Dynamic Mesh CFD Simulations of Orion Parachute Pendulum Motion During Atmospheric Entry

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This paper demonstrates the usage of computational fluid dynamics to study the effects of pendulum motion dynamics of the NASAs Orion Multi-Purpose Crew Vehicle parachute system on the stability of the vehicles atmospheric entry and decent. Significant computational fluid dynamics testing has already been performed at NASAs Johnson Space Center, but this study sought to investigate the effect of bulk motion of the parachute, such as pitching, on the induced aerodynamic forces. Simulations were performed with a moving grid geometry oscillating according to the parameters observed in flight tests. As with the previous simulations, OVERFLOW computational fluid dynamics tool is used with the assumption of rigid, non-permeable geometry. Comparison to parachute wind tunnel tests is included for a preliminary validation of the dynamic mesh model. Results show qualitative differences in the flow fields of the static and dynamic simulations and quantitative differences in the induced aerodynamic forces, suggesting that dynamic mesh modeling of the parachute pendulum motion may uncover additional dynamic effects.

Nomenclature

θ_{max} Maxumum angle of pendulum oscillation
f Frequency of pendulum oscillation

I. Introduction

The Orion Multi-Purpose Crew Vehicle (MPCV) utilizes a 3-parachute system for subsonic deceleration during atmospheric reentry. Flight testing has demonstrated that this deceleration system has the potential of exhibiting dynamic instability when only two of three parachutes deploy. Under this failure mode, the flight vehicle/parachute system can enter oscillatory pendulum motion, an unstable condition that could pose potential hazard to the flight vehicle and crew.[1]

Various testing methods have been employed to better understanding and mitigate the nature of this instability, including drop testing, wind tunnel testing, and Computational Fluid Dynamics (CFD). Static

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CFD simulations were performed using the OVERFLOW flow solver, under the assumptions of a rigid, non-permeable geometry. Simulations were for a single parachute and sought to demonstrate static stability characteristics for a parachute with no bulk motion (such as pitching).[3]

However, pendulum motion is a result of rate-dependent, dynamic forces, and it was of interest to the authors to investigate the effect of parachute motion on the CFD results. For this purpose, a moving geometry CFD simulation was performed, where the existing grid systems were modified to allow pendulum motion according to a prescribed equation during the simulation.

II. Computational Methods

CFD simulations were performed using the OVERFLOW flow solver. It is an implicit Navier-Stokes solver, which employs finite-differencing methods on structured, overset grids.[4]

Solutions were derived in a two-step process, first resolving the time-accurate flow over the static (non-pitching) parachute, then initiating movement and acquiring dynamic data after transient effects and the static wake had dissipated. Similar to the static CFD cases, the two-equation Shear Stress Transport turbulence model by Menter was employed.[2]

As with the static cases, the simulation Mach number was scaled from the MPCV flight condition of Mach 0.03 at a dynamic pressure of around 1.3 [psf] to Mach 0.15 to improve numerical stability and avoid low-Mach preconditioning.[3] Solutions for both Mach numbers were compared and demonstrated similarity between these freestream conditions. To achieve appropriate velocity scaling, the rate of the prescribed pendulum motion was also scaled proportionately, as detailed in Section III.

III. Prescribed Pendulum Motion

To simulate pendulum motion of a single parachute, OVERFLOW flow solvers Geometry Manipulation Protocol (GMP) tool was utilized to prescribe the motion of the parachute geometry to a simple, harmonic motion function.[7] Operating in I6DOF=2 mode activates GMP, allowing geometry configurations and prescribed motion commands to be read from the Extensible Markup Language (XML) files 'Config.xml and 'Scenario.xml.

