SOLUTIONS

SLS
Space Launch System

JACOBS
ESSSA Group

NASA

Development of an Aerodynamic Method and Database for the SLS Service Module Panel Jettison Event Utilizing Inviscid CFD and MATLAB

Mike Applebaum/CRM
Les Hall/CRM
Marc Eppard/CRM
Dave Purinton/Gray
John Blevins/MSFC
Ricky Campbell/MSFC

Introduction

Goal: Create an analysis tool which can be coupled with a 6-DOF model to accurately predict SM panel separation from SLS in a time efficient manner.

•Requires spatial prediction of SM panel flight space in proper environment, generated with CFD analysis. The resultant database is divided into three zones:

- **panels on the hinge during initial separation in which not only body, but panel to panel effects are important**
- **panels in near proximity to the body**
- **panels alone in freestream environment**

• Data placed into Matlab, which utilizes the interpolation routines

• Coupled with 6-DOF, which includes the spring design, and tested

• For the customer, a completed and tested analysis tool which we will help integrate with their own 6-DOF model if needed

• Panel 2, the windward panel, poses greatest risk of recontact and will be the focus of this presentation

Introduction

This Analysis Draws Upon Prior Experience for this Class of Problem:

- **Hall, L.H., Eppard, W.M., Applebaum, M.P., Mitchell, C. R., "Computational Simulation Techniques of Panel Fairing Jettison from a Launch Vehicle System". JANNAF 959, 2008.**
    - **Comparisons between fully time accurate and quasi-unsteady**

- **Hall, L.H., Applebaum, M.P., Eppard, W.M.,"Debris Transport Modeling Techniques on Launch Vehicle Systems",49th AIAA Aerospace Sciences Meeting, Orlando, Fl, Jan 4-7, 2011.**

    - **Comparisons between fully time accurate and quasi-unsteady**

- **Hall, L.H., Parthasarathy, V., "Validation of an Automated Chimera/6-DOF Methodology for Multiple Moving Body Problems", AIAA 98-0753, 1998**

Bounding the Database

- Provided bounding trajectory points from GNC:

Mach number	5.99	5.53	5.85	5.9	8.55	7.45	8.48	8.32
Angle-of-attack, deg	−20.6	−20.75	−20.85	−20.43	−15.92	−15.01	−15.81	−15.09
Sideslip angle, deg	−4.51	−4.78	−4.77	−5.01	3.6	3.72	3.45	3.21

- From these points we determined the bounding flight conditions.

- It was noted a clear bias of beta associated with the alpha and Mach number.

    - Was it worth the computational space to model positive beta at the lower Mach or negative beta at higher Mach? Could those conditions ever exist?

Bounding the Database

• Two choices were considered:

1) Construct the database in a traditional manner, bounded by alpha/beta. Due to time constraints, a single Mach number would be chosen. It was determined the single Mach number would split the bounds provided by GNC; Mach = 7.0.

2) Produce a database with associated alpha/beta tied to Mach, and simulate results at the bounding end of the Mach numbers, approximately 5.5 and 8.5. For the same number of stations in time, this requires exactly half the simulations.

• Which would be the more dominant effect? Flow turning due to the Mach number variation, or small variations of alpha/beta?

○ From 2D shock tables, we might expect a differential of shock wave angle on the order of several degrees for the bounding Mach numbers.

Bounding the Database

•It was decided to have a quick look at Mach number versus Alpha/Beta effects:

Cases 1,2: Panels open at 30 degrees, Mach 5.4, alpha -21, beta -5 and +4
Cases 3,4: Panels open at 60 degrees, Mach 5.4, alpha -21, beta -5 and +4
Cases 5,6: Panels open at 30 degrees, Mach 8.55, alpha -21, beta -5 and +4
Cases 7,8: Panels open at 60 degrees, Mach 8.55, alpha -21, beta -5 and +4

•The results show that for the most windward panel, the most significant Mach number effect between Mach 5.4 and Mach 8.55 produced a moment difference of 5.9% seen at 30 degree panel rotation. The maximum beta effect on panel moment was coincidentally also 5.9%, but was observed at 60 degree panel rotation.

•It should be noted the beta percentage difference is obtained over the full range of beta, a range that should not exist at a given Mach number. So ultimately, it appears the Mach number effect could be more significant for expected range of possible conditions. It appears the untraditional approach of Mach tied to alpha/beta is a viable and cost-efficient choice that would provide roughly the same accuracy as modeling alpha/beta variation with half the simulations.

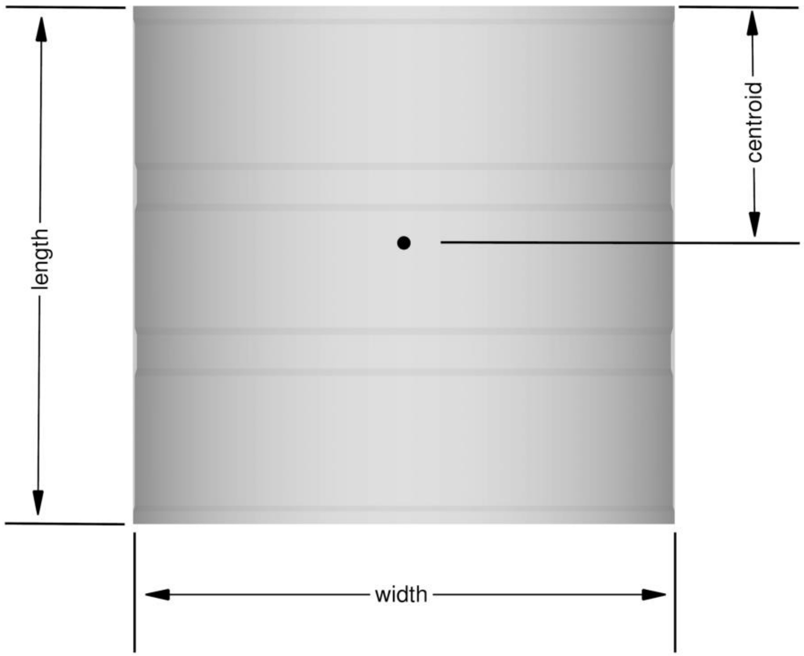
Bounding the Database

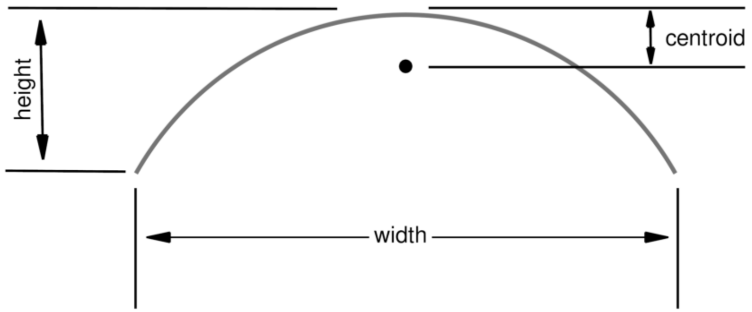
- **HOWEVER: the limitation of a chosen Mach number being tied to alpha/beta seems like a restrictive element of the database that could cause the database to lose relevance it might otherwise maintain if dispersed conditions change. It was determined that time existed for the larger computational matrix to be obtained by delivery date, so that option was chosen.**

- **The chosen bounds for the database were:**

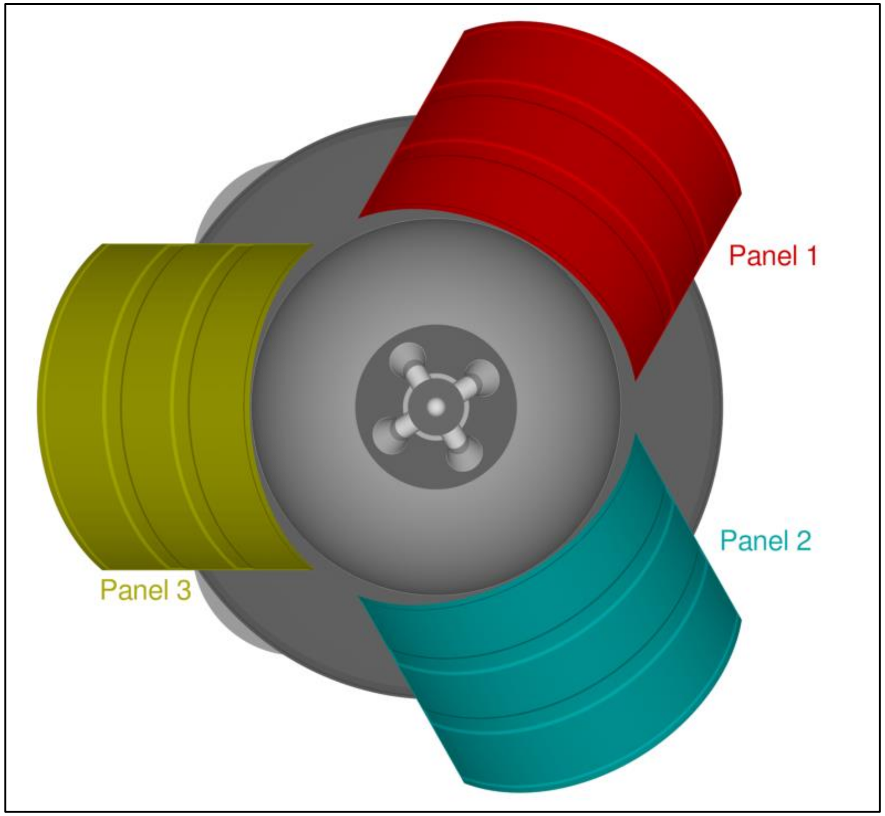
Case #	Mach	Alpha	Beta
1	7.0	-21	-5
2	7.0	-21	5
3	7.0	-15	-5
4	7.0	-15	5

Panel Geometry





Panel Orientation



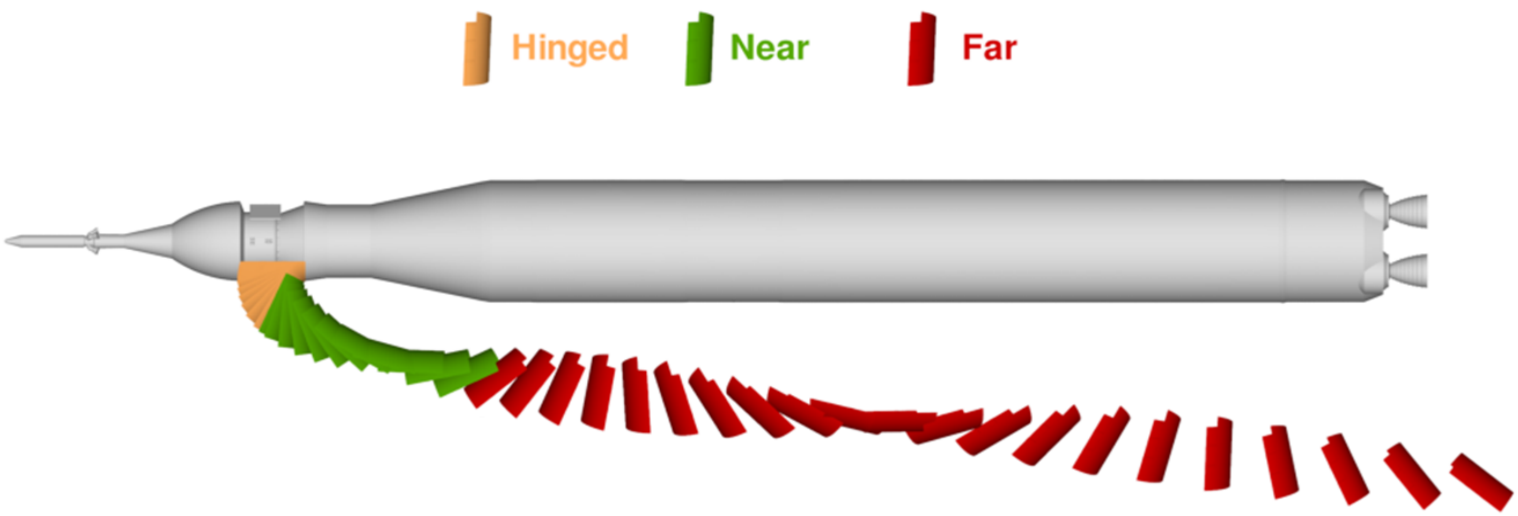
Database Zones

Database will Consist of Three Zones:

