CCDEV Aerodynamics TIM

Orion Database Development Process and Lessons Learned

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Agenda

- MPCV Orion Aerodynamics Database Overview
- Aerodynamics API Overview
- Aero Database Lessons Learned

Aeroscience Database Overview

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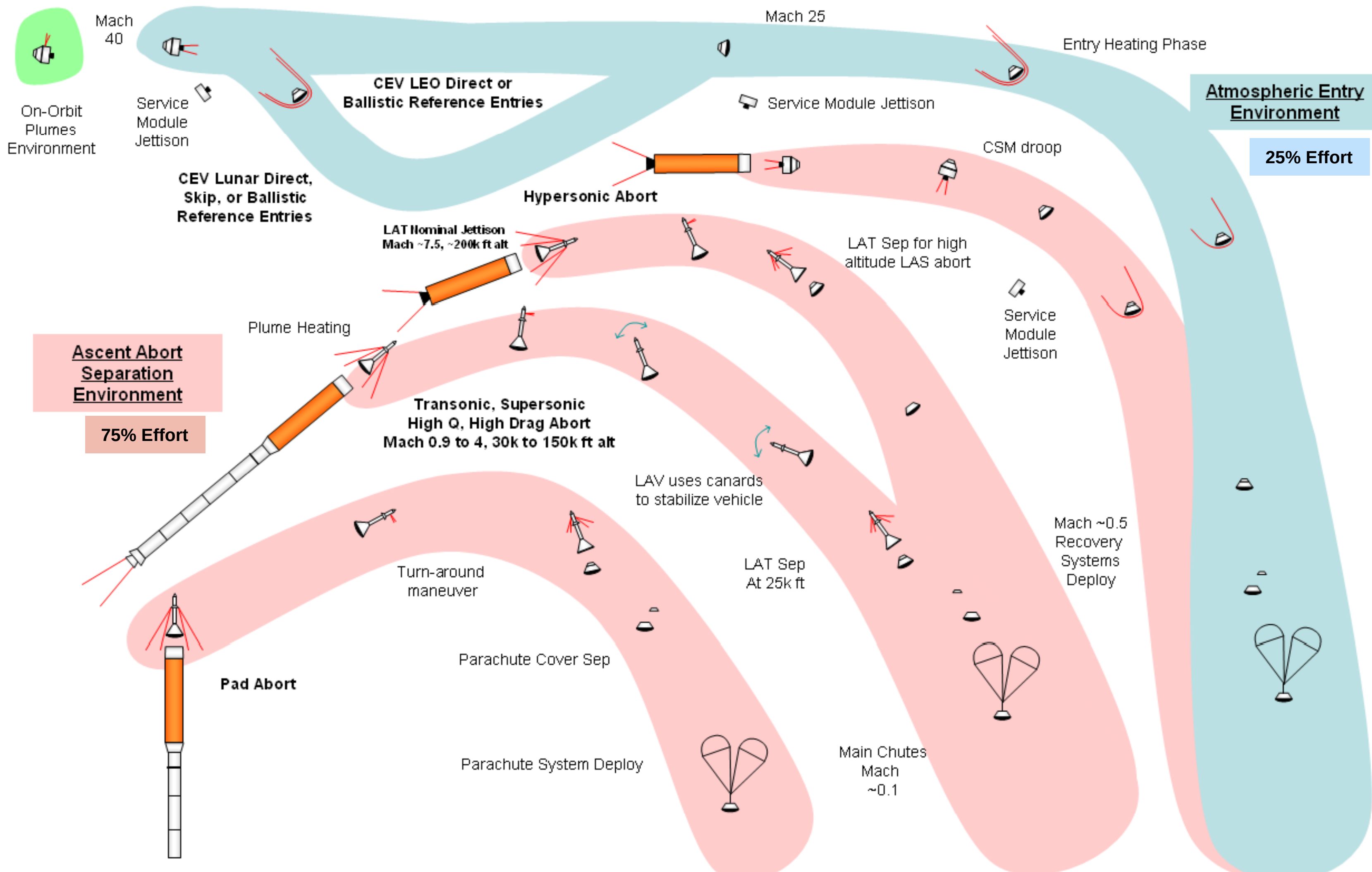
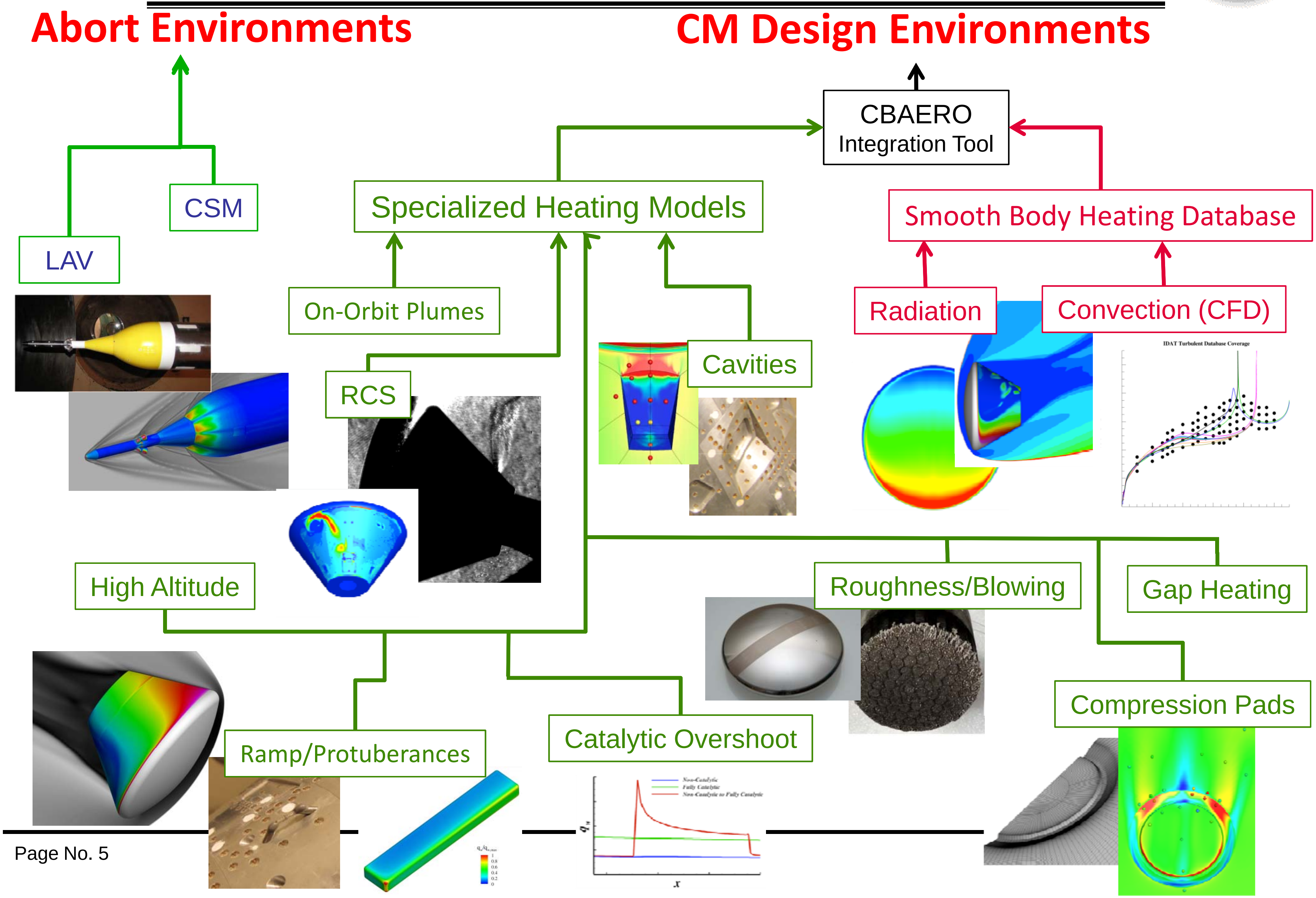


