Development of Automated Aerodynamic Analysis Process Using Open-source Software

2023. 07.12
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NEXTFOAM

Contents

Introduction

○ Missile Aerodynamic Design

- Aerodynamic performance evaluation with data using multiple flow conditions
  - ✓ Stability, Maneuverability
- Require evaluation for a number of configuration in design stage

○ Aerodynamic Solver

- Semi-empirical code (Missile DATCOM, AeroPrediction)
  - ✓ Low computational cost, Low accuracy
- CFD
  - ✓ High computational cost, High accuracy
  - ✓ Performing tedious tasks of geometry and mesh generation

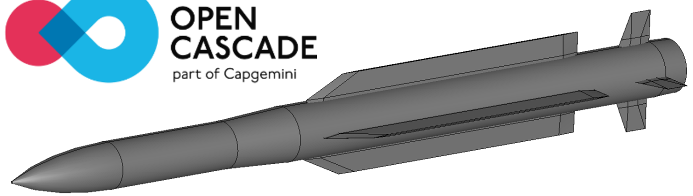
Introduction

○ Objective

- Develop automated aerodynamic analysis process for missile design
- Consists of geometry, mesh, flow analysis and post-processing modules
- Aim to minimize user intervention in each module
- All modules are developed using open-source software

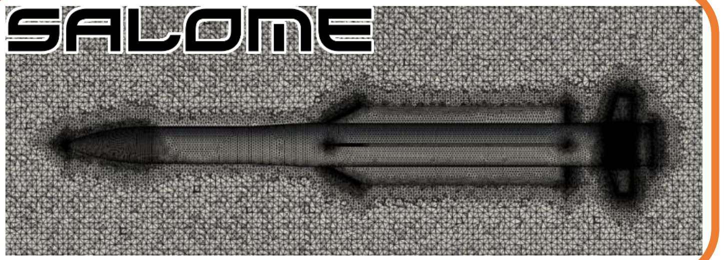
Geometry

OPEN CASCADE
part of Capgemini



Mesh

SALOME

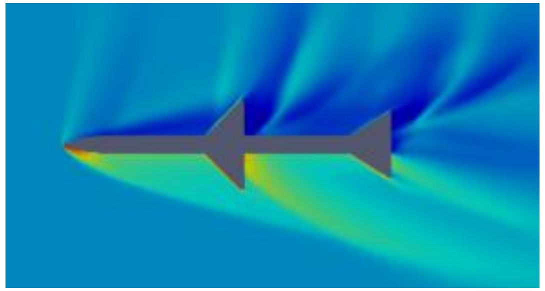


Flow Analysis

OpenFOAM®

Post-processing

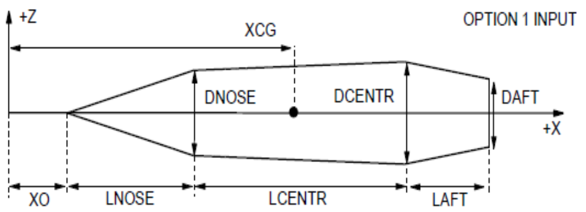
ParaView



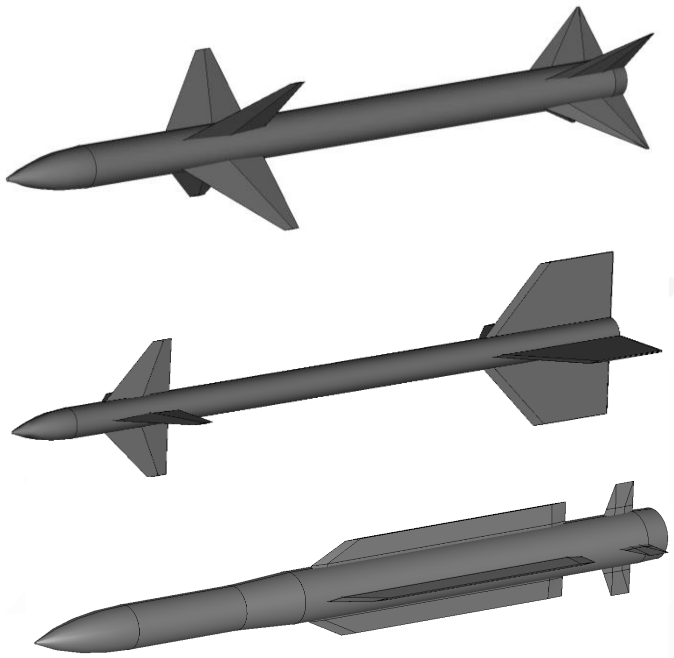
Automated Aerodynamic Analysis Process

○ Geometry Modeling

- Adopt geometry definition of Missile DATCOM
  - ✓ Axisymetric Body + Multiple Finset
  - ✓ Fin Deflection for aerodynamic control
- Geometry representation using OpenCASCADE
- Export CAD to STEP file format



OPEN CASCADE
part of Capgemini

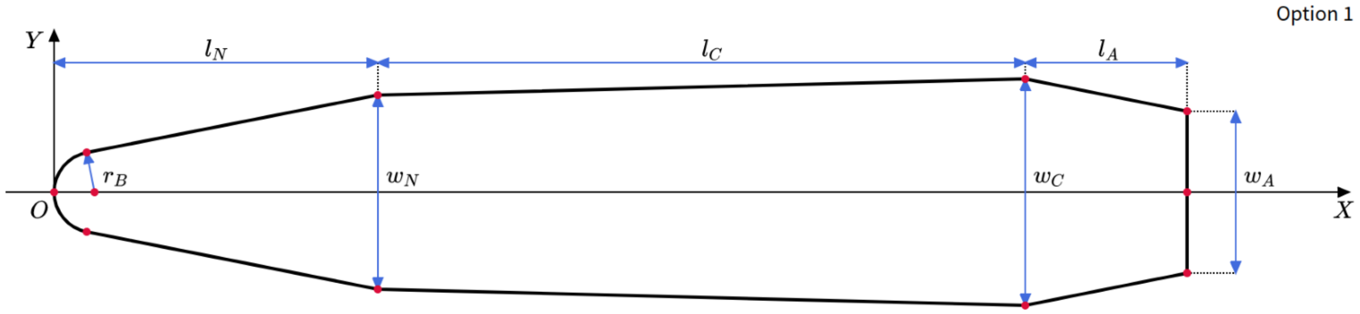


Automated Aerodynamic Analysis Process

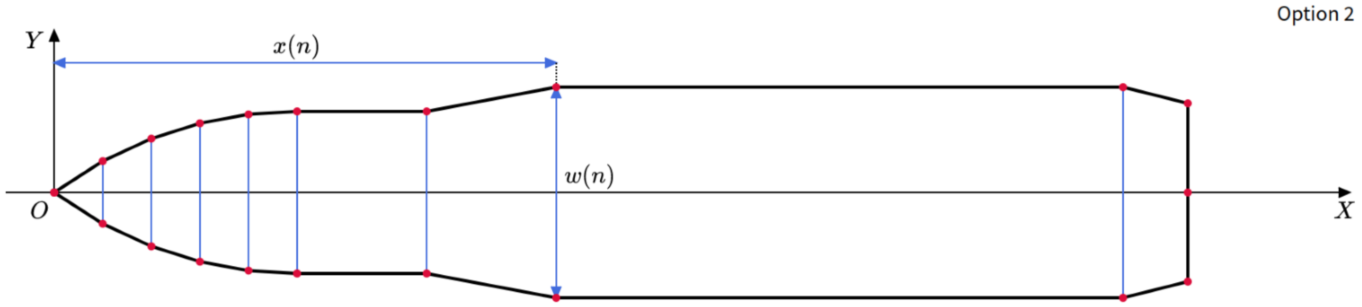
○ Geometry Modeling – Body

- Option 1 : Composition of Nose, Centerbody, Afterbody
  - ✓ Nose : Cone, Ogive, Power, Haack, Karman
  - ✓ Afterbody : Cone, Ogive

- Option 2 : Longitudinal Coordinate (X, R)



