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

David M. Schuster  
NASA Technical Fellow for Aerosciences  
NASA Langley Research Center

CFD2030 Grand Challenge Problems for Numerical Simulation in Aerospace Engineering  
2021 AIAA SciTech Forum

This material is a work of the U.S. Government and is not subject to copyright protection in the United States.  
14 January, 2021
Outline

• Introduction to Space Vehicle Design Challenges
• Space Applications of Interest
  ▪ Ascent/Abort
  ▪ Entry Descent and Landing (EDL)
• CFD Vision 2030 Study Technology Gaps and Impediments
  ▪ Challenging Space Vehicle Flow Physics
  ▪ Geometry Modeling, Grid Generation, and Automation
  ▪ Computational Considerations
  ▪ Multidisciplinary/Multiphysics Simulation Challenges
• Conclusion
Space Vehicle Design Challenges

- Space vehicle flight qualification is substantially different from that of aircraft.
  - Little to no flight demonstration/test, often in environments with high degrees of uncertainty.
  - Monte Carlo (MC) flight simulation and probabilistic methods used to evaluate design.
  - Aerosciences databases required to fuel MC simulations.
    - Large aerosciences parameter matrices involving dozens of independent variables with uncertainties.
    - Data developed from ground tests, empirical and analytical data, CFD, past flight performance data and engineering judgment.
    - Can require years to develop.
- Space Vehicles usually fly preset trajectories with little opportunity for placarding.
  - Fly through the complete range of flow conditions from low subsonic to hypersonic.
  - Fly a narrow trajectory corridor, but require broad parameter matrices to cover off-nominal performance cases.
  - Transient and acceleration effects can be important.
    - Not accurately represented in the present database approach.
- Replacing the aerodynamic database with a direct CFD simulation has substantial advantages.
  - Designers have early access to MC simulation without waiting for aerosciences database development.
  - Aerosciences unsteady and transient effects more accurately represented in the simulation.
  - Design changes can be more readily evaluated.
  - If desired, a trajectory-focused database can be extracted from the simulations conducted to date.
• Credible efforts toward 6-DOF coupled CFD Simulation through DoD’s CREATE-AV and NASA Entry Systems Modeling projects.
Space Applications of Interest
Ascent

- Ascent flight phase spans the entire flow regime from stationary on the pad to hypersonic flight in rarefied atmosphere.
- Pad operations involve ground wind simulations and complex ground support geometries.
  - Vehicle oriented “90°” to the flow.
  - Engine ignition transients can be particularly important to the design and simulation.
- Liftoff transition involves rapid acceleration and transition from 90° to 0° total angle of attack.
  - Combination of vehicle pitch and roll maneuvering.
- Acceleration through transonic speed regime can involve strong buffet and aeroacoustic effects.
  - Potentially harmful to the vehicle structure, flight systems, and crew.
- Vehicle staging and separation events.
  - Complex multi-body and plume vehicle interactions.
- High altitude flight in non-continuum flow.
Abort systems are used for crew rescue in the event of a catastrophic failure. Most provide full abort coverage from stationary on the launch pad, along the complete ascent trajectory, to orbit insertion.

Two primary concepts in use today:
- Tractor systems as used on Mercury, Apollo, Soyuz, and Orion.
- Pusher Systems as employed on most commercial crew launch systems.

Launch abort vehicles must be maneuverable and most require stable flight from $0^\circ$ to $180^\circ$ total angle of attack.
- Control is afforded by both propulsive and mechanical systems and can be passive or active.

Staging and separation events required for most abort scenarios.
Parachutes and/or propulsive systems required to land the payload.
Aero/Plume, Plume/Plume, and Plume/Vehicle interactions can be important and difficult to predict.
- Vehicles routinely fly through their own plumes.
Space Applications of Interest
Entry Descent and Landing

- Entry systems reverse the ascent process transitioning from hypersonic flight to landing.
- Atmospheric heating at hypersonic conditions is of primary concern.
  - Entry interface typically occurs in rarefied atmospheres requiring non-continuum flow simulations.
  - Chemical reactions and shock radiation effects can be important to the analysis.
- Vehicle control is usually provided through a propulsive reaction control system.
  - Aero/plume interactions can have a large impact on control authority.
- A variety of vehicle decelerator concepts can be employed.
  - Hypersonic inflatable and mechanically deployed heatshields, supersonic and subsonic parachutes, retro propulsion and vehicle maneuvering.
- Staging, separation, and mass redistribution events.
- Plume/surface interaction important to terrain navigation and landing.
CFD Vision 2030 Gaps and Impediments