Aerothermodynamic Database Overview

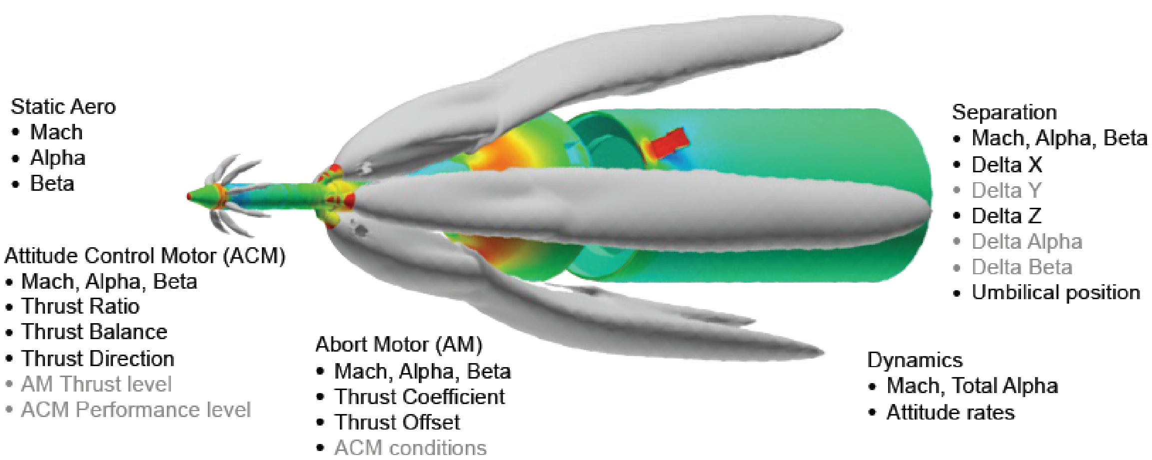


Aerodynamics Database Overview

- **Aeroscience Team (CAP) is charged with delivering aerodynamic (and aerothermodynamic) environments for development and operation of the MPCV Orion vehicles**
  - Originally (2005) directed to use Computational Fluid Dynamics (CFD) as primary source to develop databases to save costs
  - Limited wind tunnel testing program largely designed to validate CFD based database models and Apollo models
  - This initial plan did not survive long as it was soon discovered that CFD was insufficiently accurate in critical areas and more expensive in personnel and CPU hours than originally estimated
    - ✓ Ascent abort jet interactions – complex turbulent interactions
    - ✓ Blunt body entry wake modeling – turbulence
- **Scope of aerodynamics work determined iteratively based on GN&C needs and vehicle performance**
  - Content of initial plan significantly modified as vehicle design matured
  - 35+ aerodynamic wind tunnel tests – vast majority for launch abort & dynamics
  - 5000+ 3-D Navier-Stokes CFD solutions

Aerodynamic Databases Overview

- ❑ **Self-contained Application Program Interface (API) provided by CAP to GN&C and other users**
  - Aerodynamic data tables – 195 tables, 6,000,000+ entries, 465 MB
  - Database documentation, Users Guide – 17,000+ pages combined tables / documentation
  - API code – 50 files, 12,000+ code lines, 12,000+ comment lines
  - Implementation test cases
  - Used in GN&C and other vehicle simulations (ANTARES, Osiris, OrionSim, Adams, ITL)
- ❑ **In previous flight programs the aerodynamics team provided data tables to users who then created their own tools to implement the equations and use the data**
  - Lessons learned from X-43 and other programs showed that this old process left too many opportunities for mistakes, misunderstandings, and inefficiencies
  - Turnaround time from aerodynamic model release to a working GN&C implementation significantly reduced
  - Significant effort to ensure API can be used on multiple platforms and across multiple teams
- ❑ **Database built from CFD, wind tunnel data, engineering tools, & historical data**
  - **CM may look like Apollo, but completely different ascent abort system**



- CM on-orbit through entry
  - Function of M, α, β, RCS, & FBC
- CSM on-orbit
- SM entry through break-up
- LAV ascent abort (7-Dimensional)
  - LAV separation
  - LAV boost (AM + ACM)
  - LAV coast (ACM)
  - LAT jettison (JM)
  - LAT free-flight
- Rate-based dynamic damping for LAV & CM
- Uncertainties for 95%+ of aerodynamic terms

Aeroscience API Overview

API Overview

- **The Orion configuration presents many challenges to the design of an aerodynamic database**
  - Wide range of angles of attack and sideslip
  - Complex jet plume interactions
  - Wide range of flight velocities
  - Shifting c.g. locations
  - Range of entry L/D
  - Several separation events
  - Severe abort environment
  - Multiple vehicle configurations
- **Many of these items result in highly dimensional databases**
  - Required use of interpolation or surface fitting techniques
- **Special techniques developed to account for some these issues**