Option 1

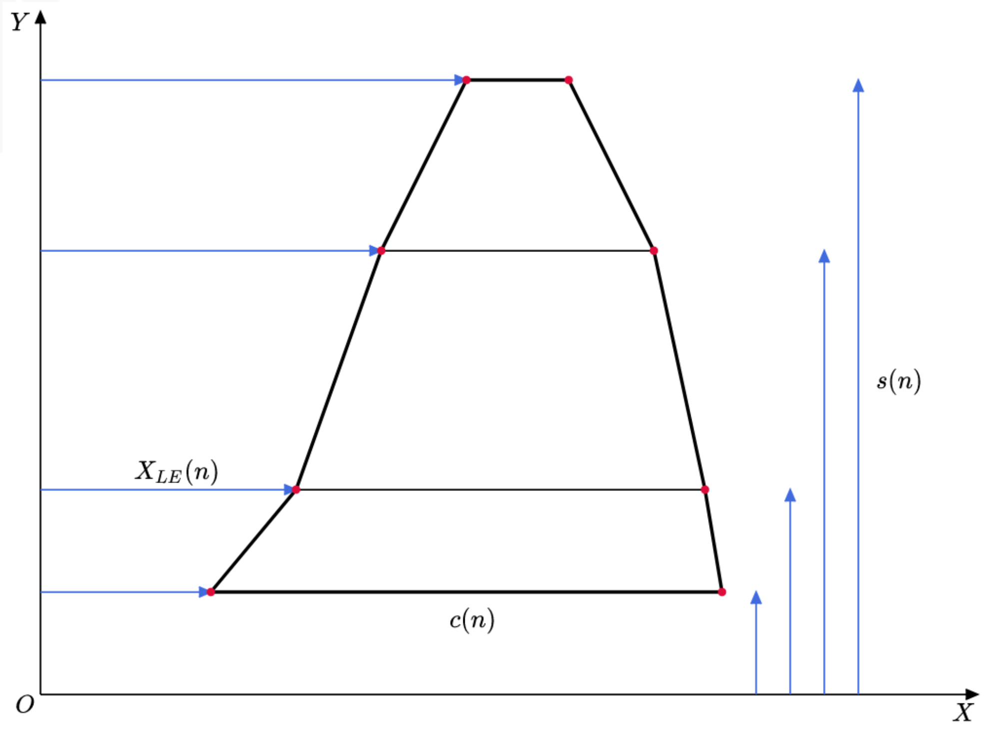


Option 2

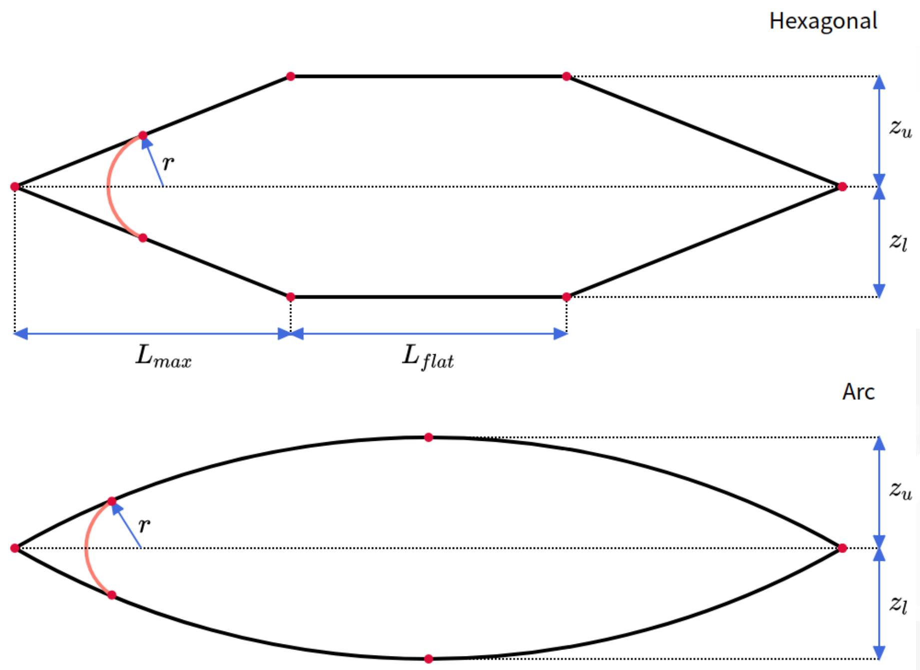
Automated Aerodynamic Analysis Process

○ Geometry Modeling – Finset

- Planform : Consist of position of leading edge, chord, semispan
- Airfoil : Support Hex, Arc and NACA 4 series



Planform

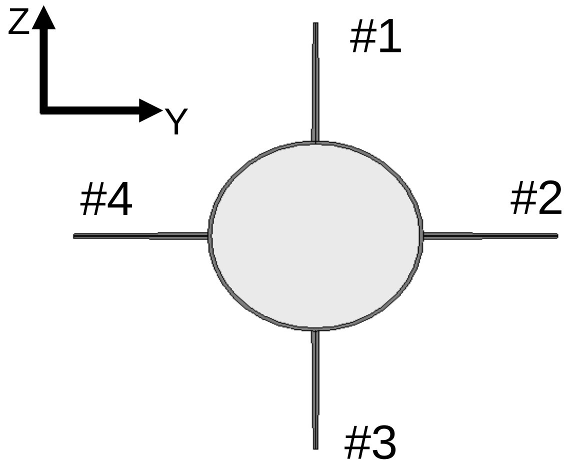


Airfoil (Hex, Arc)

Automated Aerodynamic Analysis Process

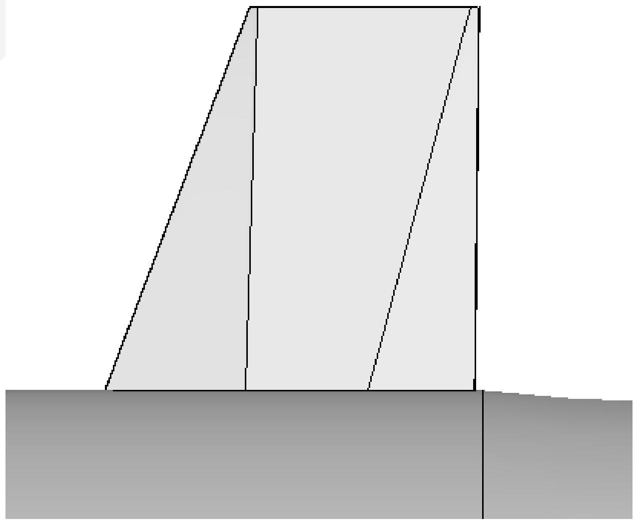
○ Geometry Modeling – Fin Deflection

- Deflection angle sign convention

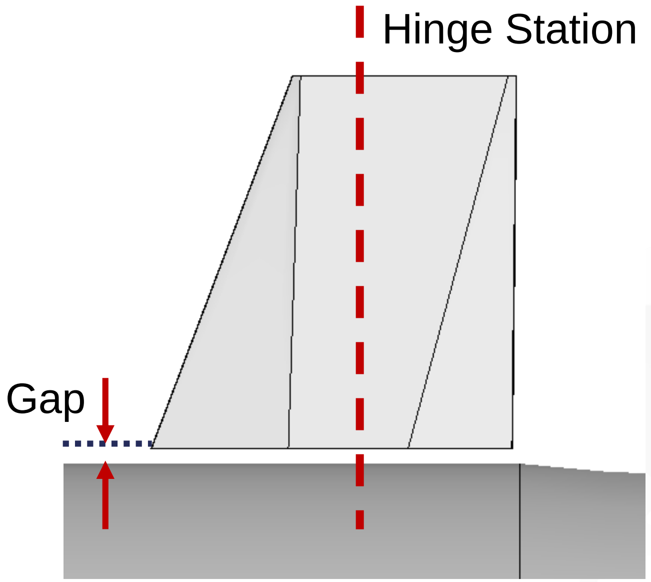


$$\delta_P = \frac{\delta_2 - \delta_4}{2} \qquad \delta_Y = \frac{\delta_3 - \delta_1}{2} \qquad \delta_R = \frac{\delta_1 + \delta_2 + \delta_3 + \delta_4}{4}$$

- Apply gap between body and fin to generate volume mesh



without Deflection

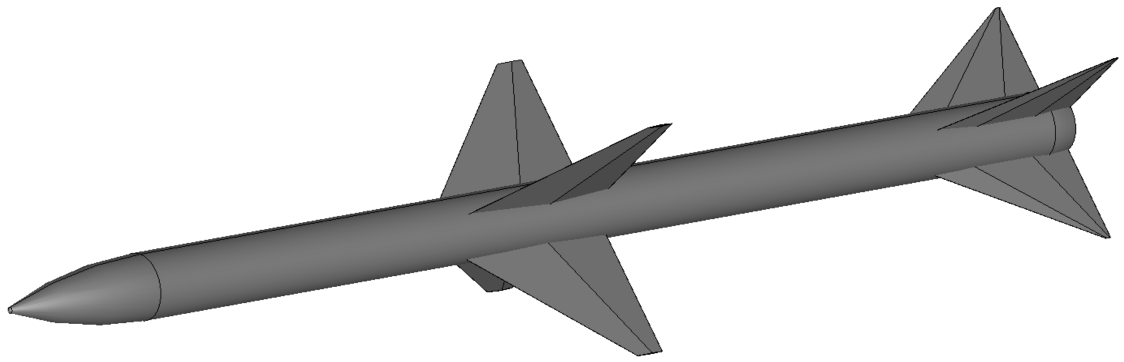


with Deflection

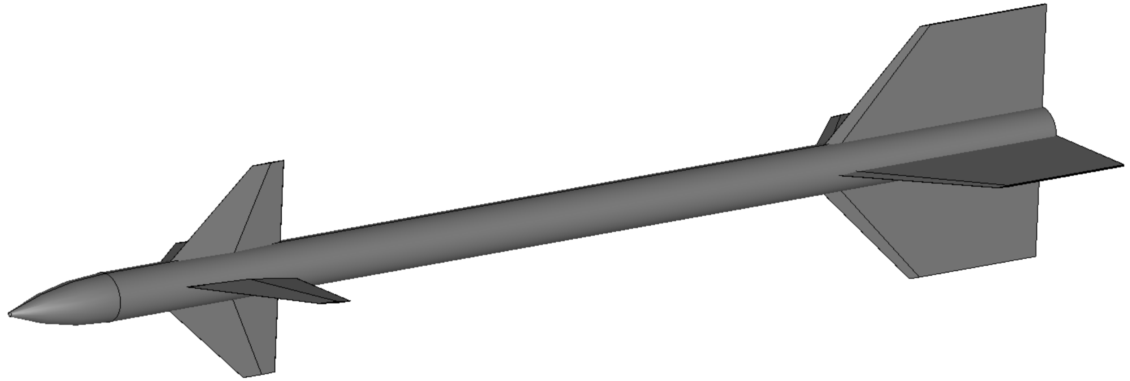
Automated Aerodynamic Analysis Process

- Geometry Modeling – Example

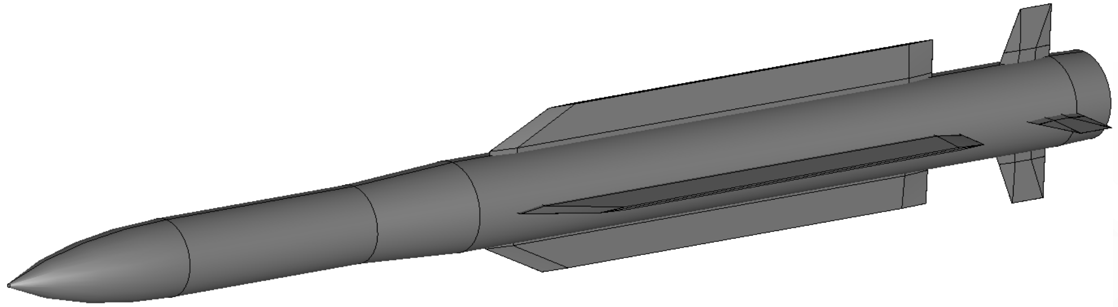
  1. NASA TP 1078 (Sparrow)
     - ✓ Body : Nose + Centerbody + Afterbody



  2. NASA TP 2157
     - ✓ Body : Nose + Centerbody



  3. NASA TM 2005
     - ✓ Body : Longitudinal Coordinate



Automated Aerodynamic Analysis Process

- **Mesh Generation**
  - Generate unstructured Tetrahedral with prism layer
  - Use NETGEN algorithm in SALOME software
  - Export Mesh to I-Deas Universal unv format
    - ✓ Convertible to OpenFOAM format using IdeasUnvToFoam utility

