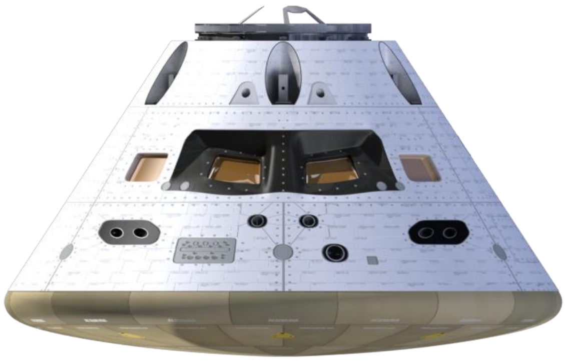

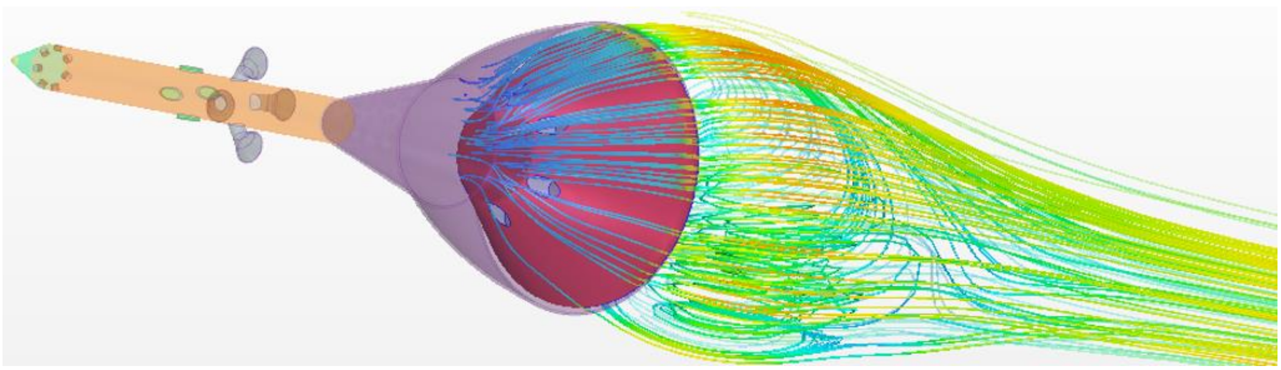

Orion Capsule Launch Abort System Analysis

Assignment 2

AE 4802 Spring 2016 – Digital Design and Manufacturing
Georgia Institute of Technology

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Abstract

The objective of this report is to provide an analysis the Orion spacecraft's Launch Abort System (LAS). A launch abort system aims to remove the crew away from a failing launch vehicle as soon as possible during the liftoff and ascent phase. A survey of other designs for launch abort was carried out to compare the tower system with integrated retrorockets or ejectable rockets. The Orion LAS undergoes 5 distinct stages including liftoff, reorientation, LAS jettison, parachute deployment, and water landing which can east be tested for loads analysis. A model was created in CATIA V6, and will undergo CFD analysis in STAR-CCM+ and FEA analysis in Abaqus to determine the optimal design parameters for crew safety such as drag coefficient, ballistic coefficient, G-loading due to thrust, and structural loads on the vehicle during flight.

1. Introduction

Human launches are a necessity for future space exploration by the United States, as well as other countries. People are able to perform mission tasks and improvise in response to unforeseen circumstances that may occur on a space exploration mission in ways that robotics are yet unable to match. For any mission involving human lives, safety is a top priority at all stages of the mission. There are a number of safety features that have been historically used for human missions in a scenario involving a critical failure resulting in the crew requiring an immediate escape. These include Launch Abort Systems (LAS) during launch and ascent, as well on orbit such as crew escape vehicles such as the Soyuz capsule that is kept at the International Space Station (ISS) at all times in the event of an emergency egress due to a critical failure in the station.

To date, an active launch abort system has only been used in an emergency once. In 1983, The Russian Soyuz T-10-1 mission had a fire at the base of the launch vehicle at T-90 seconds left. The crew was able to safely abort using the escape rocket system onboard seconds before the explosion.[1]

A notable exception to the launch abort system was NASA's Space Shuttle. This system used boosters and an orbiter vehicle, with no actual launch abort option. This was glaringly evident with the two accidents that occurred with the 1986 *Challenger* and the 2003 *Columbia* space shuttle disasters both resulting in loss of crew. The *Challenger* vehicle failed upon launch due to an O-ring failure, and *Columbia* failed upon reentry due to a damaged heat shield tile. Though both of accidents happened very quickly, even if they had known with enough time to react, there was no option to survive using the capabilities of the space shuttle orbiter itself other than using a second shuttle to assist *Columbia* on-orbit. At the time, visual inspections of the vehicle status were not even carried out on orbit.

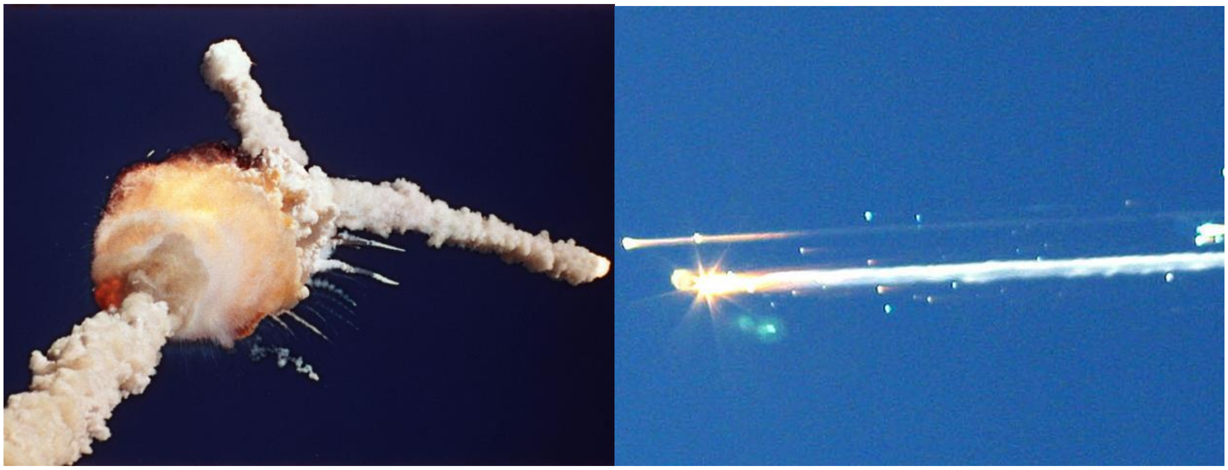

Figure 1. *Challenger* disaster after launch in 1986 (left) and *Columbia* disaster upon reentry in 2003 (right).[2]

The Orion capsule, currently contracted by NASA to Lockheed Martin, will sit atop NASA's next heavy lift launch vehicle, the Space Launch System (SLS). Currently under development, SLS is scheduled for its first uncrewed test flight, EM-1, in 2018. The first crewed SLS and Orion flight, EM-2, is scheduled for 2023.

SLS is a capability that can have multiple destinations including cis-lunar space, lunar orbit, Lagrange points, an asteroid, or Mars. It is the primary vehicle NASA has slated to lift the Orion capsule to Mars on the space agency's flagship Journey to Mars space exploration program.

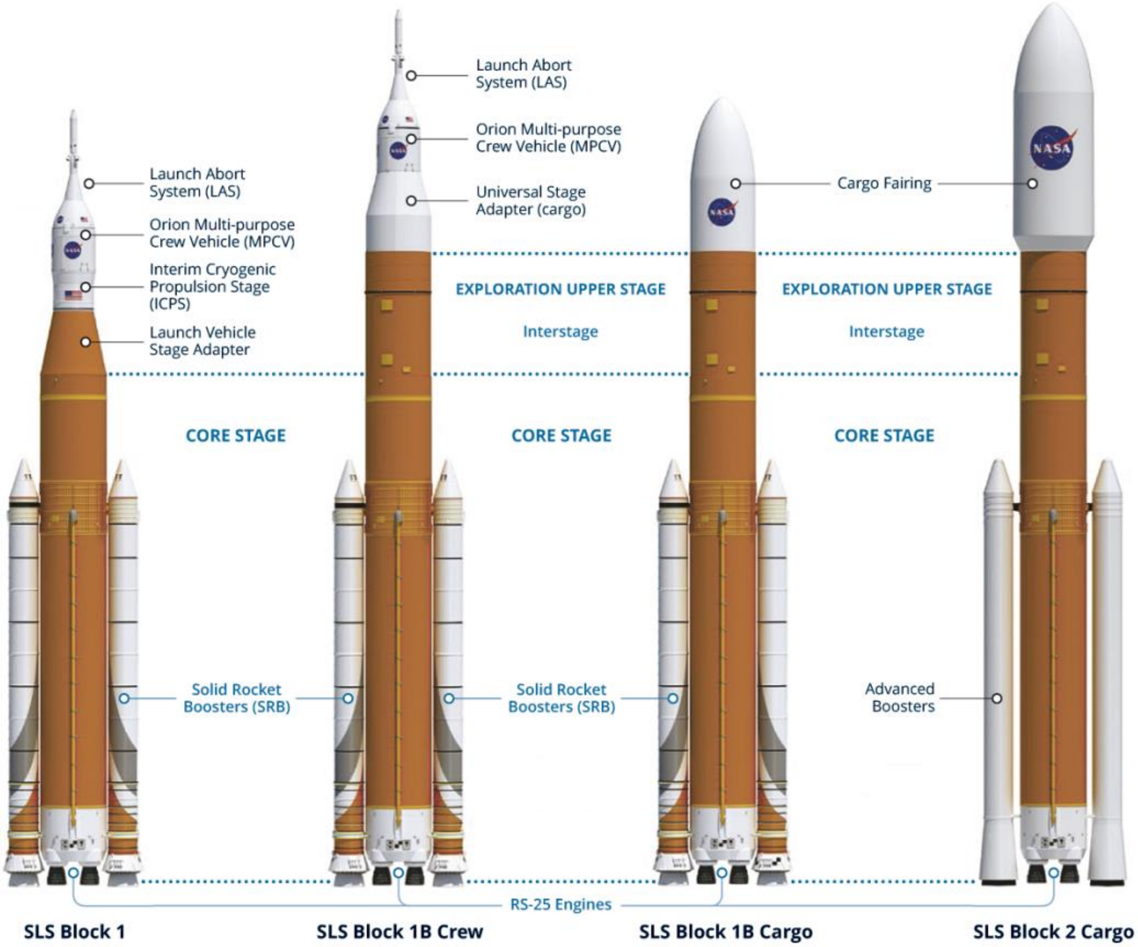

Figure 2. Space Launch System evolvable capability.[3]

This work is important because it exists to design systems that save human lives. Unlike the Space Shuttle, a capsule design allows for multiple options for launch abort during liftoff and ascent. This can be in the form of a tower, which tips atop the capsule during liftoff and ascent and in the event of an emergency, is able to remove the crewed capsule away from the failing rocket and to safety using abort rocket motors. Another form of a launch abort system are rockets that are attached to the capsule itself. These can be either a removable attachment to save mass, or integrated into the capsule inner structure. The third form of launch abort system is ejection seats, which are rarely used in spaceflight.

The focus of this work is on the safety of astronauts during the launch stage, including liftoff and ascent. Specifically, launch abort systems are designed to consider possible vehicle events at specific stages during a particular abort scenario.

Objectives of launch abort system design include:

- Safely remove the crewed capsule from the failed launch vehicle, by ensuring:
- Abort launch does not exceed maximum allowed g-forces for humans
- Internal and external vehicle environment does not exceed specific design ranges during abort events including liftoff, reorientation, jettison, parachute deployment, landing
- Correct trajectory by LAS from launch vehicle after LAS activation
- Autonomous failure detection by vehicle to initiate LAS activation sequence

1.1 Mission Profile

Orion will undergo five distinct stages during its launch abort mission profile. These are:

1. Liftoff
    - Abort Motor (AM) and Attitude Control Motor (ACM) are ignited
2. Reorientation
    - ACM changes angle of attack by 155 degrees
3. LAS jettison
    - Orion detaches from the LAS
4. Parachute deployment
    - Drogue chute deployment, main chute deploys
5. Water landing

Figure 3. Orion Launch Abort System mission profile artist depiction.[4]

1.2 Literature Review

A number of existing concepts are similar to the Orion LAS design. American capsules include NASA's original Mercury, Gemini, and Apollo crew capsules from the 1950s and 1960s, Boeing's CST-100 Starliner under development, and SpaceX's Crew Dragon currently under development. Capsule designs from other countries include the Chinese Shenzhou capsule, Russian Soyuz capsule, and the Russian PTK-NP capsule.

Some of the domestic capsules are shown in Figure 3 below with capsule diameters labeled.

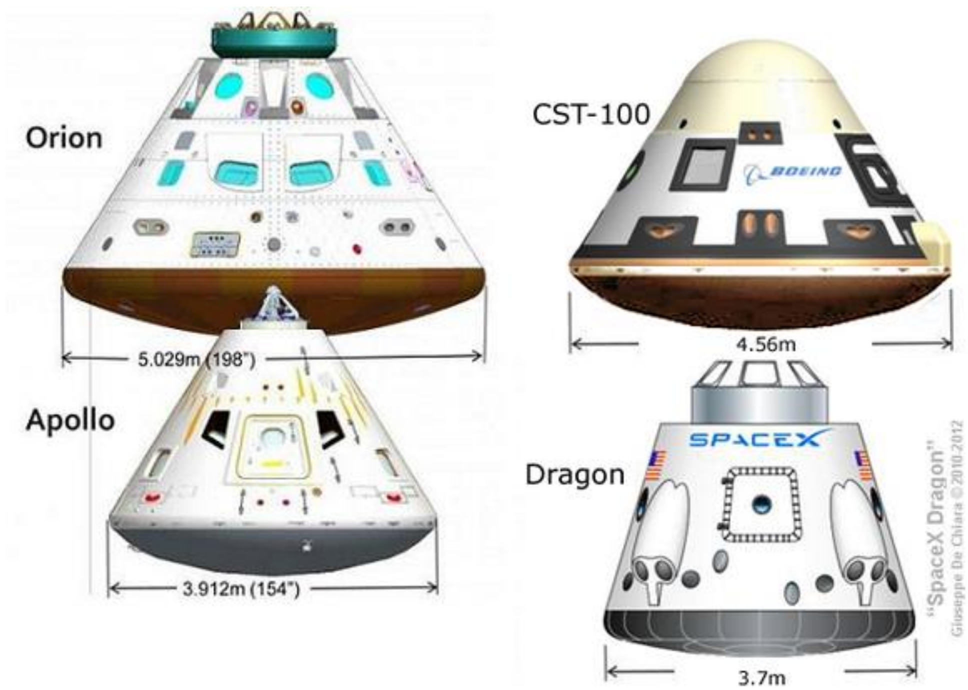

Figure 4. United States capsule design diameter comparison.[5]

Of the domestic capsules previously built or currently in development, Orion has the largest diameter. Another comparison considers the total mass, diameter, habitable and pressurized volume, and crew capacity among the Russian Soyuz capsule, the Chinese Shenzhou capsule, Boeing's CST-100 Starliner, SpaceX's Crew Dragon, Orion, and Russian PTK-NP vehicle in development. Figure 4 below shows this comparison.

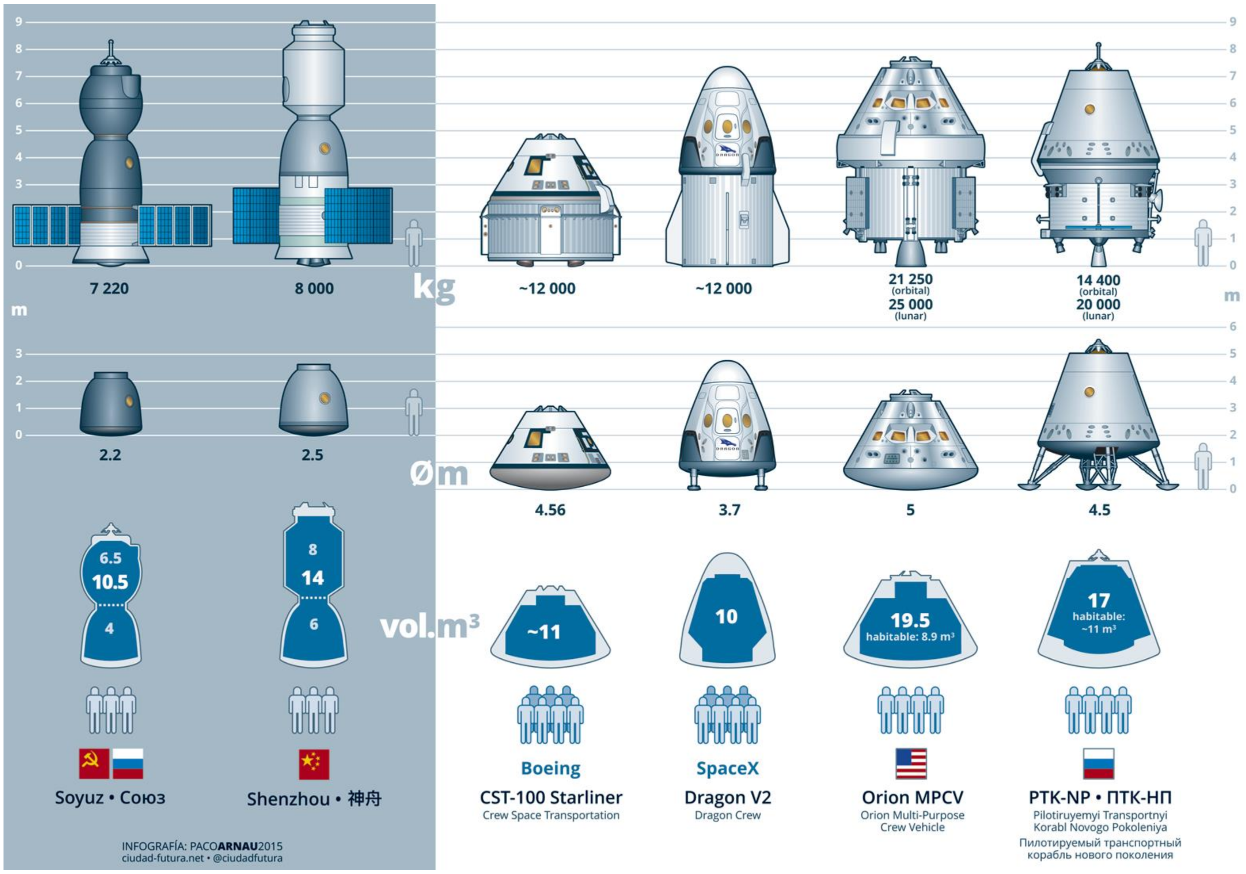

Figure 5. Comparison of international capsule design parameters.[6]

The advantage of Orion is its size compared to other capsule designs. This allows for more cargo space than others, although the Crew Dragon vehicle and CST-100 Starliner can carry more passengers. Orion and its service module do have significantly more mass than other designs. Although more mass requires more propellant or thrust from the launch vehicle, it is a careful balance that is chose to allow for greater cargo capabilities. A wider ablative heat shield on Orion also translates to more surface area to divert heat concentrations from the vehicle during reentry. However, a detailed analysis of reentry capabilities is beyond the scope of this work due to the heat transfer and chemical interaction analysis required.

Like Orion, most of the other designs including the Soyuz, Shenzhou, and Starliner will use launch abort towers for their launch abort system. SpaceX has opted to use retrorocket engines using the company's SuperDraco engines on their Crew Dragon vehicle integrated into the structure itself. This can be a disadvantage in that the vehicle must carry that mass wherever it goes, including during launch and on-orbit activities. This was chosen because SpaceX intends to also make the system dual-use, as the same SuperDraco engines would be used for the descent and landing sequence of the crewed capsule. In the design phase, one advantageous option for Orion was to carry a detachable retrorocket system for launch abort capability which would separate once the vehicle had attained a certain altitude. This system was unproven, and NASA chose to perfect the already well-tested launch abort tower system similar to heritage vehicles it had launched. Figure 5 shows the manned vehicles from multiple countries, most of which have launch abort towers as a common practice. Not shown include the CST-100 Starliner or any of the historical NASA vehicles that also used launch abort tower systems.

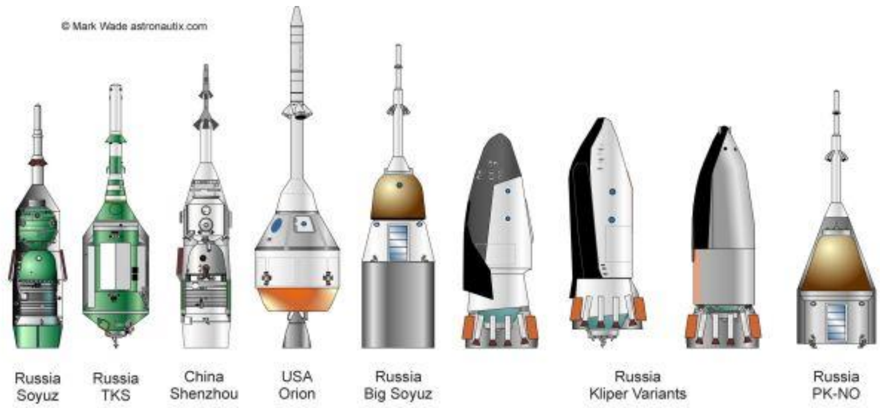

Figure 6. Launch abort towers are common practice in human spaceflight.[7]

A common practice in the launch abort and re-entry business is using a blunt vehicle shape. This allows one to minimize the ballistic coefficient (BC), by spreading the airflow over the surface area of the heat shield.

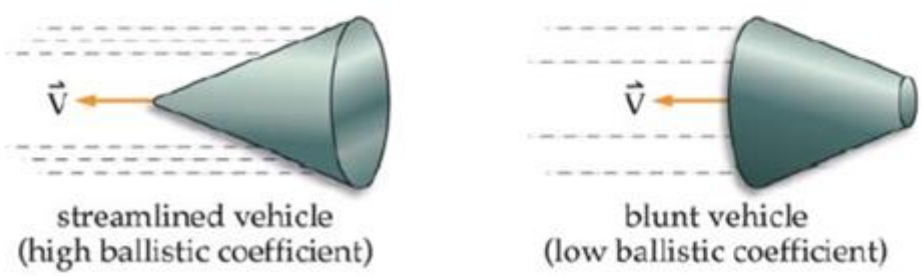

Figure 7. Blunt vehicle shapes are typically chosen.[8]

Before the ballistic coefficient is considered, first the force of drag is defined,

$$F_{Drag} = \frac{1}{2} \varrho V C_d A$$

Where F_{drag} is the drag force on the vehicle (N), C_D is the drag coefficient, A is the vehicle cross-sectional area (m^2), ρ is the atmospheric density (kg/m^3), and V is the vehicle velocity (m/s).[8]

The ballistic coefficient can be defined using the mass of the vehicle, the drag coefficient, and the vehicle cross-sectional area,

$$BC = \frac{m}{C_d A}$$

Where BC is the vehicle's ballistic coefficient (kg/m^2), and m is the vehicle mass (kg).[8] It can be seen that by increasing the vehicle cross-sectional area A, the ballistic coefficient is decreased. Thus, a blunter vehicle will have a lower ballistic coefficient. A low BC vehicle slows down more rapidly due to drag than streamlined vehicles that have high BC.

2. Conceptual Design

2.1 Design Process

Two important design parameters include the drag coefficient C_D and the ballistic coefficient BC as described in the previous section. These drive the shape of the vehicle body as required for reentry later in the mission. This shape also allows for the LAS to have an aerodynamic profile to cover Orion as seen by the Ogive fairing in Figure 7.

Figure 8. Ogive fairing of LAS fits over Orion, model image from NASA.[9]

Other design drivers include the overall mass of the vehicle, which will determine the fuel costs required. The choice of material for the structure is also integral to the decision. The material needs to be lightweight to reduce mass costs but also have the strength to not yield under the mission requirement loads. Figure 8 shows a flowchart detailing the design process.