Wide range of Alpha and Beta

- **Although the Crew Module generally flies at a trim angle of attack, data for all angles of attack are needed for some situations**
  - Abort conditions
  - Dynamics under chutes
- **The Launch Abort Vehicle requires a database for all attitudes because it reorients as part of its normal flight**
- **Databases based on an assumption of an axisymmetric body used to simplify the database**
  - Coefficients based on total alpha
  - Reduces amount of data required to create the database
- **Axisymmetric aero database considerations**
  - Value of C_N and C_m must be zero at total alpha of 0 and 180
  - Failure to do so will result in erratic aero near total alpha 0 and 180
- **Full Alpha/Beta database considerations**
  - Values of coefficients at Beta 90 must be identical for all alphas
  - Failure to do so will result in erratic aero near beta 90

Complex Jet Plume Interactions

- ❑ **Multiple jet plumes result in highly complex databases**
  - Orion includes both abort motors and control motors
- ❑ **Sensitivity to thrust variations must be well understood**
- ❑ **Techniques were used to simplify the model**
  - Superposition of jet effects
  - Jet reference frame model
  - Assumption of alpha and beta symmetry
  - Limiting thrust ratio coverage to expected flight profile
- ❑ **Each of these techniques has cautions to their use**

Sensitivity to Thrust Variations

- Early versions of the database only covered a few motor thrust levels
  - Linear interpolation used between available data
- Additional evaluation showed that aerodynamics was much more sensitive to small thrust variations than earlier believed
- Required significantly more analysis and testing to complete database
- Resulted in changes to the GN&C design

Superposition of Jet Effects

- **Early versions of the database assumed that effects of the control jets could be added to the effects of the abort motors**
  - Assumed larger abort motors would be dominant
  - Allowed for effects to be developed independently
  - Avoided complex interaction database
  - Made possible an earlier release of the database model
- **Further analysis showed that the interaction of control jets with the abort motor plumes could be very significant**
  - Required a complex wind tunnel test to build a database that included the jet plume interaction

Jet Reference Frame Model

- **Early version of the control motor database used a design based of a jet reference frame**
  - Coefficients are based on a coordinate frame that rotates with the control jet firing direction
  - Coefficients are dependant on the angle between the wind clocking angle and the jet firing direction
  - Final coefficients are rotated back to body axis
- **Jet reference frame data has symmetry concerns that must be understood**
- **Assumes axisymmetric body and firing direction independent effects on the coefficients**
- **Orion jet reference frame model was later replaced with a single quadrant alpha/beta model**

Alpha / Beta Symmetry

- **Several Orion database assume alpha and/or beta symmetry**
- **Beta symmetry is most common**
- **The control jets used a more complex alpha/beta symmetry model**
  - Data was measured for +/- alpha and +/- beta but for only 90° of firing directions
  - Symmetry was used to model the jet effects to all firing directions
  - Required special symmetry considerations in the database to avoid inflections as the jet direction passed between quadrants
- **Errors in the data due to symmetry assumptions were included in uncertainty development**

Limiting of Jet Thrust Ratio Coverage

- **Jet thrust ratios included in the database design were limited to those used in typical flight profiles**
  - Results in large areas of the database that use interpolated or hold last value data
- **Aero database was designed based on Ares 1 ascent abort trajectories**
  - Important to relate this limitation to the API users who are tempted to use existing data for all ascent trajectories
  - Update for SLS and EFT-1 trajectories ongoing

Incremental Models

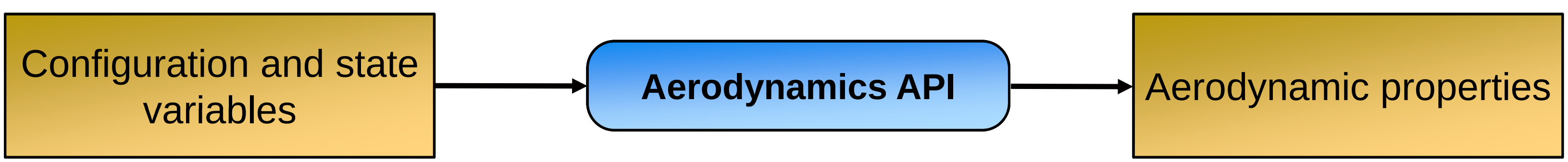
- **The use of incremental models has been very helpful in managing the growing database**
- **Allows for easier adaption of the database to vehicle or flight profile variations**
- **Example:**
  - Crew module tower jettison data is an incremental database
  - Change to Crew Module data for OML change did not require an update to the tower jettison aerodynamics