1) Panel on the Hinge: considered most crucial in trajectory determination. Panel-to-panel effects captured

2) Near the body: where body proximity effects are taken into account

3) Far from the body: panel alone data utilized in this region where body proximity effects considered small or unimportant



Panel 3, α = -18, β=0
Not all hinged cases shown

Panels on Hinge

Objective:

Case #	Mach	Alpha	Beta
1	7.0	-21	-5
2	7.0	-21	5
3	7.0	-15	-5
4	7.0	-15	5

- Develop hinged-panel zone of database
  1. Provide 6-DOF forces and moments
  2. Rotation constrained about hinge
- **Assumption: panel to panel effects matter,**

And should become negligible by panel rotation of 65 degrees

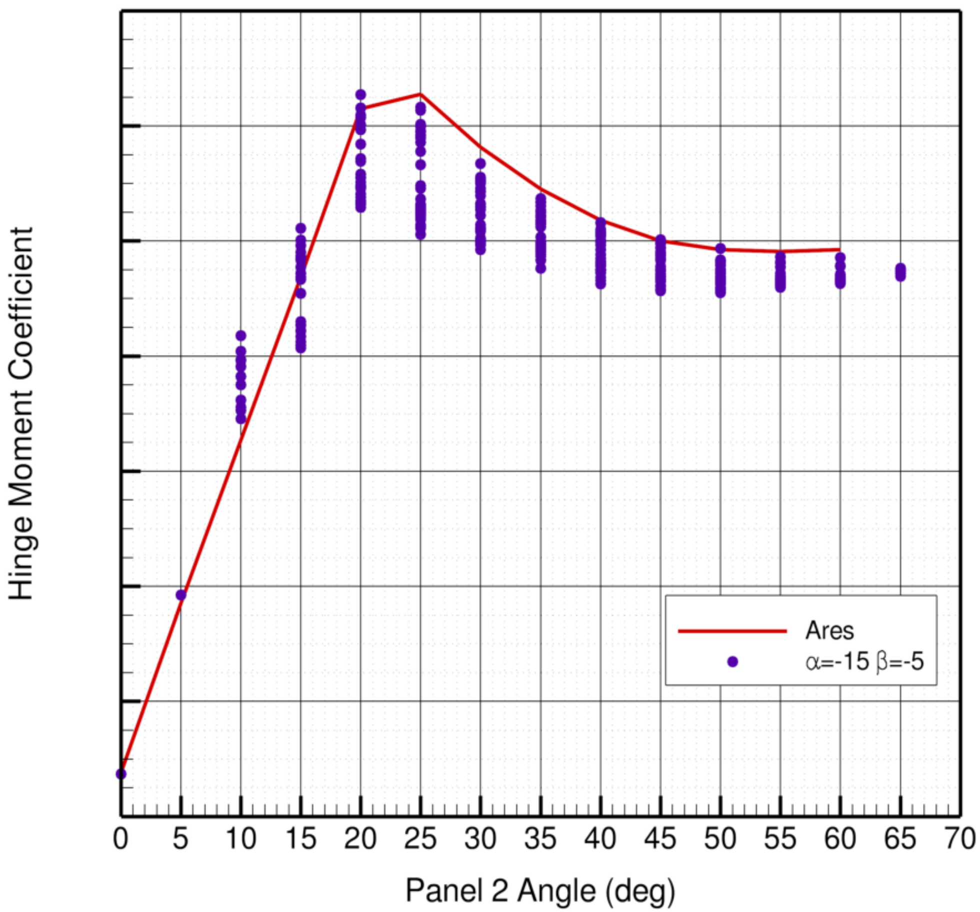
- Matrix:
  - Panels rotated from 0 to 65 by 5 degree increments.
  - Maximum of 15 degree difference between any two panels
  - Yields 362 simulations per condition.
  - Four M, α, β combinations
  - Panel hinged database contains 1,448 simulations

- MRP = Panel hinge
- Panel rotations about hinge

Panels on Hinge

- Matrix:
  - For 0, 5, and 10 degrees, the panels were not allowed to vary from each other.
- Cart3D inviscid flow solver
  - Adaptive algorithm
    - 9 adaptation cycles
    - Adapt to forces on panels alone
    - Goal 3+ million cells (in cavity region)
- Loci/Chem viscous flow solver (check cases)
  - 50+ million cell meshes
  - Mentors baseline turbulence model + Wilcox compressibility correction

Comparison To Ares Panel 2



Mach = 7.0, a = -15, b = -5

- Hinge moment magnitude shown
- For each panel location (x-axis) there are 37 potential orientations of the other two panels.
    - Less at the bottom (0,5,10) and top (55, 60, 65) of the matrix.
- Best match to Ares A104 is Case 3 (α = -15, β = -5)
- We see highest moment with lower angle of attack, as the capture region in the cavity is more aligned with the flow. Negative beta as opposed to positive has same effect
- All cases collapse into narrow band by panel rotation of 65 degrees, indicating panel-to-panel effects become secondary

Viscous Check Cases

- Loci/Chem
  - Roe inviscid flux
  - Mentor's baseline turbulence model w/Wilcox compressibility correction.
  - Meshes approximately 50+ million cells
  - Converged quickly with only small oscillations
  - Cases chosen at random to keep from biasing check cases

Viscous Check Cases
Windward Panel

Condition	Orientation	% Difference
α = -21 β = -5	30-30-30	8.1
α = -21 β = +5	30-30-30	0.6
α = -15 β = -5	30-30-30	2.3
α = -15 β = +5	30-30-30	3.4
α = -21 β = -5	45-45-45	3.7
α = -21 β = +5	45-45-45	1.4
α = -15 β = -5	45-45-45	7.3
α = -15 β = +5	45-45-45	0.6
α = -15 β = -5	15-15-15	21.1
α = -21 β = -5	35-40-25	4.5
α = -21 β = +5	45-50-55	3.1
α = -15 β = +5	55-60-45	2.7

Average % Diff = 4.9

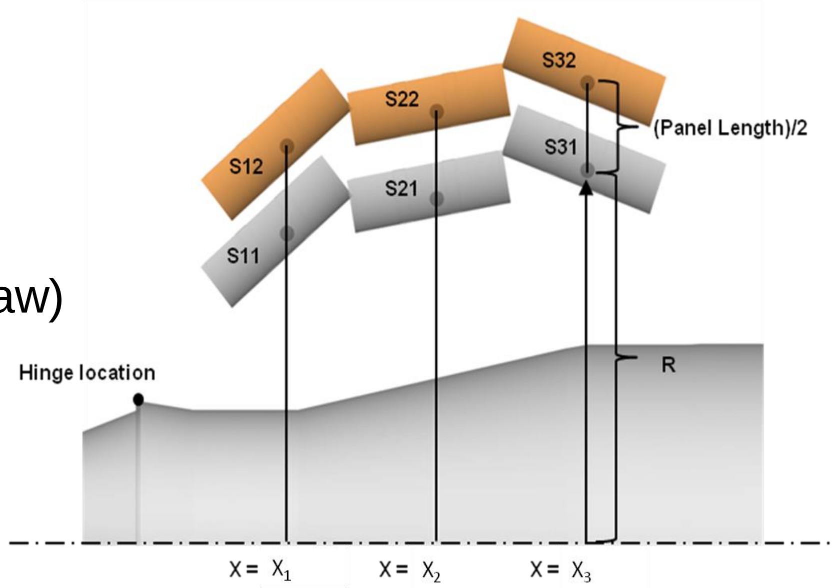
Viscous Check Cases

- Single outlier in the cases examined occurring when all three panels are at 15 degrees rotation, where difference between inviscid and viscous predicted hinge moment is 21.1%
- This outlier does not decrease confidence in results for two reasons:
  - This is but a single orientation at a transient point in time which may or may not actually occur and if so, only occurs for a brief moment.
  - Secondly, and more importantly, the motion of the panels at 15 degrees hinge-rotation orientation is still dominated by the spring force used to initiate panel separation. As the panels rotate further on the hinge, the aerodynamics become significantly more important for trajectory determination and integrated results between viscous and inviscid solutions show much closer agreement.
- For the panel of interest, good agreement between inviscid and viscous predictive techniques is obtained due to physics of the hypersonic flow experienced by the windward panel. In the more leeward panels which experience significant flow separation, larger deviations between inviscid and viscous results occur.