- CFD Vision 2030 Study identified five primary gaps and impediments:
  1. Effective Utilization of High Performance Computing (HPC)
  2. Unsteady Turbulent Flow Simulation Including Transition and Separation
  3. Autonomous and Reliable CFD Simulation
  4. Knowledge Extraction and Visualization
  5. Multidisciplinary/Multiphysics Simulations and Frameworks

  - Gaps and impediments 1, 2, 3, and 5 present the greatest roadblocks to meeting the challenge.
Challenging Space Vehicle Flow Physics

• Space vehicle aerosciences encompasses majority of critical flow phenomena addressed in the CFD Vision 2030 Study.
  - Unsteady flows due to smooth body and shock induced separation.
    - Launch vehicle and spacecraft ground winds.
    - Transonic buffet and aeroacoustics.
    - Bluff body entry systems.
  - Aero/plume, plume/plume, and plume/surface interactions.
    - Chemistry and flow structure resolution are often critical.
    - RCS firing into separated wakes problematic for entry systems.
• Transient analysis is a “must have” for most space vehicle simulations.
  - Accelerating and maneuvering flight, staging and component separations, naturally occurring flow unsteadiness, geometries not optimized for aero.
• Require strong focus on development of accurate and efficient unsteady CFD techniques that are competitive with current steady flow simulations.
  - Physics complexity pushing space vehicle aerosciences community more often to Detached Eddy Simulation and Hybrid Reynolds Averaged Navier-Stokes/Large Eddy Simulation capability.
Geometry Modeling, Grid Generation, and Automation

- Efficient geometry modeling, grid generation, and automation critical to solving the grand challenge.
  - MC simulation requires accurate modeling, both geometry and physics, of a vehicle maneuvering arbitrarily and unpredictably as it responds to dispersed flight condition uncertainties.
- MC simulations can require 1000’s of simulations.
  - User must be removed from the geometry modeling and grid generation process as much as possible.
- Flow physics can evolve rapidly during a given trajectory simulation requiring robust automatic mesh refinement techniques.
  - Adaptation to a specified accuracy metric likely required to manage simulation cost.
HPC Considerations

• Typical MC flight simulation for design purposes requires 3000 or more independent flight simulations dispersing up to 100 design parameters.
  - Simulations employing table lookup aerodynamic databases can be performed on desktop workstations and small computing clusters.
  - Adding CFD-in-the-loop moves the simulation off the desktop.

• Tuning efficiency of a single CFD-in-the-loop flight simulation is pacing item for this challenge.
  - Multiple simulations required for MC analysis is embarrassingly parallel.

• Near term progress may require development and implementation of novel Model Order Reduction and/or Machine Learning techniques.

• Access to emerging HPC hardware, CFD tool adaptation, and algorithm development are enabling.
  - Problem is increasingly a computer science problem over a flow physics problem.
Multidisciplinary/Multiphysics Simulation Challenges

- Aero/plume interaction, chemically reacting flows, fluid/structure interaction are a few multidisciplinary and multiphysics problems important to space vehicle aerosciences.
- Efficient CFD-in-the-loop MC simulation presents a different set of challenges.
  - 6-DOF flight simulation for vehicle design is highly developed and diverse in available tools.
  - Not likely that the comprehensive capability of these tools could be built directly into the CFD solver.
- Frameworks effectively coupling the CFD and simulation tools will allow the integration of CFD capability tailored to a given problem.
  - Dichotomy of computing platforms required for CFD code and simulators could prove to be a challenge for developers and users alike.
Conclusion

• Detailed Aerosciences analysis is required in two primary flight phases for space vehicles: Ascent/Abort and Entry Descent and Landing.
  ▪ Vehicles not optimized for aerodynamics.
  ▪ Prediction of unsteady flows, plume/surface/aerodynamic interaction, shock effects, heating, and vehicle flight stability are prime requirements.

• Designers regularly deal with unsteady flow.
  ▪ Steady CFD implementation can be clumsy and prone to large variation.
  ▪ Community increasingly turning to DES and HR-LES for select cases.

• CFD-in-the-loop MC simulation has potential to significantly reduce design development time and lessen the cost and schedule impact of vehicle design changes and/or block upgrades.

• Challenges to realizing this capability are significant and well-aligned with the goals proposed in the CFD Vision 2030 Study.

• The grand challenge is partially scalable and could be initially demonstrated on only a segment of a flight simulation.
  ▪ EDL may be a good choice for demonstrating capability; several initial efforts in free-flight CFD EDL analysis are underway.

• Model Order Reduction and Machine Learning techniques may be required for near-term implementation of CFD tools capable of simulating space vehicle flows of interest.