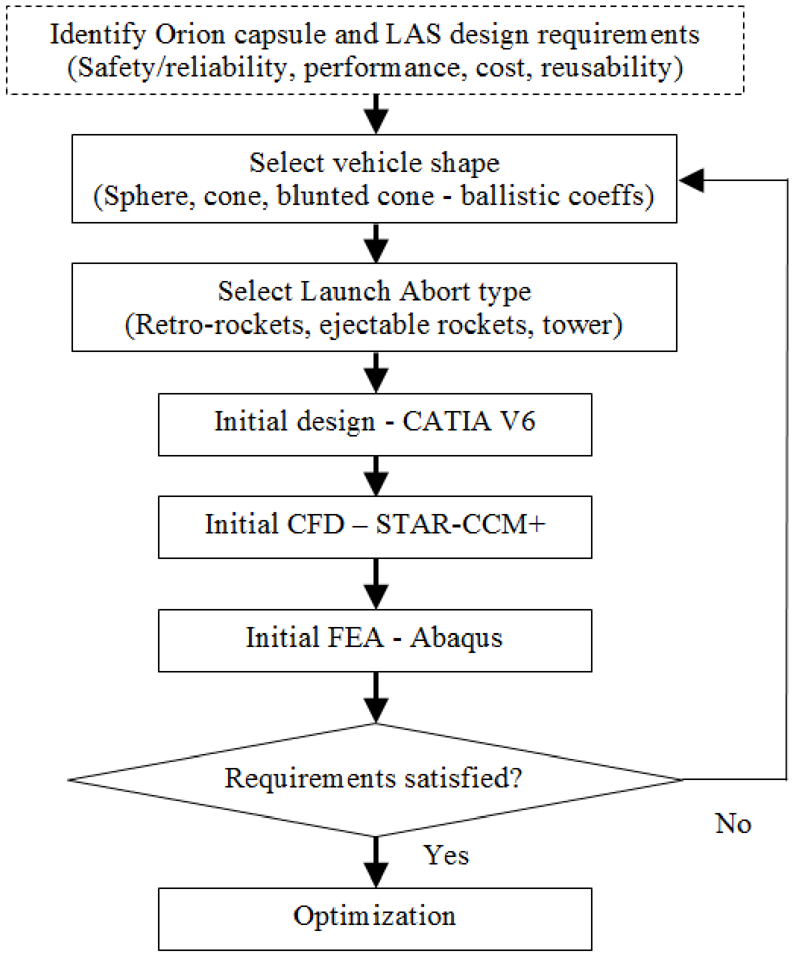

Figure 9. Design process flowchart for Orion LAS analysis.

2.2 Vehicle Performance Characteristics

Vehicle requirements include a internal temperature range of 70 to 100°F, with a passenger crew of up to 6. Aluminum-lithium alloy is the baseline material for the pressure vessel.

Parameter	Value
Max G Loading	11 G
LAM Thrust	400,000 lb
Acceleration	0-800 kph, 3 sec
Range	1 mile ascent and downrange
Reorientation angle	155°
Reorientation rate	25°/s
Pressurized volume	19.5 m^3 (8.9 m^3 habitable)
Dry mass	14,045 kg

Table 1. Performance Parameters for the Orion Capsule and Launch Abort System.

2.3 Vehicle/Sub-Component Sizing

The External Aerodynamics of the vehicle contain information related to each section of the Launch Abort System, including the Orion Crew Module itself. Those parameters consist of physical, geometrical and dynamic parameters that affect the aerodynamic of the whole system. In this section the system is presented in: Launch Abort System (LAS) - Integrated, LAS Abort Motor, LAS Attitude Control Motor, LAS Jettison Motor and Orion Crew Module.

2.3.1 Launch Abort System - Integrated

The External Aerodynamics of the item Launch Abort System(LAS) - Integrated are shown in the Table 2. Its geometry is shown in the Figure 10.

Launch Abort System - Integrated	
Parameter	**Value**
RCS Coarse No x Thrust	8 x 11 kN
RCS Specific Impulse	227s
Gross mass	6,176 kg
Unfueled mass	3,696 kg
Height	11.60 m
Diameter	0.40 m
Thrust	2,253 kN
Specific Impulse	250s

Table 2. LAS - Integrated External Aerodynamics parameters.[10]

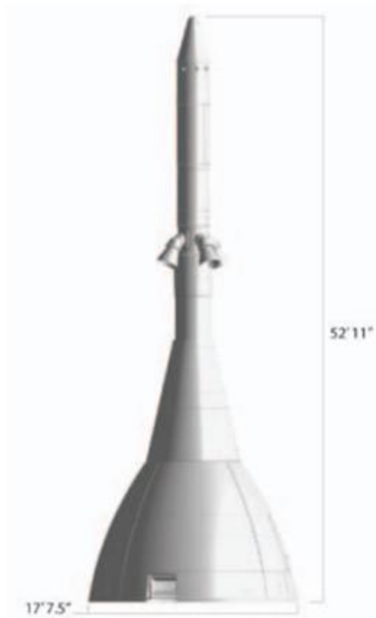

Figure 10. LAS Integrated geometry.[11]

2.3.2 Launch Abort System - Abort Motor

The External Aerodynamics of the item LAS - Abort Motor are shown in the Table 3.

Launch Abort System – Abort Motor	
Parameter	**Value**
Nozzles	4
Nozzle Cant Angle (to CL)	30°
Isp (sea level)	250s
Thrust (total in vehicle axis)	2,253 kN
Burn Time	2.0s
T/W	15:1

Table 3. LAS Abort Motor External Aerodynamic parameters. [10]

2.3.3 Launch Abort System - Attitude Control Motor

The External Aerodynamics of the item LAS - Attitude Control Motor are shown in the Table 4.

Launch Abort System – Attitude Control Motor	
Parameter	**Value**
Nozzles	8
Nozzle Cant Angle (to CL)	90°
Isp (sea level)	227 s
Thrust (total in vehicle axis)	11 kN
Burn Time	20 s

Table 4. LAS Attitude Control Motor External Aerodynamic parameters. [10]

2.3.4 Launch Abort System - Jettison Motor

The External Aerodynamics of the item LAS - Jettison Motor are shown in the Table 5.

Launch Abort System – Jettison Motor	
Parameter	**Value**
Nozzles	4
Nozzle Cant Angle (to CL)	35°
Isp (sea level)	221s
Thrust (total in vehicle axis)	43 kN
Burn Time	1.5s

Table 5. LAS Jettison Motor External Aerodynamic parameters. [10]

2.3.5 Orion Crew Module

The External Aerodynamics of the item Orion Crew Module are shown in the Table 6. Its geometry are shown in the Figure 11, Figure 12, Figure 13, Figure 14 and Figure 15.

Orion Crew Module	
Parameter	**Value**
RCS Coarse No x Thrust	16 x 445 kN
RCS Specific Impulse	227s
Gross mass	21,500 kg
Unfueled mass	11,750 kg
Height	9.10 m
Diameter	5.03 m
Thrust	33.40 kN
Habitable Volume	10.23 m^3
Delta V	1,855 m/s
Span	17.00 m

Table 6. Orion Crew Module External Aerodynamic parameters. [10]

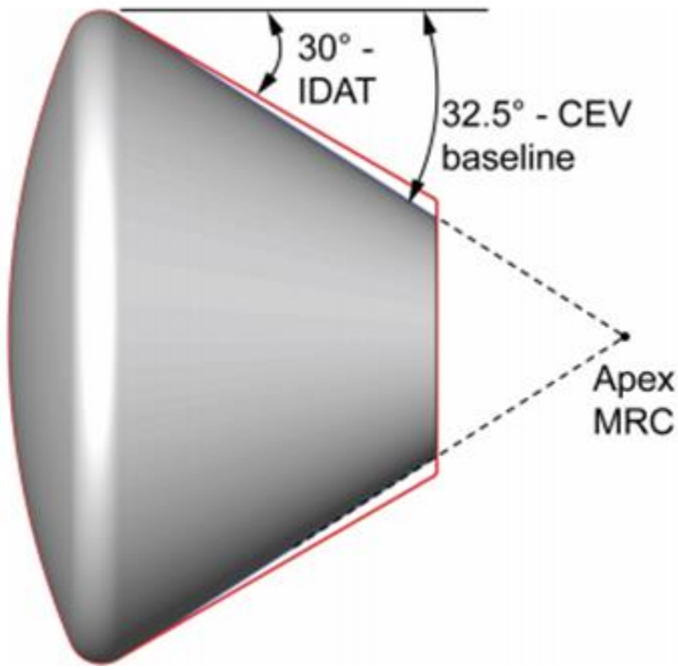

Figure 11. Orion Crew Module fundamental geometric relations.[11]

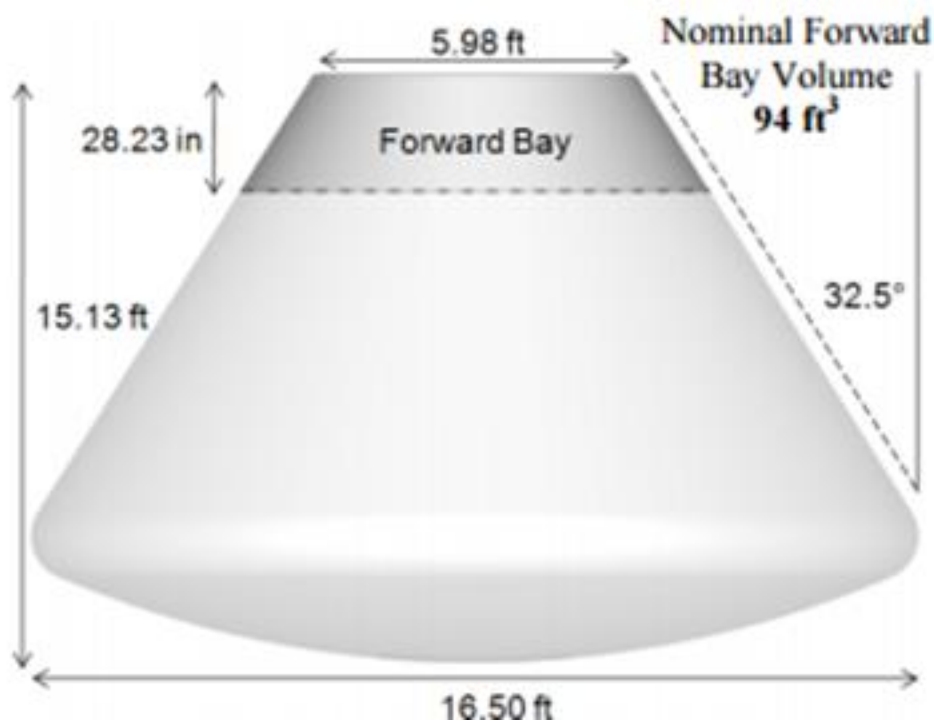

Figure 12. Orion Crew Module fundamental geometric parameters and dimensions.[12]

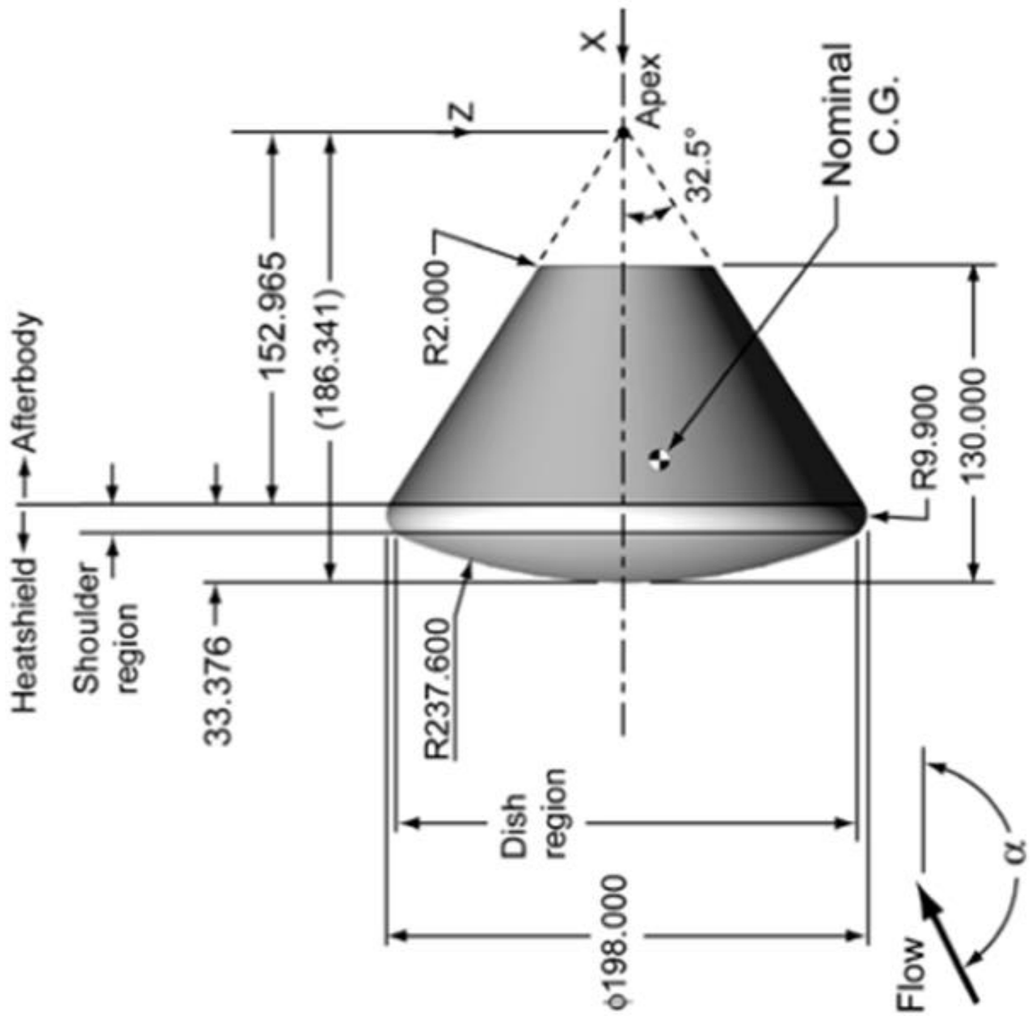

Figure 13. Orion Crew Module fundamental geometric dimensions.[11]

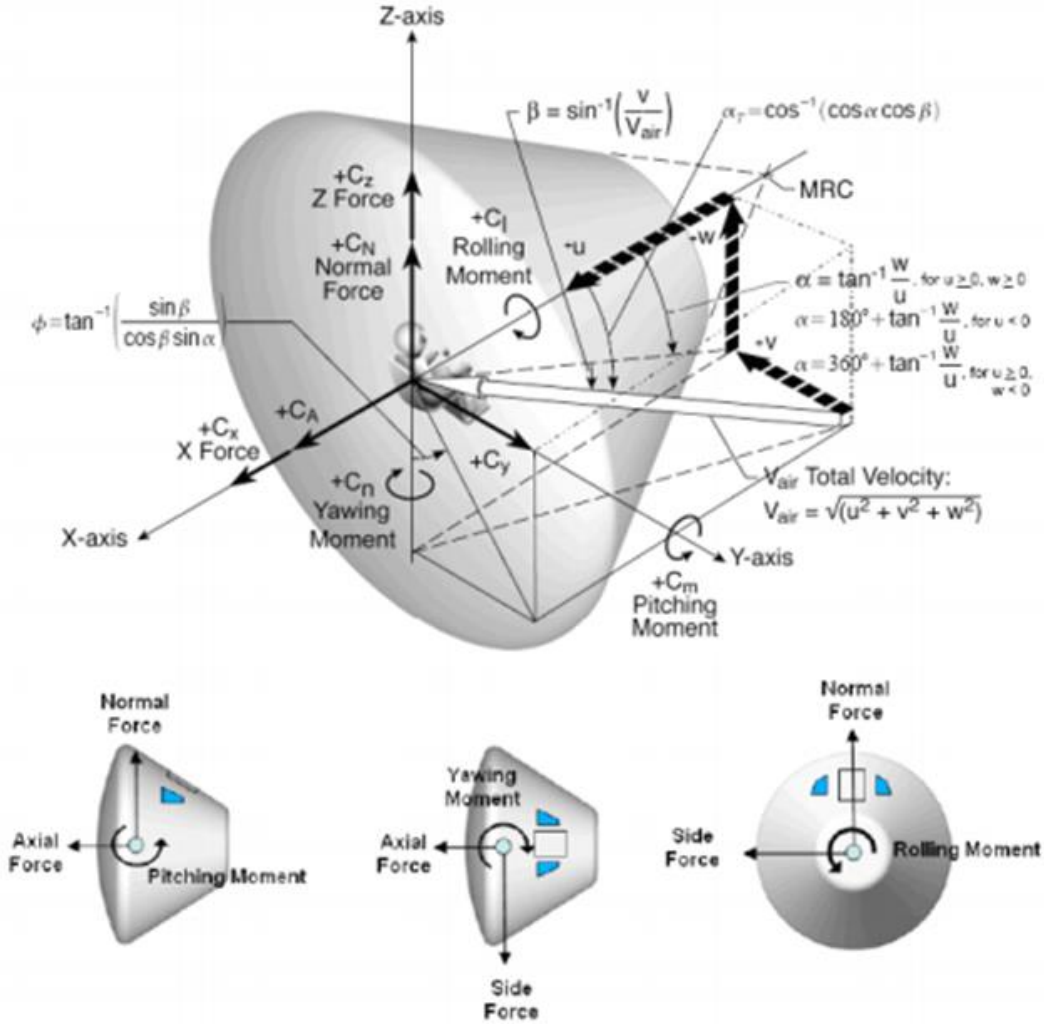

Figure 14. Orion Crew Module fundamental geometric orientation.[13]

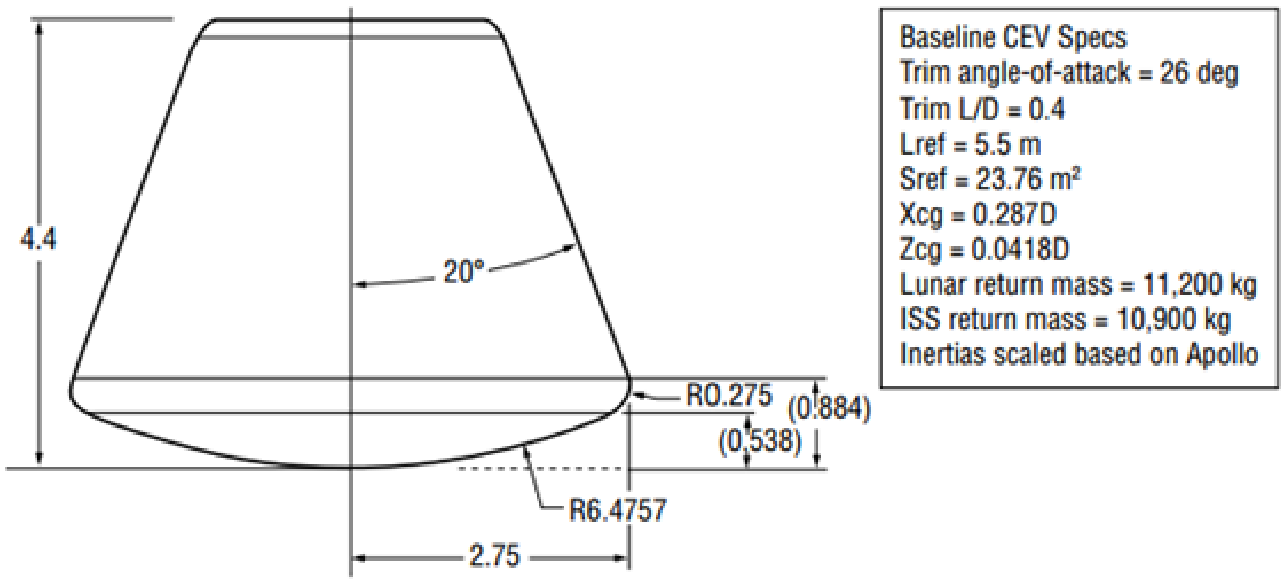

Figure 15. Orion Crew Module fundamental geometric parameters.[13]

The development of the Orion Crew Module evolved from initial Apollo studies and later developments. The Figure shows this comparison.

	Apollo (based on flt aero) Actual – 0.3 L/D	**Apollo** (based on flt aero) 0.4 L/D	**Axisym. CEV** (based on CFD) 0.4 L/D	**AFE CEV** (based on CFD) 0.4 L/D
Base radius/D	1.18	1.18	1.18	Original AFE
Corner Radius/D	0.05	0.05	0.05	Original AFE
Cone angle	32.5 deg	32.5 deg	20 deg	20 deg
Height/D (to docking adapter)	0.75 (4.1 m)	0.75 (4.1 m)	0.8 (4.4 m)	0.8 (4.4 m)
α	20 deg	27 deg	28 deg	25 deg
OML Volume	44.3 m_3	44.3 m_3	63.7 m_3	~64 m_3
Xcg/D	0.265 (< 0.22 for monostab.)	0.265 (< 0.23 for monostab.)	0.29 (<0.31 for monostab.)	0.29
Zcg/D	0.038 (> 0.04 for monostab.)	0.05 (> 0.052 for monostab.)	0.053 (> 0.051 for monostab.)	0.032
% Vol below Xcg	55% (< 39% for monostab.)	55% (< 42% for monostab.)	45% (< 49% for monostab.)	~45%
Monostable?	No	No	Yes	Yes
C_m-alpha @ cg	-0.0023	-0.0025	-0.0028	
ΔL/D per ΔZcg	0.022/cm	0.018/cm	0.016/cm	

Note: All are scaled to a 5.5-m diameter.

Figure 16. Parameters comparison during Orion Crew Module Development.[14]

3. Vehicle 3D Model in CATIA

3.1 3D Modeling Roles and Responsibilities:

Team member	Responsibilities
Tyler Scogin (CATIA Designer)	Launch Abort Tower • Profile • Attitude Control Motors (8) • Jettison Motors (4)
Michel Lacerda (CATIA Designer)	Orion Capsule • Profile • RCS Motors (6) • Windows
Jordan Marshall (CATIA Designer)	LAS Abort Motor (4) • Profile • Nozzles • Angles

Table 7. Modeling roles and responsibilities.

3.2 Design Parameters and Relations:

The Orion capsule and launch abort system were designed with specific parametric relations to enable quick modifications after CFD and FEA analysis are completed. The parameters are displayed in three parts, the Launch Abort Tower, the Orion capsule, and the LAS Abort Motor. The LAS tower design parameters and formulas are shown in Table 8 below.

Parameter Name	Value	Formula
Transition Cone bottom radius	47.92 in	
Ogive faring bottom radius	105.75 in	= (Transition Cone bottom radius)*2.2068
Pole radius	16.52 in	
Nose cone cap radius	3.3 in	
Nose cone cap height	3.3 in	= Nose cone cap radius
Nose cone height	38.806 in	
Pole length	320.021 in	
Transition cone height	122.676 in	
Ogive fairing height	153.291 in	

Table 8. LAS Tower design parameters and formulas.

The Orion capsule design parameters are displayed in Table 9 below.

Parameter Name	Value
Bottom Shield radius	99 in
External wall angle	32.5°
Capsule height	130 in
Bottom Shield curve	237.6 in
Bottom Shield Border radius	9.9 in
Apex height	237.6 in
External wall length	113.033 in

Table 9. Orion capsule parameters.

The LAS Abort Motor parameters are displayed in Table 10 below.

Parameter Name	Value
Abort Nozzle Base Diameter	10 in
Abort Nozzle Base Angle	38.7°

Table 10. LAS Abort Motor design parameters.

3.3 3D Model:

A 3D view of the geometry is shown in Figure 17 below. This model shows the Launch Abort System with the Orion capsule as it would be attached during ascent.

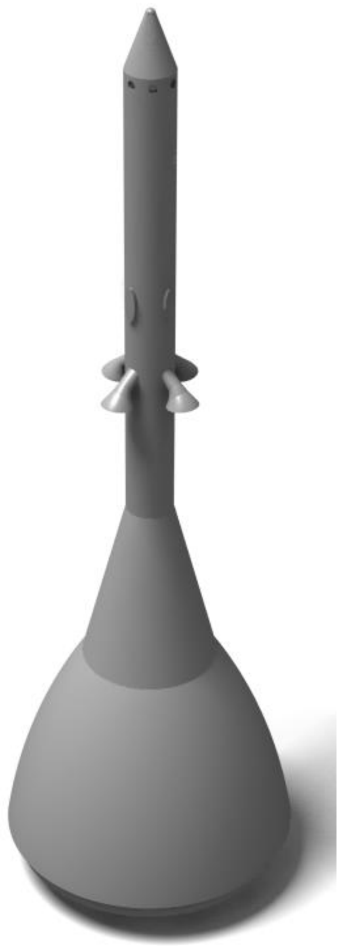

Figure 17. 3D isometric view of LAS and Orion model.

To provide another view so that the Orion capsule can be seen, Figure 18 was also included below. There is a notable gap between the Orion capsule and the Ogive fairing, which allows for a smooth separation procedure during the LAS jettison phase of the abort process.

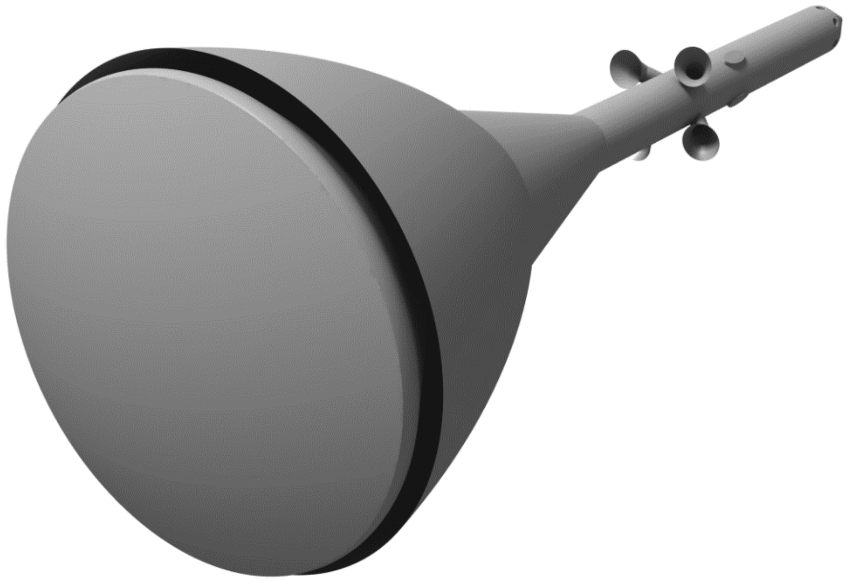

Figure 18. Additional view of the LAS and Orion model.