Near-Body Zone of Database

Objective:

- Develop near-body zone of panel database
  1. Provide 6-DOF forces and moments
  2. Rotation order: Z (Pitch), X (Roll), Y (Yaw)



- Matrix:
  - 6 panel stations: (3 axial) x (2 radial)
  - Pitch (Rz') = +/- 45 degrees from baseline (in 15 degree increments)
  - Roll (Rx') = +/- 10 degrees from baseline
  - Yaw (Ry') = +/- 10 degrees from baseline
  - Four M, α, β combinations
  - Total simulations = 1,512

- F&M provided in stability frame
- MRP = Panel centroid
- Panel rotations about centroid

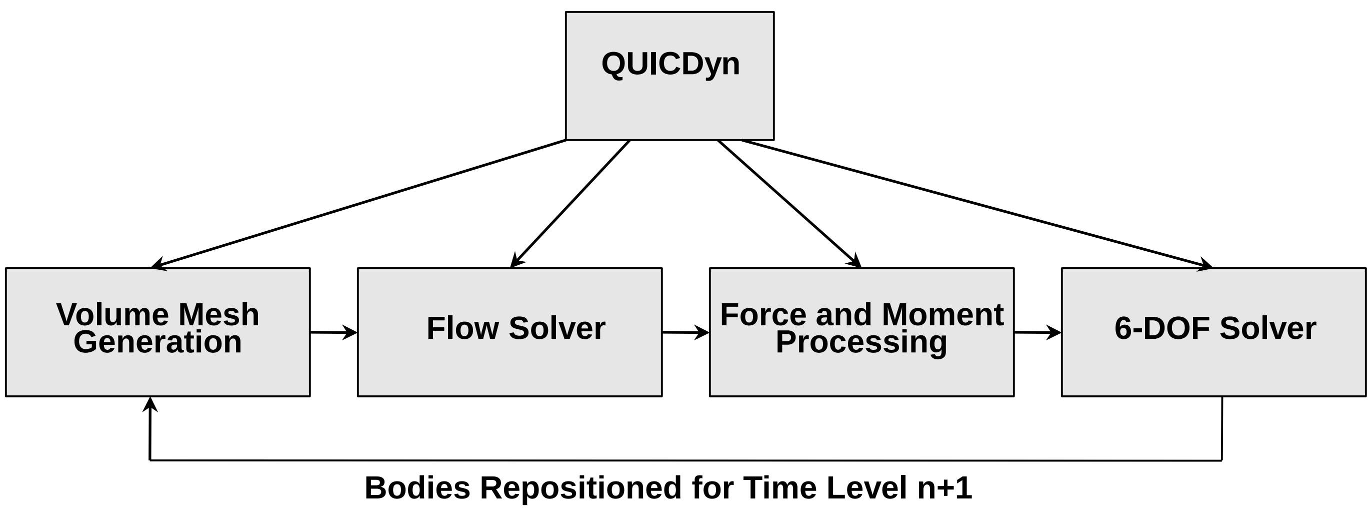
Near-Body Zone

- Matrix:
  - Baseline stations were determined from an average of four Cart3D/6DOF analyses for each of the M, α, β combinations using the current estimate of panel mass properties and torsional spring design.
  - Panel-to-Panel influence is ignored and each panel is allowed to be perturbed independently thereby reducing the number of simulations necessary.
- Cart3D inviscid flow solver
  - Adaptive algorithm
    - 9 adaptation cycles
    - Adapt to forces on panels alone
    - Goal 3+ million cells
- Loci/Chem viscous flow solver (check cases)
  - 65+ million cell meshes
  - Mentors baseline turbulence model + Wilcox compressibility correction

Baseline Stations

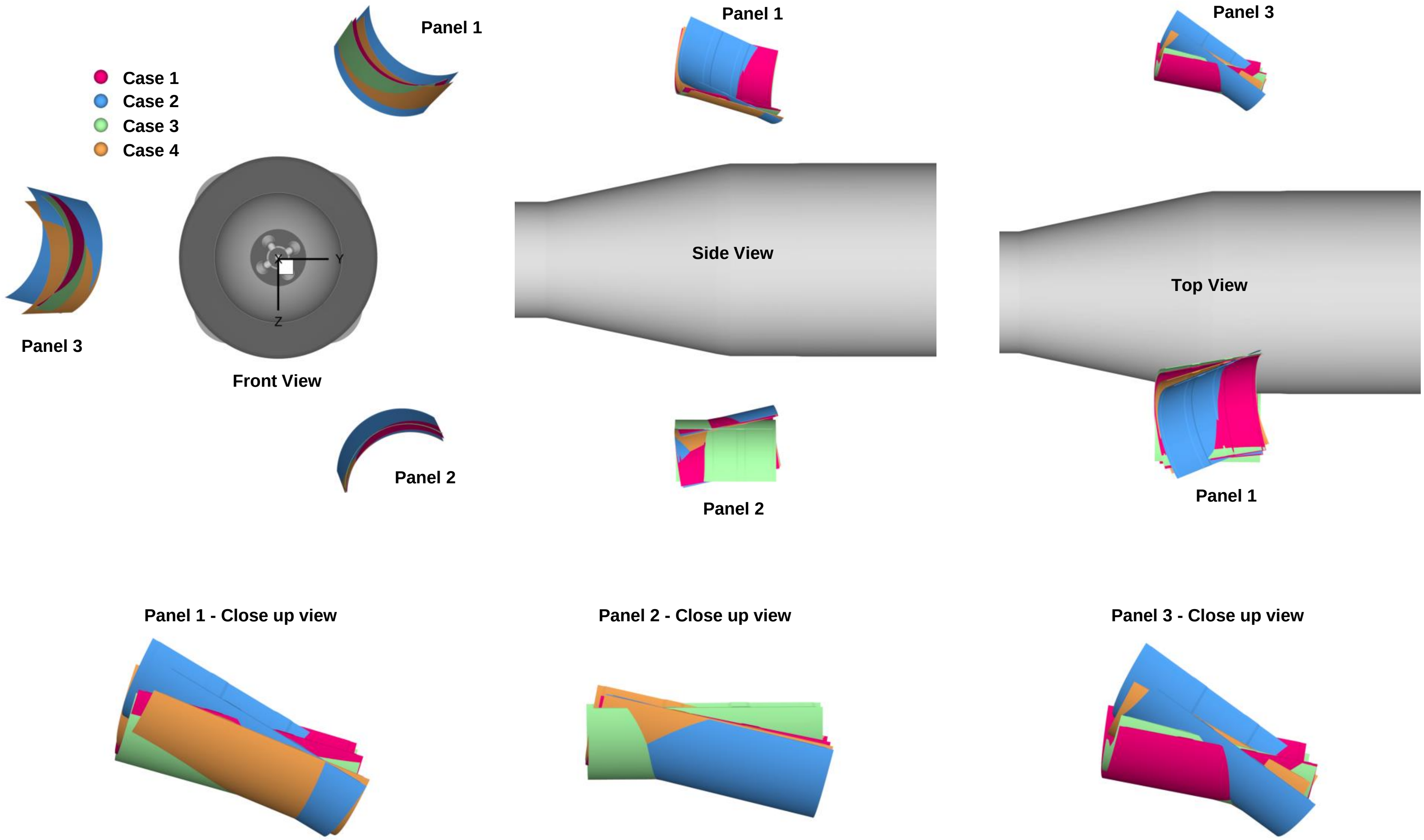
- Baseline stations were determined from an average of Cart3D/6-DOF analyses for each of the four M, α, β combinations.
  - The analyses utilized the Quasi-Unsteady Inviscid Coupled Dynamics (QUICDyn) software package.
  - Used to approximate motion of jettisoned components
  - Provides automated control for coupled FlowCart/6-DOF motion modelling
  - Simulates multi-body motion using sequential steady-state simulations

Case	Mach	Alpha	Beta
1	7.0	-21	-5
2	7.0	-21	5
3	7.0	-15	-5
4	7.0	-15	5



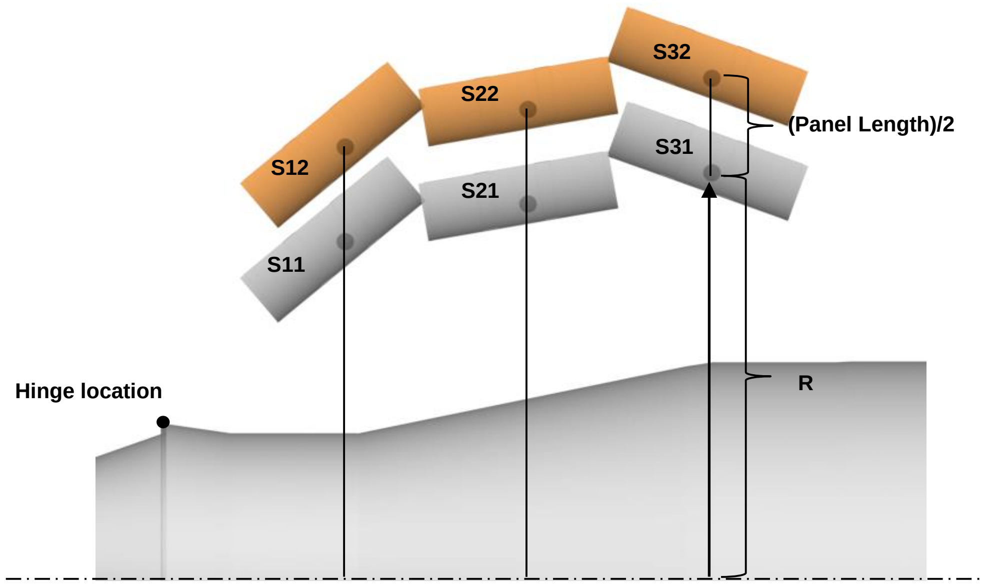
Baseline Stations

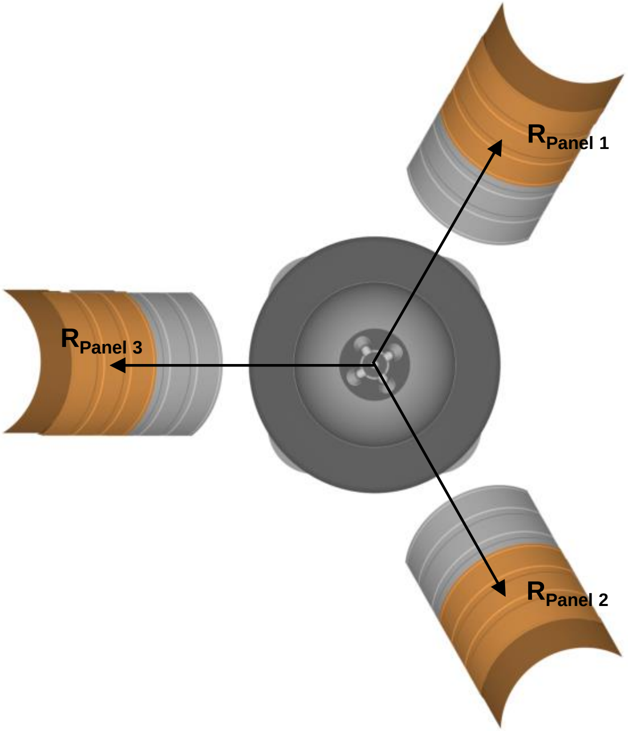
- Panel orientations predicted by QUICDyn at end of frustum for all 4 cases.



Baseline Stations

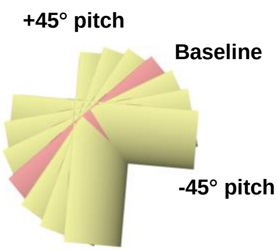
- Baseline average panel locations/orientations were obtained from the QUICDyn solutions at 3 axial stations between the hinge location and the end of the frustum.
  - Stations S11, S21, S31 are the average QUICDyn orientations
  - Three additional stations were included at an increased radial distance of half the panel length from the center line. These are stations S12, S22, S32.