Automated Aerodynamic Analysis Process

○ Mesh Generation – Parameter

- Computational Domain & Refinement Region
  - ✓ Position, Radius, Height

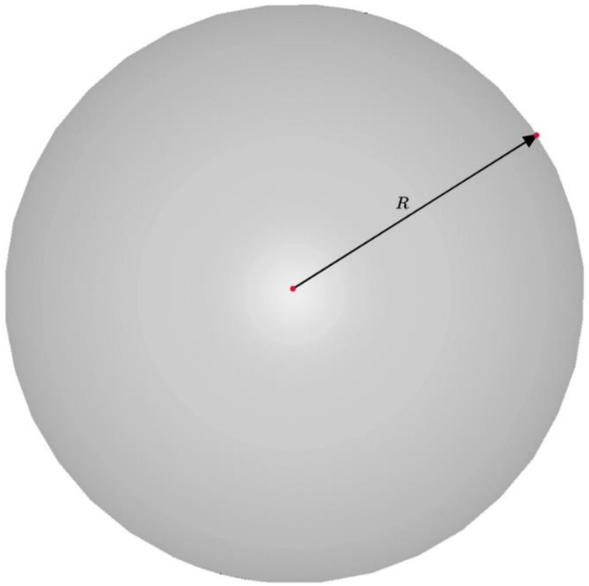
- Mesh Size
  - ✓ Max size, Min size, Growth rate

- Prism Layer
  - ✓ Number of Layer, First layer height, Stretch Factor

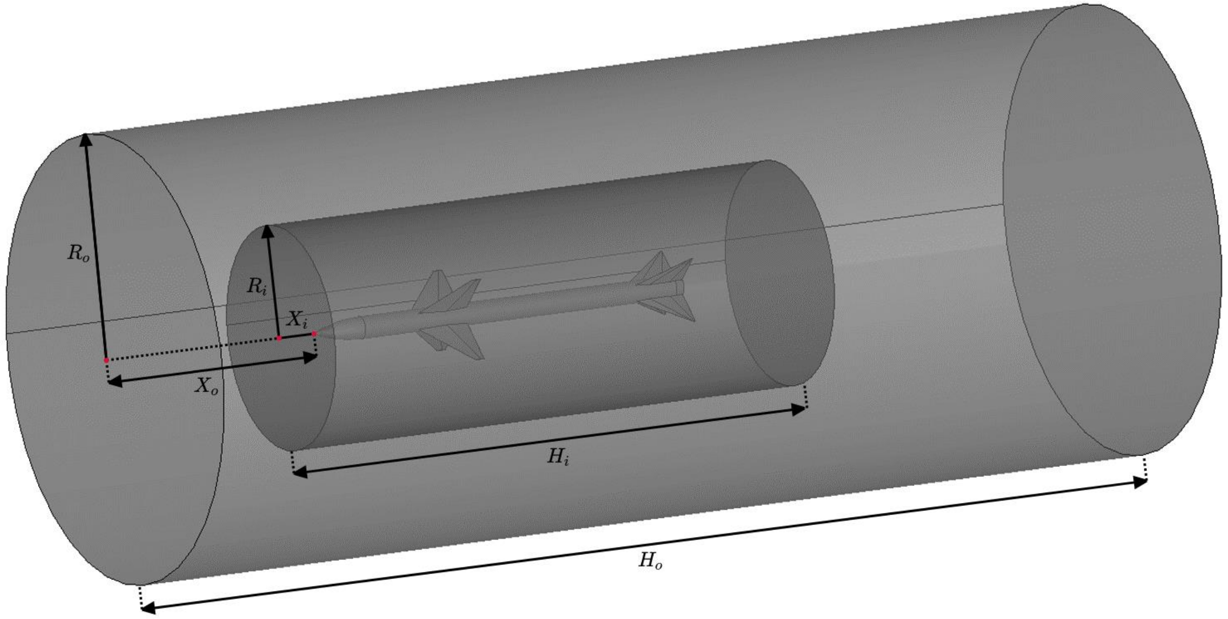
Automated Aerodynamic Analysis Process

○ Mesh Generation – Domain & Refinement Region

- Use spherical computational domain
- Use two cylinderical refinemt region
  - ✓ Capture Shock and wake flow accurately
  - ✓ Guarantee consistent mesh quality regardless of geometry changes



Computational Domain



Refinement Region

Automated Aerodynamic Analysis Process

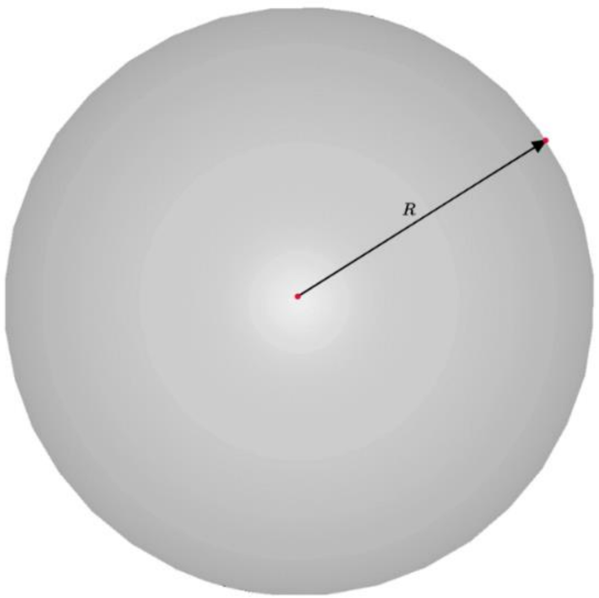
○ **Mesh Generation – Grouping**

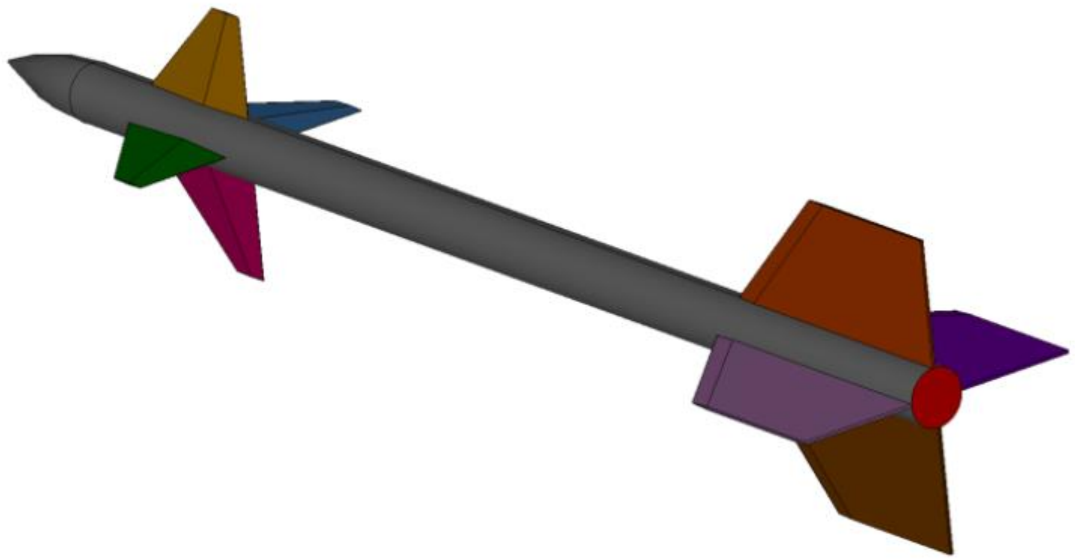
- Search & Group face based on geometric parameter
  - ✓ Computational Domain
  - ✓ Missile Component

- Used for face refinement
  - ✓ Nose
  - ✓ Leading edge and trailing edge of Finset

- Used for setting boundary & intial condition for flow analysis

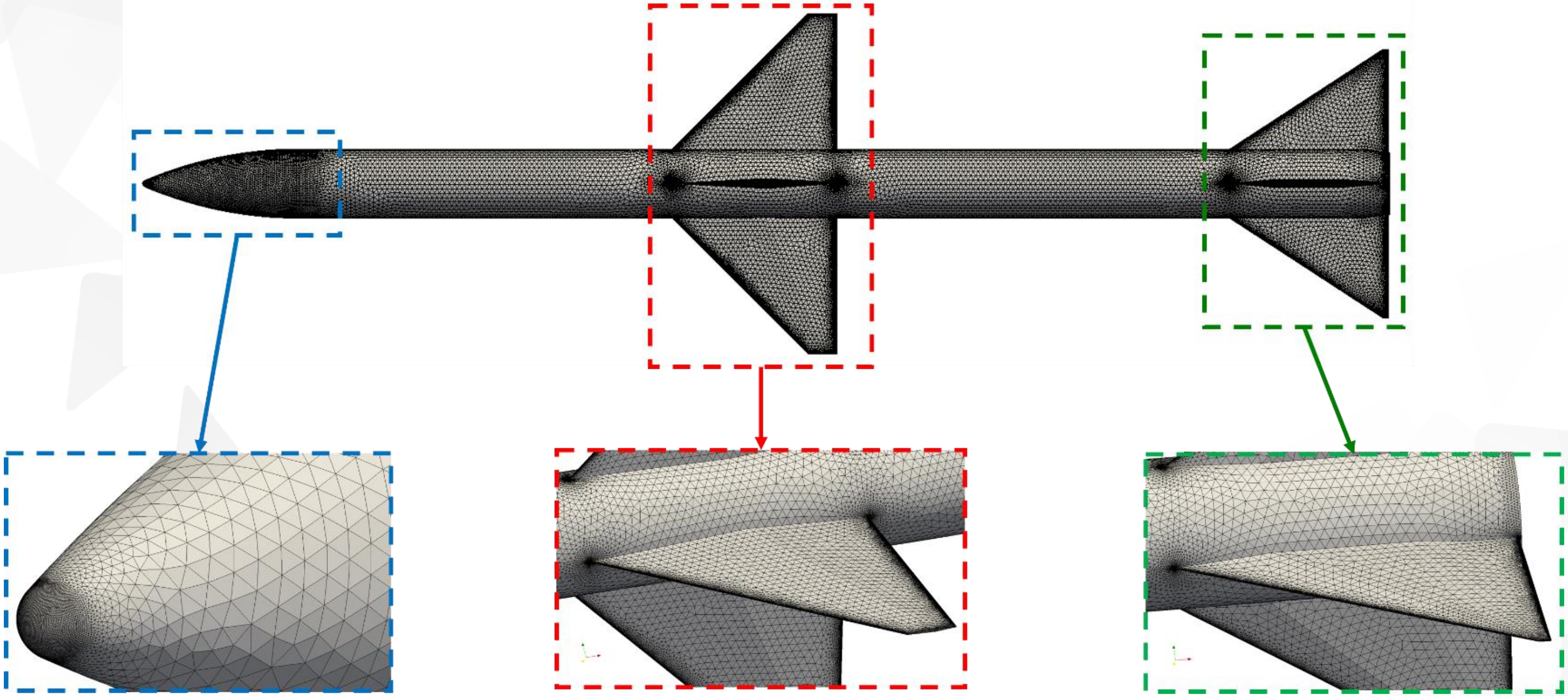
- Grouping information is saved when exporting volume mesh