An exploded view of the model captures both the LAS and Orion separately. All of the motors that were modeled were created as a direct surface add-on to the existing component. Thus, the four Jettison Motors, four Abort Motors, and eight Attitude Control Motors were all directly integrated into the design of the LAS tower itself.

Orion is a separate 3d part component, with the windows and RCS thrusters build directly into the design as well. Figure 19 below shows the exploded view.

Figure 19. Exploded view of LAS and Orion.

More descriptions of the modeling for the subcomponents can be found in the Appendix.

4. Aerodynamic Analysis

4.1 Team members and Associated Tasks

Team member	Task
Tyler Scogin	Pre-Processing
Michel Lacerda	Solver Setup
Jordan Marshall	Post-Processing

Table 11. Team members and tasks.

4.2 Geometry Snapshot (Mesh Scene) as Original Surface mesh in STAR-CCM+ and Surface Repair Threshold Statistics

This section details the use of the computational fluid dynamics (CFD) software STAR-CCM+ for the Orion LAS model. The model was imported from CATIA V6, and then treated as a surface with multiple errors. The original model is shown below in Figure 20, and the model with errors highlighted and the categorized in the Surface Repair Threshold is shown in Figure 21.

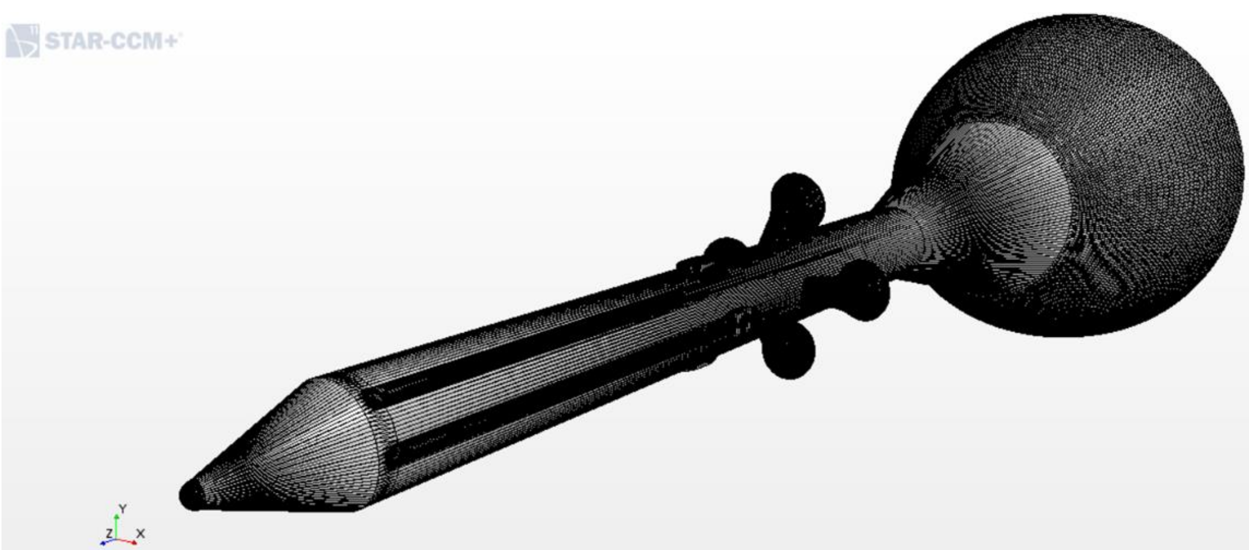

Figure 20. Original LAS and Orion surface model as imported from CATIA V6.

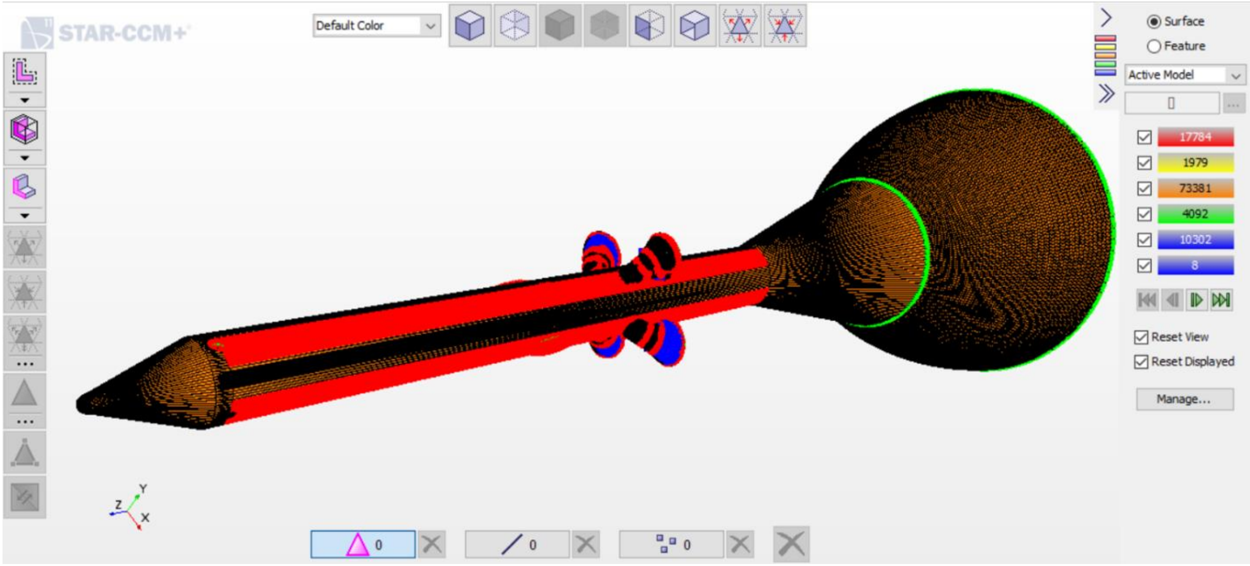

Figure 21. Surface Repair Threshold statistics.

More views of the original model as imported from CATIA V6 can be seen in the Appendices.

4.2 Surface Mesh Regeneration, Surface Wrapper Snapshots, and Error Statistics

Default Control	Value
Base Size	1.0 m
Target Surface Size, Percentage of Base	30%
Target Surface Size, Absolute Size	0.3 m
Minimum Surface Size, Percentage of Base	10%
Minimum Surface Size, Absolute Size	0.1 m
Basic Curvature, #Pts/circle	60 points
Volume of Interest	External

Table 12. Surface Wrapper default controls for LAS.

Custom Control	Value
Target Surface Size, Percentage of Base	30%
Target Surface Size, Absolute Size	0.3 m
Minimum Surface Size, Percentage of Base	5%
Minimum Surface Size, Absolute Size	0.05 m

Table 13. Surface Wrapper custom controls for LAS Abort and Jettison motors.

Custom Control	Value
Target Surface Size, Percentage of Base	10%
Target Surface Size, Absolute Size	0.1 m
Minimum Surface Size, Percentage of Base	1%
Minimum Surface Size, Absolute Size	0.01 m
Basic Curvature, #Pts/circle	120 points

Table 14. Surface Wrapper custom controls for LAS Nose tip and holes.

Contact Prevention	Value
Abort Motor/Upper Section	Mimimum size: 0.05 m
Jettison Motors/Upper Section	Mimimum size: 0.05 m
Nose cone transition/Nose tip	Mimimum size: 0.05 m

Table 15. Contact prevention and values.

Default Control	Value
Base Size	1.0 m
Target Surface Size, Percentage of Base	30%
Target Surface Size, Absolute Size	0.3 m
Minimum Surface Size, Percentage of Base	10%
Minimum Surface Size, Absolute Size	0.1 m
Basic Curvature, #Pts/circle	60 points
Volume of Interest	External

Table 16. Surface Wrapper default controls for Orion.

Custom Control/Mesh Control on Curve	Value
Target Surface Size, Percentage of Base	Parent
Minimum Surface Size, Percentage of Base	10%
Minimum Surface Size, Absolute Size	0.1 m

Table 17. Surface Wrapper custom controls for Orion edges and Ogive fairing edges.

Custom Control/Mesh Control on Surface	Value
Target Surface Size, Percentage of Base	10%
Target Surface Size, Absolute Size	0.1 m
Minimum Surface Size, Percentage of Base	1%
Minimum Surface Size, Absolute Size	0.01 m
Basic Curvature, #Pts/circle	60 points

Table 18. Surface Wrapper custom controls for Orion holes.

The automated mesh for LAS has the following activated:

- Surface resmesher
- Automated surface repair

Default Control	Value
Base Size	1.0 m
Project to CAD	Activated
Target Surface Size, Percentage of Base	30%
Target Surface Size, Absolute Size	0.3 m
Minimum Surface Size, Percentage of Base	10%
Minimum Surface Size, Absolute Size	0.1 m
Basic Curvature, #Pts/circle	60 points

Table 19. Automated Mesh default controls for LAS.

Custom Control	Value
Target Surface Size, Percentage of Base	30%
Target Surface Size, Absolute Size	0.3 m
Minimum Surface Size, Percentage of Base	5%
Minimum Surface Size, Absolute Size	0.05 m

Table 20. Automated Mesh custom controls for LAS Abort and Jettison motors.

Custom Control	Value
Target Surface Size, Percentage of Base	10%
Target Surface Size, Absolute Size	0.1 m
Minimum Surface Size, Percentage of Base	1%
Minimum Surface Size, Absolute Size	0.01 m
Basic Curvature, #Pts/circle	120 points

Table 21. Automated Mesh custom controls for LAS Nose tip and holes.

The automated mesh for Orion has the following activated:

- Surface resmesher
- Automated surface repair

Default Control	Value
Base Size	1.0 m
Project to CAD	Activated
Target Surface Size, Percentage of Base	30%
Target Surface Size, Absolute Size	0.3 m
Minimum Surface Size, Percentage of Base	10%
Minimum Surface Size, Absolute Size	0.1 m

Basic Curvature, #Pts/circle	60 points

Table 22. Automated Mesh default controls for Orion.

Custom Control/Mesh Control on Curve	Value
Target Surface Size, Percentage of Base	Parent
Minimum Surface Size, Percentage of Base	10%
Minimum Surface Size, Absolute Size	0.1 m

Table 23. Automated Mesh custom controls for Orion edges and Ogive fairing edges.

Custom Control/Mesh Control on Surface	Value
Target Surface Size, Percentage of Base	10%
Target Surface Size, Absolute Size	0.1 m
Minimum Surface Size, Percentage of Base	1%
Minimum Surface Size, Absolute Size	0.01 m
Basic Curvature, #Pts/circle	60 points

Table 24. Automated Mesh custom controls for Orion holes.

The automated mesh for the Block has the following activated:

- Surface resmesher
- Automated surface repair

Default Control	Value
Base Size	1.0 m
Project to CAD	Activated
Target Surface Size, Percentage of Base	600%
Target Surface Size, Absolute Size	6 m
Minimum Surface Size, Percentage of Base	50%
Minimum Surface Size, Absolute Size	0.5 m
Basic Curvature, #Pts/circle	36 points

Table 25. Automated Mesh default controls for Block.

Custom Control/Mesh Control on Surface	Value
Target Surface Size, Percentage of Base	25%
Target Surface Size, Absolute Size	0.25 m
Minimum Surface Size, Percentage of Base	Parent

Table 26. Automated Mesh custom controls for Symmetry.

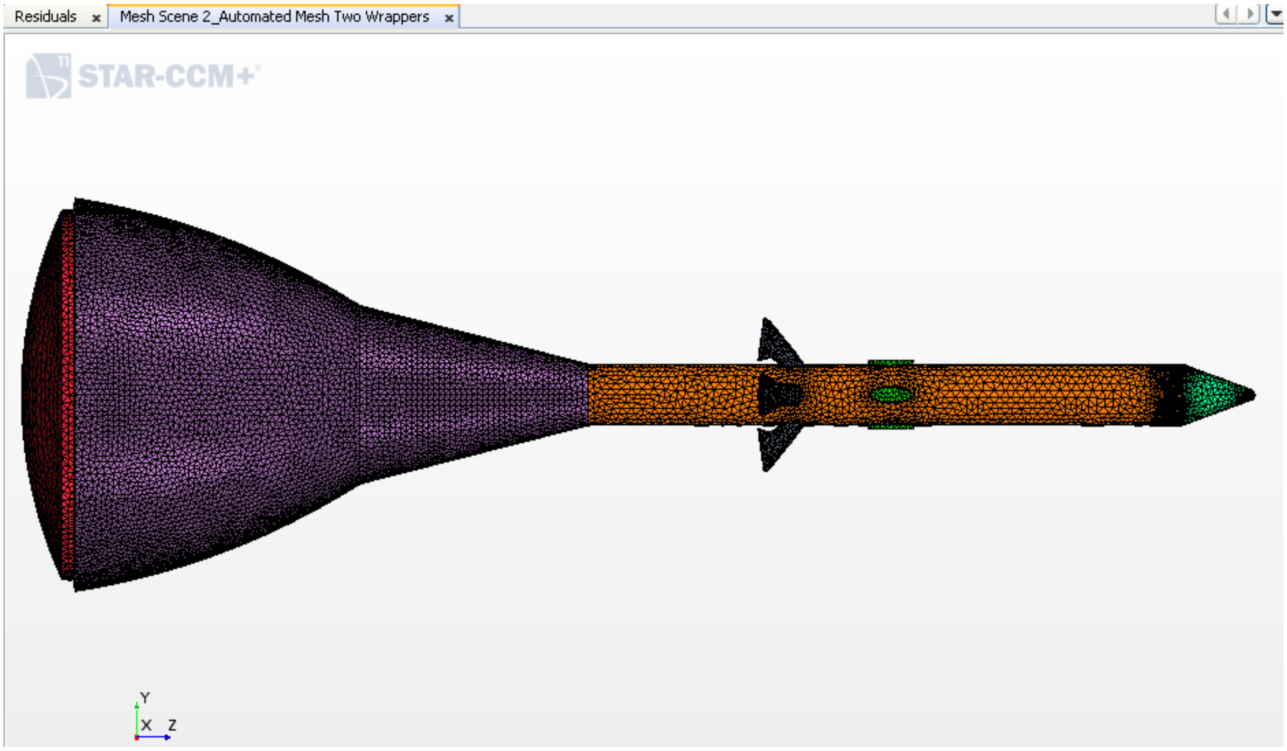

Figure 22. Automated mesh scene for two surface wrappers.

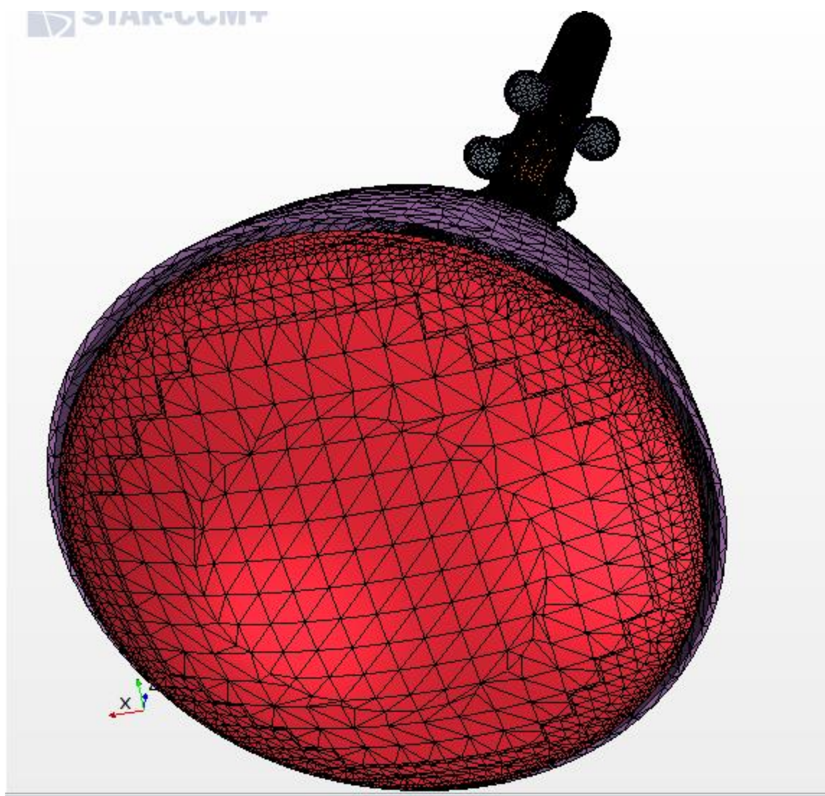

Figure 23. Automated mesh scene with view of Orion inside LAS.

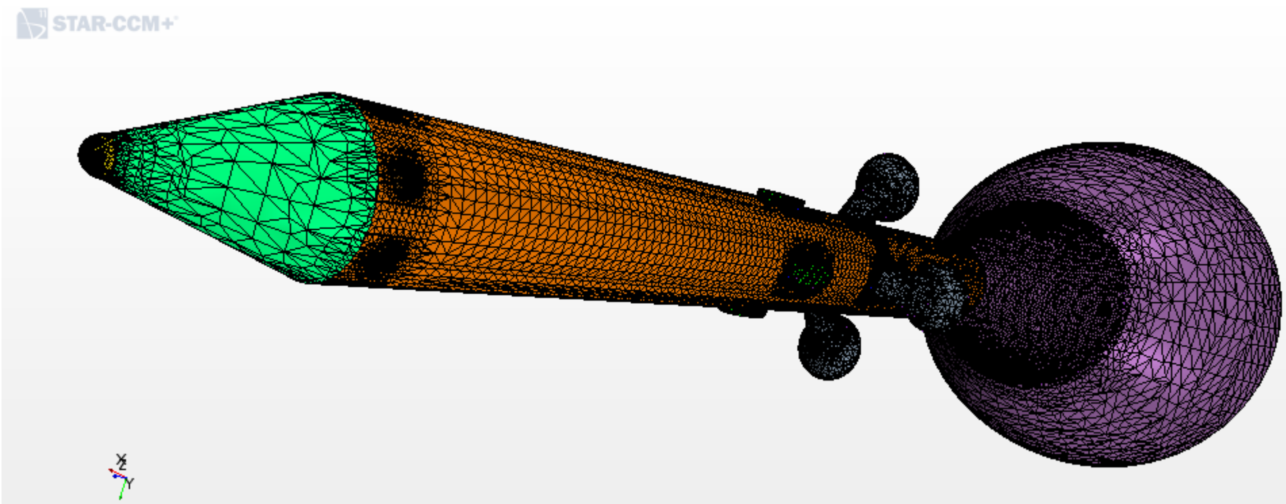

Figure 24. Mesh snapshot after Surface Wrapper and Automated Mesh Repair.

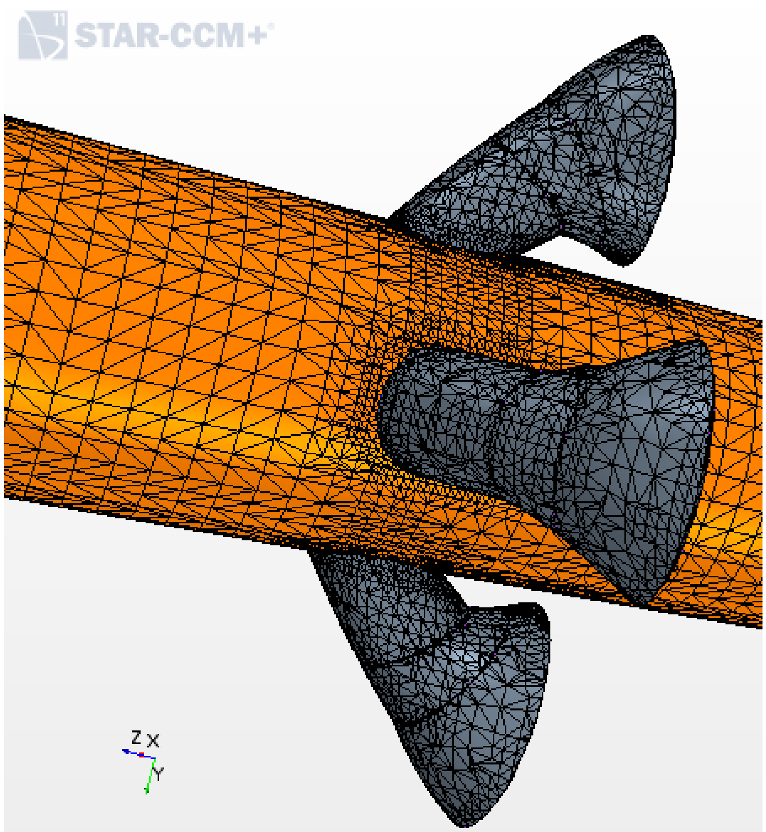

Figure 25. Mesh snapshot after Surface Wrapper and Automated Mesh Repair of abort motors.

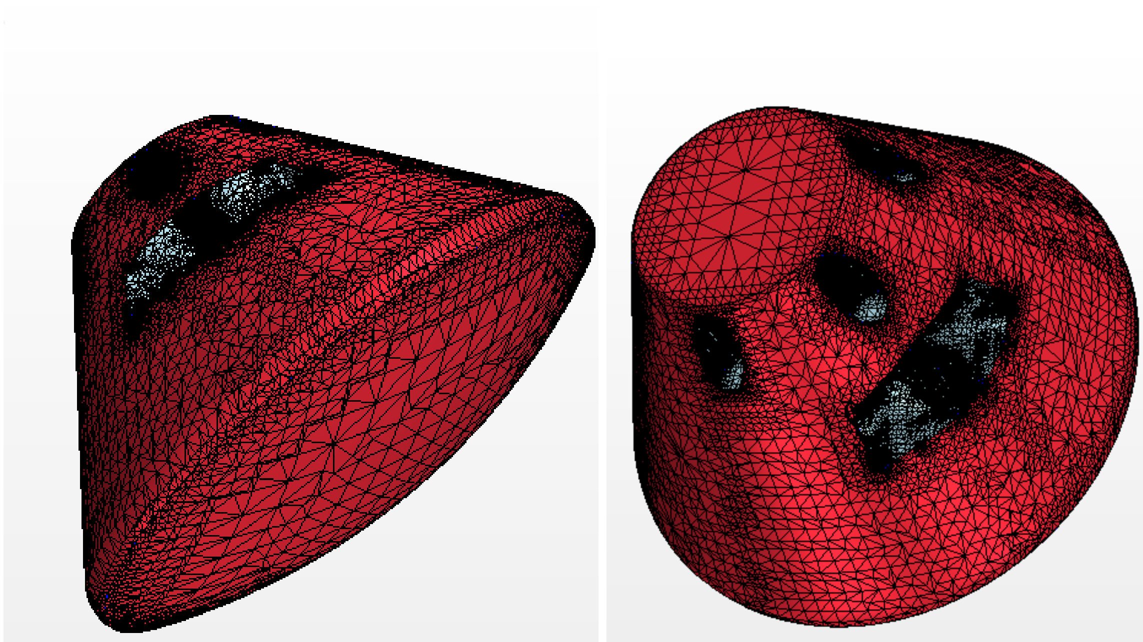

Figure 26. Mesh snapshot after Surface Wrapper and Automated Mesh Repair of Orion module.

The Orion and LAS were subjected two separate surface wrapper operations, with the repair threshold charts and output text shown below in Figures 27 to 30.