Kriging and Surface Fitting

- **Multidimensional interpolation and surface fitting techniques were used to develop highly dimensional databases**
  - Allows for database creation from sparser sets of source data
- **Some data sets required division of the space into separate overlapping regions**
- **Extra caution must be used in checking the results from these techniques**
  - Check for appropriate trends in the sparser database areas
  - Extrapolated data regions must be verified
  - One testing technique is to remove measured points from the development and then use them to check interpolation results

API Design Overview

- **Specifically designed for the MPCV Orion spacecraft**
  - Aborts, on orbit, and reentry
  - CM, LAV, CSM, and SM configurations
- **All ANSI standard 'C' for best portability to all types of systems**
- **Uses optimized multi dimensional linear interpolation algorithm**
- **Does not require any special functions or libraries from the host application/system**
  - All table processing code is self contained
  - Matrix functions are self contained
- **Provides the aerodynamics for a given state**
  - Results for subsequent calls are not dependent on previous calls



Value to Program of an API

- **This API is currently being used within the MPCV program as the sole source for an Orion aerodynamics model**
  - Single implementation allows for consistency of aerodynamics across the program
- **Replaces older method of delivering database as a set of tables and a formulation document**
  - Significantly reduces time to implement a new database release
- **Used to design Orion flight control software, analyze flight designs, and test flight hardware and software**
- **Additionally, the API provides a means for access to the Orion aerodynamics data for other analysis purposes**
  - Preliminary flight analysis/design
  - Comparison to wind tunnel test results
  - Comparison to computational aerodynamics results such as CFD
  - Development of future aerodynamic databases
- **Also available via a Matlab toolbox**

API Verification and Validation

- Being a single source for the aerodynamic code, extra effort is required for verification and validation
- Check delivered code with an independently developed code
- Perform hand checks of results where possible
- Check API output against development input data
- Perform regression analysis on parts of the database that did not change
- Perform sweeps through the database where code transitions occur
- Run software checking tools on the API code
- Deliver test case points for users to check implementation
- Perform a beta test cycle with a single GN&C user before approving the database for production work

API Release History

- There have been 26 releases from May 2006 to April 2011
- Updates included results of maturing testing and CFD analyses as well as maturing vehicle design
- Many updates motivated by need to improve database in regions where flight design challenges exist - GN&C feedback on accuracy needs
- Updates will continue through the development of the Orion spacecraft

API Complexity and Innovation

- **The API implements the CAP Orion aerodynamics model for many Orion components/configurations**
  - Crew Module (CM), the Launch Abort Vehicle (LAV), the Service module (SM), the launch abort tower (LAT), and the combined Crew and Service module (CSM)
- **Aerodynamic data are provided throughout the entire Orion flight profile, from the initialization of an abort through landing**
  - The abort phase LAV model is extremely complex including multiple plume flow conditions and separation configurations that requiring the use of over 100 data tables, some of which have 7 dimensions
- **The API includes an uncertainty model, used in monte-carlo analyses, that provides variable uncertainties for nearly all of the aerodynamic coefficients**
- **In the latest release the data file is 640MB in size, contains 194 tables, and has about 49 million data values**

API Future Plans

- **Plan is to continue the development of the API as the Orion design matures/evolves and as additional aerodynamic test and CFD data becomes available**
  - General expectation is for 1 to 2 releases per year through initial flight testing phase of MPCV
- **Possible innovations to include**
  - Generalization of the code to allow for easier modifications for use with other programs
  - Additional interpolation options
  - Use of non-square table formats
  - Conversion to C++ object oriented design