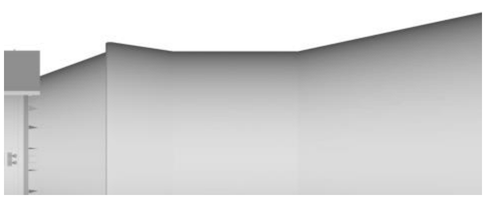




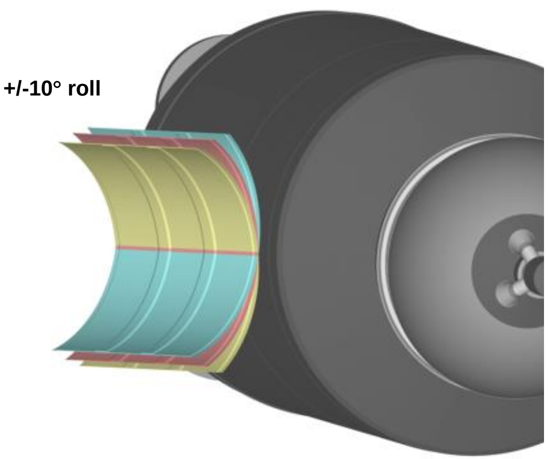
Panel Perturbations

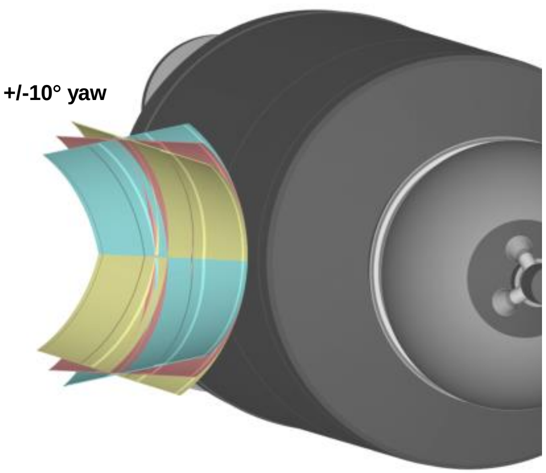
- Each panel is perturbed about a body-fixed coordinate system
  - Pitch +/- 45 degrees from baseline in 15 degree increments
  - Roll +/- 10 degrees from baseline
  - Yaw +/- 10 degrees from baseline
  - (7 pitch angles)(9 roll/yaw orientations)(4 M, α, β combinations) = 252 runs per station
  - (252 runs per station)(6 stations) = 1,512 total simulations

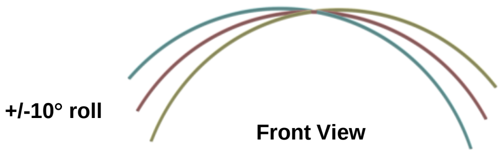




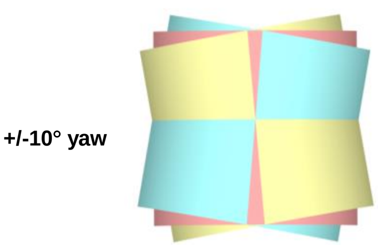
Δ_{Roll}	Δ_{Yaw}
-10	-10
-10	0
-10	10
0	-10
0	0
0	10
10	-10
10	0
10	10







Front View



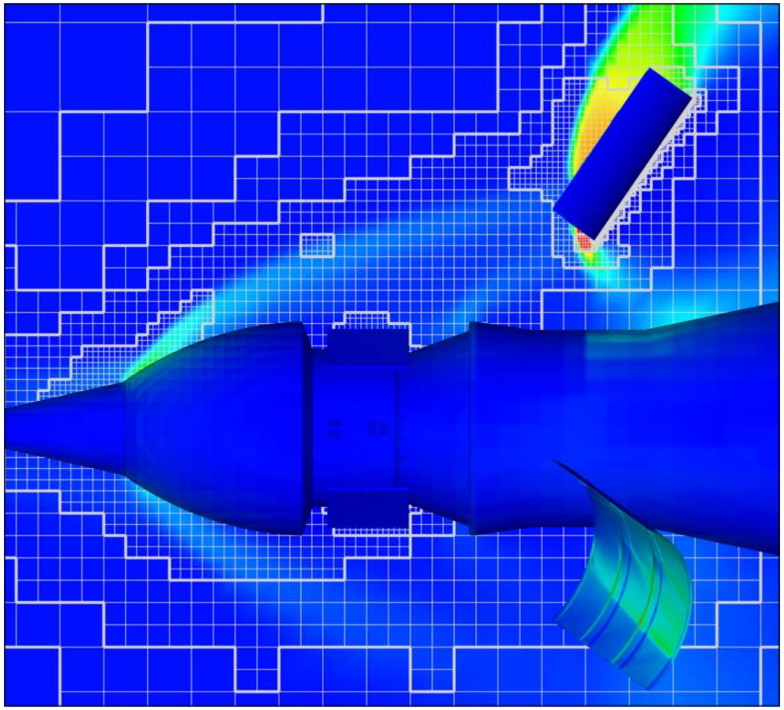
Top View

Results
Pressure Contours

- Panel 3 adapted mesh and pressure contours for S11, Case 1

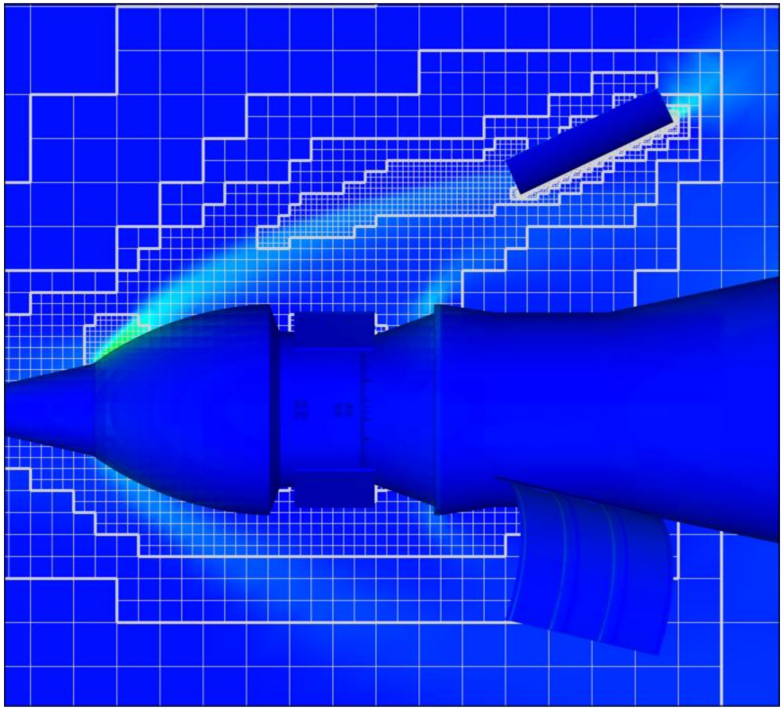
$\Delta_{Pitch} = 30°$, $\Delta_{Roll} = \Delta_{Yaw} = 0°$

Mesh of 5.2 million cells



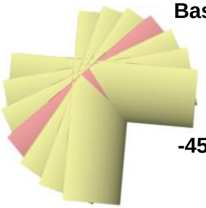
$\Delta_{Pitch} = -15°$, $\Delta_{Roll} = -10°$, $\Delta_{Yaw} = 0°$

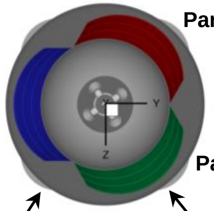
Mesh of 5.5 million cells

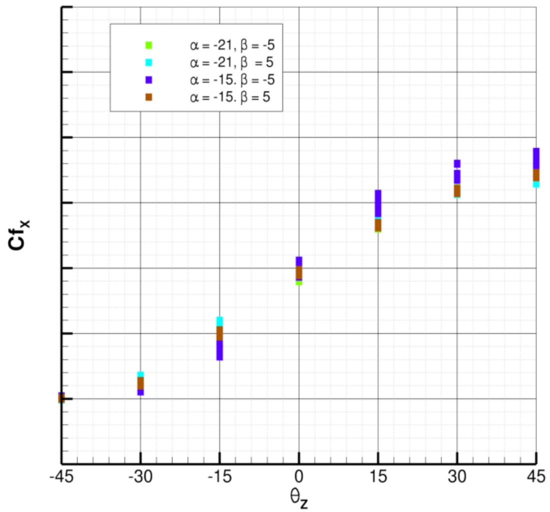


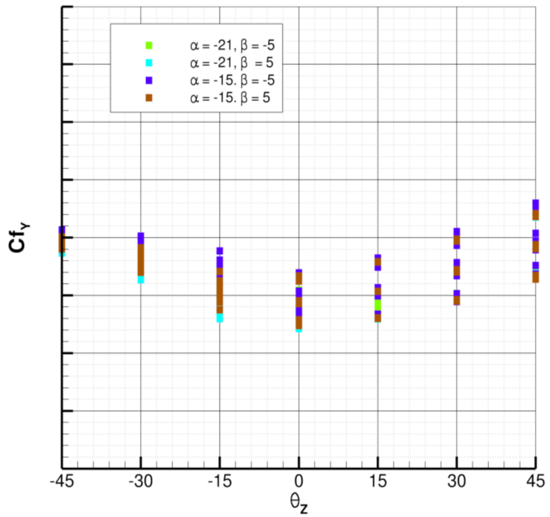
Results – Force and Moment Coefficients

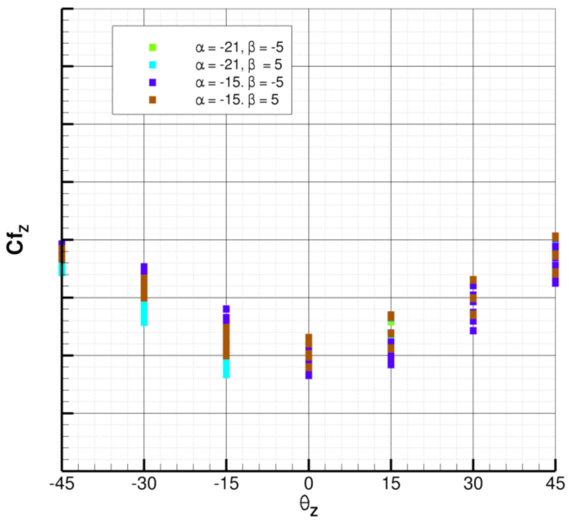
- Aero Coef Predictions for station S11
  - Plots show data for all M, α, β combinations and panel orientations (represents 252 runs)





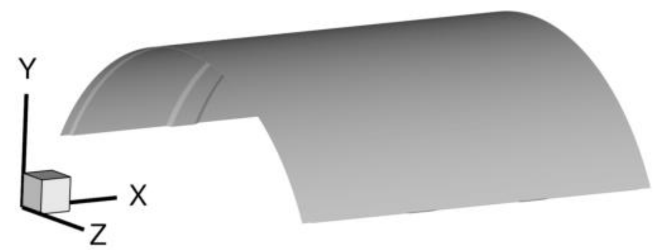






Panel-Alone Zone

Objective:



