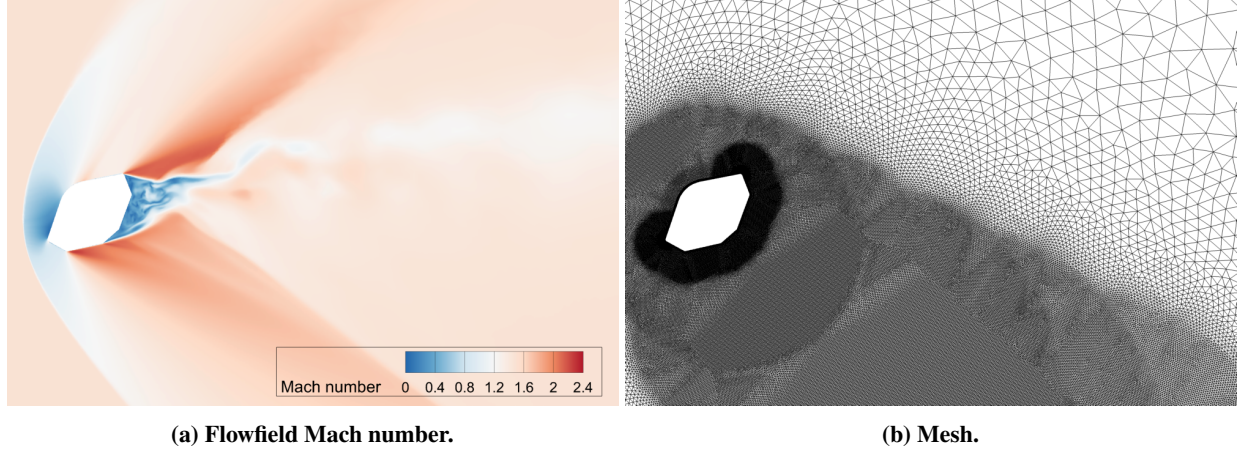


Fig. 18 Monolithic grid flowfield in the x - z plane at $\alpha = 50^\circ$

IV. Wake Motion Driver Based on Vehicle Behavior

Both the fixed-attitude and free-flight simulations show that the wake for this vehicle does not point exactly in the direction of the body-relative freestream vector, as was assumed in Section II.C. Instead, the geometry and attitude of the vehicle affect the orientation of the wake. However, the simulations provide information that can be used to construct a more complex motion driver for the wake grid.

The orientation of the wake was measured graphically using snapshots of the Mach number flowfield at different times. α_T was determined at corresponding times from the trajectory response. Figure 19 plots the difference between these two angles as a function of α_T . Measurements for $\alpha_T > 15^\circ$ were taken from the free-flight simulation, and measurements under 15° were taken from the forced-motion startup. A clear relationship can be seen in the wake orientation as a function of α_T . A quadratic fit with an intercept at $(0, 0)$ was applied to the data using least squares:

$$\Delta\theta_{T,wake} = 0.751 \alpha_T - 0.0115 \alpha_T^2 \quad (5)$$

This fit shows good agreement when overlaid on the data in Fig. 19. Given the lack of data at higher angles of attack, $\Delta\theta_{wake}$ would have to be held constant for $\alpha_T > 55^\circ$. Similarly this relationship is also only known to be valid around Mach 1.5; additional simulations would be necessary to extend the model to other Mach numbers.

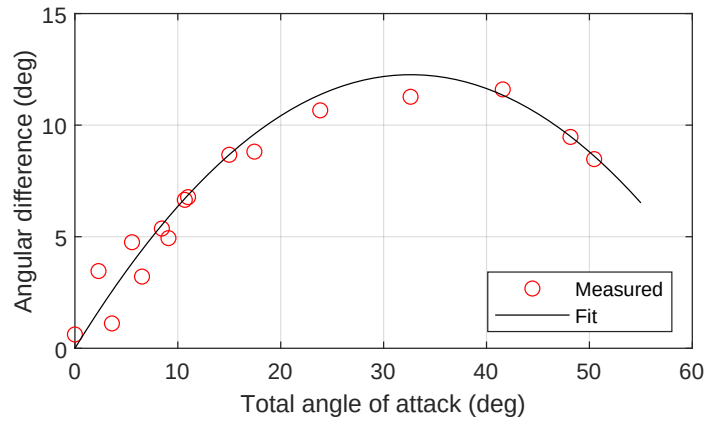


Fig. 19 Difference between angle of attack and wake angle for Genesis at Mach 1.5.