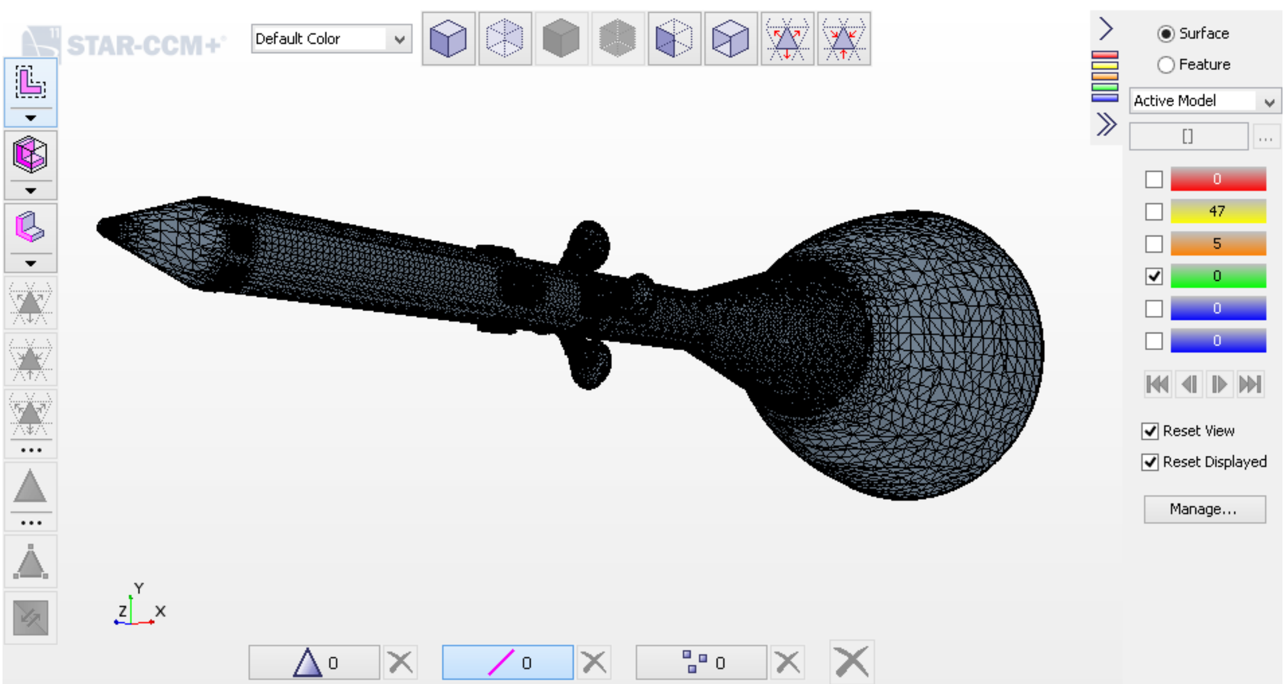

Figure 27. Surface repair threshold statistics chart after the repair for LAS only.

```
Running surface diagnostics:
  Diagnostic "Pierced faces (default)". Found 0 pierced faces and 0 pierced edges.
  Diagnostic "Face quality (default)". Found 47 face quality faces.
  Diagnostic "Face proximity (default)". Found 5 close proximity faces.
  Diagnostic "Free edges (default)". Found 0 free edges.
  Diagnostic "Non-manifold edges (default)". Found 0 non-manifold edges.
  Diagnostic "Non-manifold vertices (default)". Found 0 non-manifold vertices.
A total of 35 problem areas were found.
```

Figure 28. Output text for the surface repair for LAS only.

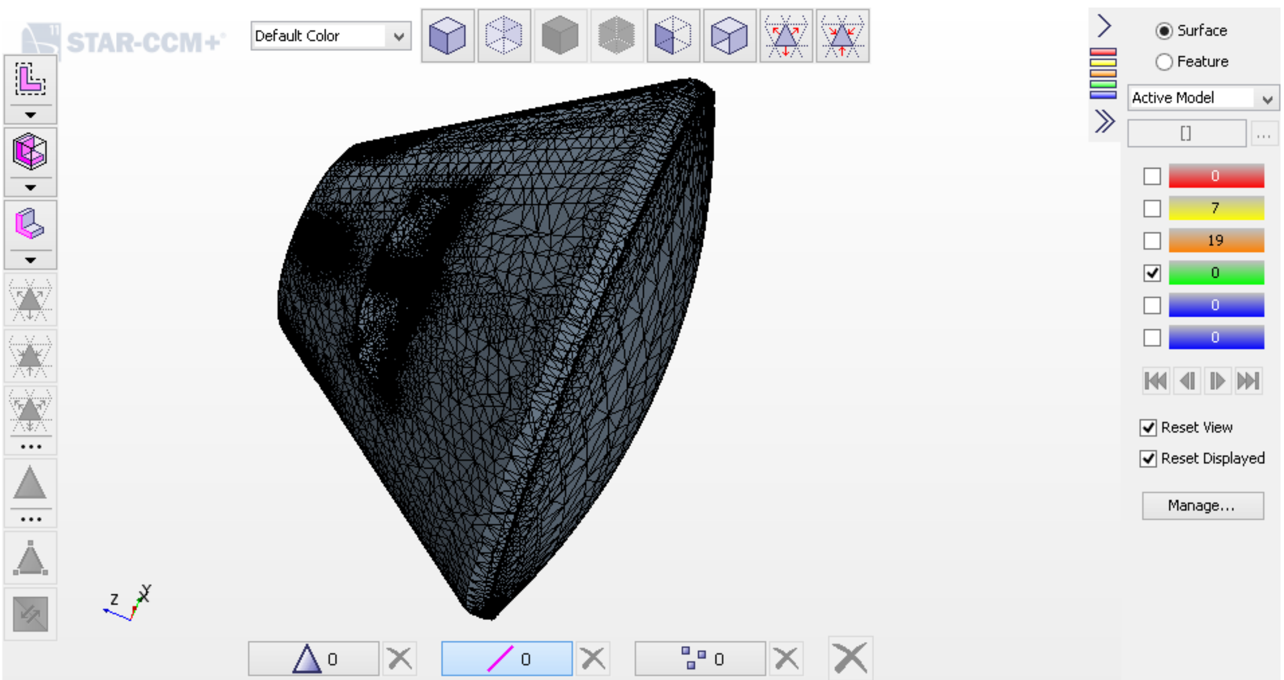

Figure 29. Surface repair threshold statistics chart after the repair for Orion only.

```
Running surface diagnostics:
  Diagnostic "Pierced faces (default)". Found 0 pierced faces and 0 pierced edges.
  Diagnostic "Face quality (default)". Found 7 face quality faces.
  Diagnostic "Face proximity (default)". Found 19 close proximity faces.
  Diagnostic "Free edges (default)". Found 0 free edges.
  Diagnostic "Non-manifold edges (default)". Found 0 non-manifold edges.
  Diagnostic "Non-manifold vertices (default)". Found 0 non-manifold vertices.
A total of 11 problem areas were found.
```

Figure 30. Output text for the surface repair for Orion only.

4.3 Volume Mesh Generation, Section Plane Snapshot, and Volume Mesh Diagnostics

In this section, the default and customs controls are shown followed by volume mesh screenshots of the model and the surrounding block mesh.

The automated mesh for the Subtract has the following activated:

- Surface resmesher
- Automated surface repair

Default Control	Value
Base Size	1.0 m
Project to CAD	Activated
Target Surface Size, Percentage of Base	30%
Target Surface Size, Absolute Size	0.3 m
Minimum Surface Size, Percentage of Base	10%
Minimum Surface Size, Absolute Size	0.1 m
Basic Curvature, #Pts/circle	60 points

Table 27. Automated Mesh default controls for the Subtract.

Custom Control	Value
Target Surface Size, Percentage of Base	30%
Target Surface Size, Absolute Size	0.3 m
Minimum Surface Size, Percentage of Base	5%
Minimum Surface Size, Absolute Size	0.05 m

Table 28. Automated Mesh custom controls for Subtract Abort and Jettison motors.

Custom Control	Value
Target Surface Size, Percentage of Base	10%
Target Surface Size, Absolute Size	0.1 m
Minimum Surface Size, Percentage of Base	1%
Minimum Surface Size, Absolute Size	0.01 m
Basic Curvature, #Pts/circle	120 points

Table 29. Automated Mesh custom controls for Subtract Nose tip and holes.

Custom Control/Mesh Control on Curve	Value
Target Surface Size, Percentage of Base	Parent
Minimum Surface Size, Percentage of Base	10%
Minimum Surface Size, Absolute Size	0.1 m

Table 30. Automated Mesh custom controls for Subtract Orion edges and Ogive fairing edges.

Custom Control/Mesh Control on Surface	Value
Target Surface Size, Percentage of Base	10%
Target Surface Size, Absolute Size	0.1 m
Minimum Surface Size, Percentage of Base	1%
Minimum Surface Size, Absolute Size	0.01 m
Basic Curvature, #Pts/circle	60 points

Table 31. Automated Mesh custom controls for Subtract Orion holes.

Custom Control/Mesh Control on Surface	Value
Target Surface Size, Percentage of Base	30%
Target Surface Size, Absolute Size	0.3 m
Minimum Surface Size, Percentage of Base	10%
Minimum Surface Size, Absolute Size	0.1 m
Wake Refinement	
Distance	10 m
Direction	[0.0, 0.0, -1.0]
Spread Angle	5.0 deg
Percentage of Base	25%
Absolute Size	0.25 m
Growth Rate	1.3

Table 32. Automated Mesh custom controls for Subtract Orion main body.

Custom Control/Mesh Control on Surface	Value
Target Surface Size, Percentage of Base	600%
Target Surface Size, Absolute Size	6 m
Minimum Surface Size, Percentage of Base	5%
Minimum Surface Size, Absolute Size	0.05 m

Table 33. Automated Mesh custom controls for Subtract Symmetry.

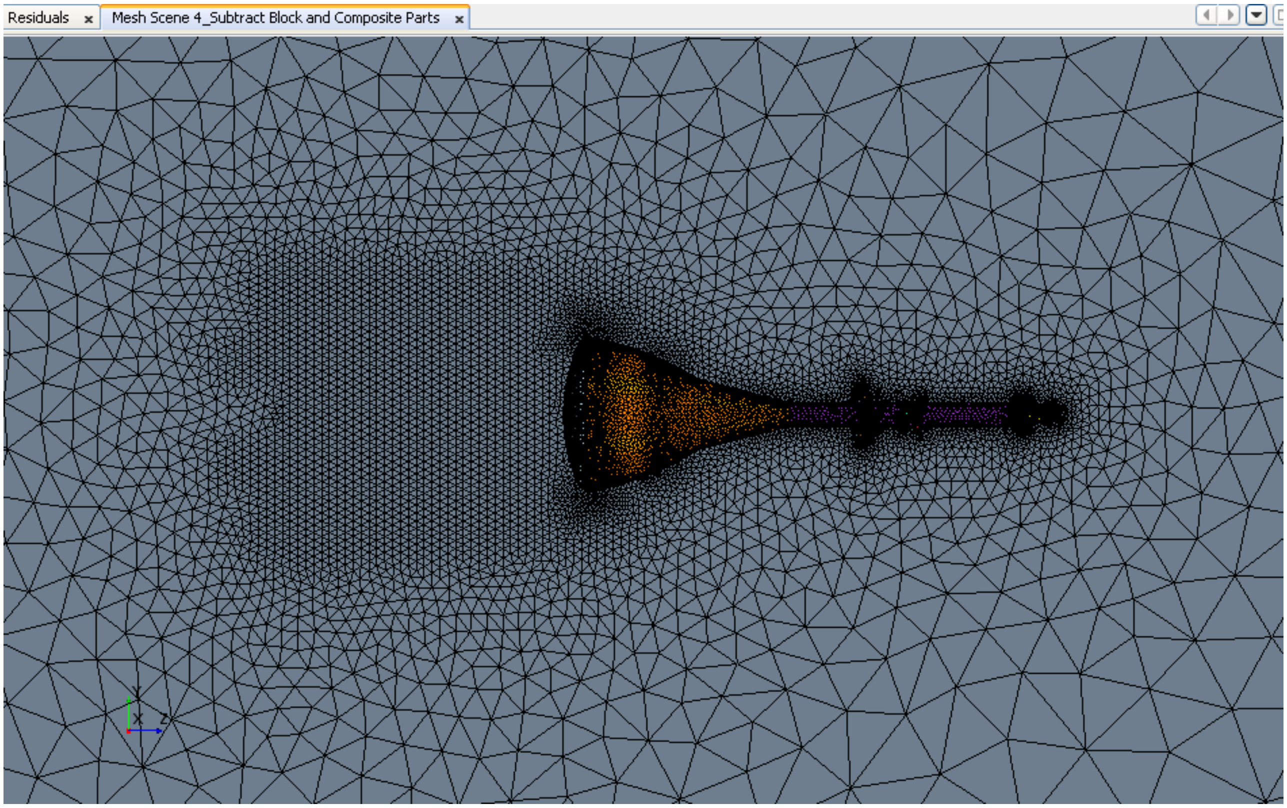

Figure 31. Mesh of the subtract block and LAS.

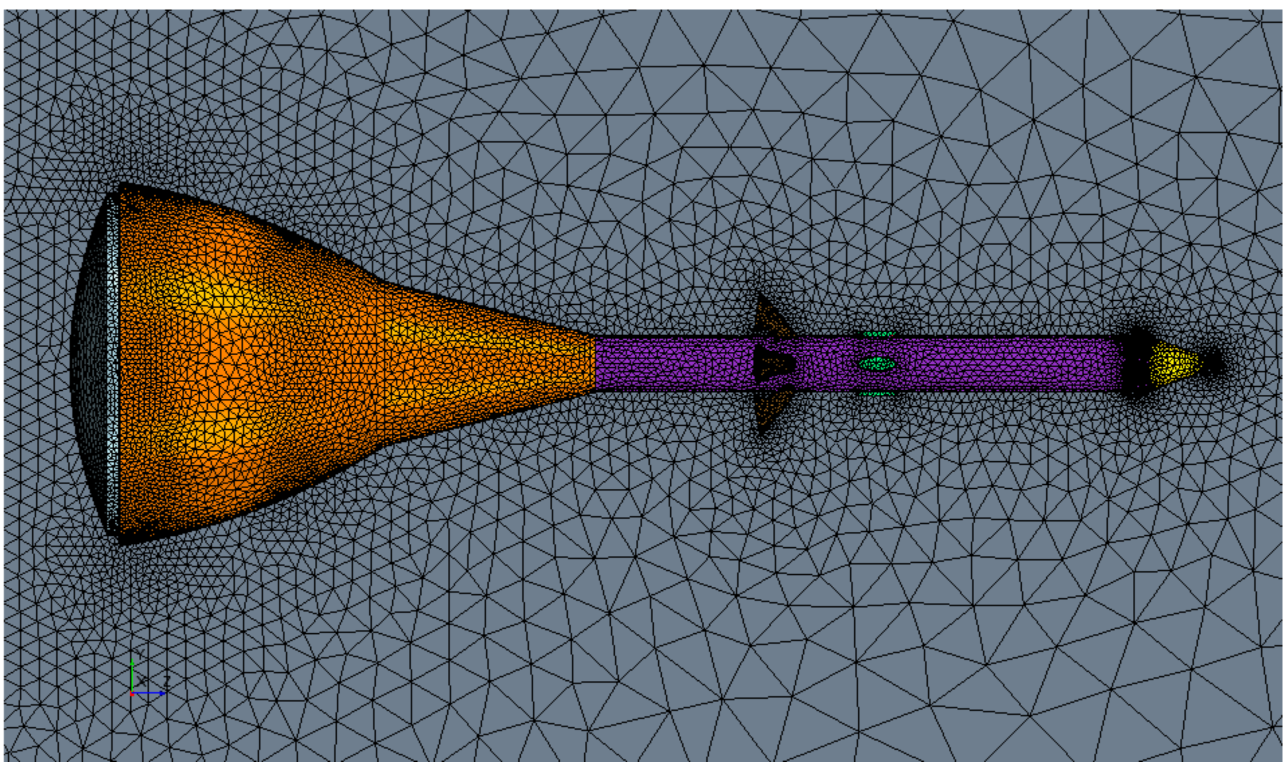

Figure 32. LAS and Orion close up view inside the subtract block mesh.

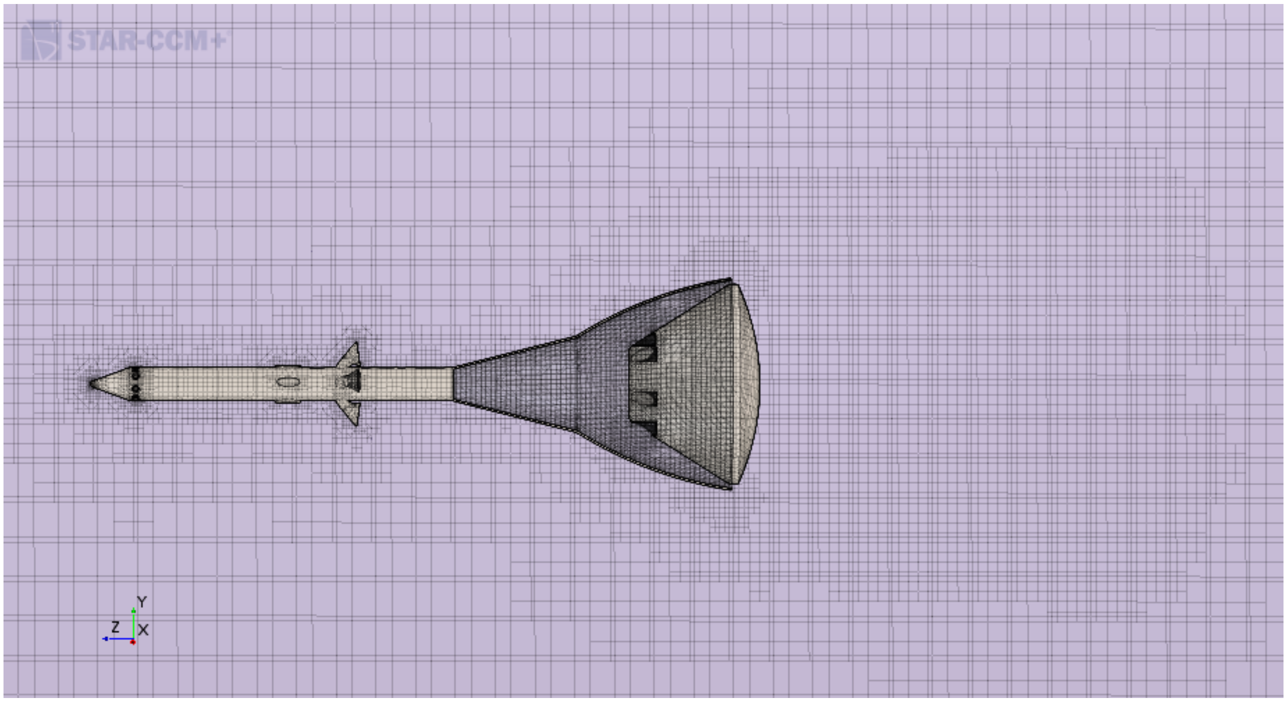

Figure 33. Section Plane with wake.

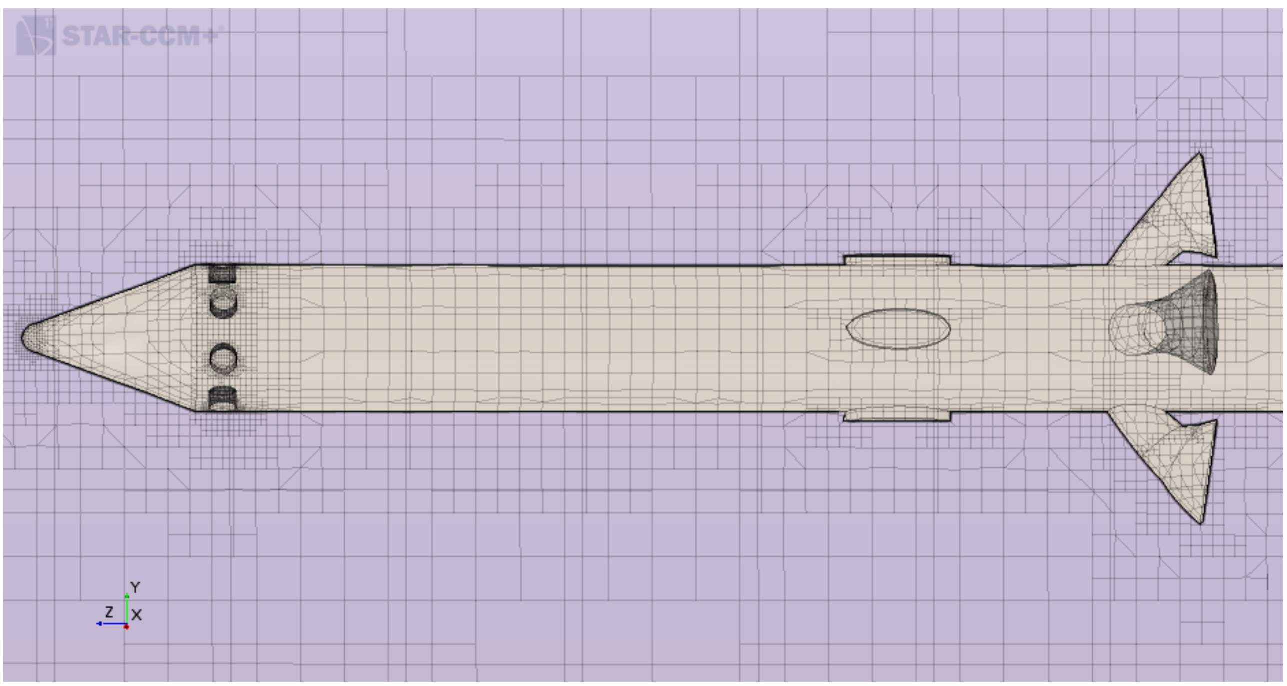

Figure 34. Section Plane view of upper section of LAS.

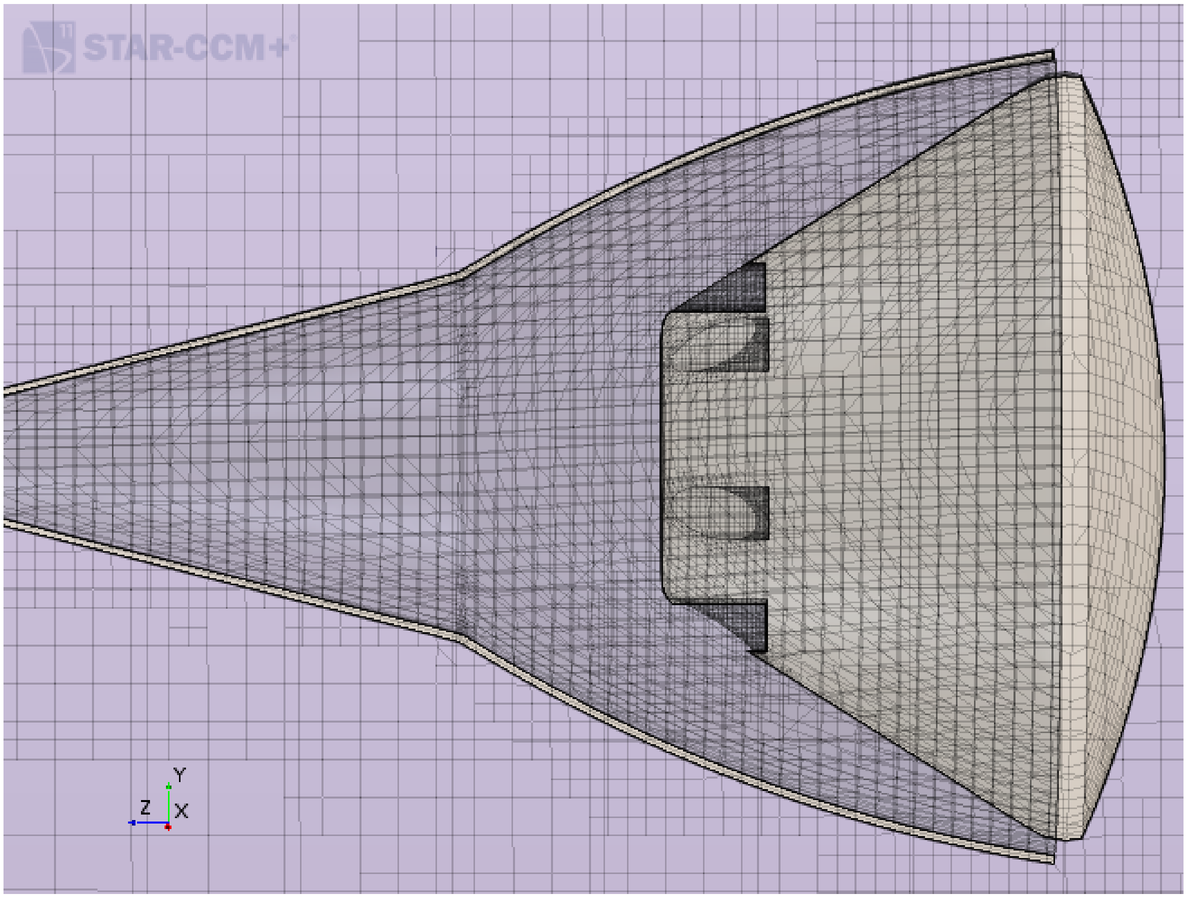

Figure 35. Section Plane view of Orion capsule and Ogive fairing.

```
---------------------------------------------------
--- Computing statistics in Region: Subtract_Block and Two Wrappers
---------------------------------------------------
-> ENTITY COUNT:
  # Cells: 501151
  # Faces: 1476096
  # Verts: 613868
-> EXTENTS:
  x: [-8.1382e+01,  4.0000e-01] m
  y: [-8.1441e+01,  8.2109e+01] m
  z: [-7.6716e+01,  8.3721e+01] m
-> MESH VALIDITY:
  Mesh is topologically valid and has no negative volume cells.
-> FACE VALIDITY STATISTICS:
Minimum Face Validity: 9.690742e-01
Maximum Face Validity: 1.000000e+00
       Face Validity <  0.50          0    0.000%
0.50 <= Face Validity <  0.60          0    0.000%
0.60 <= Face Validity <  0.70          0    0.000%
0.70 <= Face Validity <  0.80          0    0.000%
0.80 <= Face Validity <  0.90          0    0.000%
0.90 <= Face Validity <  0.95          0    0.000%
0.95 <= Face Validity <  1.00         14    0.003%
1.00 <= Face Validity             501137   99.997%
-> VOLUME CHANGE STATISTICS:
Minimum Volume Change: 2.117112e-04
Maximum Volume Change: 1.000000e+00
        Volume Change <  0.000000e+00          0    0.000%
0.000000e+00 <= Volume Change <  1.000000e-06          0    0.000%
1.000000e-06 <= Volume Change <  1.000000e-05          0    0.000%
1.000000e-05 <= Volume Change <  1.000000e-04          0    0.000%
1.000000e-04 <= Volume Change <  1.000000e-03         18    0.004%
1.000000e-03 <= Volume Change <  1.000000e-02        715    0.143%
1.000000e-02 <= Volume Change <  1.000000e-01      16164    3.225%
1.000000e-01 <= Volume Change <= 1.000000e+00     484254   96.628%
```

Figure 36. Volume mesh diagnostic report.