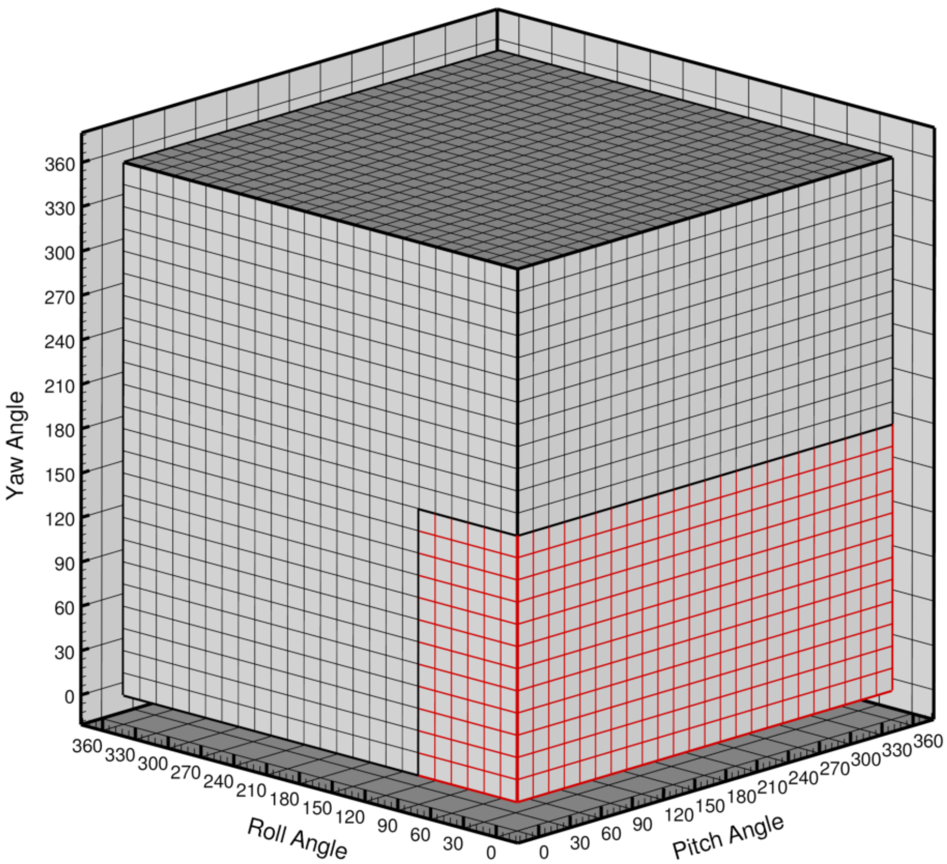
- Develop a free-panel zone of database
  1. Provide 6-DOF forces and moments
  2. Rotation order: Z (Pitch), X (Roll), Y (Yaw)

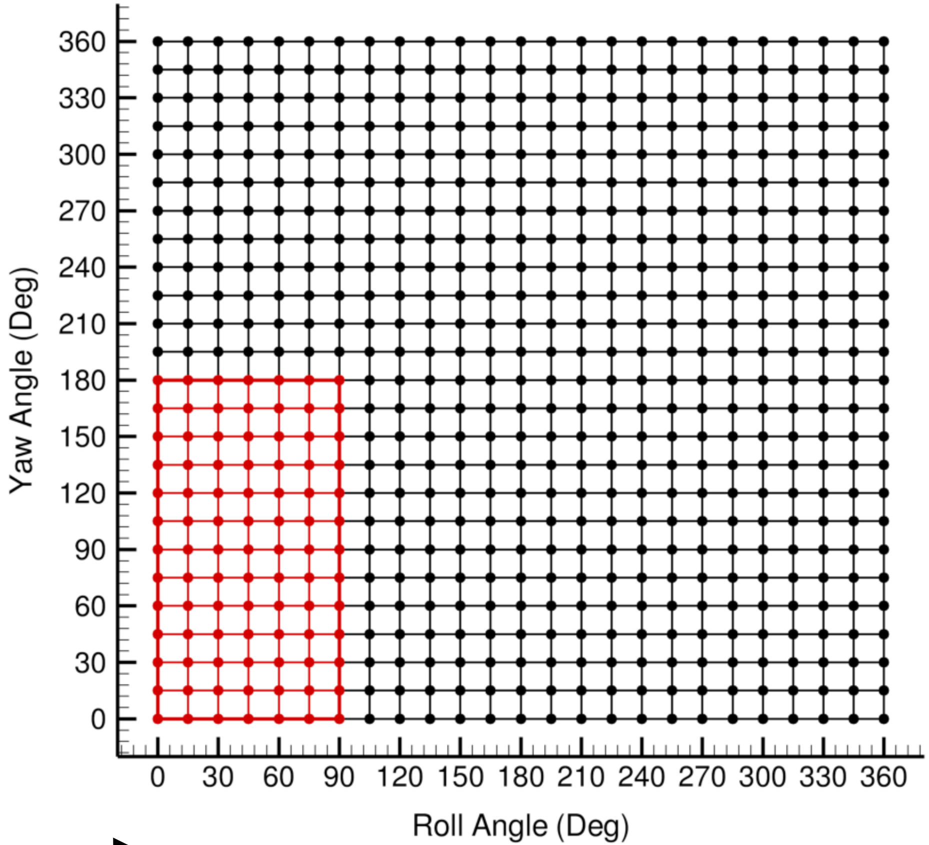
- Matrix:
  - Mach = 7.0
  - Alpha = Beta = 0.0
  - Pitch (Rz) = 0 to 345 by 15 degrees
  - Roll (Rx) = 0 to 90 by 15 degrees
  - Yaw (Ry) = 0 to 180 by 15 degrees
  - Total simulations = 2,184
  - Mirrored data points = 15,000

- F&M provided in stability frame
- MRP = Panel centroid
- Panel rotations about centroid

Solution Matrix

- Red = Simulated Condition (2,148 data points)
- Black = Mirrored Condition (15,000 data points)

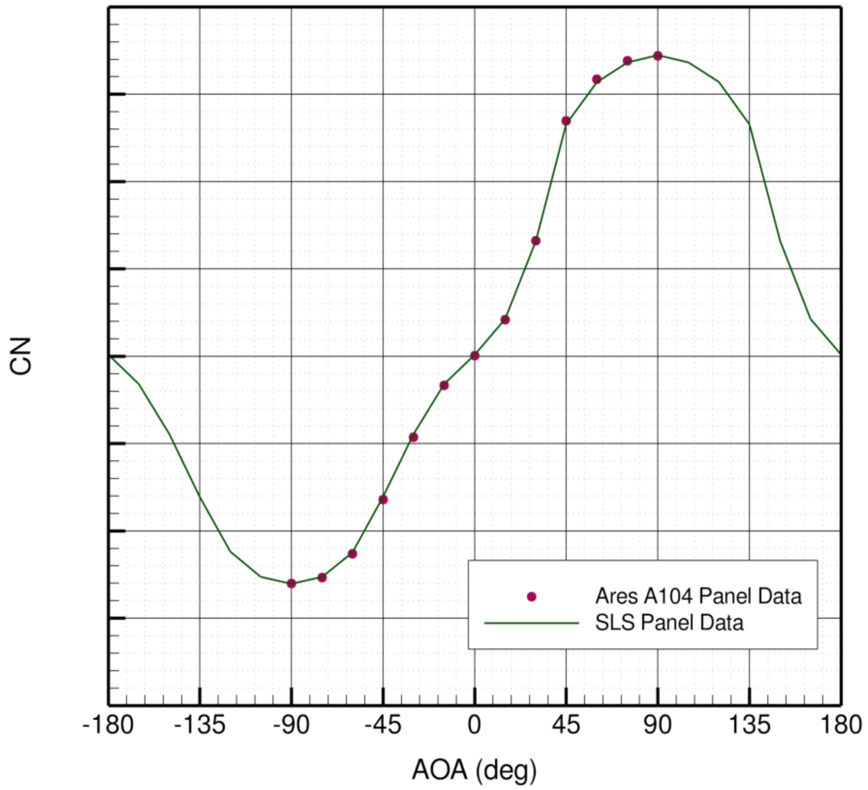


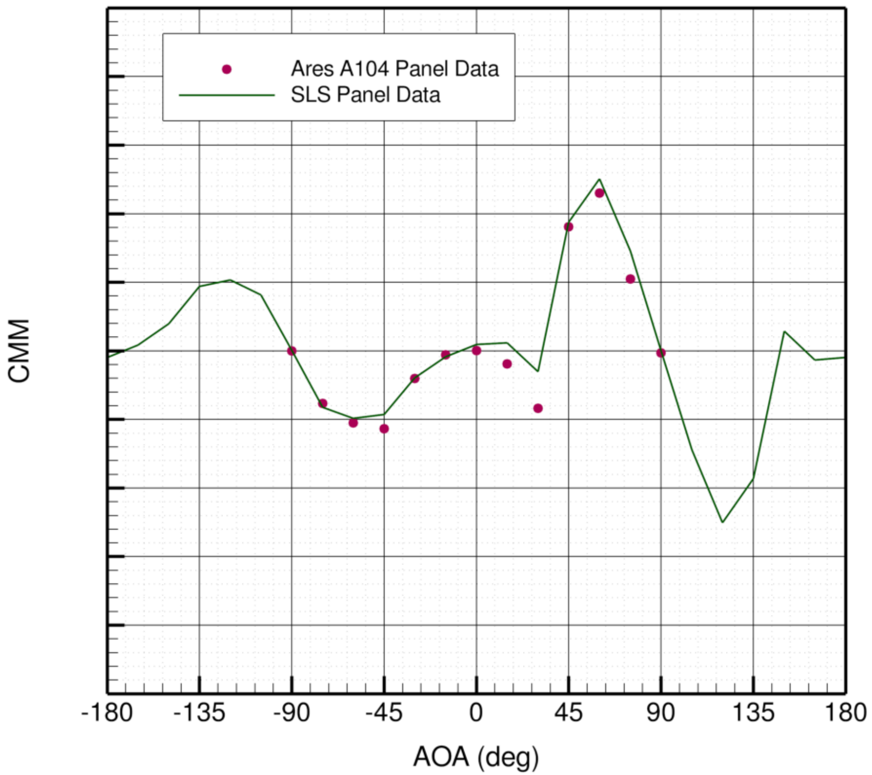


Constant Pitch Angle Slice

Comparison to A104 Panel Data

- Normal force and pitching moment in body fixed coordinate system.
- Moment reference point at center of panel (not the centroid of the panel).