For the primary simulation, the parachute geometry and the box grid immediately surrounding the parachute were prescribed to oscillate about the Orion MPCV attachment point at the frequency and amplitude of oscillation observed in flight tests of the MPCV decent system. The GMP XML files specifically assign the angular rate of the geometry, which is detailed for this case in Eqn. (1).

$$\dot{\theta}(t) = \theta_{max} \cdot 2\pi f \cdot \cos(2\pi f \cdot t) \tag{1}$$

where $\dot{\theta}$ is the pitch rate of the parachute, θ_{max} is the maximum angular amplitude of the oscillation, f is the frequency of the oscillation in Hertz, and t is the simulation time.

As previously mentioned in Section II, the Mach number (and thus velocity) of the parachute was scaled up by a factor of five for numerical solver considerations. This required that the frequency of oscillation of the parachute system also be scaled by that same factor so that the dynamic pressure of the parachute would scale accordingly, preserving the similarity parameters of the problem.

IV. Grid Generation and Movement

Grid motion was accomplished in OVERFLOW using a prescribed function of oscillation. This required setting new rules for cell blanking and creating data processing scripts to account for the relative motion of the grids within the simulation.

IV.A. Grid Generation

Grids for dynamic CFD simulations were developed from the grid scripts utilized in static cases, which are developed using Chimera Grid Tools (CGT).[3] Overset grids proved to be beneficial for representing moving parachute geometry, not only because of the complexity of the interaction of the many structures within the grid system but also due to the need to recalculate overset interpolation stencils during the simulation after relative grid motion.

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IV.B. Domain Connectivity Function

Unlike the static CFD simulations, PEGASUS5 domain connectivity software could not be used for cell blanking as it is not built into OVERFLOW and domain connectivity must be recalculated within the simulation for moving geometries.[5] Instead, the Domain Connectivity Function (DFC) was utilized to perform hole cutting and calculation of interpolation stencils.[6]

Hole cutting was accomplished by extracting surfaces from the volume grids of each parachute segment, creating "phantom" cutter surfaces (See Fig. 1). X-raying these surfaces and using a zero-cutting distance allowed for almost exact control of interpolation regions and allowed for fine cutting within the small parachute gaps and expansive cutting elsewhere around the segment.
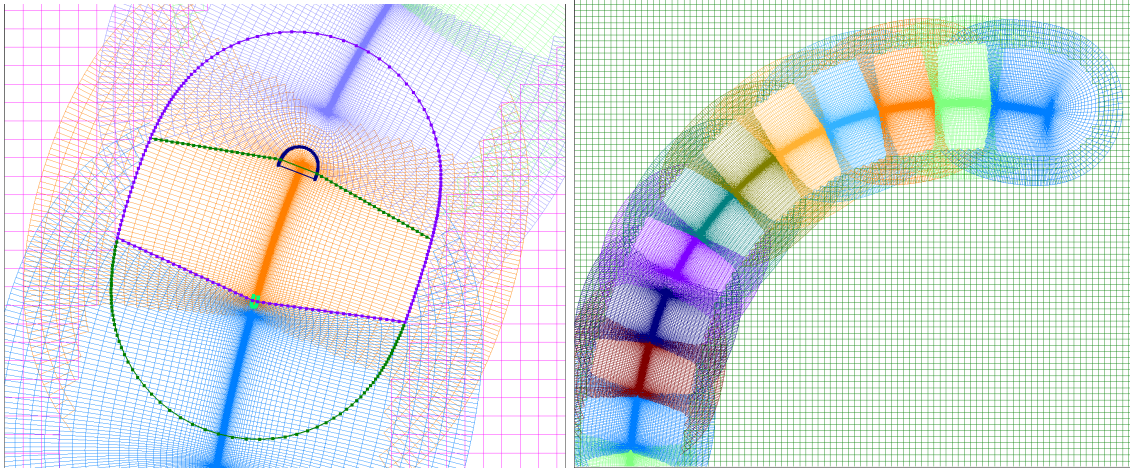

Figure 1. Phantom cutter grids for single chute segment (left) and the final half cross-sectional view of DCF hole cutting for the parachute grid system)right

IV.C. Data Post-Processing

A series of data post-processing scripts were written in Python to condition the raw data produced by the OVERFLOW flow solver. Since OVERFLOW does not bookkeep the relative motion of grids for non-dimensionalization parameters, the OVERFLOW output force coefficients were corrected for the actual dynamic pressure of the parachute due to freestream velocity as well as its oscillatory velocity.