4.4 Physics Selection and Initial Conditions

The following physics were active:

- Exact Wall Distance
- Gas
- Gradients
- Ideal Gas
- K-Epsilon Turbulence
- Realizable K-Epsilon Two-Layer
- Reynolds-Averaged Navier-Stokes
- Segregated Flow
- Segregated Fluid Temperature
- Steady
- Three Dimensional
- Turbulent
- Two-Layer All y+ Wall Treatment

Initial Condition	Value
Pressure	0.0 Pa (Reference: 101.3 kPa)
Static Temperature	300.0 K
Turbulence Intensity	0.01
Turbulent Velocity Scale	1.0 m/s
Turbulent Viscosity Ratio	10
Velocity	[0.0, 0.0, 0.0] m/s

Table 34. Initial conditions.

Stopping Criteria	Value
Maximum Steps	10000
Tdr Minimum Value	1.0E-4
Tke Minimum Value	1.0E-4
X-momentum Minimum Value	1.0E-4
Y-momentum Minimum Value	1.0E-4
Z-momentum Minimum Value	1.0E-4

Table 35. Stopping Criteria.

4.5 Surface Names, Boundary Types and BC Values

Surface Name	Boundary Type	BC Value
Block		
Symmetry	Symmetry Plane	None
Inlet	Velocity Inlet	222.22 m/s
Outlet	Pressure Outlet	None
Wall x neg	Wall	None
Wall y neg	Wall	None
Wall y pos	Wall	None
Surface Wrapper		
Abort Motors	Wall	None
Internal Upper Section	Wall	None
Internal ogive fairing	Wall	None
Jettison Motors	Wall	None
Nose cone transition	Wall	None
Nose tip	Wall	None
Ogive fairing	Wall	None
Orion	Wall	None
Upper section	Wall	None

Table 36. Boundary names, type, and value for all boundaries.

4.6 Solver Information

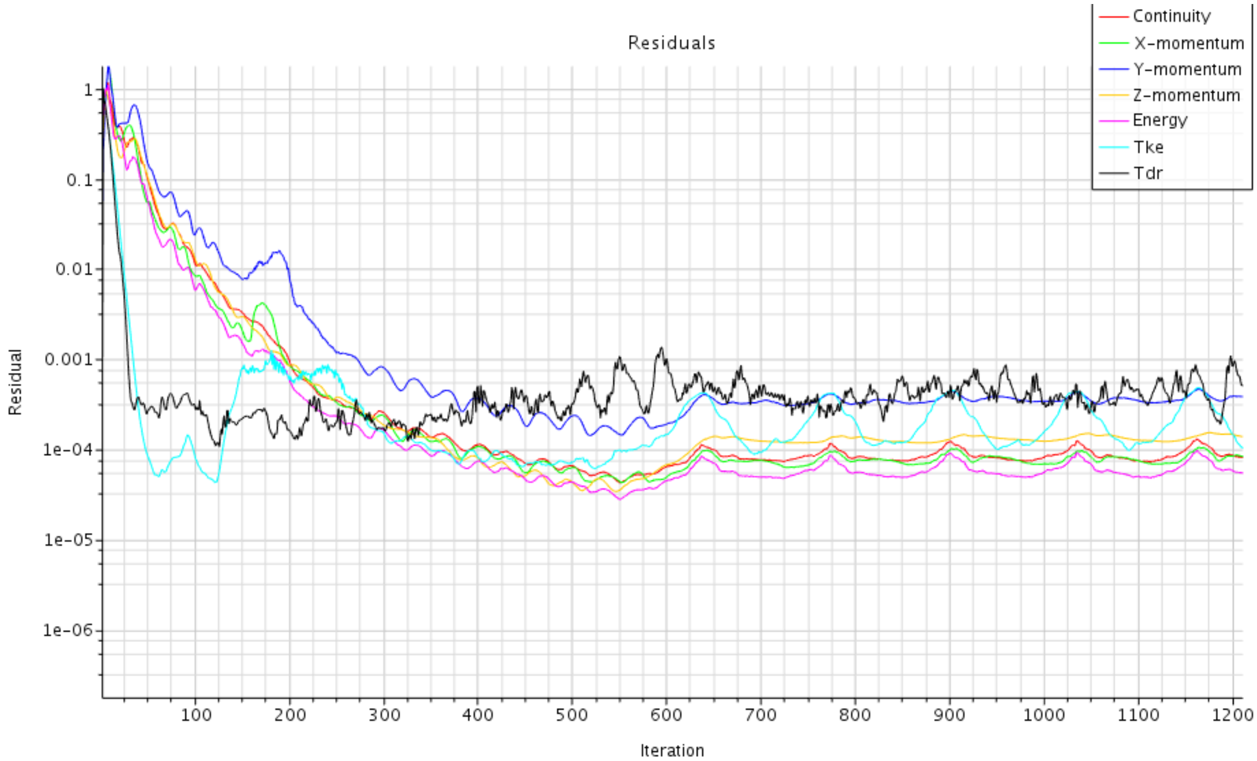

Figure 37. Plot of the residuals showing convergence.

Figure 37 shows the residuals plot. The simulation was run for 1200 iterations, and found convergence after approximately 400 iterations.

Solver Iteration CPU time was reported to be 0.391750 minutes.

Stopping criteria is shown in Table 35 above.

4.7 Post-Processing

<u>Pressure Scene</u>

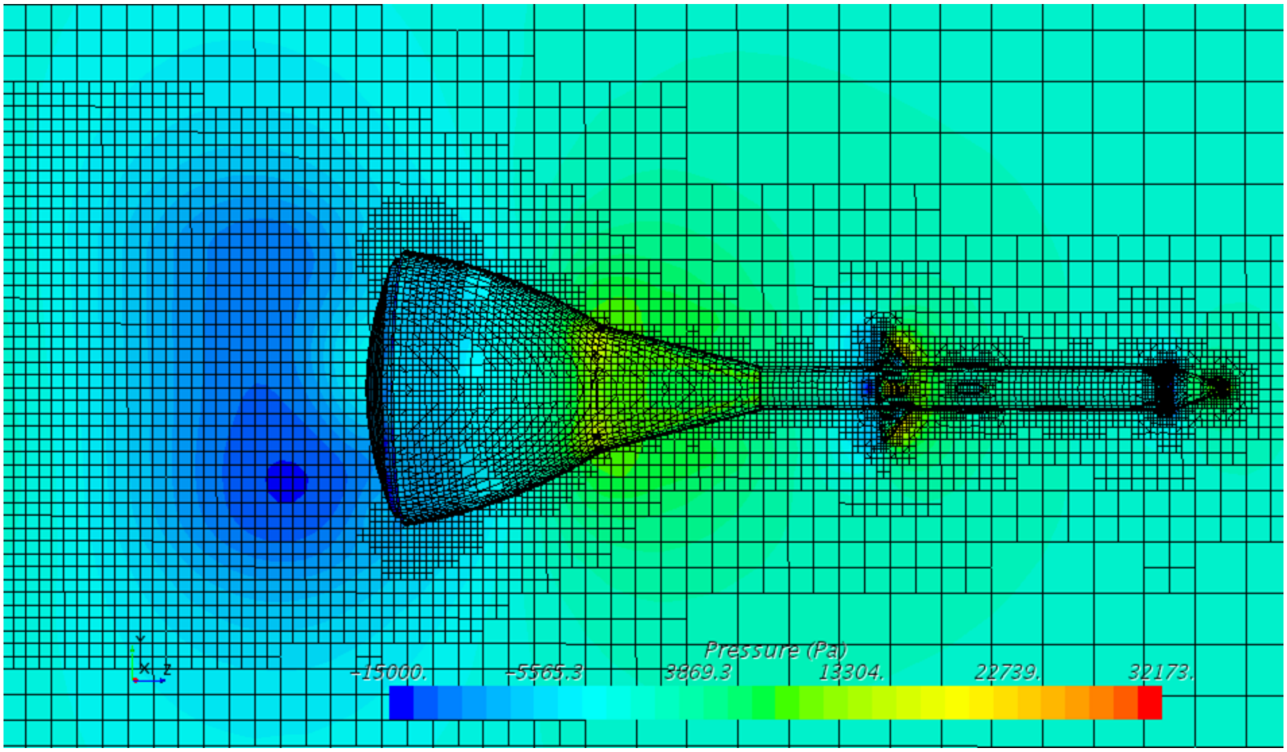

Figure 38. Pressure scene for LAS and Orion.

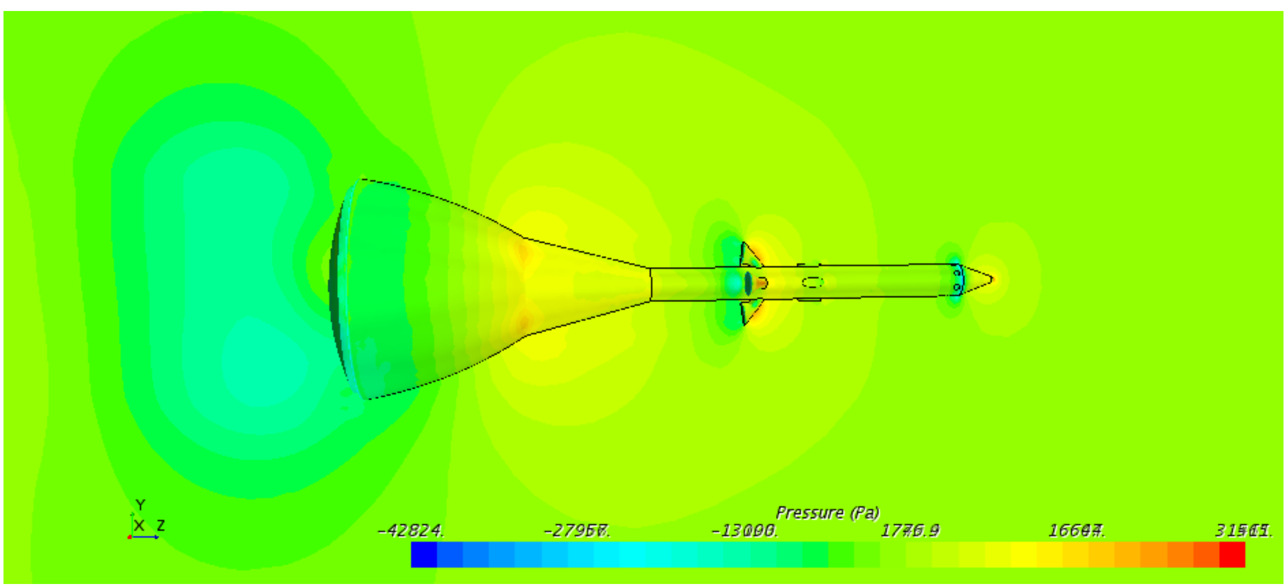

Figure 39. Contour plot of pressure for LAS and Orion.

In Figure 38, we can notice a pressure drop occurring below the abort motors as well as after the Orion capsule and around the edges of the Ogive fairing. There are high pressure locations on the nose cone tip, the top of the abort motors, and on the line between the transition cone and the Ogive fairing.

Velocity Scene

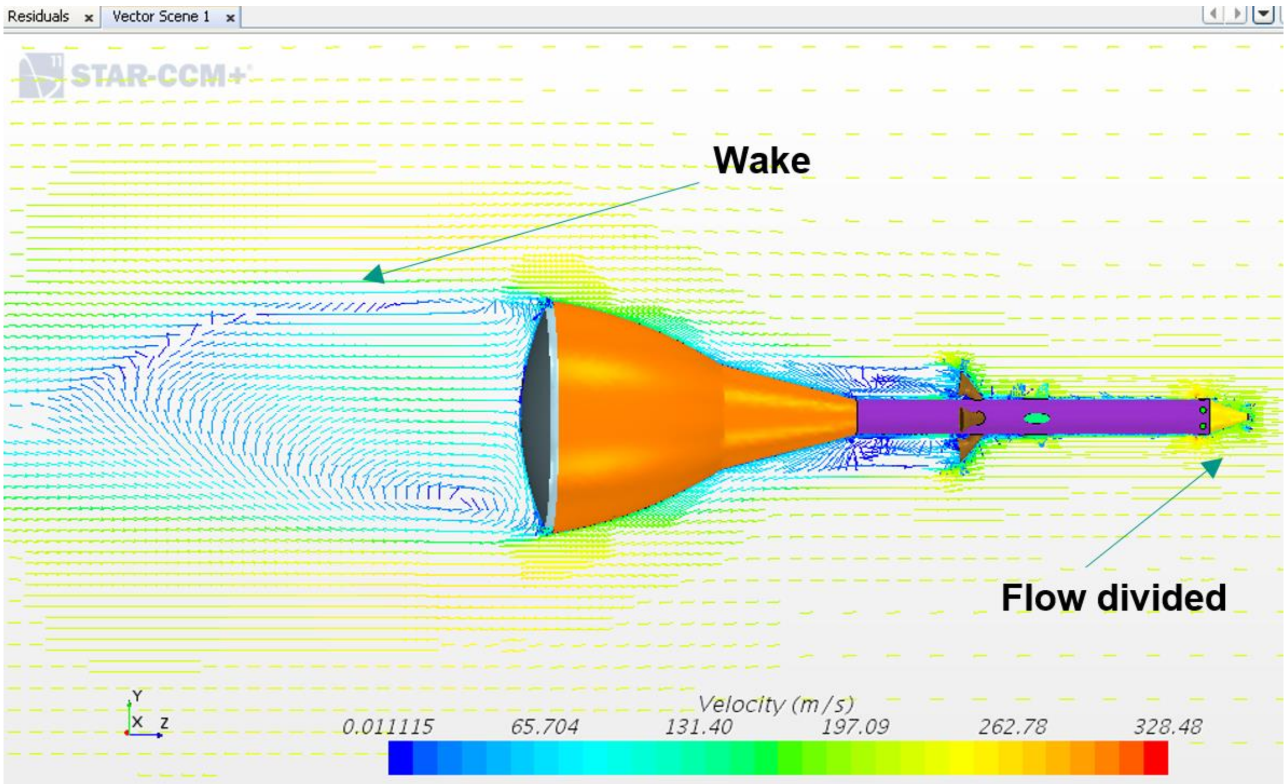

Figure 40. Vector scene for velocity magnitude for Orion and LAS.

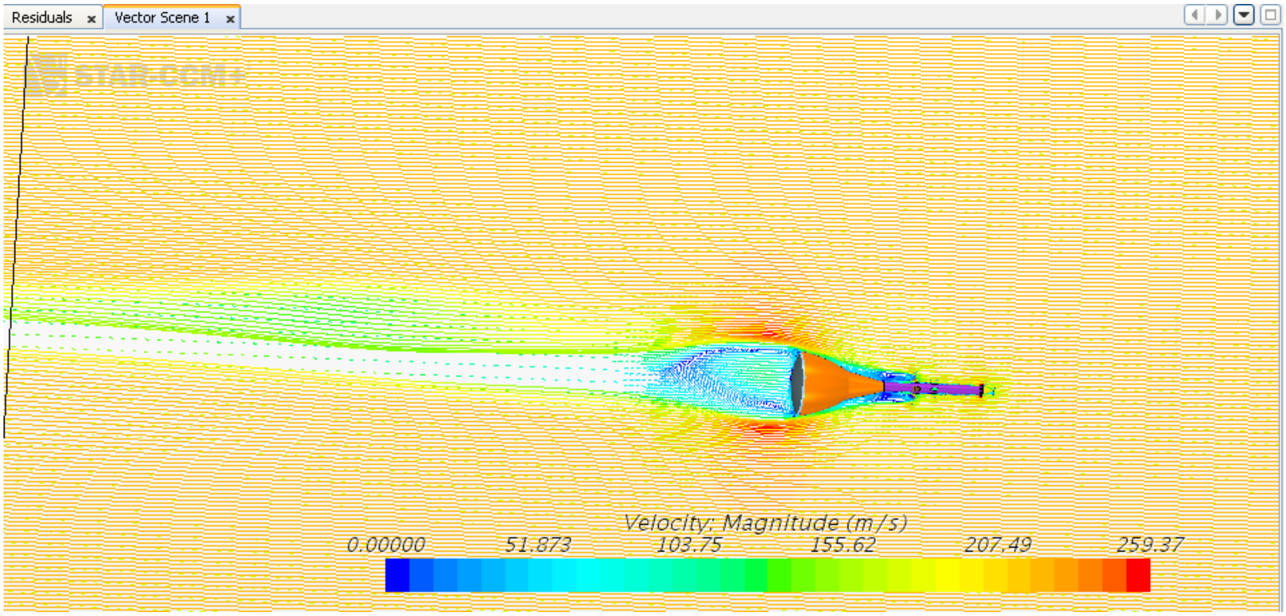

Figure 41. Vector scene showing the wake behind Orion.

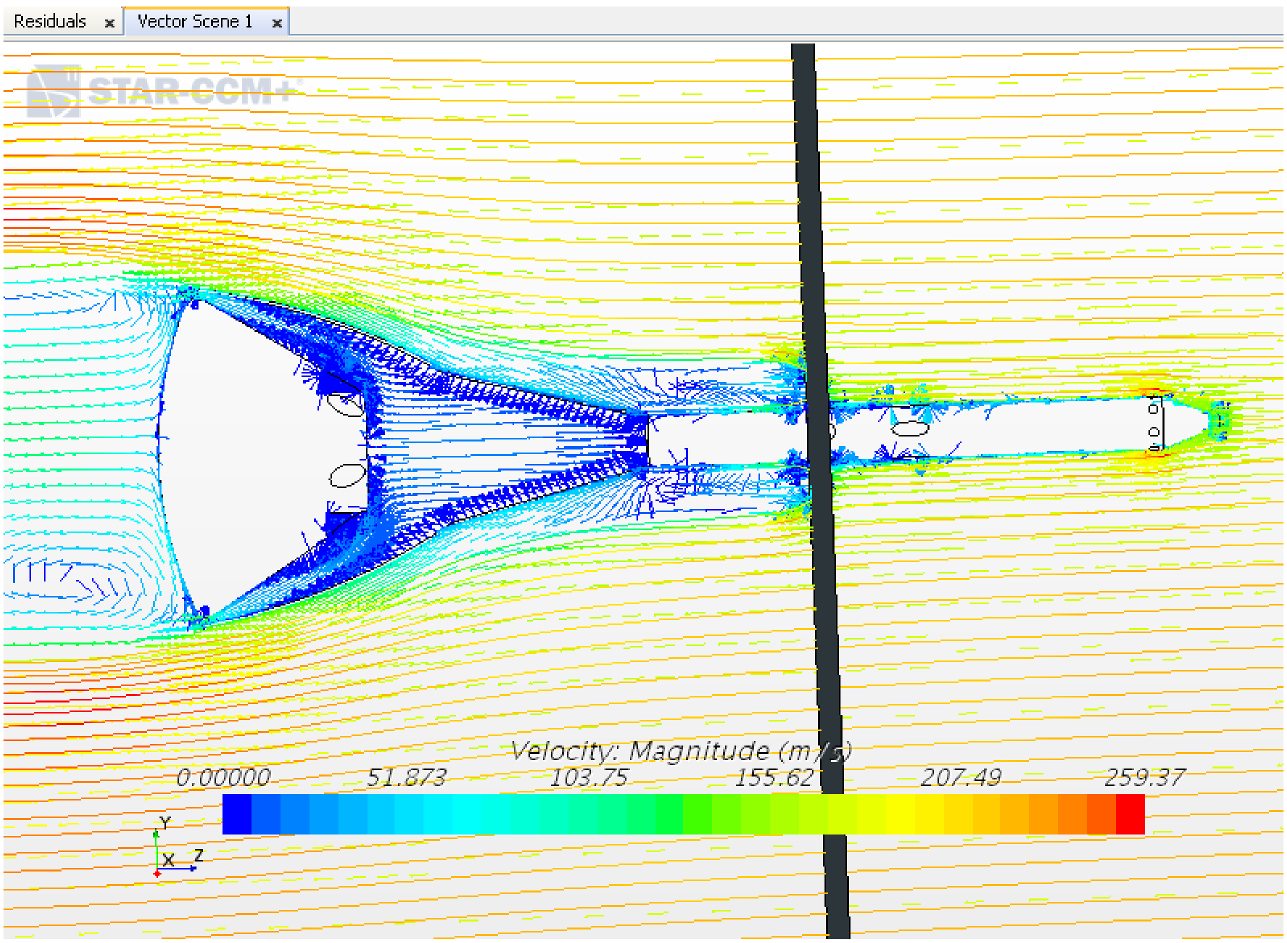

Figure 42. Vector scene showing flow inside LAS.

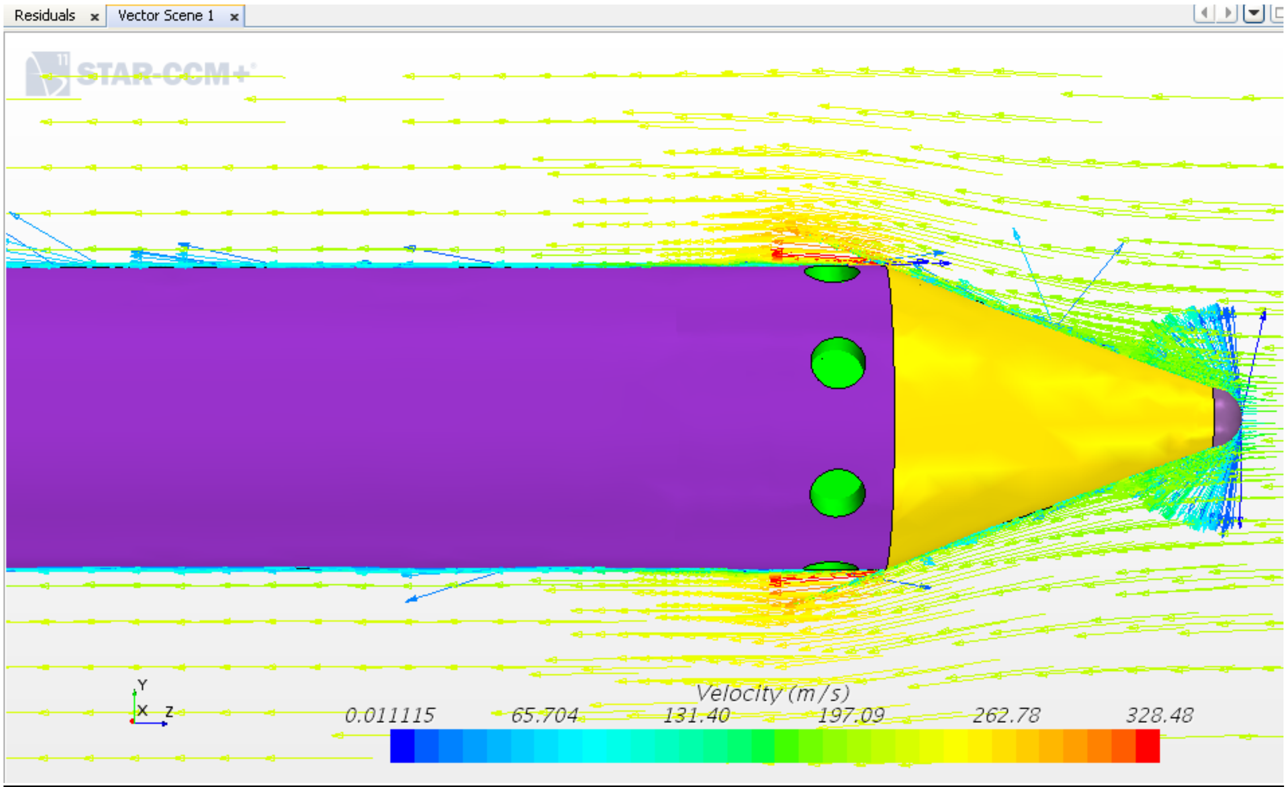

Figure 43. Vector scene showing flow at the nose cone and nose cone tip in detail.