Matlab Interface Development

Objective:

- Implement the SM panel database into QUICDyn
    - QUICDyn_to_Matlab … converts QUICDyn's 6 DOF solver output into input for the MATLAB interpolation
    - MATLAB interpolation (written by David Purinton, MSFC)
    - Matlab_to_QUICDyn … converts MATLAB output into input for QUICDyn's 6 DOF solver
- Five cases considered

Case #	Mach	Alpha	Beta	Note
1	7.0	-21	-5	Database Condition
2	7.0	-21	5	Database Condition
3	7.0	-15	-5	Database Condition
4	7.0	-15	5	Database Condition
5	7.0	-18	0	Average Condition

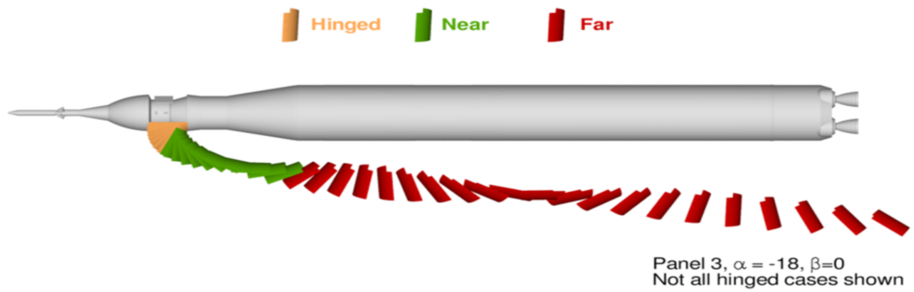
MATLAB Interpolation

Implementation of “black box”:

- Customer desired a “black box” that would take input variables defining the ESM panels location and output the six aerodynamic coefficients
- “Black box” was developed using Matlab R2013b
  - This release necessary for included Matlab functions utilized
  - Response surfaces are generated from the CFD data based on the independent variables for each panel regime
  - The response surfaces are queried at the desired input values of the independent variable to obtain the ESM panel aerodynamic coefficients
- Three different panel regimes incorporated into the analysis based on the breakdown of the CFD analysis
  - Steps taken to ensure smooth data transition from one regime to the next
- ESM Panel code is called using a standard Matlab function call:
  - [CFX, CFY, CFZ, CMX, CMY, CMZ] = ESM_Panel_Code(Fpath, Alpha_In, Beta_In, P_Del, Radial_In, Axial_In, Roll_In, Yaw_In, Pitch_In, Pan_loc, CFX, CFY, CFZ, CMX, CMY, CMZ)

ESM Panel regimes from CFD analysis:

- Three different panel regimes incorporated into the analysis:
  - Attached (hinged) – ESM panels still attached to body via hinge and influenced by both the vehicle and other ESM panel aerodynamics
    - Function of angle of attack and angle of sideslip of the vehicle and the panel hinge angle
  - Near – ESM panels detached from the body but still in close proximity to be influenced by the vehicle aerodynamics
    - Function of vehicle angle of attack, vehicle angle of sideslip, panel euler angles (roll, yaw, pitch), radial and axial location relative to vehicle
  - Far - ESM panels detached from the body and away from the influence of the vehicle aerodynamics (free panel in space)
    - Function of panel euler angles (roll, yaw, pitch) only



Execution of "black box":

- Input variables are defined as follows:
  - FPath – File path of input files (97 files containing CFD data)
    - FPath = '*C:\\Folder1\Folder2\...\DataFiles*\'
  - Alpha_In – vehicle angle of attack (degrees)
  - Beta_In – vehicle angle of sideslip (degrees)
  - P_Del – angle of ESM panel rotation while attached to hinge (0 – 65 degrees)
    - P_Del = [*xx.x*, *yy.y*, *zz.z*]
  - Radial_In – radial location of panel in "near" regime (inches)
    - Radial_In = [*xx.x*, *yy.y*, *zz.z*]
  - Axial_In – axial location of panel in "near" regime (inches)
    - Axial_In = [*xx.x*, *yy.y*, *zz.z*]

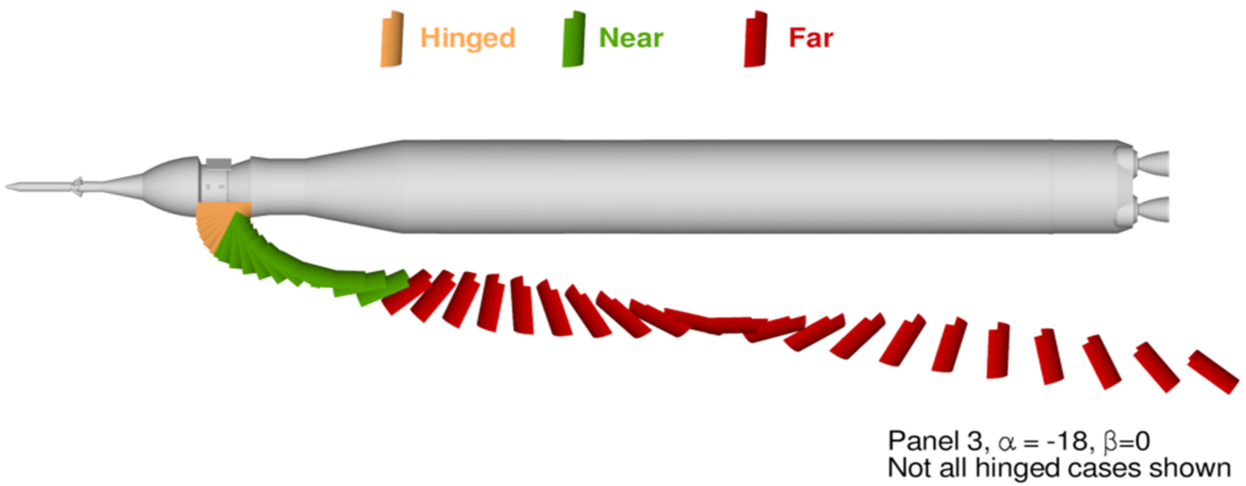
Execution of "black box":

- Input variables are defined as follows:
  - Roll_In = euler angle of ESM panel in "near" and "far" regimes (degrees)
    - Roll_In = [*xx.x*, *yy.y*, *zz.z*]
  - Yaw_In = euler angle of ESM panel in "near" and "far" regimes (degrees)
    - Yaw_In = [*xx.x*, *yy.y*, *zz.z*]
  - Pitch_In – euler angle of ESM panel in "near" and "far" regimes (degrees)
    - Pitch_In = [*xx.x*, *yy.y*, *zz.z*]
  - Pan_loc – regime of each ESM panel: '*Attach*', '*Near*', or '*Far*'
    - Pan_loc = [{'*value*'}, {'*value*'}, {'*value*'}]
  - CFX, CFY, CFZ, CMX, CMY, CMZ – included as inputs as needed for program execution but do not need to be predefined by calling routine

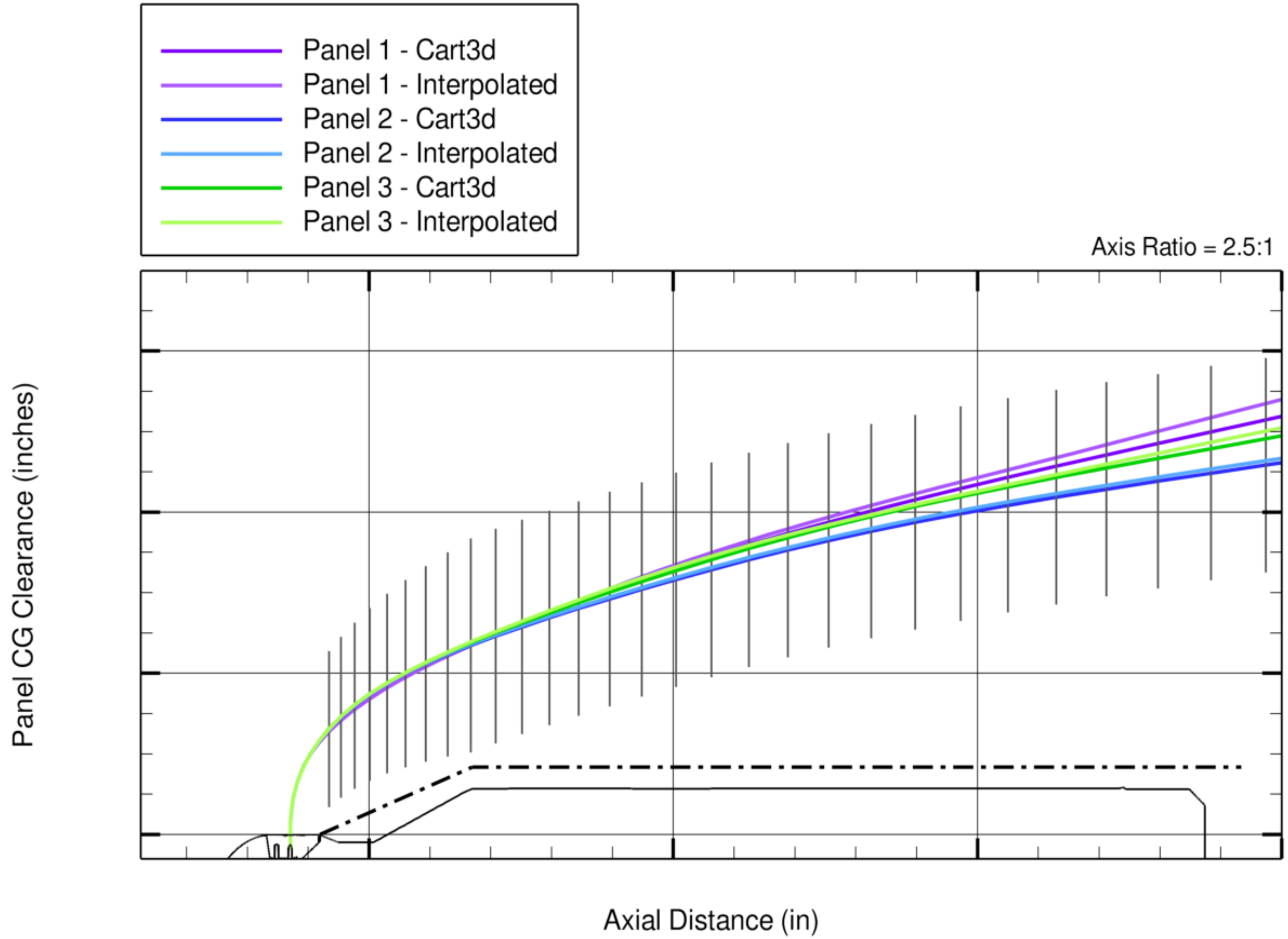
Interfacing QUICDyn to Matlab

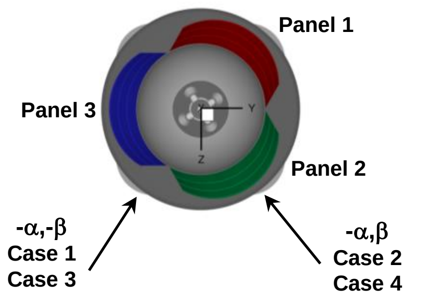
QUICDyn_to_Matlab

- Determines region (hinged, near, far) for each panel.
- Converts QUICDyn's panel centroid and Euler parameters to database geometric parameters.