Automated Aerodynamic Analysis Process

- **Mesh Generation – Example**
  - Surface Mesh



Automated Aerodynamic Analysis Process

○ Flow Analysis

- Use TSLAeroFoam Solver
  - ✓ Density-based compressible coupled solver

- Develop Python script for pre-processing automation
  - ✓ Using same mesh for multiple flow conditions
  - ✓ Performing mesh conversion and decomposition process only once
  - ✓ Save on storage usage

https://www.nextfoam.co.kr/proc/DownloadProc.php?fName=181113104806.pdf&realfName=Ppt05-2013.pdf

Automated Aerodynamic Analysis Process

- **Flow Analysis – Parameter**
  - Flow Conditions
    - ✓ Mach Number*
    - ✓ Static Pressure (Pa)
    - ✓ Static Temperature (K)
    - ✓ Angle of attack (deg)*
    - ✓ Bank angle (deg)*

* Multiple inputs available

Automated Aerodynamic Analysis Process

○ Flow Analysis – Directory Setting

- Set the directory name with the entered flow conditions
  - ✓ Mach : 2.5, AoA = 5°, Bank 0° : M2.5_AoA5.0_Bank0.0
- Default Directory
  - ✓ All cases use same volume mesh and setting file
  - ✓ Store **const** and **system** directory

- Missile
  - M1.5_AoA0.0_Bank0.0
  - M1.5_AoA5.0_Bank0.0
  - M1.5_AoA0.0_Bank45.0
  - M1.5_AoA5.0_Bank45.0
  - M2.5_AoA0.0_Bank0.0
  - M2.5_AoA5.0_Bank0.0
  - M2.5_AoA0.0_Bank45.0
  - M2.5_AoA5.0_Bank45.0
  - Default

Automated Aerodynamic Analysis Process

○ Flow Analysis – Mesh Converting

- IdeasUnvToFoam is used for mesh converting
- All boundaries are set as patch type by default
- Modify type of missile components surface to wall

```
Forebody
{
    type            patch;
    nFaces          99211;
    startFace       43960821;
}
Base
{
    type            patch;
    nFaces          3770;
    startFace       44060032;
}
Finset1_Panel1
{
    type            patch;
    nFaces          45857;
    startFace       44063802;
}
```

```
Forebody
{
    type            wall;
    nFaces          99211;
    startFace       43960821;
}
Base
{
    type            wall;
    nFaces          3770;
    startFace       44060032;
}
Finset1_Panel1
{
    type            wall;
    nFaces          45857;
    startFace       44063802;
}
```

Automated Aerodynamic Analysis Process

○ Flow Analysis – Mesh Decomposing

- Modify the content of files in **0** directory in processor directory
  - ✓ Search Domain keyword
  - ✓ Change Mach number and flow direction

- Apply symbolic link in **const** directory in processor directory
  - ✓ Save storage space

```
Domain
{
    type            farfieldRiemann;
    flowDir         ( 1 0 0 );
    TInf            281.651;
    MInf            1.5;
    pInf            89876.3;
    value           nonuniform 0();
}
```

Processor0 / 0 / U

```
Domain
{
    type            farfieldRiemann;
    flowDir         ( 0.9993908270190958 -0.0 0.03489949670250097);
    TInf            281.651;
    MInf            1.5;
    pInf            89876.3;
    value           nonuniform 0();
}
```

Processor0 / 0 / U (Modified)

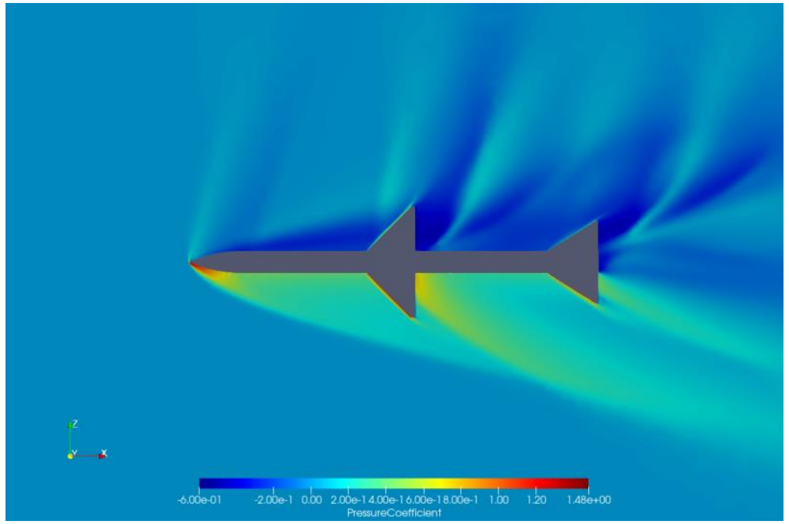
Automated Aerodynamic Analysis Process

○ **Post-processing**

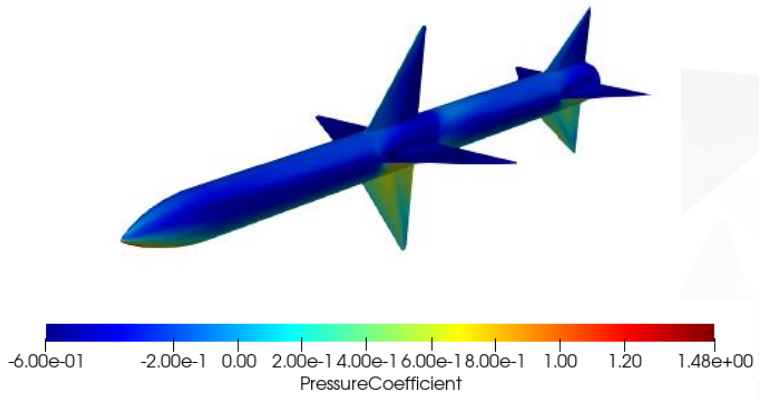
- Use ParaView software to extract image of flow field

- Generate contour images for the X-Z and X-Y planes
  - ✓ Set camera position based on geometry parameter
  - ✓ Mach, Static pressure, Static temperature field

- Generate images for the missile surfaces
  - ✓ Fixed camera direction to Isometric view



Contour Image

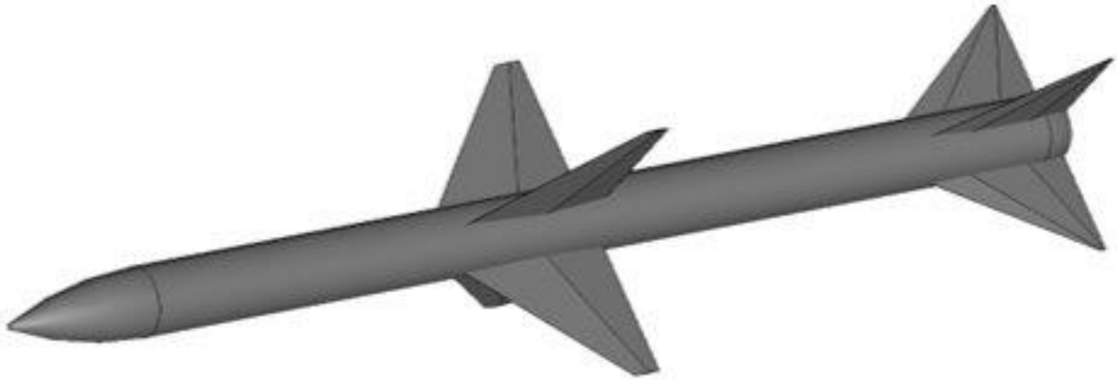


Surface Image

Benchmark Test

○ Case 1 (Sparrow)

- Geometry
  - ✓ Body : Nose+ Centerbody + Afterbody
  - ✓ Finset : X Configuration

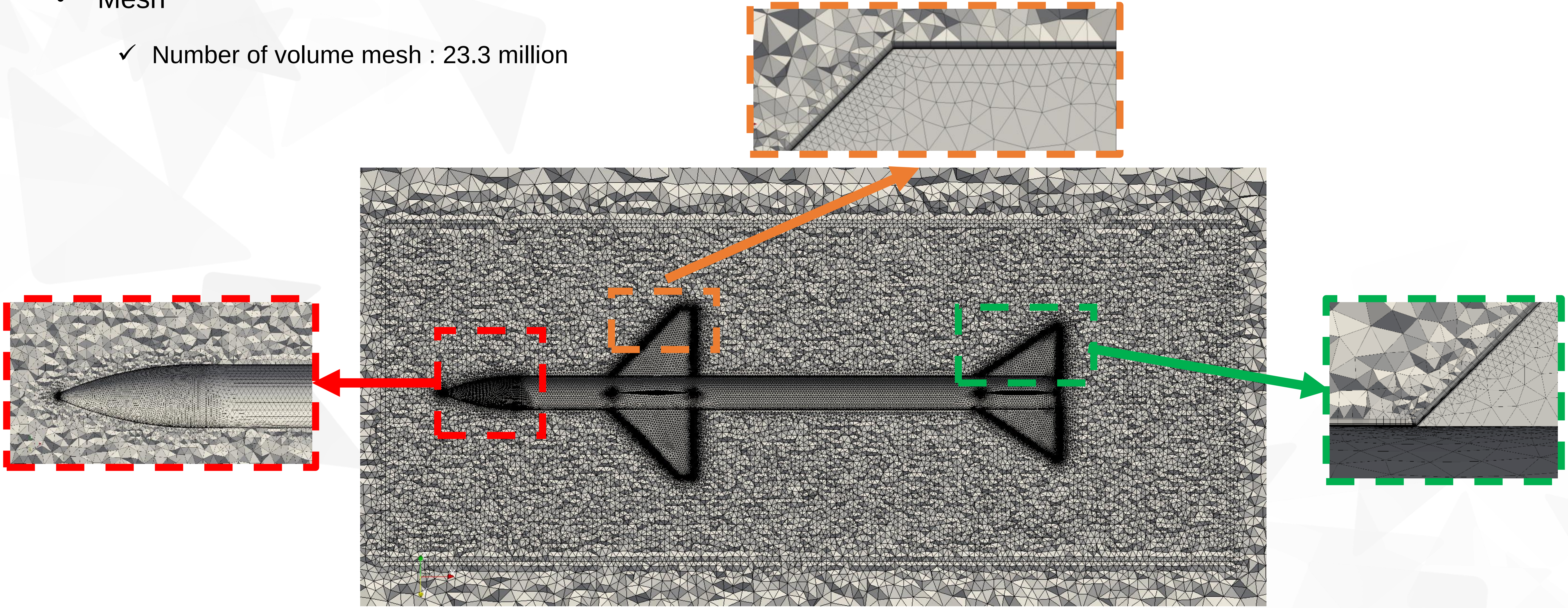


- Flow Condition
  - ✓ Mach Number : 1.5
  - ✓ Static Pressure (Pa) : 18114.8
  - ✓ Static Temperature (K) : 233.793
  - ✓ Angle of attack (°) : 0, 5, 11, 17, 23, 27, 32