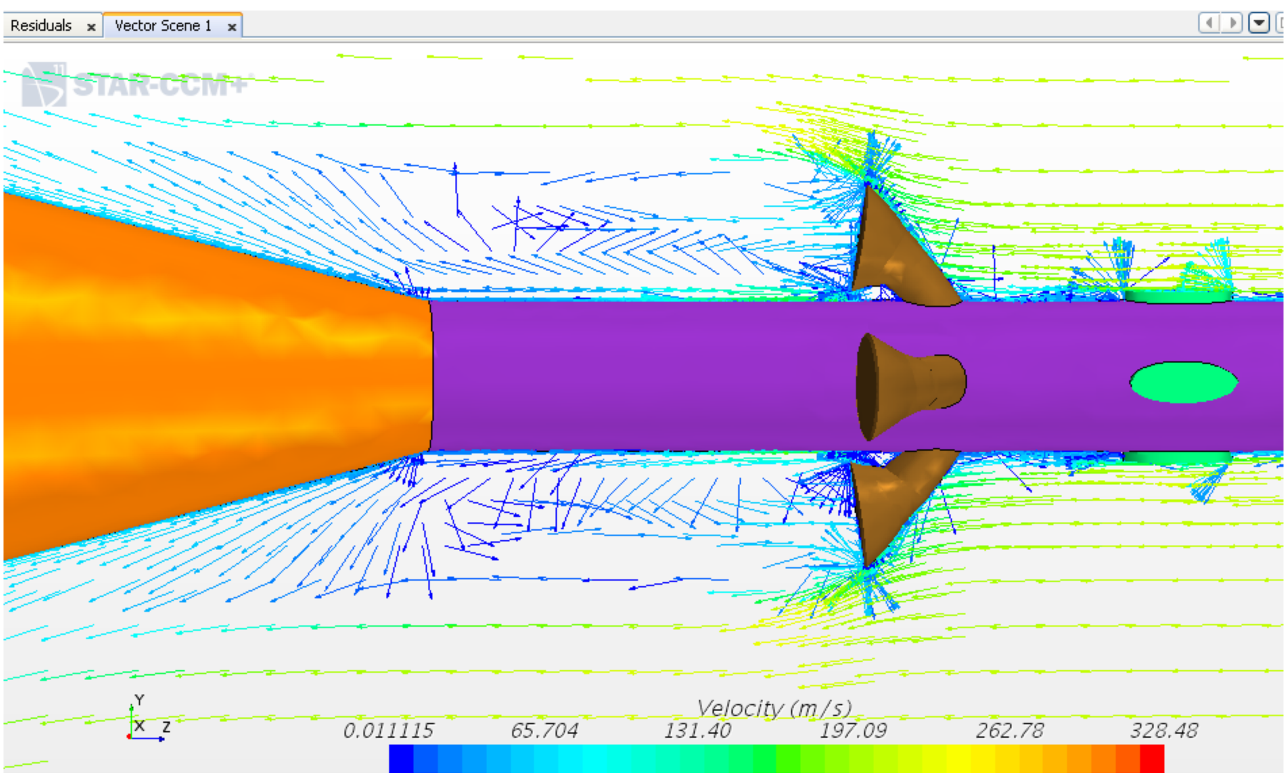

Figure 44. Vector scene showing flow at the abort motors in detail.

In Figures 40 and 41, we have pointed out the wake behind Orion and LAS. We have also shown the flow separation as the nose cone tip as expected. Figure 42 has detailed the direction of flow in vector format in the space in between the LAS and Orion. The velocity magnitude of the flow inside the LAS is considerably lower than the outside flow velocity also as expected. Figure 43 provides an excellent view of the flow separation direction using vectors at the nose cone tip. The velocity of this flow at the separation ranges from 0 m/s at the actual center tip up to approximately 160 m/s in the area immediately surrounding the nose cone tip. In Figure 43, we see the effect that the abort motors have on the incoming flow from the upper section and nose cone.

Streamlines

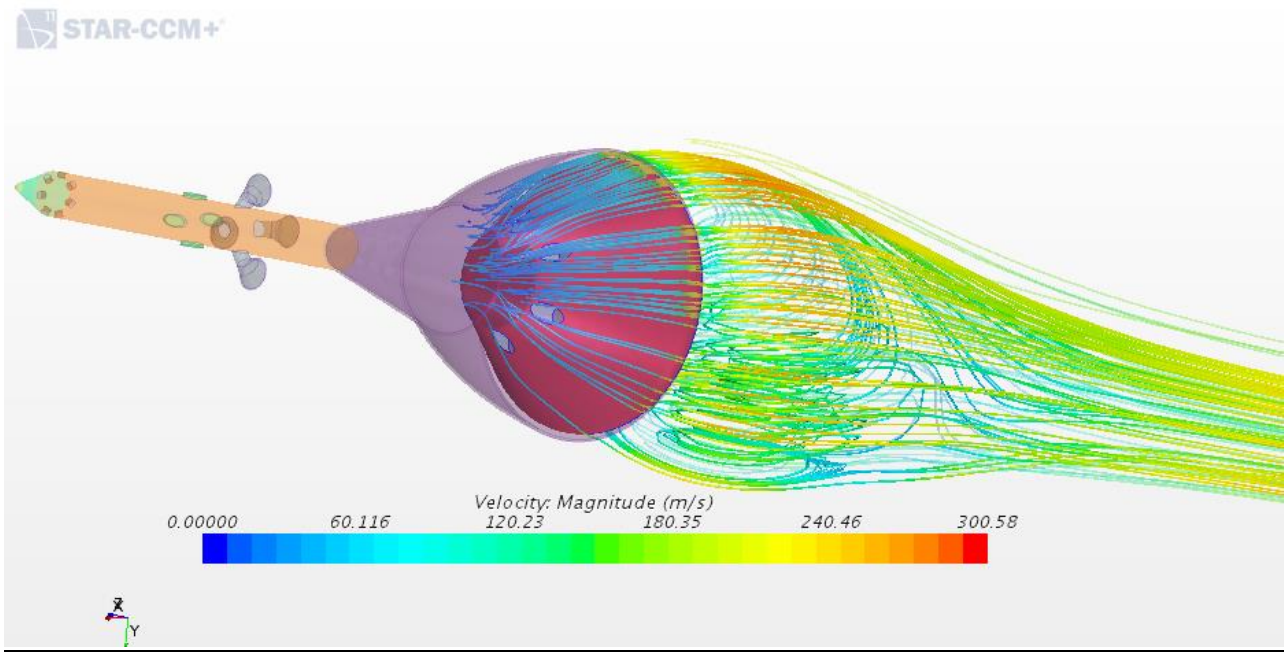

Figure 45. Streamline velocity scene for flow around and behind the Orion capsule, with semi-transparent LAS.

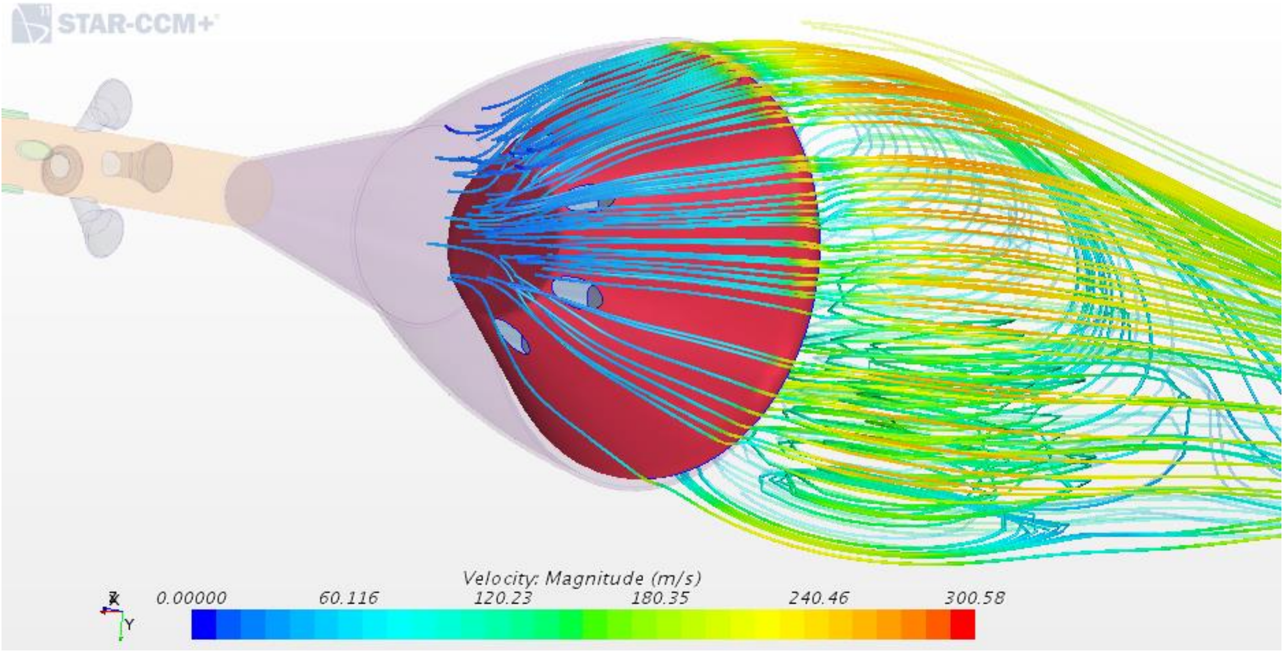

Figure 46. Streamline velocity scene for flow around and behind the Orion capsule, with semi-transparent LAS in detail.

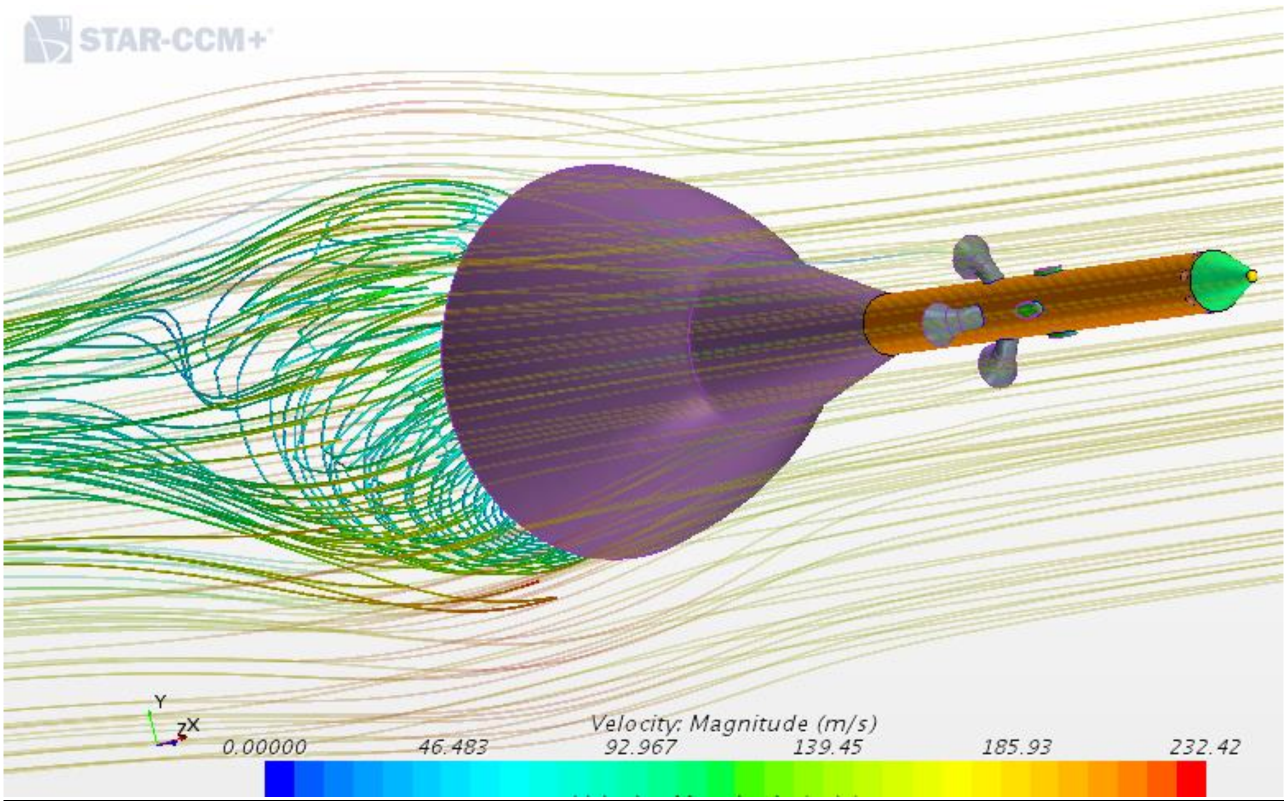

Figure 47. Streamline velocity scene showing flow around LAS and in the wake behind Orion.

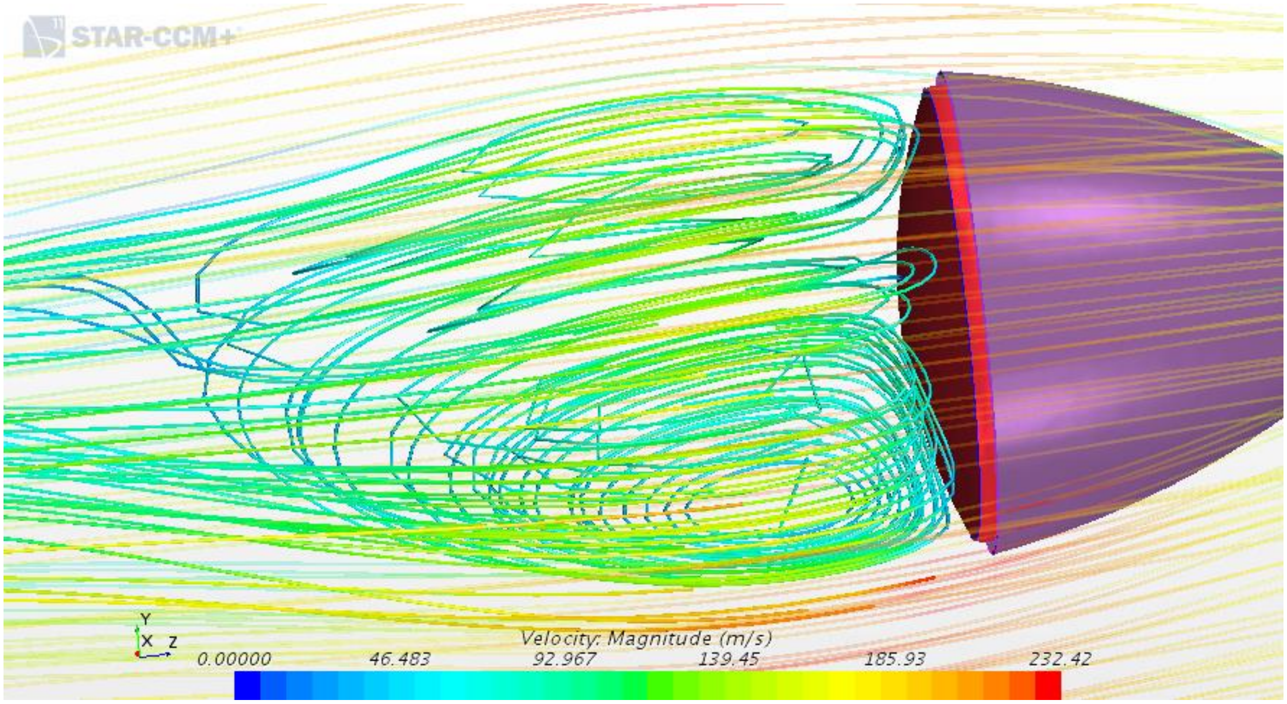

Figure 48. Streamline velocity scene showing a detail of the vortices in the wake behind Orion.

In Figure 45 and 46, we see streamlines in the cavity between the LAS and Orion, which allows one to visualize the flow around the Orion surfaces in this low pressure zone. Notice the high pressure spike at the exit boundary where the Ogive fairing ends, averaging about 220 m/s in this ring-shaped zone. We also notice the vortices behind Orion, shown in detail in Figures 47 and 48. It is possible to see Karman vortices at these locations. This creates a backpressure zone as the turbulent flow travels up to the surface of the heat shield, then follows the circular vortex pattern with an approximate velocity magnitude range of 60 m/s up to 160 m/s.

Another noticeable feature is the change in flow velocity immediately after exiting from the LAS-Orion cavity. There is a sharp decrease in velocity from about 190 m/s down to 150 m/s, which quickly transitions back up to about 280 m/s in the outer flow following this cavity, which flows around the vortex behind Orion. A smooth transition follows this region.

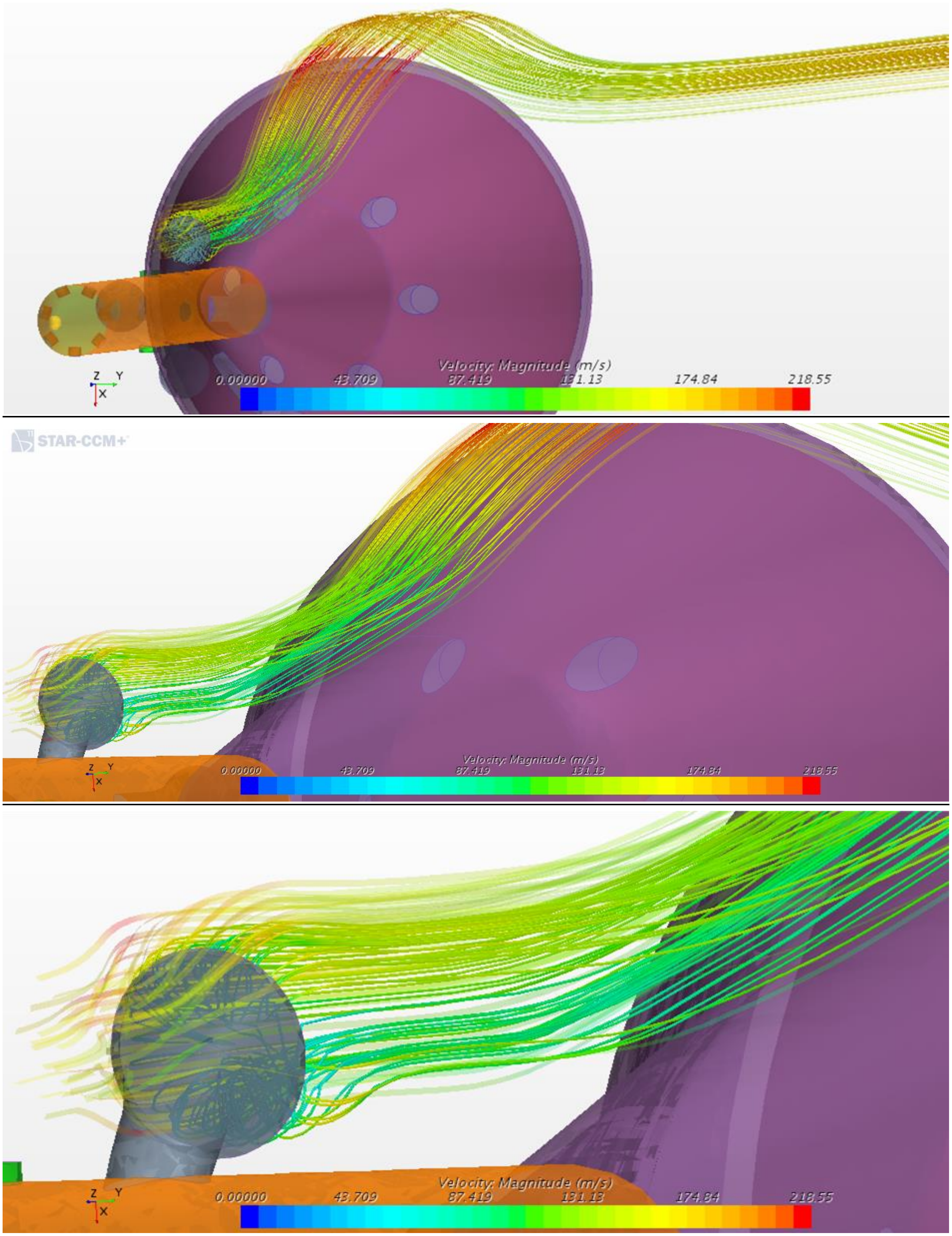

Figure 49. Streamline velocity for single abort motor with a progressively more detailed view.

In Figure 49, we can see exclusively see the flow pattern directly after one abort motor nozzle. The flow at the outer edge of the abort motor nozzle is comparable in magnitude to the flow at the edge of the Ogive fairing. However, the flow immediately after the nozzle is lower at approximately 60 m/s due to the velocity vector seen in Figure 44.

Notice how in Figure 44 we have velocity vectors pointing away from the primary direction of flow. At the boundary between the transition cone and the Ogive fairing we notice an average flow velocity of 110 m/s. Further evidence of the pressure drop after the end of the Ogive fairing surface is seen in the velocity change of the flow at this location. The flow changes from about 218 m/s at the region to 170 m/s in a very short distance.

STAR-CCM+ Report Generation

Direction: [0.0, 0.0, -1.0]
Coordinate System: Laboratory
Reference Density: 1.223 kg/m^3
Reference Velocity: 222.22 m/s
Reference Area: 1.0 m^2

Vectors

Part Pressure() Shear() Net()
------------------------------ --- --- ---
Surface Wrapper_LAS.LAS.Abort Motors [-1.548205e+00, 3.104242e-03, -4.182557e-01] [-3.775627e-04, -2.147010e-05, -2.367116e-03] [-1.548583e+00, 3.082772e-03, -4.206228e-01]
Surface Wrapper_LAS.LAS.Holes [-1.481692e-01, 8.422118e-05, -1.116934e-03] [2.941082e-06, 9.044303e-07, 4.736952e-05] [-1.481663e-01, 8.512561e-05, -1.069565e-03]
Surface Wrapper_LAS.LAS.Jettison Motors [-5.909185e-01, -9.450792e-04, -8.961314e-03] [-3.954153e-05, 7.244989e-06, -4.892498e-04] [-5.909580e-01, -9.378343e-04, -9.450563e-03]
Surface Wrapper_LAS.LAS.Nose cone transition [-1.474436e+00, -1.580514e-03, 8.701103e-01] [-2.858216e-04, -9.469007e-06, -1.673678e-03] [-1.474722e+00, -1.589983e-03, 8.684366e-01]
Surface Wrapper_LAS.LAS.Nose tip [-3.214629e-02, 7.014489e-06, 3.280658e-02] [-1.843670e-05, 2.132204e-07, -4.697214e-05] [-3.216472e-02, 7.227710e-06, 3.275960e-02]
Surface Wrapper_LAS.LAS.Ogive fairing [-4.317913e+00, -1.456617e-01, -7.253584e-01] [-1.032277e-02, -5.915930e-04, -6.374621e-02] [-4.328235e+00, -1.462533e-01, -7.891046e-01]
Surface Wrapper_LAS.LAS.Upper section Front [-2.160884e+01, -1.979271e-03, -2.863159e-02] [-1.565301e-04, -6.955638e-05, -1.073156e-02] [-2.160899e+01, -2.048827e-03, -3.936315e-02]
Surface Wrapper_Orion.Orion.Orion_Holes [-1.520898e-01, -2.071588e-01, 9.533592e-01] [-1.395355e-05, 4.277744e-06, 1.449804e-05] [-1.521037e-01, -2.071545e-01, 9.533737e-01]
Surface Wrapper_Orion.Orion.Orion_Main [-3.827995e+01, -3.166025e-02, -4.237526e+00] [-4.798279e-03, -2.599266e-03, -4.524943e-03] [-3.828475e+01, -3.425952e-02, -4.242051e+00]
------------------------------ --- --- ---
Totals: [-6.815266e+01, -3.857901e-01, -3.563574e+00] [-1.600996e-02, -3.278714e-03, -8.351786e-02] [-6.816867e+01, -3.890688e-01, -3.647092e+00]

Component in direction: [0.000000e+00, 0.000000e+00, -1.000000e+00] in Laboratory coordinate system
Part Pressure() Shear() Net()
------------------------------ ------------- ------------- -------------
Surface Wrapper_LAS.LAS.Abort Motors 4.182557e-01 2.367116e-03 4.206228e-01
Surface Wrapper_LAS.LAS.Holes 1.116934e-03 -4.736952e-05 1.069565e-03
Surface Wrapper_LAS.LAS.Jettison Motors 8.961314e-03 4.892498e-04 9.450563e-03
Surface Wrapper_LAS.LAS.Nose cone transition -8.701103e-01 1.673678e-03 -8.684366e-01
Surface Wrapper_LAS.LAS.Nose tip -3.280658e-02 4.697214e-05 -3.275960e-02
Surface Wrapper_LAS.LAS.Ogive fairing 7.253584e-01 6.374621e-02 7.891046e-01
Surface Wrapper_LAS.LAS.Upper section Front 2.863159e-02 1.073156e-02 3.936315e-02
Surface Wrapper_Orion.Orion.Orion_Holes -9.533592e-01 -1.449804e-05 -9.533737e-01
Surface Wrapper_Orion.Orion.Orion_Main 4.237526e+00 4.524943e-03 4.242051e+00
------------------------------ ------------- ------------- -------------
Totals: 3.563574e+00 8.351786e-02 3.647092e+00

Monitor value: 3.6470921683272164

Figure 50. CD report.