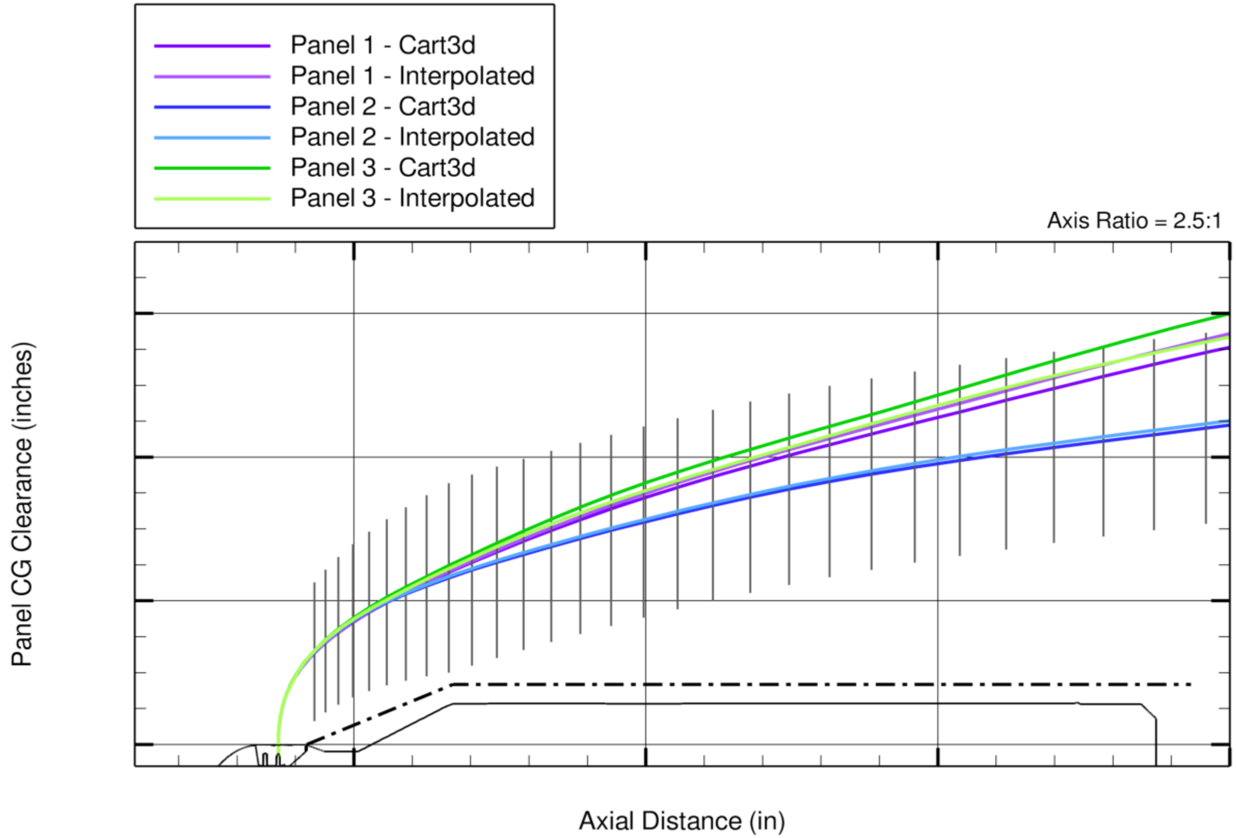
Comparison of Near Body with Free Panel Data

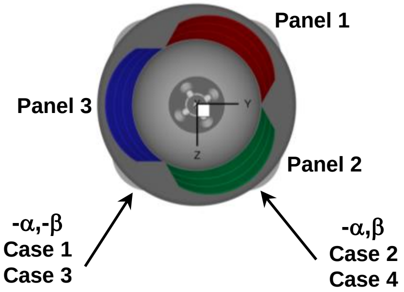




Case 1: Mach = 7, a = -21, b = -5

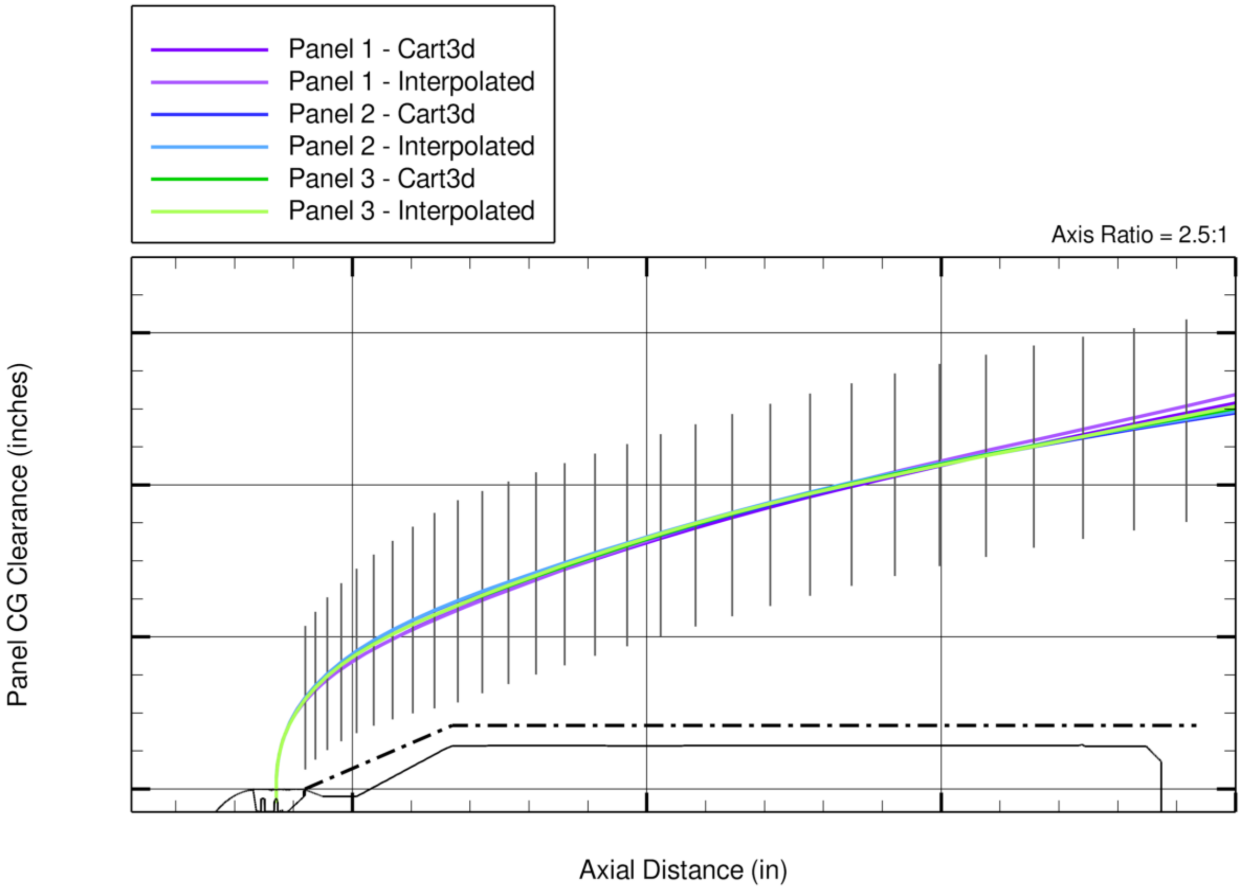
Comparison of Near Body with Free Panel Data

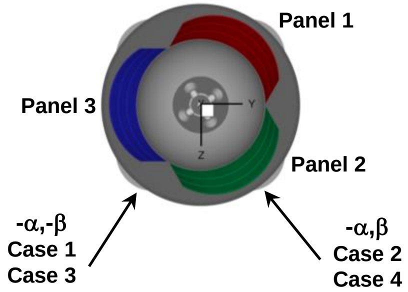




Case 2: Mach = 7, a = -21, b = +5

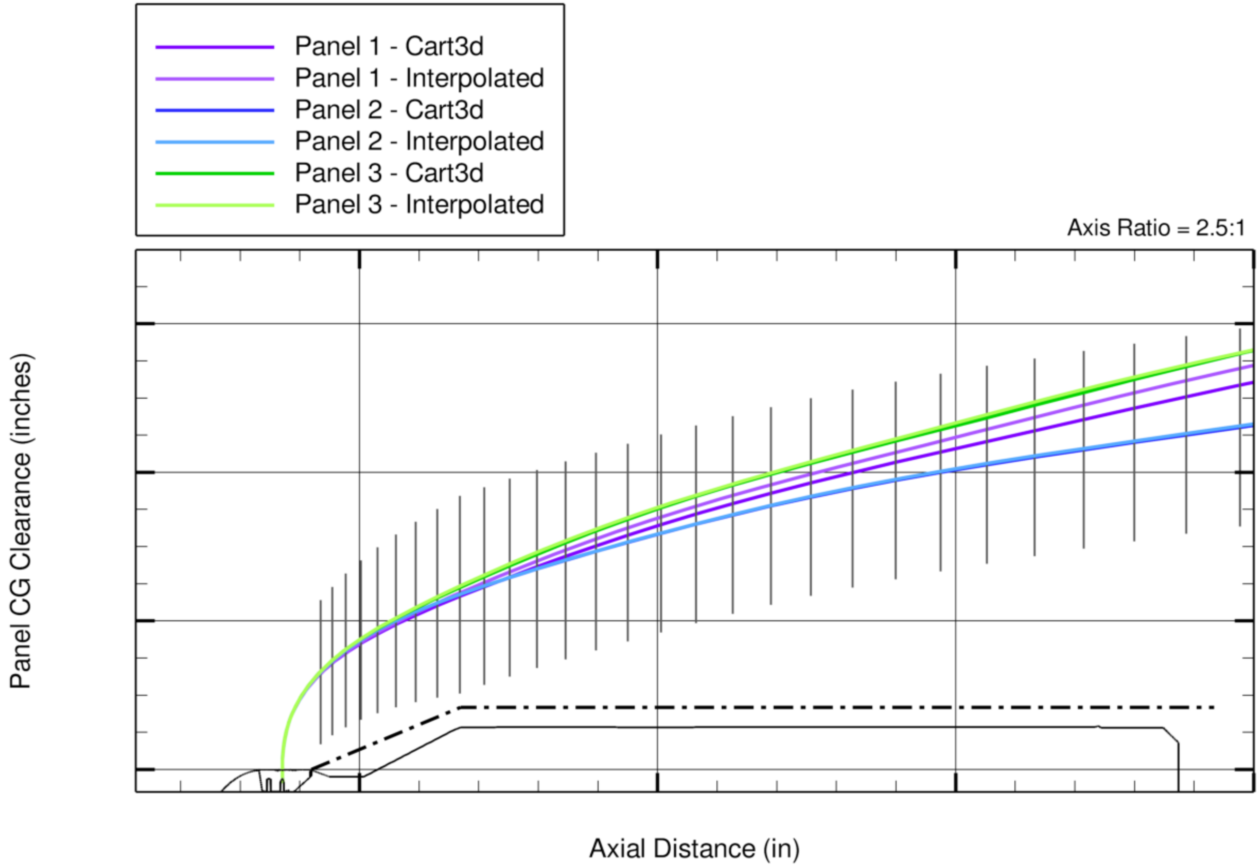
Comparison of Near Body with Free Panel Data