Velocity of oscillation was calculated according to the equations of prescribed motion, which also allowed the calculation of the effective angle of attack of the parachute.

V. Wind Tunnel Test

For validating the dynamic force simulation capability of the moving CFD model, results were compared to tests of a one-third scale MPCV parachute in the National Full-scale Aerodynamic Complex (NFAC) 80x120 wind tunnel. In this test, the parachute was secured by its risers upstream of the parachute, and maneuvered by tethers attached to the aft vent. For the dynamic tests, the parachute was released at the vent an allowed to precess about the test section of the wind tunnel. Load forces on the risers were recorded, allowing the direct calculation of aerodynamic coefficients for comparison with dynamic CFD.,[89]

VI. Results and Comparisons

After initial calibration and a time step sensitivity study, multiple simulations were performed with a variety of maximum oscillation angles to vary the tangential velocity of the parachute during pendulum motion.

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VI.A.   Dynamic CFD Results

The purpose of this work was to demonstrate the differences, if any, between the CFD results for static and moving parachute geometries. Fig. 2 represents the flow surrounding the parachute at an angle of attack of $\alpha = 0^o$. For the static case, flow is approaching the parachute head-on, and a symmetric wake is produced. For the dynamic case, the parachute has just passed its maximum amplitude angle and is traveling back toward the center of its oscillation. The vector sum of the freestream velocity and the tangential velocity of oscillation is such that the effective velocity vector of the moving parachute is also head-on into the chute.
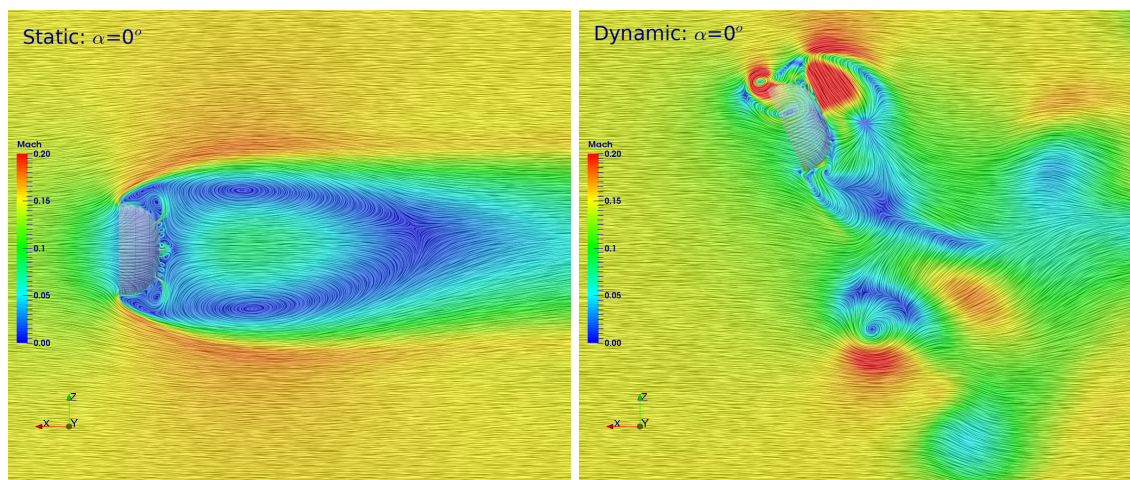

Figure 2. Flow visualizations for static (left) and dynamic (right) CFD simulations, each at an angle of attack of $\alpha = 0^o$