Direction: [0.0, 1.0, 0.0]
Coordinate System: Laboratory
Reference Density: 1.223 kg/m^3
Reference Velocity: 222.22 m/s
Reference Area: 1.0 m^2

Vectors

Part Pressure() Shear() Net()
------------------------------ --- --- ---
Surface Wrapper_LAS.LAS.Abort Motors [-1.548205e+00, 3.104242e-03, -4.182557e-01] [-3.775627e-04, -2.147010e-05, -2.367116e-03] [-1.548583e+00, 3.082772e-03, -4.206228e-01]
Surface Wrapper_LAS.LAS.Holes [-1.481692e-01, 8.422118e-05, -1.116934e-03] [2.941082e-06, 9.044303e-07, 4.736952e-05] [-1.481663e-01, 8.512561e-05, -1.069565e-03]
Surface Wrapper_LAS.LAS.Jettison Motors [-5.909185e-01, -9.450792e-04, -8.961314e-03] [-3.954153e-05, 7.244989e-06, -4.892498e-04] [-5.909580e-01, -9.378343e-04, -9.450563e-03]
Surface Wrapper_LAS.LAS.Nose cone transition [-1.474436e+00, -1.580514e-03, 8.701103e-01] [-2.858216e-04, -9.469007e-06, -1.673678e-03] [-1.474722e+00, -1.589983e-03, 8.684366e-01]
Surface Wrapper_LAS.LAS.Nose tip [-3.214629e-02, 7.014489e-06, 3.280658e-02] [-1.843670e-05, 2.132204e-07, -4.697214e-05] [-3.216472e-02, 7.227710e-06, 3.275960e-02]
Surface Wrapper_LAS.LAS.Ogive fairing [-4.317913e+00, -1.456617e-01, -7.253584e-01] [-1.032277e-02, -5.915930e-04, -6.374621e-02] [-4.328235e+00, -1.462533e-01, -7.891046e-01]

Surface Wrapper_LAS.LAS.Upper section Front [-2.160884e+01, -1.979271e-03, -2.863159e-02] [-1.565301e-04, -6.955638e-05, -1.073156e-02] [-2.160899e+01, -2.048827e-03, -3.936315e-02]
Surface Wrapper_Orion.Orion.Orion_Holes [-1.520898e-01, -2.071588e-01, 9.533592e-01] [-1.395355e-05, 4.277744e-06, 1.449804e-05] [-1.521037e-01, -2.071545e-01, 9.533737e-01]
Surface Wrapper_Orion.Orion.Orion_Main [-3.827995e+01, -3.1660a25e-02, -4.237526e+00] [-4.798279e-03, -2.599266e-03, -4.524943e-03] [-3.828475e+01, -3.425952e-02, -4.242051e+00]
------------------------------ --- --- ---
Totals: [-6.815266e+01, -3.857901e-01, -3.563574e+00] [-1.600996e-02, -3.278714e-03, -8.351786e-02] [-6.816867e+01, -3.890688e-01, -3.647092e+00]

Component in direction: [0.000000e+00, 1.000000e+00, 0.000000e+00] in Laboratory coordinate system
Part Pressure() Shear() Net()
------------------------------ ------------- ------------- -------------
Surface Wrapper_LAS.LAS.Abort Motors 3.104242e-03 -2.147010e-05 3.082772e-03
Surface Wrapper_LAS.LAS.Holes 8.422118e-05 9.044303e-07 8.512561e-05
Surface Wrapper_LAS.LAS.Jettison Motors -9.450792e-04 7.244989e-06 -9.378343e-04
Surface Wrapper_LAS.LAS.Nose cone transition -1.580514e-03 -9.469007e-06 -1.589983e-03
Surface Wrapper_LAS.LAS.Nose tip 7.014489e-06 2.132204e-07 7.227710e-06
Surface Wrapper_LAS.LAS.Ogive fairing -1.456617e-01 -5.915930e-04 -1.462533e-01
Surface Wrapper_LAS.LAS.Upper section Front -1.979271e-03 -6.955638e-05 -2.048827e-03
Surface Wrapper_Orion.Orion.Orion_Holes -2.071588e-01 4.277744e-06 -2.071545e-01
Surface Wrapper_Orion.Orion.Orion_Main -3.166025e-02 -2.599266e-03 -3.425952e-02
------------------------------ ------------- ------------- -------------
Totals: -3.857901e-01 -3.278714e-03 -3.890688e-01

Monitor value: -0.38906883349838284

Figure 51. CL report generation.

Reference Pressure = 101325.0 Pa

Direction: [0.0, 0.0, -1.0]
Coordinate System: Laboratory

Vectors

Part Pressure(N) Shear(N) Net(N)
------------------------------ --- --- ---
Surface Wrapper_LAS.LAS.Abort Motors [-4.675105e+04, 9.373858e+01, -1.263004e+04] [-1.140123e+01, -6.483311e-01, -7.147963e+01] [-4.676245e+04, 9.309025e+01, -1.270152e+04]
Surface Wrapper_LAS.LAS.Holes [-4.474255e+03, 2.543221e+00, -3.372798e+01] [8.881163e-02, 2.731102e-02, 1.430414e+00] [-4.474167e+03, 2.570532e+00, -3.229756e+01]
Surface Wrapper_LAS.LAS.Jettison Motors [-1.784392e+04, -2.853849e+01, -2.706041e+02] [-1.194033e+00, 2.187764e-01, -1.477384e+01] [-1.784512e+04, -2.831971e+01, -2.853780e+02]
Surface Wrapper_LAS.LAS.Nose cone transition [-4.452343e+04, -4.772668e+01, 2.627466e+04] [-8.630933e+00, -2.859349e-01, -5.053992e+01] [-4.453206e+04, -4.801261e+01, 2.622412e+04]
Surface Wrapper_LAS.LAS.Nose tip [-9.707190e+02, 2.118160e-01, 9.906578e+02] [-5.567317e-01, 6.438600e-03, -1.418414e+00] [-9.712758e+02, 2.182546e-01, 9.892394e+02]
Surface Wrapper_LAS.LAS.Ogive fairing [-1.303877e+05, -4.398536e+03, -2.190359e+04] [-3.117160e+02, -1.786429e+01, -1.924940e+03] [-1.306994e+05, -4.416400e+03, -2.382853e+04]
Surface Wrapper_LAS.LAS.Upper section Front [-6.525205e+05, -5.976789e+01, -8.645861e+02] [-4.726727e+00, -2.100389e+00, -3.240600e+02] [-6.525252e+05, -6.186828e+01, -1.188646e+03]
Surface Wrapper_Orion.Orion.Orion_Holes [-4.592644e+03, -6.255558e+03, 2.878852e+04] [-4.213544e-01, 1.291747e-01, 4.377963e-01] [-4.593065e+03, -6.255429e+03, 2.878896e+04]
Surface Wrapper_Orion.Orion.Orion_Main [-1.155937e+06, -9.560423e+02, -1.279603e+05] [-1.448933e+02, -7.848983e+01, -1.366394e+02] [-1.156082e+06, -1.034532e+03, -1.280969e+05]
------------------------------ --- --- ---
Totals: [-2.058001e+06, -1.164968e+04, -1.076090e+05] [-4.834515e+02, -9.900708e+01, -2.521983e+03] [-2.058484e+06, -1.174868e+04, -1.101310e+05]

Component in direction: [0.000000e+00, 0.000000e+00, -1.000000e+00] in Laboratory coordinate system
Part Pressure(N) Shear(N) Net(N)
------------------------------ ------------- ------------- -------------
Surface Wrapper_LAS.LAS.Abort Motors 1.263004e+04 7.147963e+01 1.270152e+04
Surface Wrapper_LAS.LAS.Holes 3.372798e+01 -1.430414e+00 3.229756e+01
Surface Wrapper_LAS.LAS.Jettison Motors 2.706041e+02 1.477384e+01 2.853780e+02
Surface Wrapper_LAS.LAS.Nose cone transition -2.627466e+04 5.053992e+01 -2.622412e+04
Surface Wrapper_LAS.LAS.Nose tip -9.906578e+02 1.418414e+00 -9.892394e+02
Surface Wrapper_LAS.LAS.Ogive fairing 2.190359e+04 1.924940e+03 2.382853e+04
Surface Wrapper_LAS.LAS.Upper section Front 8.645861e+02 3.240600e+02 1.188646e+03
Surface Wrapper_Orion.Orion.Orion_Holes -2.878852e+04 -4.377963e-01 -2.878896e+04
Surface Wrapper_Orion.Orion.Orion_Main 1.279603e+05 1.366394e+02 1.280969e+05
------------------------------ ------------- ------------- -------------
Totals: 1.076090e+05 2.521983e+03 1.101310e+05

Monitor value: 110130.97566508116 N

Figure 52. Drag report.

5. Structural Analysis

The following set of images were generated using FEA software Abaqus for analysis of a three-dimensional wing.

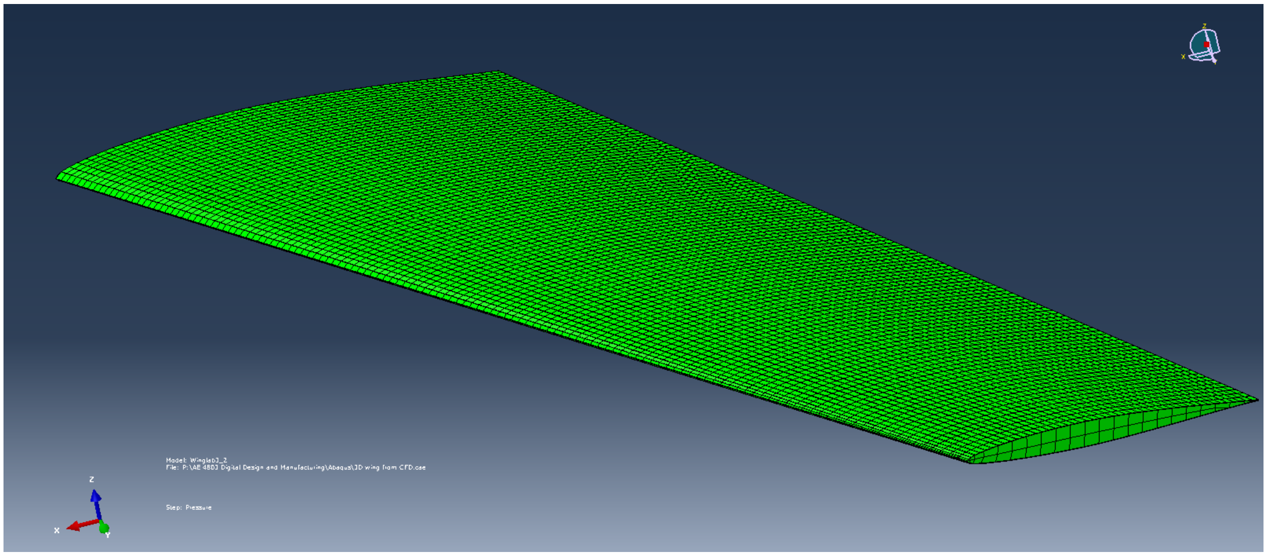

Figure 53. Mesh for three-dimensional wing in Abaqus.

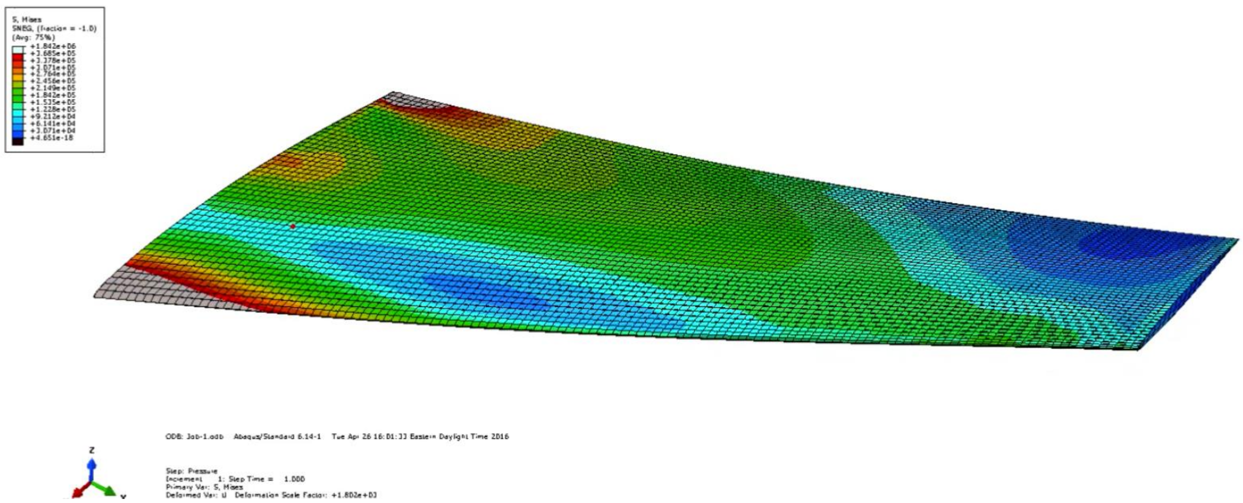

Figure 54. Von Mises stress analysis for three-dimensional wing in Abaqus.

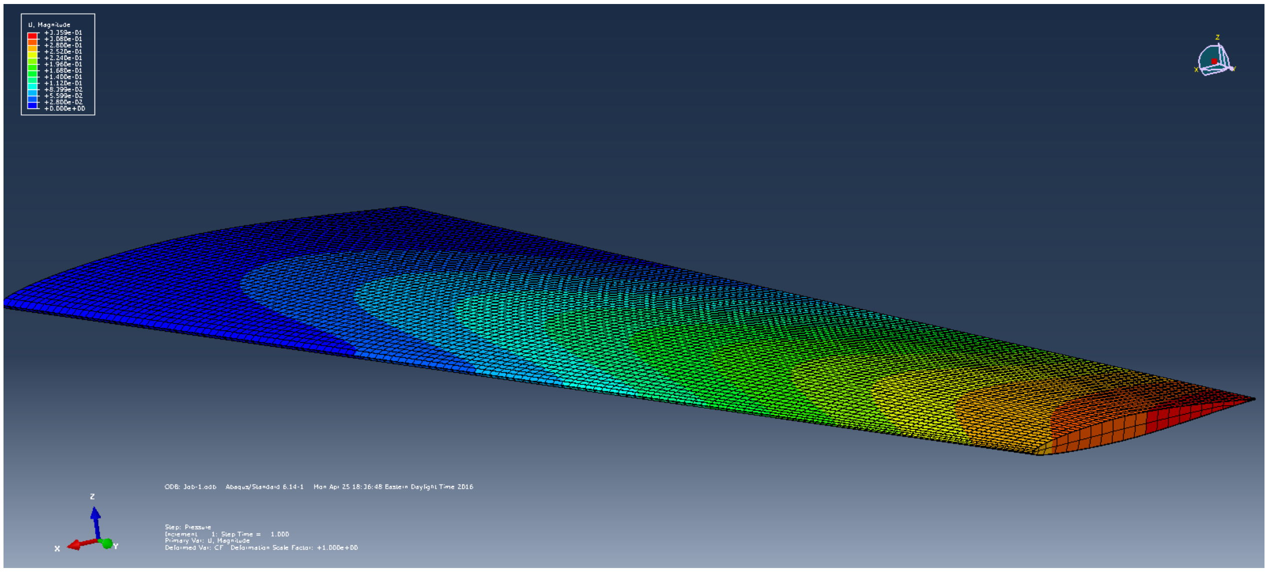

Figure 55. Original shape of three-dimensional wing in Abaqus.

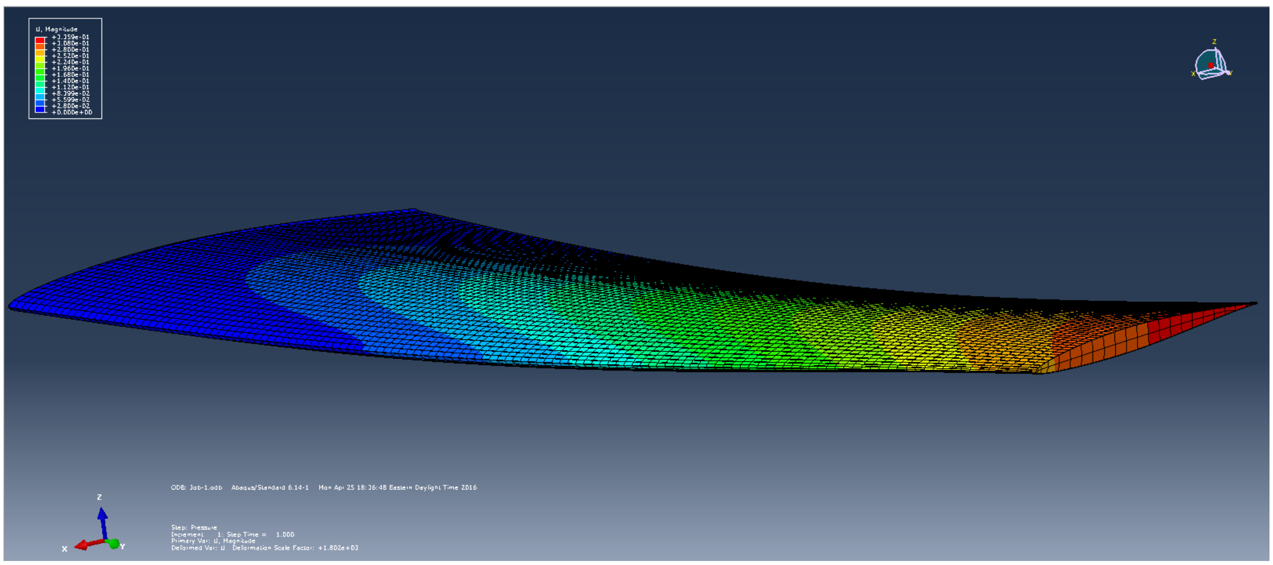

Figure 56. Deformation of three-dimensional wing in Abaqus.

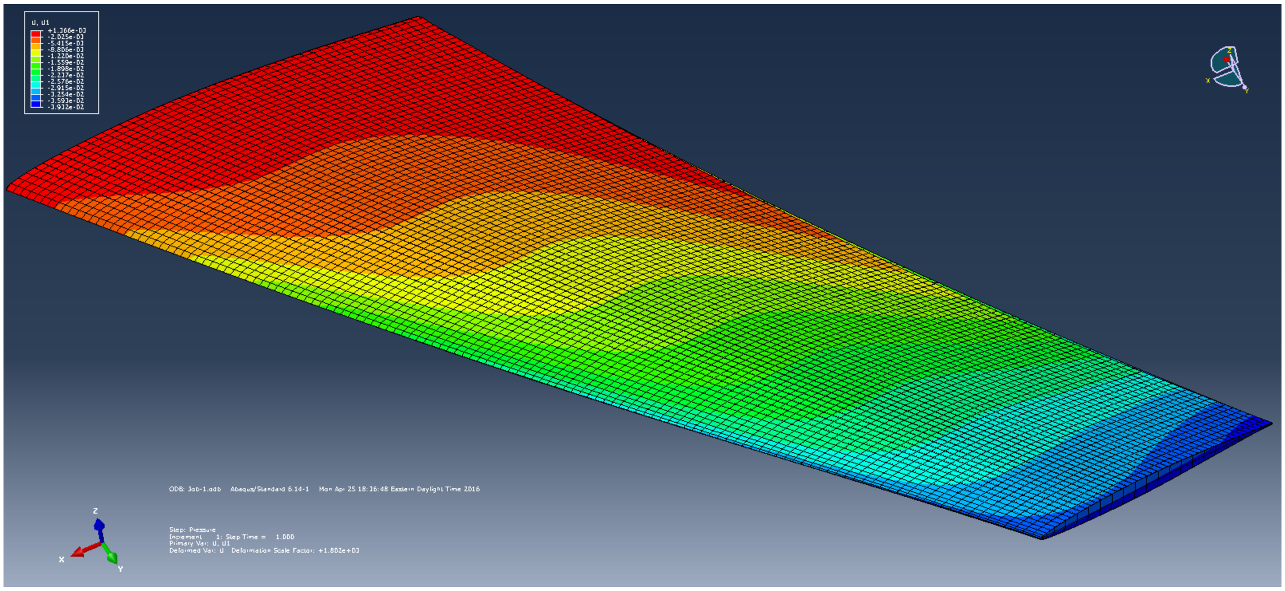

Figure 57. Stress due to deflection in the primary U1 direction.

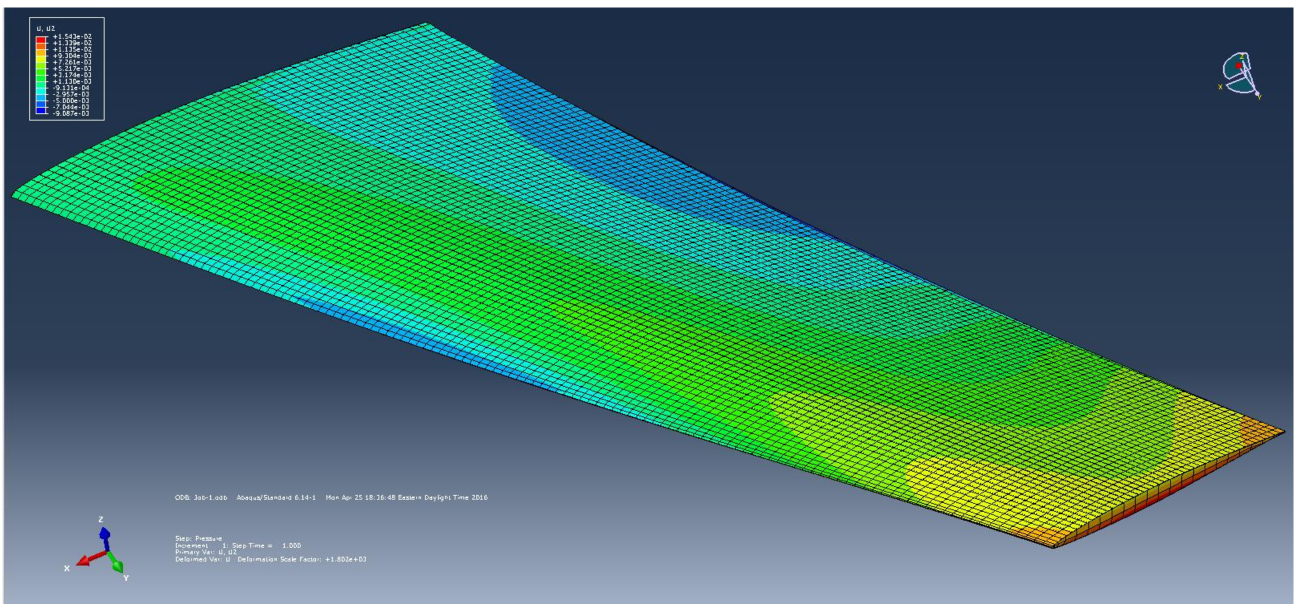

Figure 58. Stress due to deflection in the primary U2 direction.

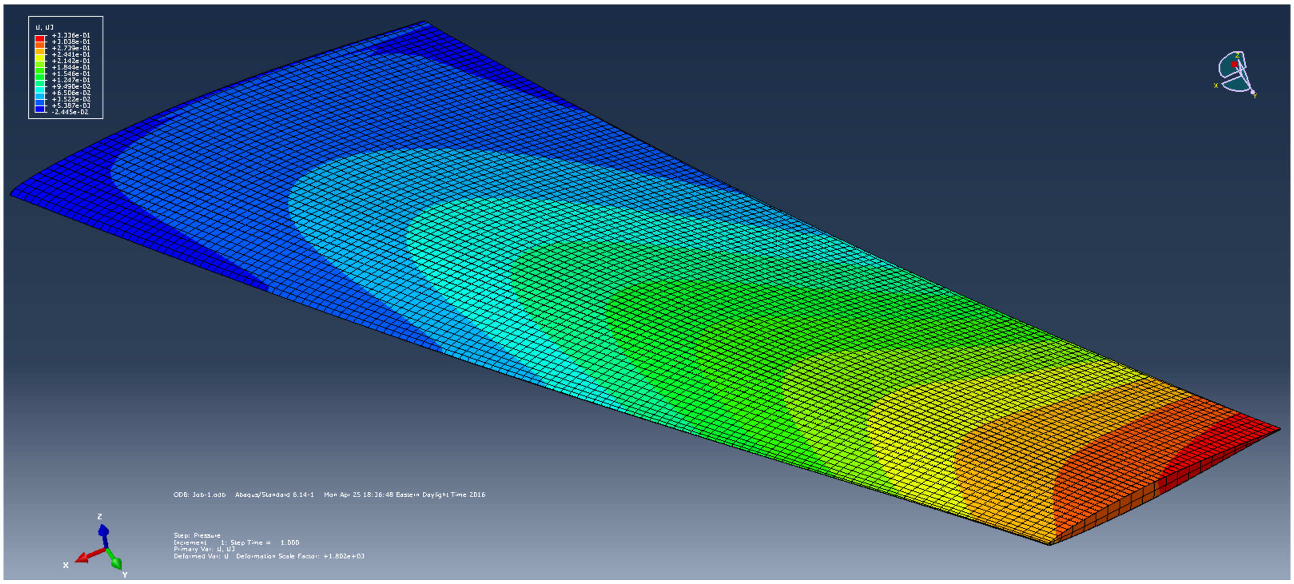

Figure 59. Stress due to deflection in the primary U3 direction.