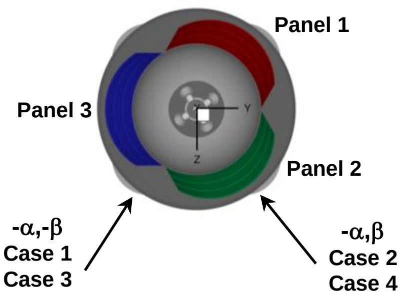




Case 3: Mach = 7, a = -15, b = -5

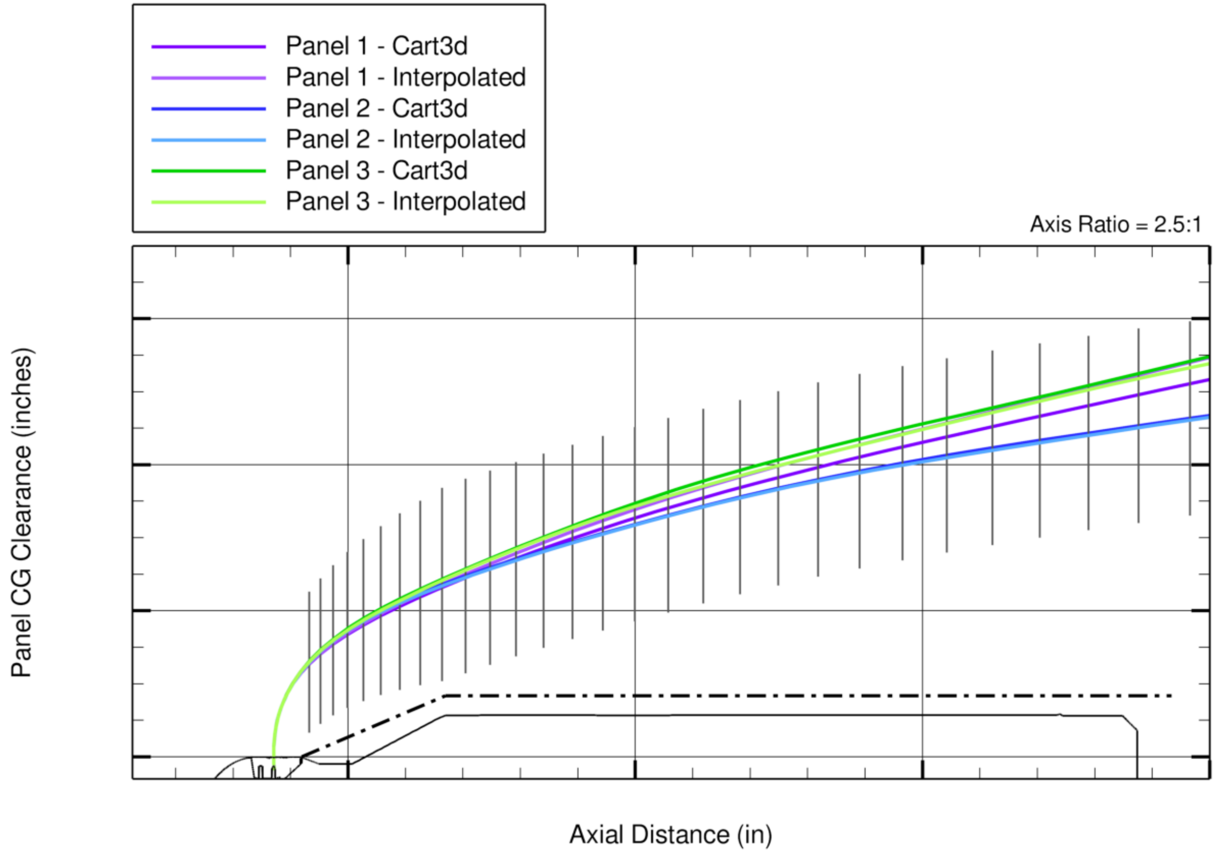
Comparison of Near Body with Free Panel Data

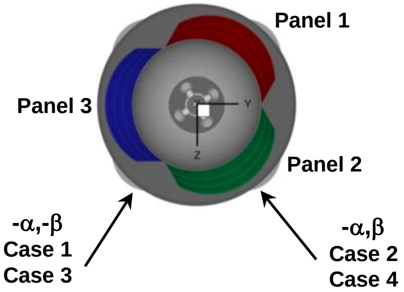




Case 4 : Mach = 7, a = -15, b = +5

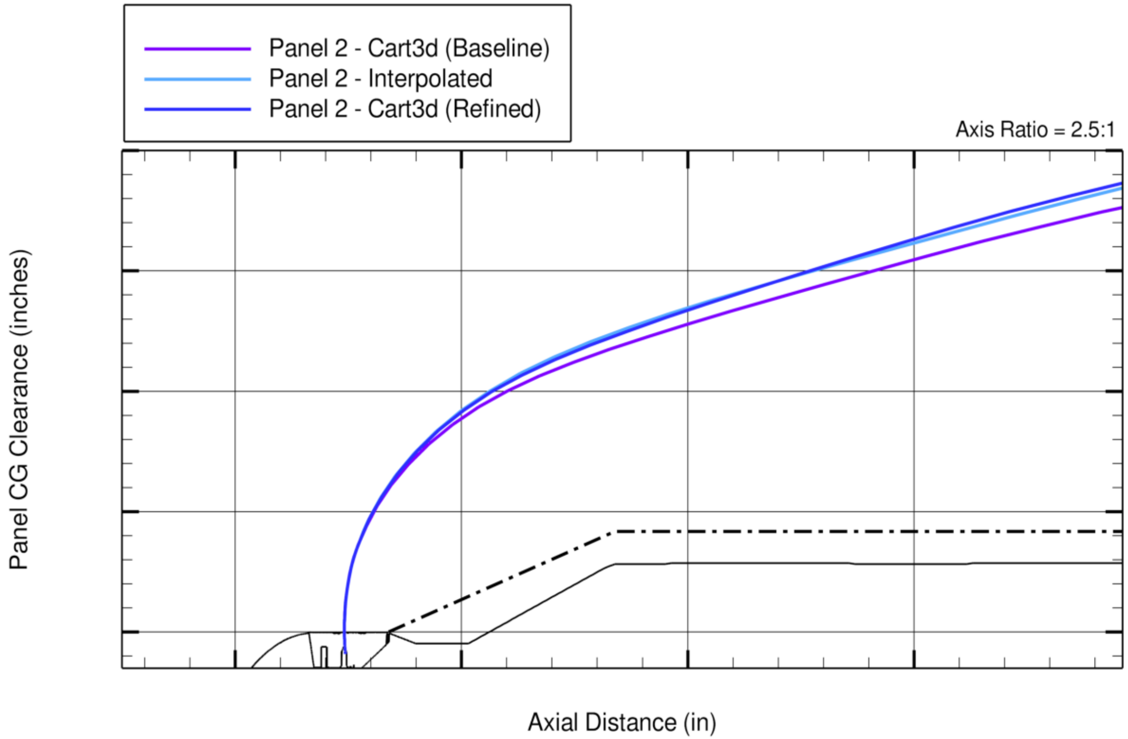
Comparison of Near Body with Free Panel Data





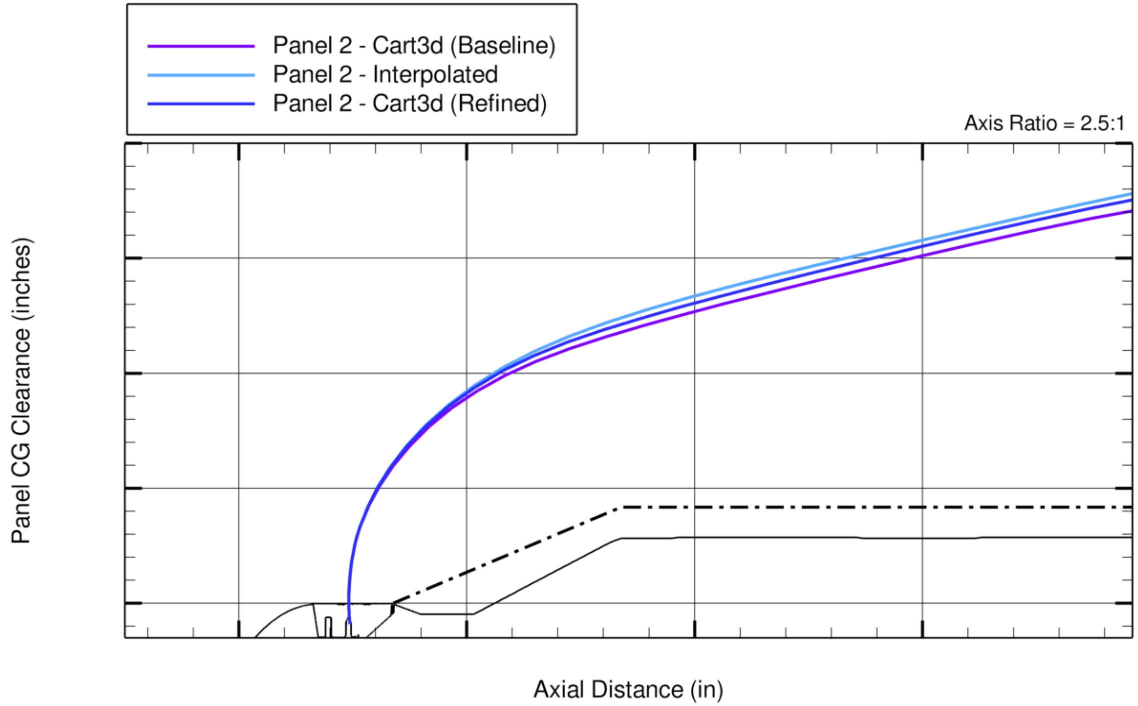
Case 5 : Mach = 7, a = -18, b = 0 (averaged freestream conditions)

Case 1
QUICDyn (Cart3d) Results



Case 1: Mach = 7, a = -21, b = -5

Case 1
QUICDyn (Cart3d) Results



Case 2: Mach = 7, a = -21, b = +5

Summary and Conclusions

- A database for SM panel jettison has been completed, with a total of 5144 CFD simulations (1448 hinged, 1512 near body, 2184 panel alone). Database due to mirroring of solutions contains 18,144 CFD simulations. All solutions obtained on local computing cluster.
- Comparisons for windward panel trajectory, which would be first to recontact with body at these conditions, show excellent agreement between quasi-unsteady analysis and the database.
- 12 Viscous check-cases for the panel on the hinge were performed. The total moment about the hinge is the most critical component to capture to ensure properly capture of imparted momentum to the panel at release. The average deviation between inviscid and viscous pitching moment was 4.85%. If the highest variant moment is removed, that difference falls to 3.4% for the remaining 11 check cases.
- Assumption that panel to panel effects become secondary for windward panel at rotation 65 degrees on hinge are valid

Summary and Conclusions

- If it is found the analysis violates the computationally modeled space, warnings would be issued in areas of extrapolation. To add expanded computational space is trivial. For example, an additional “near body” axial station would require approximately no more than 250 simulations, obtainable in a week, and the subsequent updated database would be provided within a day or two afterwards.
- If the cavity region were to change significantly, it would require perhaps a month to completely replace the zone 1 simulations. However, first we would obtain a series of runs to gage the effect on the moment. Being that we match well with Ares data performed with a clean, smooth cavity beneath the panels, doubtful any change in that region would have significant affect on panel trajectory
- Near body effects modeled in zone 2 were shown to have a small effect on predicted trajectory. This makes transition from zone 1 hinged to panel alone a possibility depending on accuracy requirements

Summary and Conclusions

- A method for computing quasi-unsteady CFD analysis for events such as SM panel jettison has been demonstrated. Moderate fidelity, deemed acceptable for these data, would require approximately 72 hours per solution. At the existing mesh fidelity of the database solutions, this single computation would require approximately 6 weeks. With the database, SM trajectory simulations with the higher fidelity data available on a workstation in approximately 5 minutes.