Supersonic aerodynamic characteristics of a Sparrow III type missile model with wing controls and comparision with existing tail-control results. NASA TP 1078

Benchmark Test

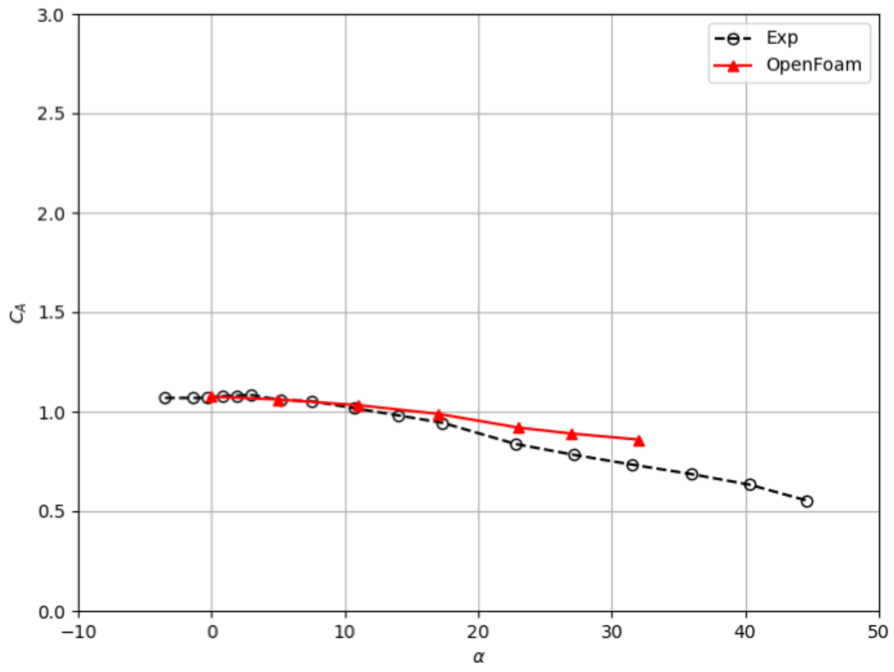
- Case 1 (Sparrow)
  - Mesh
    - ✓ Number of volume mesh : 23.3 million



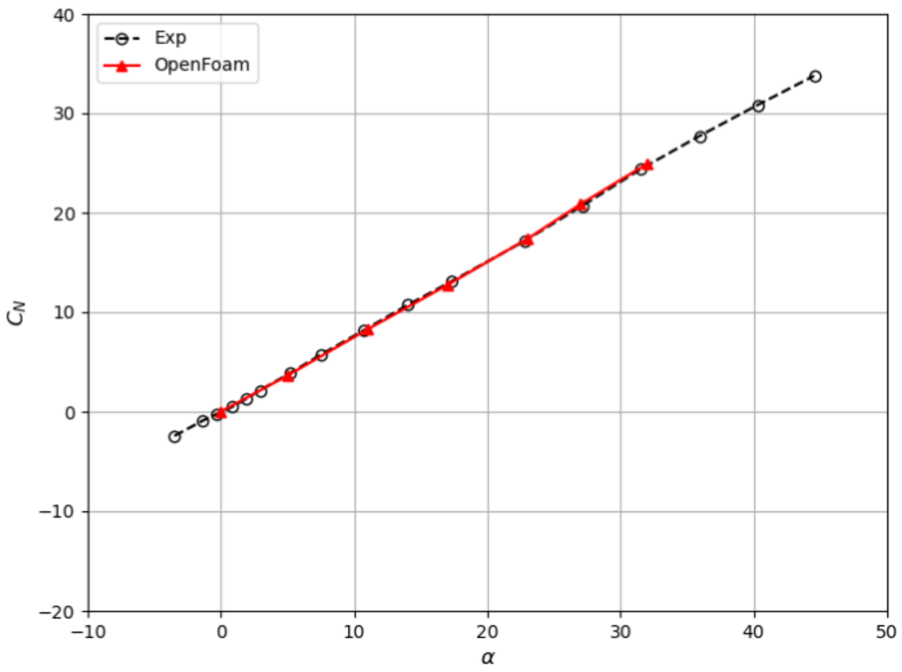
Benchmark Test

○ **Case 1 (Sparrow)**

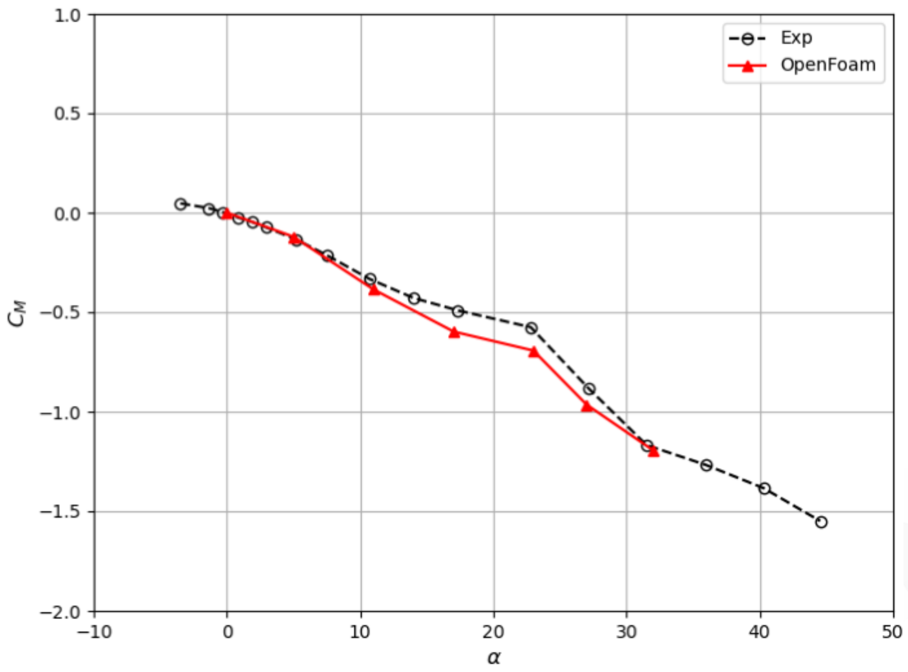
- Overpredict axial force at high angle of attack
- Normal force and pitching moment are in good agreement



