CFD 2030 Grand Challenge: CFD-in-the-Loop Monte Carlo Flight Simulation for Space Vehicle Design

David M. Schuster
NASA Langley Research Center
Hampton, VA
david.m.schuster@nasa.gov
757-864-2259

Flight qualification of space vehicles is markedly different from those typically employed for aircraft. The concept of an extensive flight test campaign for a space vehicle does not exist, and vehicle designers must look to alternative techniques for demonstrating robust and reliable performance of their vehicles prior to operational flight. A space vehicle may undergo only a handful of flight tests in its development cycle, with each flight representing a drastically different flight phase or flight configuration. For instance, NASA's Space Launch System (SLS) launch vehicle and Orion spacecraft will only see a total of four flight demonstrations before flying a crew on its first operational mission, and each flight demonstrates a unique vehicle configuration and/or set of flight conditions. The SLS will be flown only one time before it becomes operational (Artemis 1). The Orion spacecraft Crew Module (CM) will have been tested twice, once on a Delta IV launch vehicle (Exploration Flight Test 1) and once as a fully integrated system with the SLS launch vehicle (Artemis 1). The Orion Launch abort system will have been tested twice, once in a pad abort scenario (Pad Abort 1) and once in an inflight abort scenario (Ascent Abort 2) on a modified Peacekeeper booster. Both of these latter tests involve only a boiler plate CM, not a functional Orion spacecraft. Thus, unlike aircraft, there is very little opportunity for engineers to assess and evaluate their preflight predictions.

Instead, space vehicle designers rely on Monte Carlo flight simulations with detailed dispersions of predicted nominal flight behavior to determine how robust their design is to errors and uncertainties in the flight conditions their vehicle may encounter. These Monte Carlo analyses entail thousands of trajectory simulations to demonstrate that the vehicle can meet design requirements at a specified level of reliability. From an aerodynamics and aerothermodynamics perspective, these trajectory simulations are fueled by an extensive aerodynamic database that covers the complete range of expected flight conditions, vehicle configurations, and flight attitudes expected in a given mission. Today, these databases amount to a table of engineering parameters that can be quickly interrogated by the trajectory simulator. The aerodynamic and aerothermodynamic databases are assembled via a series of ground tests, empirical and analytical analysis, physics-based computational analysis, applicable past flight performance data, and in some cases, engineering judgment. These databases generally take years to assemble for a new space vehicle system and in the case of SLS/Orion, over a decade of test and analysis have been expended to develop the extensive databases required to cover the myriad of configurations and potential flight conditions required for the system.

Recently, it has been proposed that Computational Fluid Dynamic (CFD) and computing capability may be reaching a point where it is foreseeable that CFD could be integrated directly into the production trajectory simulation tools used to design NASA's space vehicles. To demonstrate this, NASA has embarked on two demonstrations of this type of capability, one

where six degree of freedom flight trajectory simulation equations are embedded in an existing CFD solver and another where a production CFD solver is loosely coupled with a production trajectory simulation tool. These efforts represent an initial demonstration of a future approach to flight trajectory simulation, but they are a far cry from the capability required to perform a full-up CFD-in-the-loop Monte Carlo trajectory simulation. Therefore, this represents a viable grand challenge for computational methods addressing space vehicle design and development.

The final paper/presentation will discuss the many hurdles, beyond simply raw computational power, to realizing this grand challenge and how they map directly to the CFD Vision 2030 ojectives. Among these are the wide range of flight conditions, including accelerating/decelerating flight, encountered by a space vehicle during launch and/or entry. The vehicle can also encounter numerous configuration changes, some of which can be quite drastic, during the course of its flight, so robust, automated geometry modeling, grid generation, and adaptation will play a huge role in reaching this goal. Multiply this by 1000's of trajectory simulations occurring simultaneously in a given Monte Carlo analysis, and the problem readily scales to absorb virtually any size of supercomputer envisioned today. The concept of CFD-in-the-loop Monte Carlo trajectory simulation poses a formidable challenge for emerging and future computing systems, and it has the potential to shave years off the development cycle for aerodynamic and aerothermodynamic performance predictions as compared to today's space vehicle design approach.