Now that information about the wake behavior is known, the relationship can be implemented in the wake grid motion driver. α_T is calculated as:

$$\alpha_T = \arccos \frac{\hat{p}_{body} \cdot \vec{v}_{rel,O}}{|\vec{v}_{rel,O}|} \quad (6)$$

where $\hat{p}_{body}$ is the body reference frame unit x -axis vector expressed in the freestream frame, found using the equation:

$$\hat{p}_{body,O} = R_{OF}\hat{x}_F \quad (7)$$

The result of Eq. 6 can be substituted into Eq. 5, and the wake angle can be found as:

$$\theta_{T,wake} = \alpha_T + \Delta\theta_{T,wake} \quad (8)$$

The wake pointing vector is found using the equation:

$$\hat{p}_{wake,O} = \hat{p}_{body,O} \cos \theta_{T,wake} + \hat{p}_2 \sin \theta_{T,wake} \quad (9)$$

where $\hat{p}_2$ is a unit vector orthogonal to $\hat{p}_{body,O}$ and in the same plane formed by $\hat{p}_{body,O}$ and $\bar{v}_{rel,O}$:

$$\hat{p}_2 = \frac{(\hat{p}_{body,O} \times \bar{v}_{rel,O}) \times \hat{p}_{body,O}}{|(\hat{p}_{body,O} \times \bar{v}_{rel,O}) \times \hat{p}_{body,O}|} \quad (10)$$

The resulting components of $\hat{p}_{wake,O}$ can be substituted for the components of $\bar{v}_{rel,O}$ in Eq. 3 to point the wake grid along the expected direction of the wake. Note that the model developed here is valid for full 6DOF motion. The capability to input a known wake pointing model implemented in the bridging code as a custom function that can be input at the start of the simulation. Once again these calculations have a negligible effect on the calculation time of the bridging code.

With the information gained in the free-flight and fixed-attitude simulations, a more precise model for driving the motion of the wake grid has been developed. Using this model for driving the wake grid orientation could theoretically yield better results or allow the high-density region of the grid to be made smaller. The benefits for this vehicle and grid combination are marginal since the angle only deviates a maximum of about 12° from the freestream, which is accommodated by the current width of the high-density region. However, the ability to more precisely predict the behavior and drive the motion of the wake mesh can be used to further decrease the cost of the mesh.

V. Conclusions

This paper documents the implementation of an overset mesh motion driver into the POST2-FUN3D bridging code, providing a new capability to the CFD-in-the-loop flight simulation framework. This method also represents an improvement in contemporary entry vehicle overset methods by allowing the orientation of the wake grid to be driven by the trajectory propagator. These results demonstrate that the motion driver successfully orients the wake mesh to capture the subsonic wake with sufficient resolution despite both the body rotation and the changing body velocity relative to the freestream. By default, the wake grid is pointed along the vehicle-relative freestream velocity vector, but more complex relationships can be modeled given additional knowledge of the vehicle. The free-flight and fixed-attitude simulations verified that the wake remains resolved within the high-density region of the grid even if the wake orientation changes significantly over time.

This capability allows for the reduction in computational cost of long-duration free-flight simulations for entry vehicles. While the methodology presented in this paper is designed for overset meshes, it could possibly be adapted for simulations that use mesh deformation. This work also forms the mathematical basis to extend the bridging code to model generalized multi-body simulations with overset meshes.

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