Axial Force Coefficient



Normal Force Coefficient

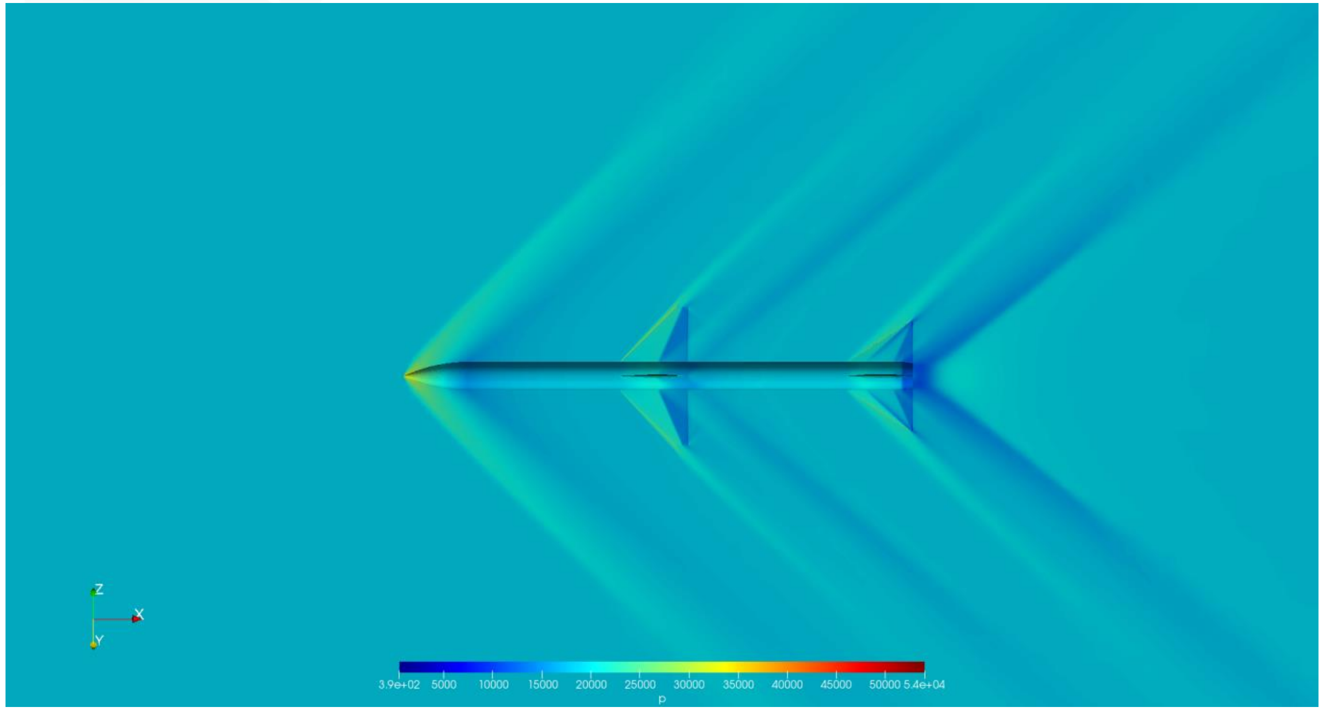


Pitching Moment Coefficient

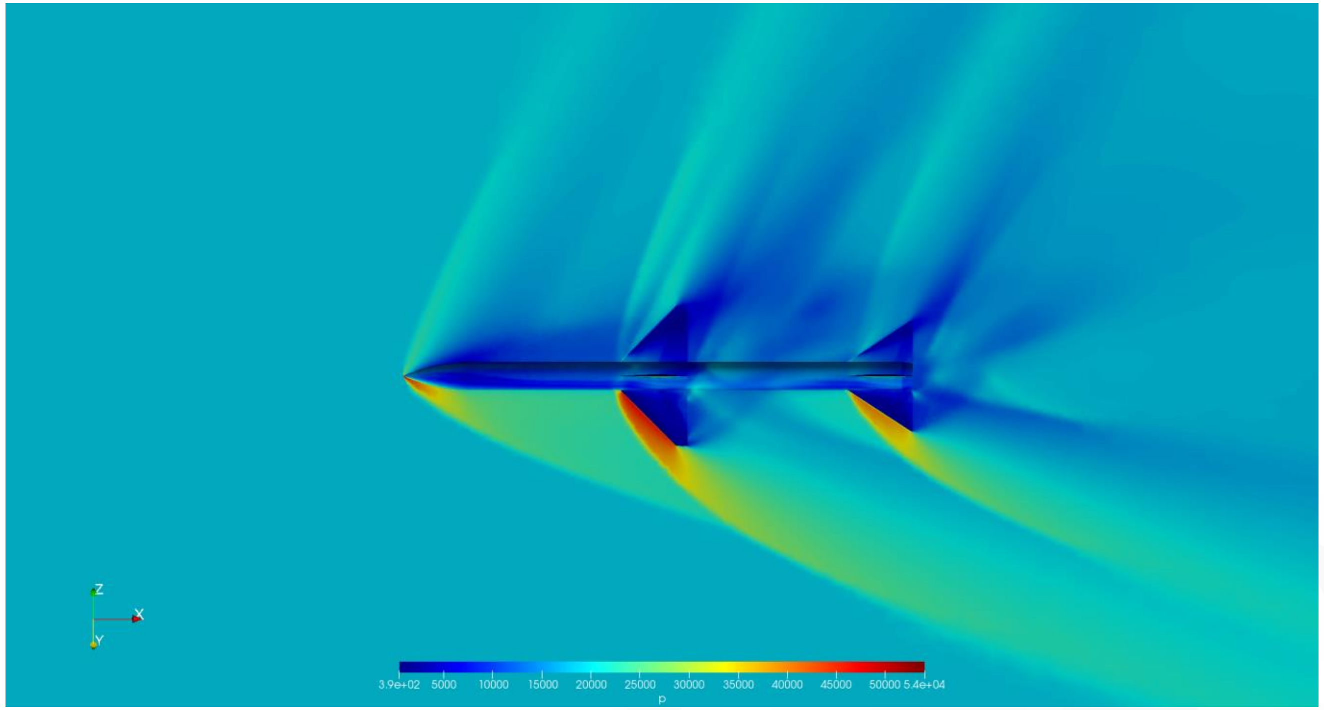
Benchmark Test

○ **Case 1 (Sparrow)**

- Shock wave and wake flow are captured clearly by the use of the refinement regions



AoA = 0°

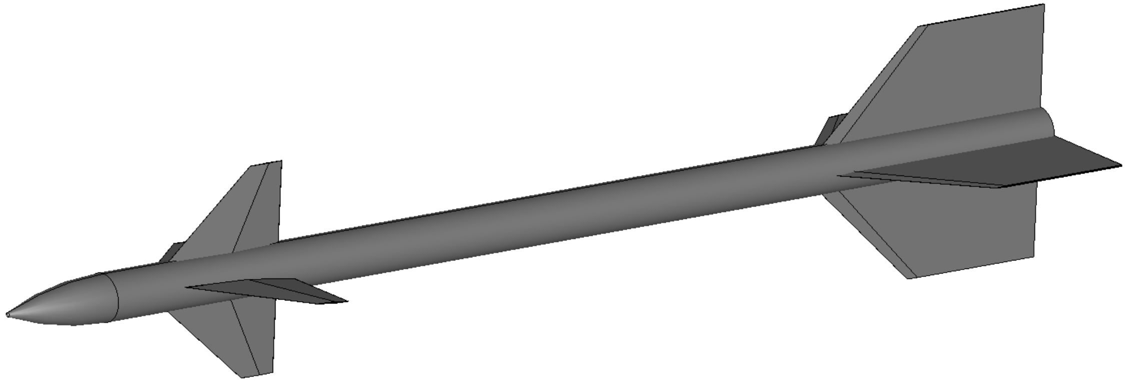


AoA = 32°

Benchmark Test

○ **Case 2 (NASA TP 2157)**

- Geometry
  - ✓ Body : Nose+ Centerbody
  - ✓ Finset : + Configuration



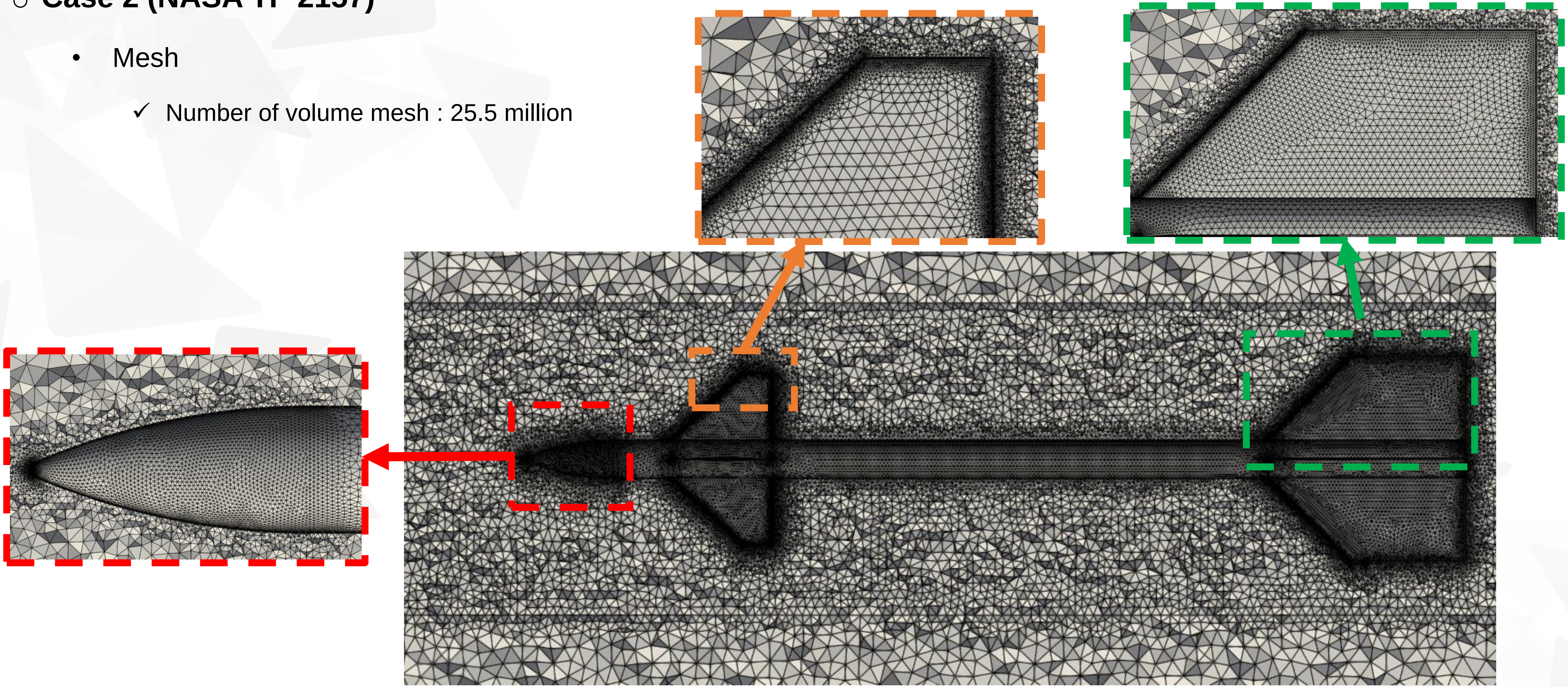
- Flow Condition
  - ✓ Mach Number : 3.5
  - ✓ Static Pressure (Pa) : 1696.55
  - ✓ Static Temperature (K) : 94.2029
  - ✓ Angle of attack (°) : -4, 0, 4, 10, 14, 18

Effect of tail-fin span on stability and control characteristics of a canard-controlled missile at supersonic Mach numbers. NASA TP 2157

Benchmark Test

○ **Case 2 (NASA TP 2157)**

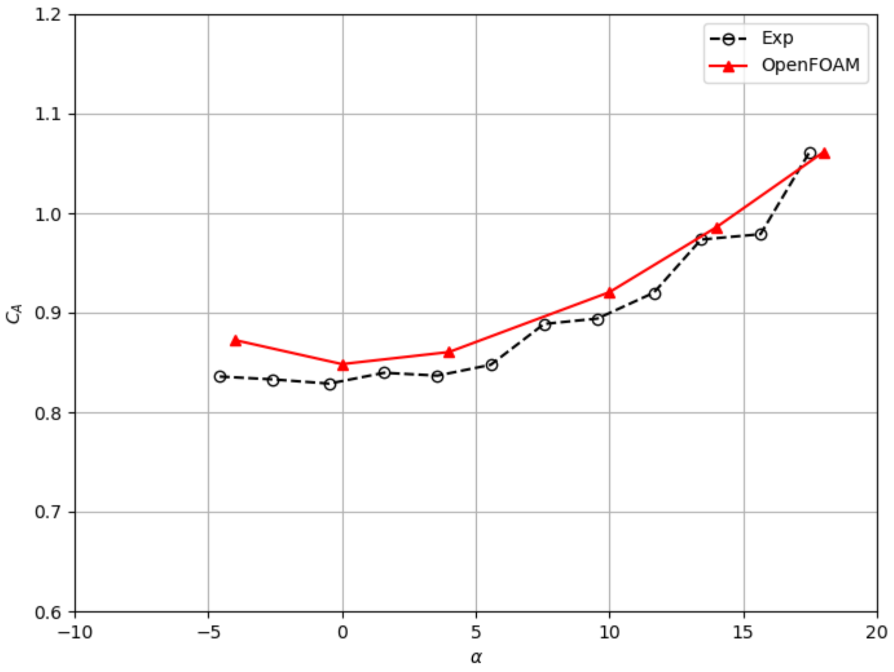
- Mesh
  - ✓ Number of volume mesh : 25.5 million