Appendices

Sub-component CATIA modeling is shown for the Launch Abort Tower, Abort Motors, and the Orion capsule in the following sections.

Launch Abort Tower

The Launch Abort Tower (LAT) was designed by first sketching a side profile. The dimensions of the LAT were scaled off of images to match the actual baseline Launch Abort System currently designed at NASA's Langley Research Center. This gave dimensions such as the overall height, the nose cone height, pole height, transition length, and the pole, transition cone, and ogive fairing radii. The nose cone cap was created using an arc that connects to the nose cone profile to the center vehicle axis. This profile was revolved to form the LAT external surface.

Next, planes were generated on the surface of the pole, and sketches from these planes formed the basis for the Attitude Control Motors (ACM) and the Jettison Motors (JM) that were extruded and shaped in and out of the pole feature. Figure A1 below shows the base profile sketch of the LAT and the revolved model including the ACM and JM features before the Abort Motors were added.

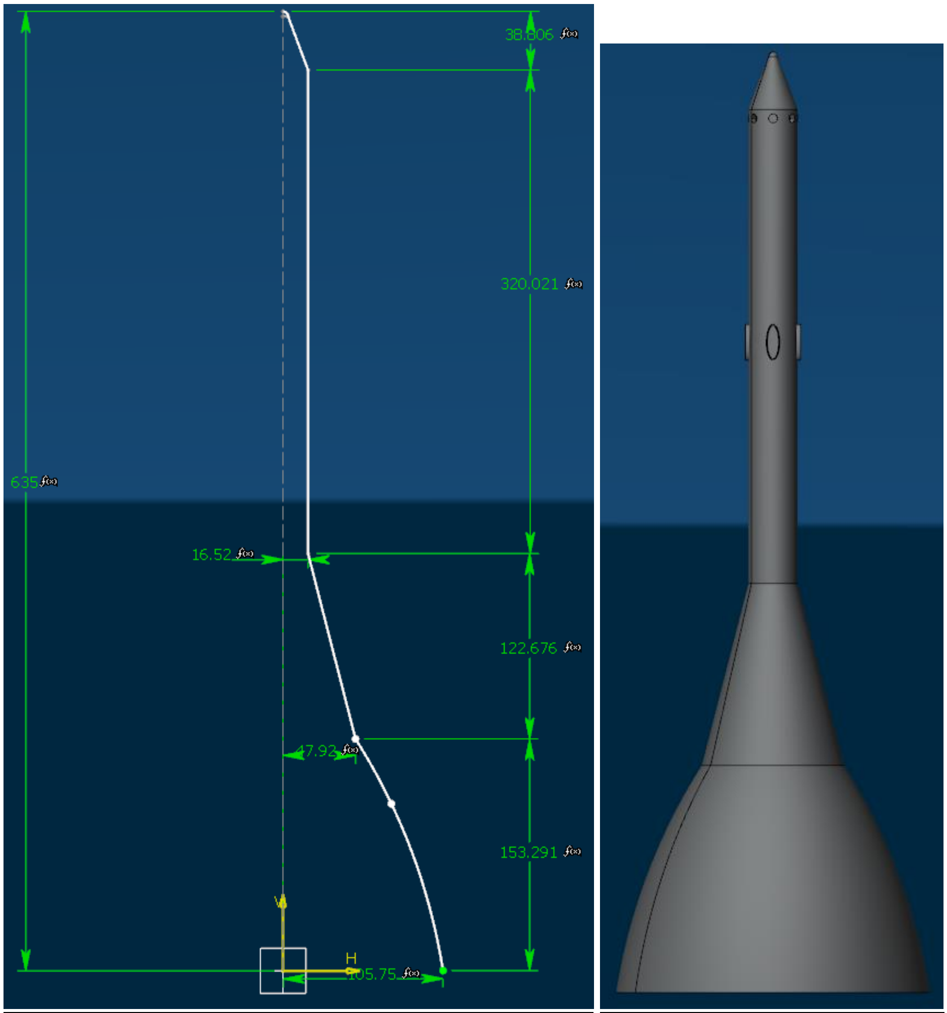

Figure A1. Sketch of the external profile for the Launch Abort Tower (left) and revolved surface with Jettison and Attitude Control Motors (right).

<u>Abort Motors</u>

The Abort Motors were added on as sub-component to the LAT, integrated directly into the LAT design itself (not a separate part).

For the design of the abort nozzles, the pre-existing designs were taken into consideration, including the relative sizes of the nozzle diameters and the angles relative to the main launch abort tower. To start, a base circle was made of a certain diameter. From this, other planes (set to specific angular differences) contained circles of diameters based off of the original circle. These circles were lofted together along with a string guide curve in order to create the nozzle design. Figures A2 through A4 shows the design process of the motors, and Figure A5 depicts the LAT integrated with the Abort Motor features.

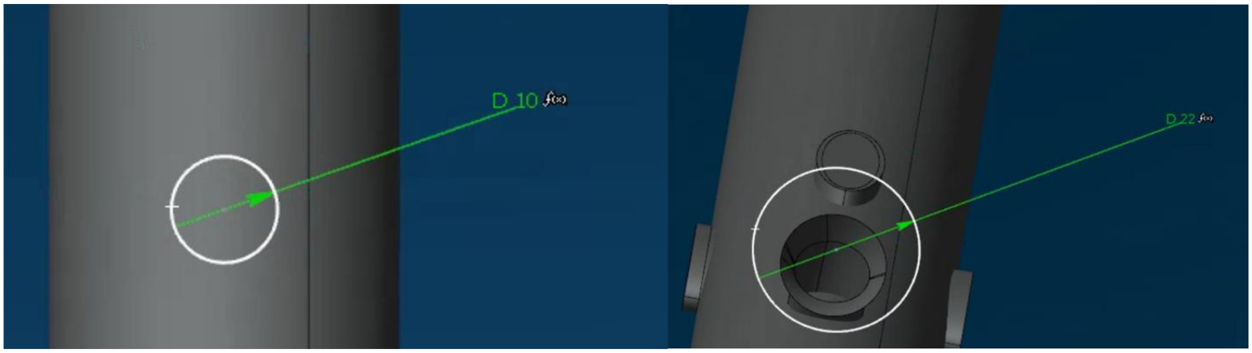

Figure A2. Abort Motor nozzle base sketch (left) and nozzle end sketch (right).

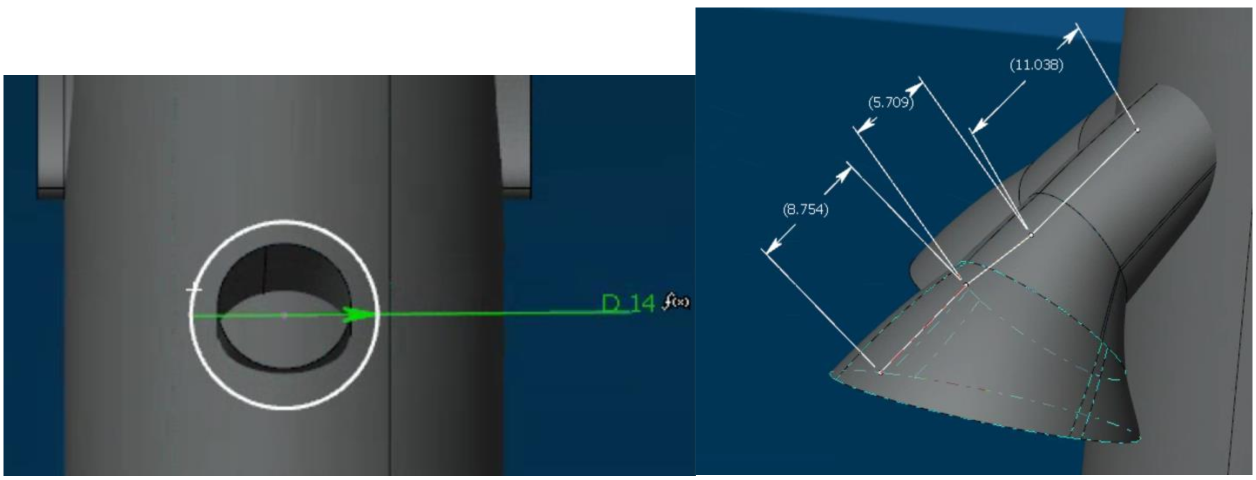

Figure A3. Abort Motor middle nozzle sketch (left) and nozzle section lengths (right).

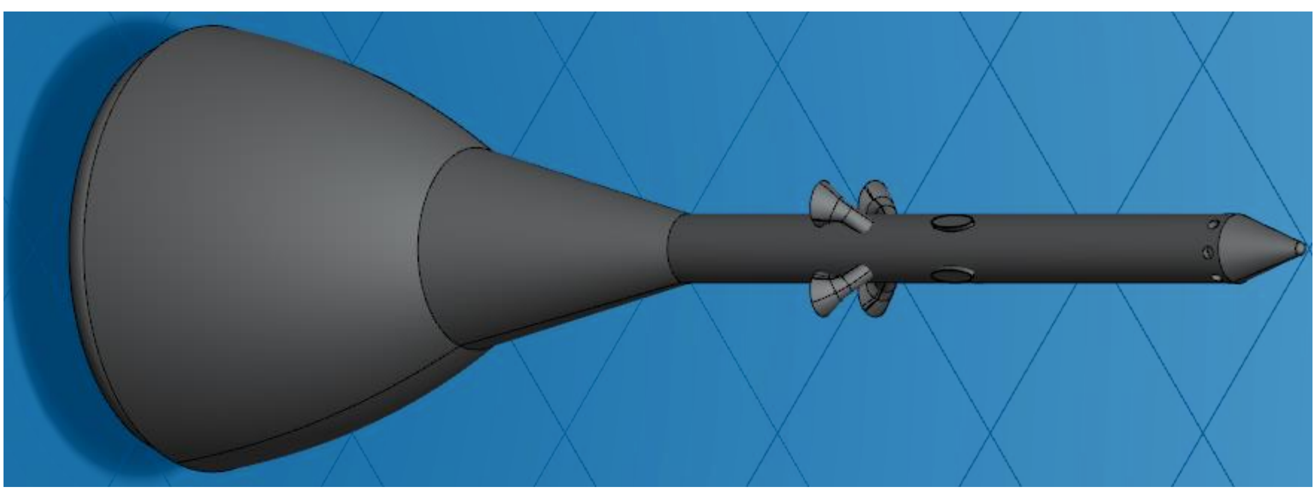

Figure A4. Abort Motors integrated into the tower design.

Orion Crew Module

In the design process of the Orion Crew Module, the starting point included the external geometry and its dimensions in the CATIA V6 software. A 2D concept was made to include all previously described parameters. It included the basic capsule shape, its windows and the thrusters. The 2D sketch was then revolved to a 3D basic surface. The sketch of the windows and of the thrusters were extruded, placed in the 3D basic surface and trimmed from it. The overall result of these operations created a 3D surface of the Orion Crew Module including features such windows, and thrusters. Those are important features in the evaluation of the external aerodynamics of the Launch Abort System. Figure A5 below depicts the Orion Crew Module sketch, and Figure A6 shows the revolved model with integrated thrusters and window features.

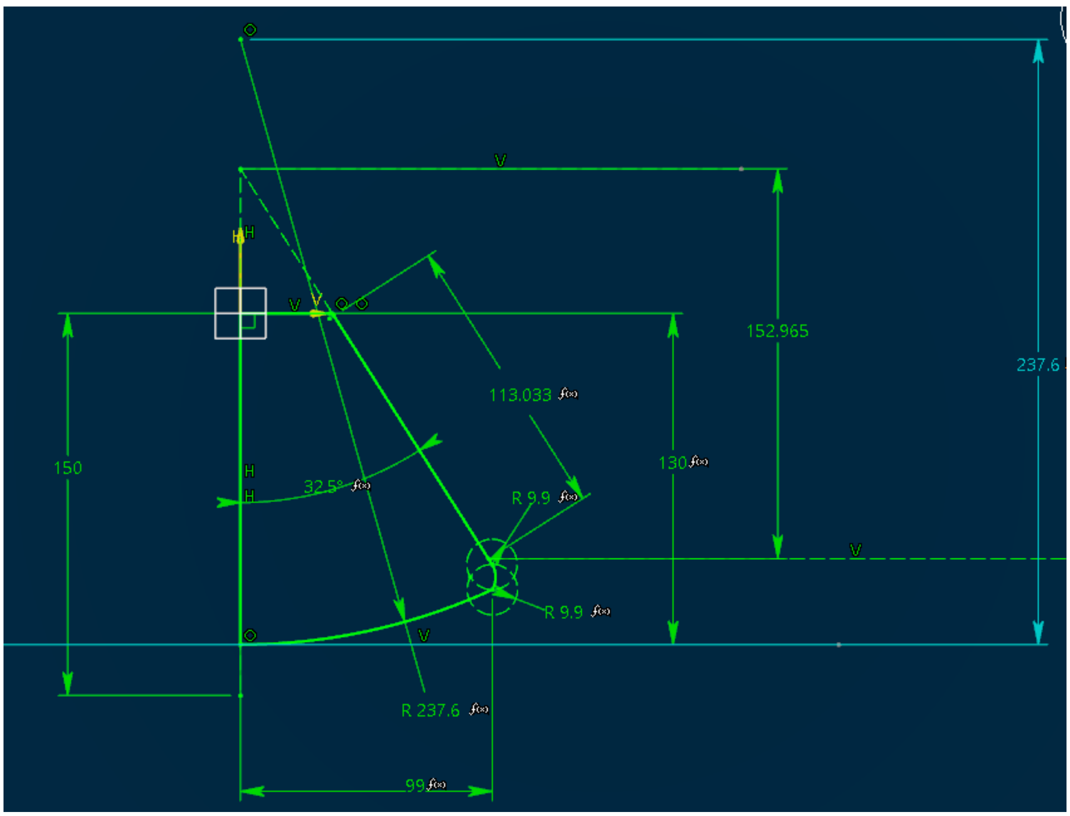

Figure A5. Orion capsule sketch.

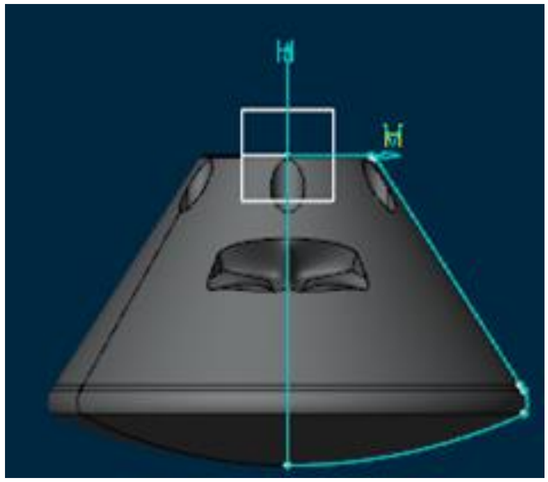

Figure A6. Revolved Orion model with RCS motors and window subcomponents integrated into the design.

Additional views for the aerodynamics analysis using STAR-CCM+ are available in the following section.

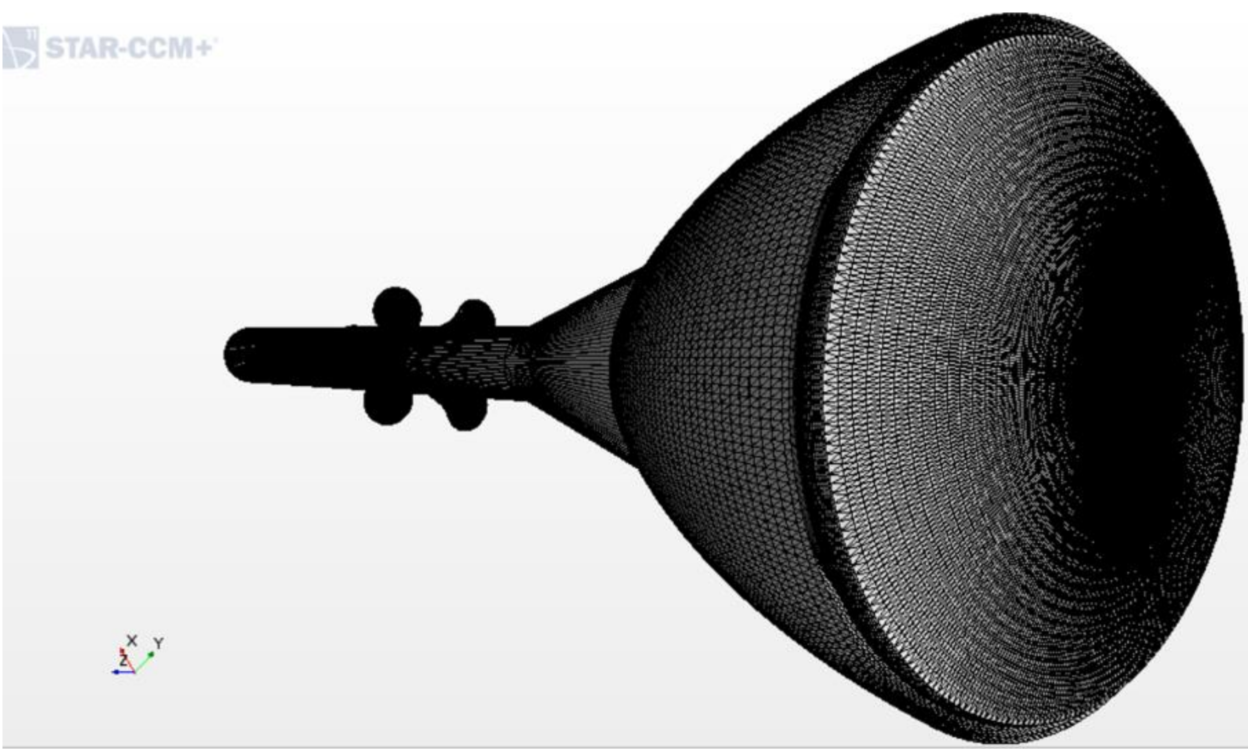

Figure A7. Original surface model from CATIA V6, view of Orion in LAS.

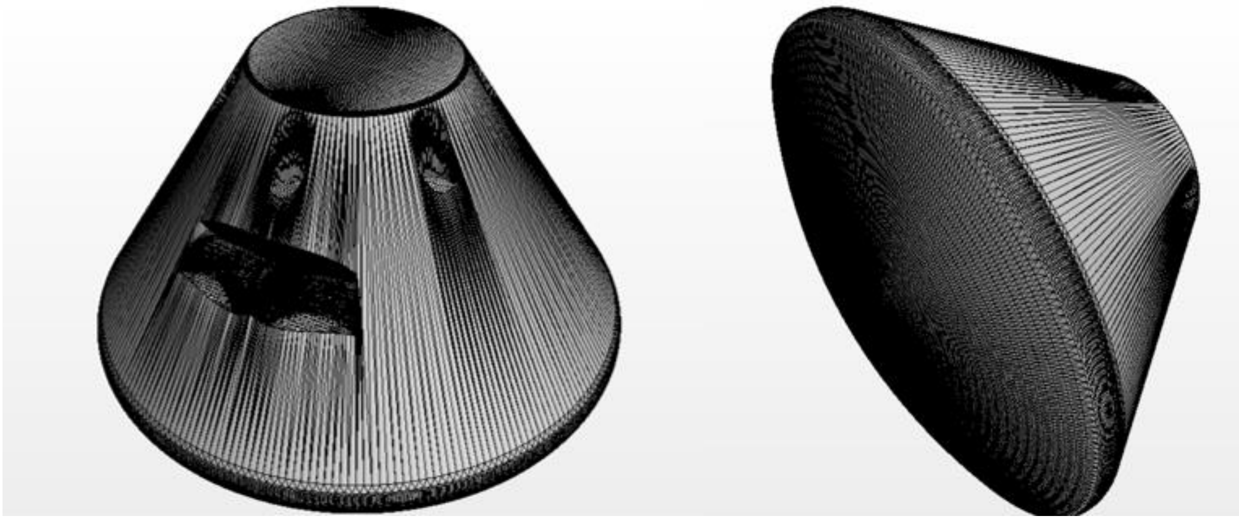

Figure A8. Original surface model from CATIA V6, view of Orion.

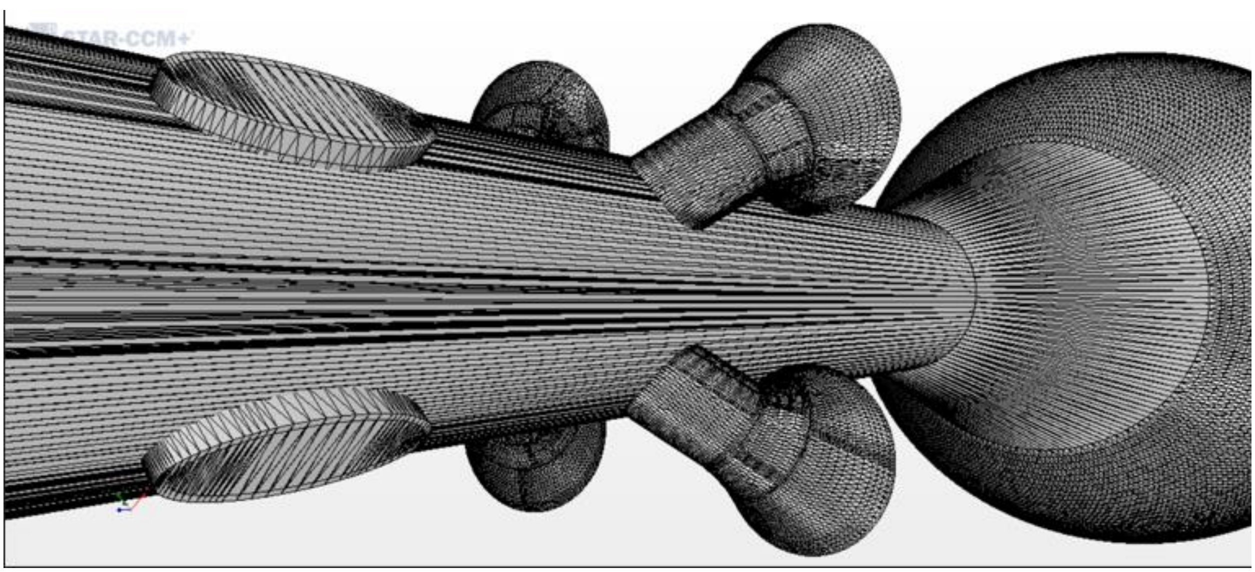

Figure A9. Original surface model from CATIA V6, detail view of abort motors.

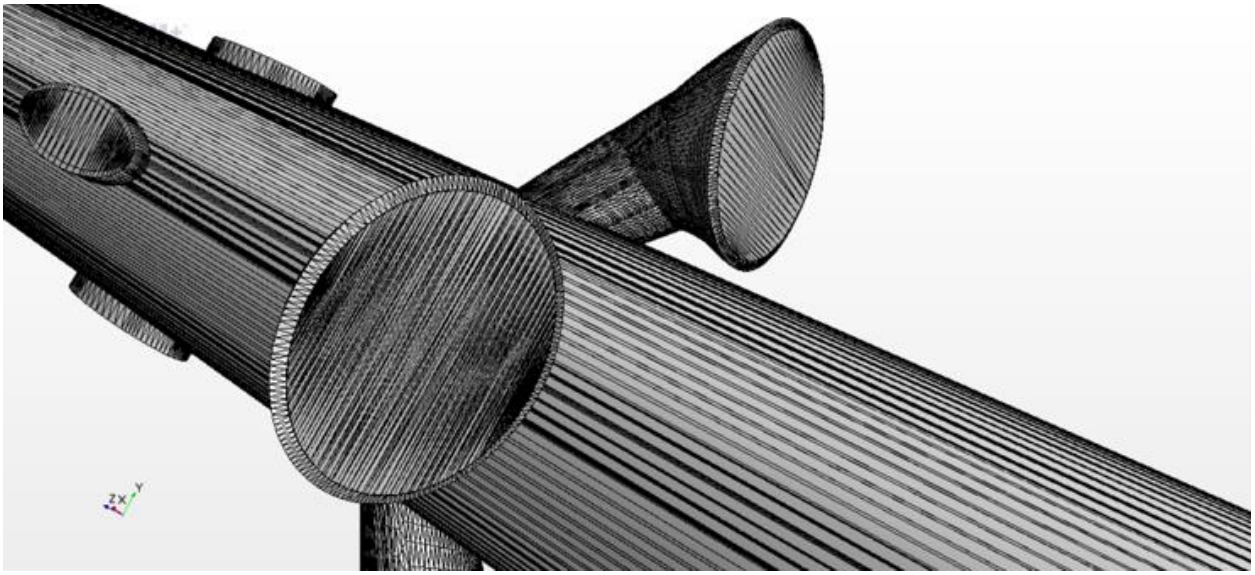

Figure A10. Original surface model from CATIA V6, detail view of caps on abort motors.

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