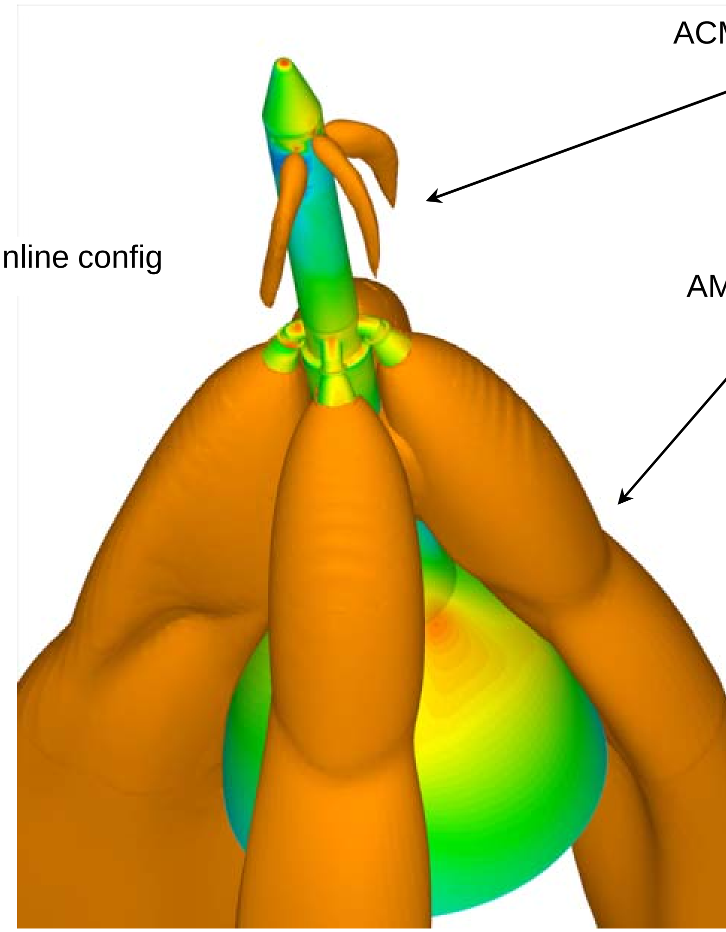
MPCV Orion Lessons Learned

Lessons Learned: Abort Plumes

- **In the beginning, everyone over-estimated how good CFD would be at database development and under-estimated the amount of non-linearity in transonic jet interaction aerodynamics on ascent**
  - CFD is currently not productive enough to generate enough data to develop a subsonic, transonic and supersonic database for non-trivial configurations
    - ✓ By necessity, CAP did use CFD, but had to use a lot symmetry assumptions
    - ✓ Lack of data decreases the understanding of the aerodynamics, decreases confidence in how good the database is, makes the aerodynamic database hard to defend, and makes it hard to be participants in the design process
  - Community experience and judgment on jet interaction aerodynamics for tractor-type LAS was really a blank slate - we didn't have much
    - ✓ The mainline Orion LAV configuration is not like Apollo with the addition of the ACM, different Abort Motor cant angle (25° vs 35°), and different OML
    - ✓ The nonlinear nature of AM and AM+ACM jet interaction meant we needed considerably more data than originally scoped and decreased team's confidence in the predictions
- **Ideal situation would be to have a robust vehicle design whose flight performance was insensitive as practical to aerodynamic uncertainty and an aerodynamic environment defined as early in the design phase as possible to drive GN&C development**

Abort Boost Phase Plume Configuration

6 to 10 simultaneous plumes firing during ascent abort drives aeroscience scope and required effort



Abort Plume Jet Interaction

- **Accurate prediction of plume aerodynamics has been very difficult for CFD, wind tunnel, and database teams**
  - 26-AA test program, the "holy grail," was a 2.5 year effort to simulate all LAV plumes, AM and ACM plumes, and separation simultaneously using cold gas
    - ✓ Multiple bellows design viewed as the <u>only way</u> to measure fully metric jet interaction with enough accuracy
      - Led us down the path of 18 months of bellows technology development
    - ✓ Used CFD to scale cold air plumes to match CFD based hot plume force and moment results (gamma x M^2 for transonic and gamma x M^2/beta for supersonic)
      - It matches force and moment results, **but** not necessarily surface pressures
    - ✓ Considerable resources have also been put in upgrading high pressure regions
  - Wind tunnel test using hot plumes at edge of technology and likely cost prohibitive
  - CFD simulation of plume jet interactions at limit of technology
    - ✓ Current OVERFLOW grid density is on the order of 50 to 80 million, and adding more points results in resolving Gortler vortices
    - ✓ Turbulence model studies shows that OVERFLOW SST model is the best model, but comparison to plume flowfield data shows experimental answer is in-between having compressibility corrections on or off
    - ✓ Solid rocket motor plume data on vehicle at transonic conditions unavailable
  - Assuming multi-phase and chemistry (afterburning?) captured by uncertainties