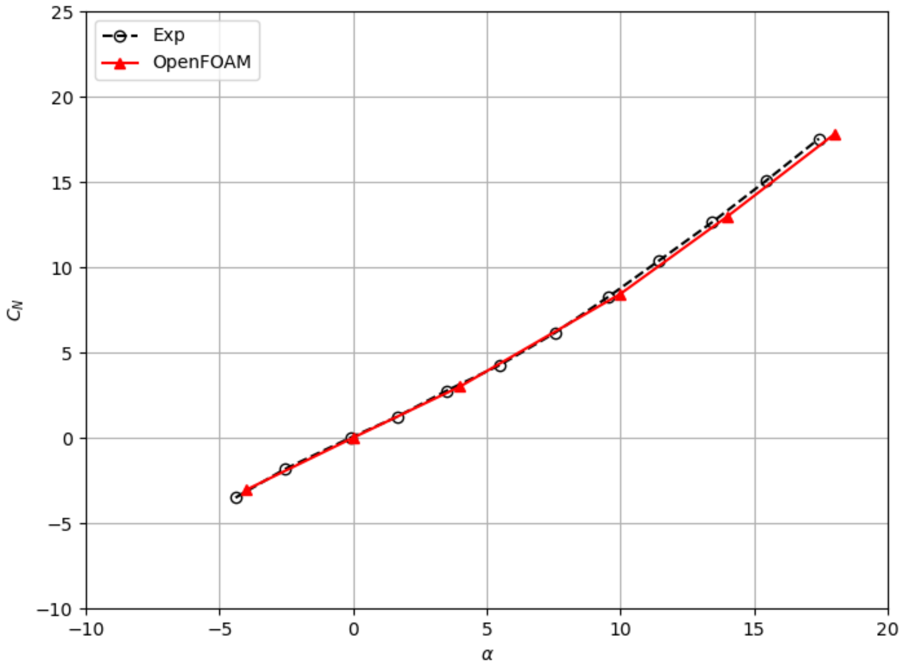
Benchmark Test

○ Case 2 (NASA TP 2157)

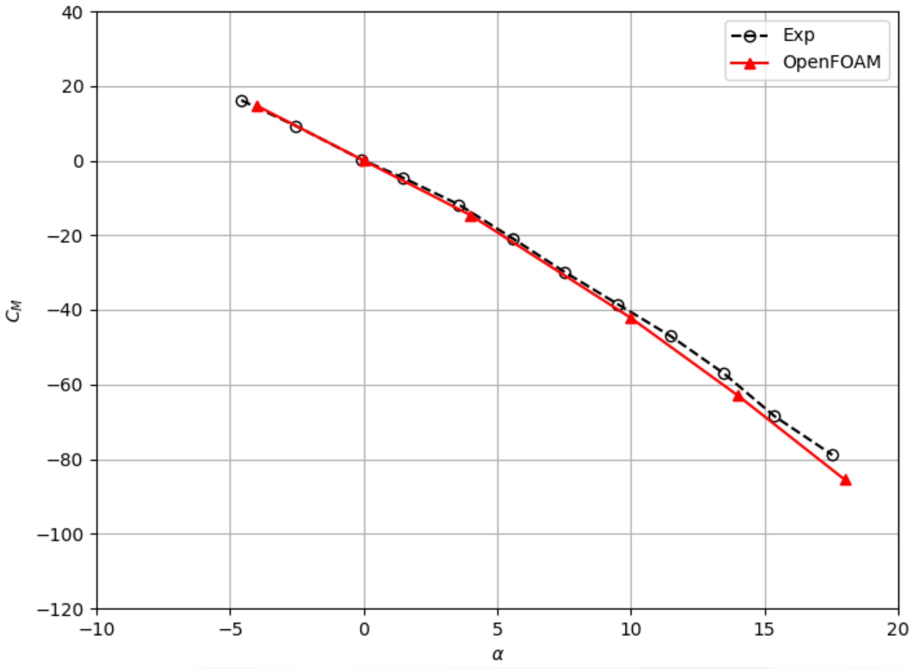
- Overpredict axial force but matces well in the overall trend
- Normal force and pitching moment are in very good agreement



Axial Force Coefficient



Normal Force Coefficient

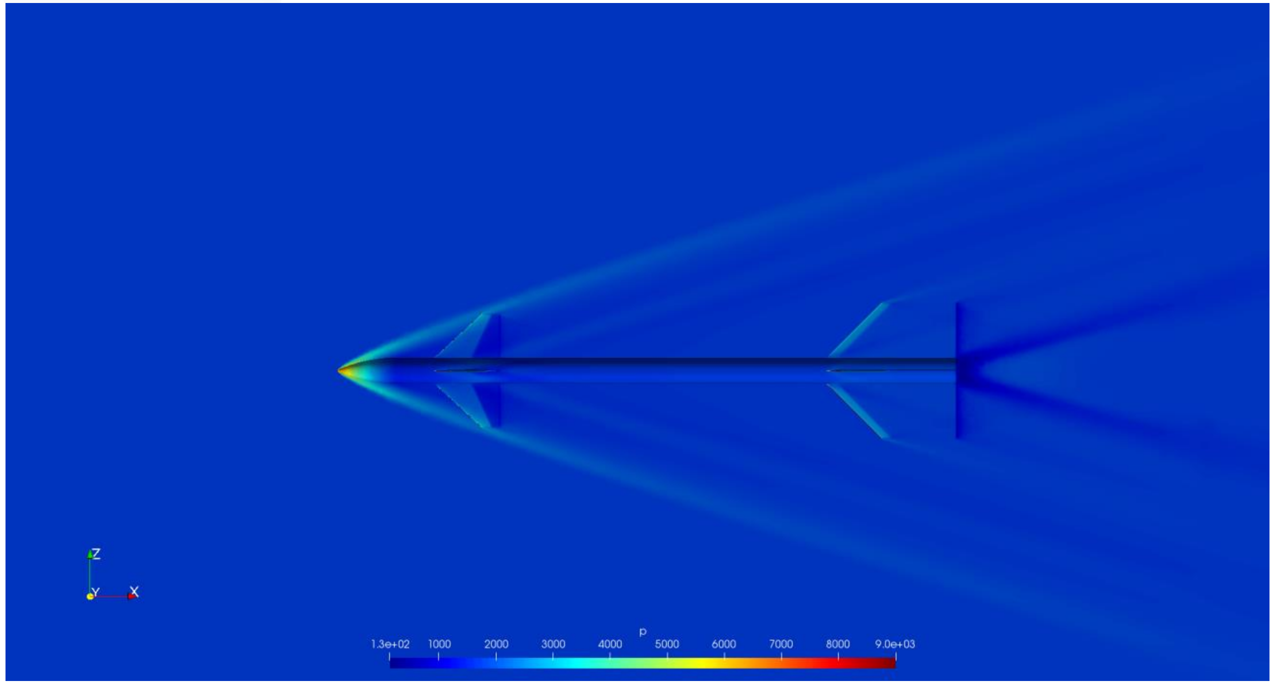


Pitching Moment Coefficient

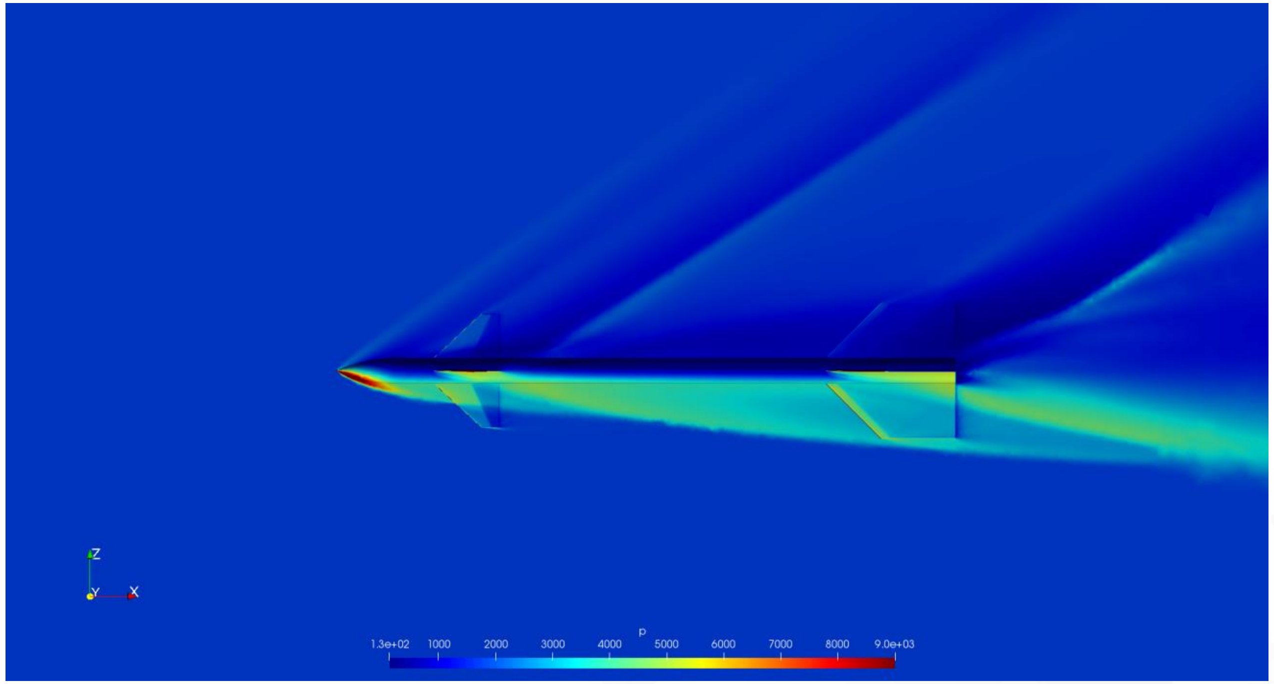
Benchmark Test

○ **Case 2 (NASA TP 2157)**

- Shock wave and wake flow are captured clearly by the use of the refinement regions



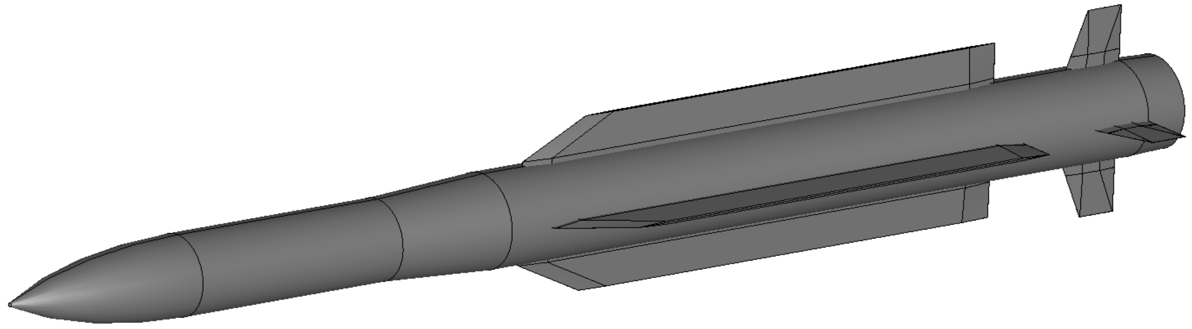
AoA = 0°



AoA = 32°

Benchmark Test

- **Case 3 (NASA TM 2005)**
  - Geometry
    - ✓ Body : (X, R) coordinate
    - ✓ Finset : + Configuration, $\delta_p = 10°$