Though the two parachute flow fields are at the same angle of attack, their appearances are significantly different, with a less resolved wake and an off-body vortex being generated in the dynamic case, suggesting that there are flow effects purely due to the dynamics of the parachute oscillation.
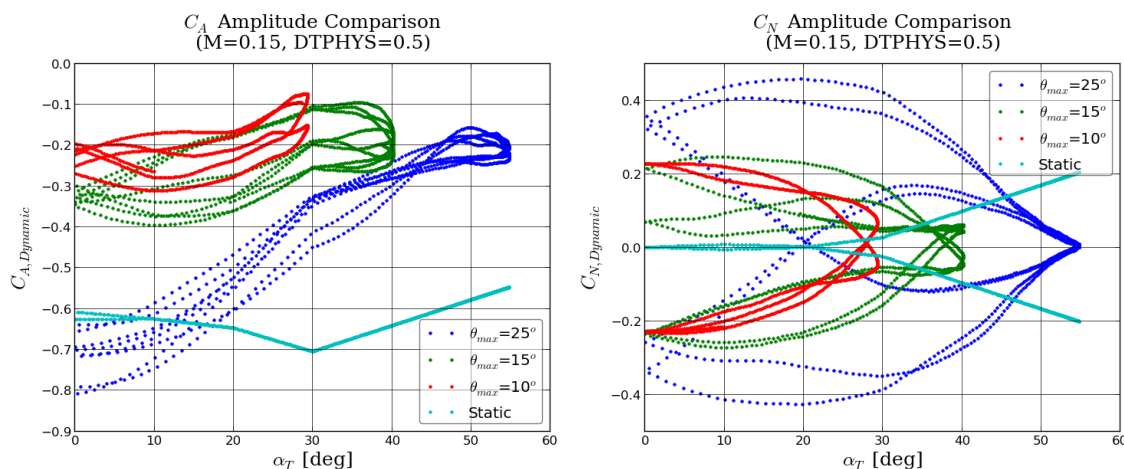

Figure 3. Dynamic and static CFD axial and normal force coefficient comparisons for simulations of various amplitudes

To more directly compare the contributions of the static and dynamic forces, the static force at a given instant was subtracted from the dynamic force to produce a representation of the dynamic addition. These static and dynamic force coefficients are compared in Fig. 3. Observing the $\theta_{max} = 25^o$ case, it can be seen that the dynamic contribution varies from approximately onethird the magnitude of the static baseline (axial force of the parachute is negative, so the negative C_A axis is increasing magnitude) to on the same order as the static forces. In the case of normal force coefficient, it can be seen that the dynamic effects truly dominate the periodic force behavior.

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VI.B. Validation

CFD results were also compared to those of the NFAC wind tunnel test to determine if the dynamic effects simulated by the CFD were comparable to those observed in actual flow. Though the simplified oscillatory path of the CFD simulation proved to be unrepresentative of the attitude track of the parachute in the wind tunnel test, general trends appear similar between the CFD and the wind tunnel.

VII. Conclusions and Future Work

This work describes the process for performing a dynamic, moving grid CFD simulation for the Orion MPCV parachute. The flows of the dynamic simulations were shown to be notably different from their static CFD counterparts, both in qualitative flow characteristics and in quantitative aerodynamic force comparisons. More study is needed to determine where these effects are significant in terms of modeling the instability of the Orion MPCV parachute system.

Preliminary validation of the dynamic CFD model was accomplished by comparison to NFAC wind tunnel test data. To improve this comparison, a prescribed motion CFD simulation could be performed that more directly followed the track of the parachute in the wind tunnel.

It is also of interest to determine the effects of forced motion on the results of these simulations. Since motion in these simulations is prescribed, some of the dynamic effects could be a result of forced oscillation. A six degree of freedom simulation, where parachute motion is influenced by the calculated aerodynamic forces, would help determine which effects, if any, are due to the forced nature of the motion in the simulations described in this paper.

Acknowledgments

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