Lessons Learned: Blunt Body Entry

- **Prediction of subsonic (Mach < 1) aerodynamics for a blunt body with rounded corners is challenging**
  - Problem will be only be resolved with a Jan 2012 High Reynolds Number Wind Tunnel Test at the NASA LaRC NTF
  - Current confidence in drag prediction is not that high
    - ✓ At trim-alphas (near 160°), wind tunnel testing at 1e6 < Re < 5e6 shows drag is highly sensitive to Reynolds number
    - ✓ CFD results are highly sensitive to turbulence model
    - ✓ At non-trim alphas (near 90°), the flow physics are different, and lessons learned at trim-alpha don't necessarily apply
    - ✓ Standard process of validating CFD codes at WTT conditions, than correcting data to FLT conditions with CFD is a leap of faith
      - How do we know turbulence model suitable for WTT conditions is good for FLT conditions?
- **Like with hot plumes data for validation of CFD, high Reynolds number data on a variety of blunt body configuration is needed**

Lessons Learned: Blunt Body Entry

- **Accurate aerodynamic predictions including uncertainty quantification critical for off-nominal design cases including chute-out and high dynamic pressure deployments**
- **Predictions of the performance of crew module + drogue parachute system is imperfect**
  - The dynamics and stability predictions of the crew module while under drogue parachutes are based on separately developed CM aerodynamics and parachute dynamics
    - ✓ Dynamics testing of the CM and drogues as one system show that the system is more stable than independent simulations predict
  - The dynamics and stability predictions of parachutes behind blunt bodies are poorly understood due to poor characterization of blunt body wakes and parachute performance behind wakes
    - ✓ CFD predictions of wakes very sensitive to turbulence model choices – none of which are validated

Lessons Learned: Blunt Body Entry

- **Characterization of subsonic and transonic dynamic damping for blunt bodies is complicated and sensitive to everything**
  - Characterization is critical to parachute design and RCS design as blunt bodies are generally dynamically unstable below Mach 1 and will tumble without control effectors or recovery system
  - Frequency of oscillation, amplitude of oscillation, rate, path, Reynolds number, and likely parachute configuration
  - MPCV attempted to use multiple techniques to characterize dynamic damping
    - ✓ Ballistic range testing at Ames HFF, Ames GDF, Eglin ARF, and Aberdeen YPG
    - ✓ Sting mounted small amplitude forced oscillation testing at Langley TDT
    - ✓ Side mounted large amplitude forced oscillation testing at Langley TDT
    - ✓ Side mounted free-to-oscillate testing at Langley TDT
    - ✓ Vertical spin tunnel testing at Langley VST
    - ✓ PA-1 aero reconstruction forthcoming
  - Current belief is that large amplitude forced oscillation is the best technique for subsonic and transonic dynamic damping characterization
    - ✓ The Langley TDT is the only facility capable to do this at transonic Mach

Final Thoughts

- **Organization**
  - Need to concentrate on being aerodynamicists versus CFD analysts or wind tunnel test engineers or uncertainty specialists
  - Aerodynamics should not simply be “environments” or “analytics” for the Program, but should be a subsystem that participates in the design process
    - ✓ The “goodness” or adequacy of an aerodynamic database cannot be judged in isolation but depends on the vehicle robustness, mission, and safety requirements
- **Use the right tools for the right job**
  - CFD excels at early configuration trades to determine trends and provide vehicle designers with initial environments
  - CDR-level aerodynamic databases require wind tunnel testing augmented with CFD in the appropriate places
  - Wind tunnel testing requires CFD analysis to maximize the data return
  - Until CFD has validated turbulence models (likely not RANS) for all flight regimes, wind tunnel and flight testing will remain critical to vehicle development
- **Uncertainty and GNC Monte Carlo analysis process**
  - Ongoing struggle to balance the desire provide rigorous values with the reality of GN&C needing realistic bounds to design viable flight control systems