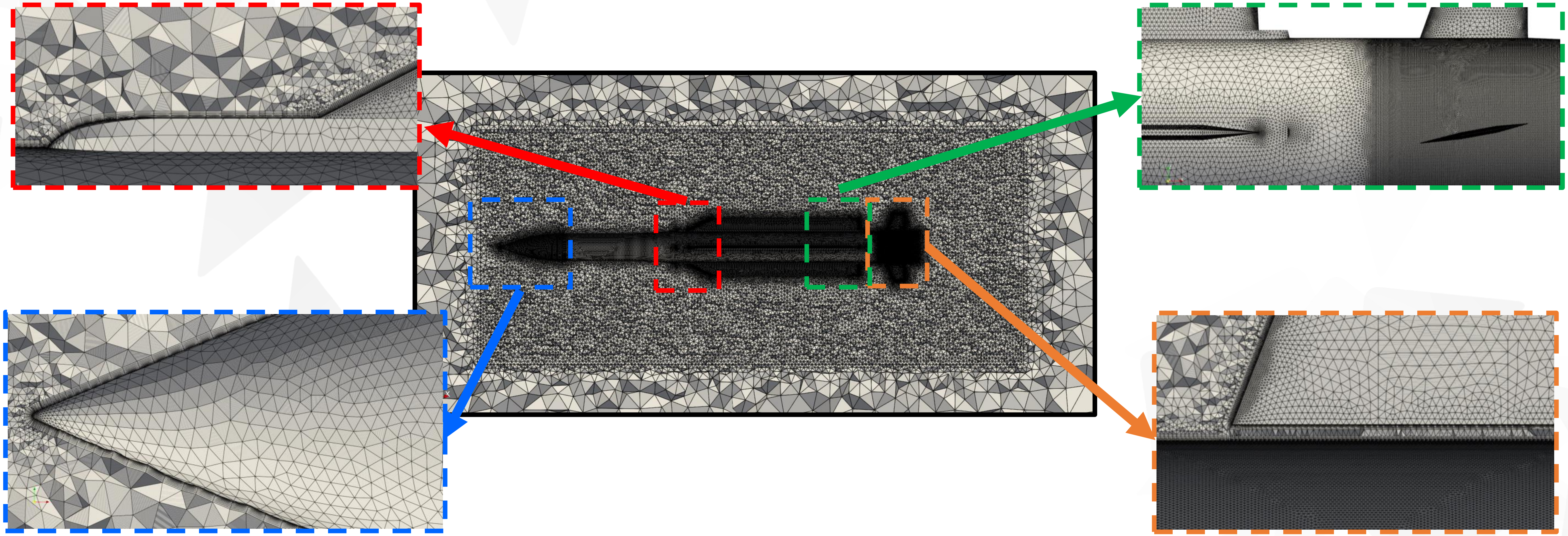
  - Flow Condition
    - ✓ Mach Number : 2.36
    - ✓ Reynolds number (per foot) : 1.5×10^6
    - ✓ Angle of attack (°) : -1.2, -0.18, 0.85, 1.79, 3.86, 5.86, 7.84, 9.85, 13.84, 16.85, 19.87

Aerodynamics of an axisymmetric missile concept having cruciform strakes and in-line tail fins from Mach 0.60 to 4.63. NASA TM 2005-213541

Benchmark Test

○ **Case 3 (NASA TM 2005)**

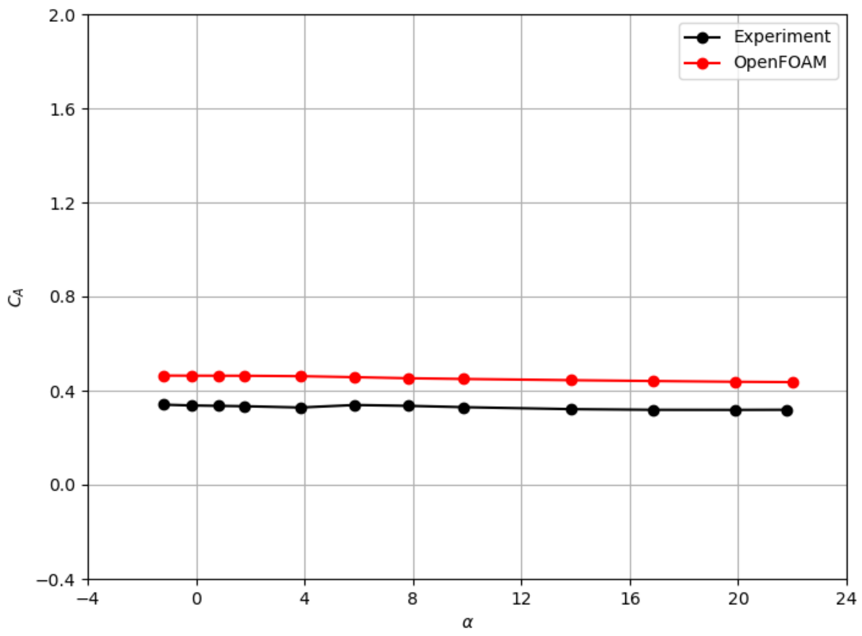
- Mesh
  - ✓ Number of volume mesh : 28.2 million



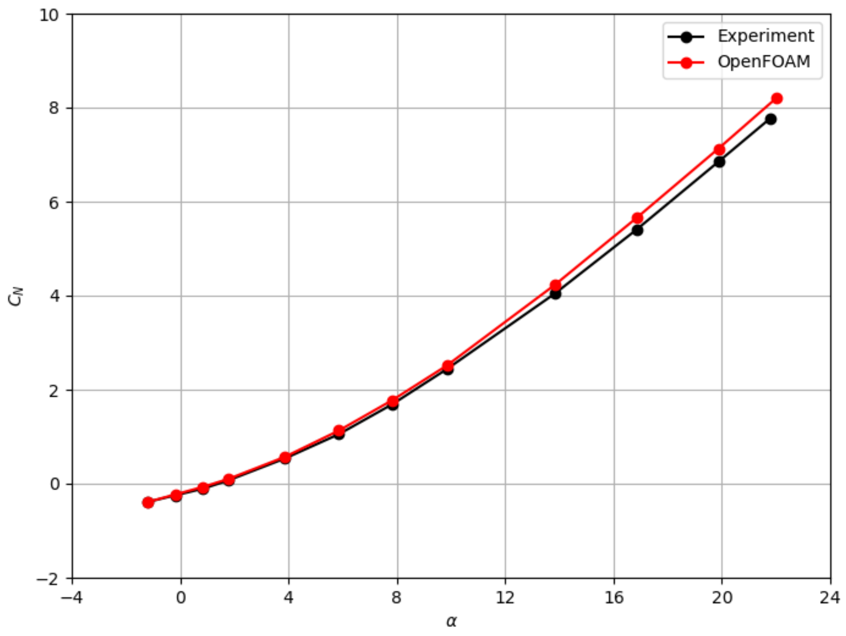
Benchmark Test

○ **Case 3 (NASA TM 2005)**

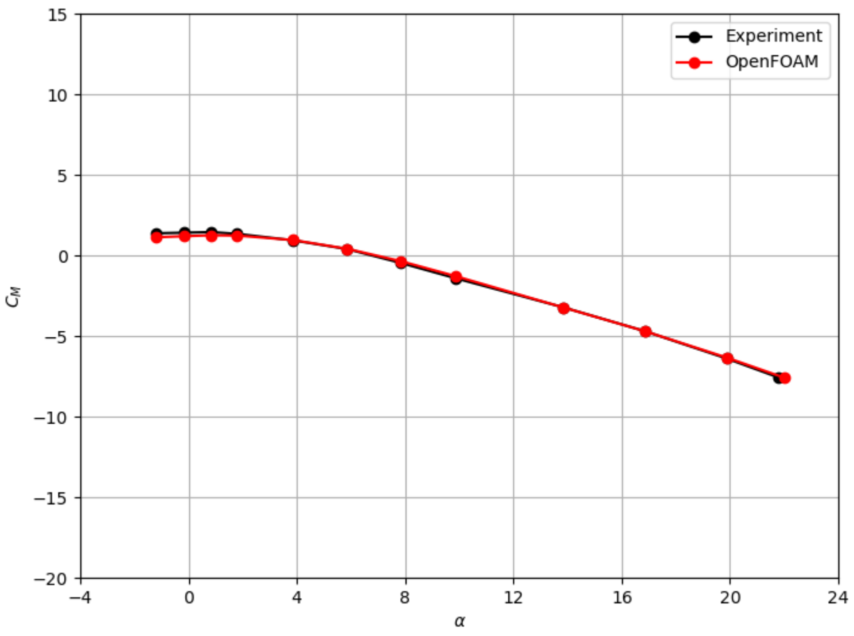
- Overpredict axial force compared to the experimental
- Normal force and pitching moment are in very good agreement



Axial Force Coefficient



Normal Force Coefficient



Pitching Moment Coefficient

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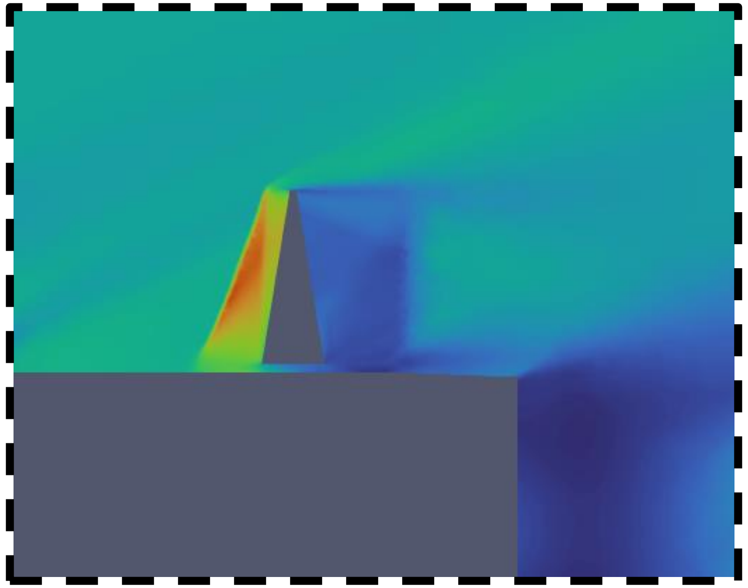
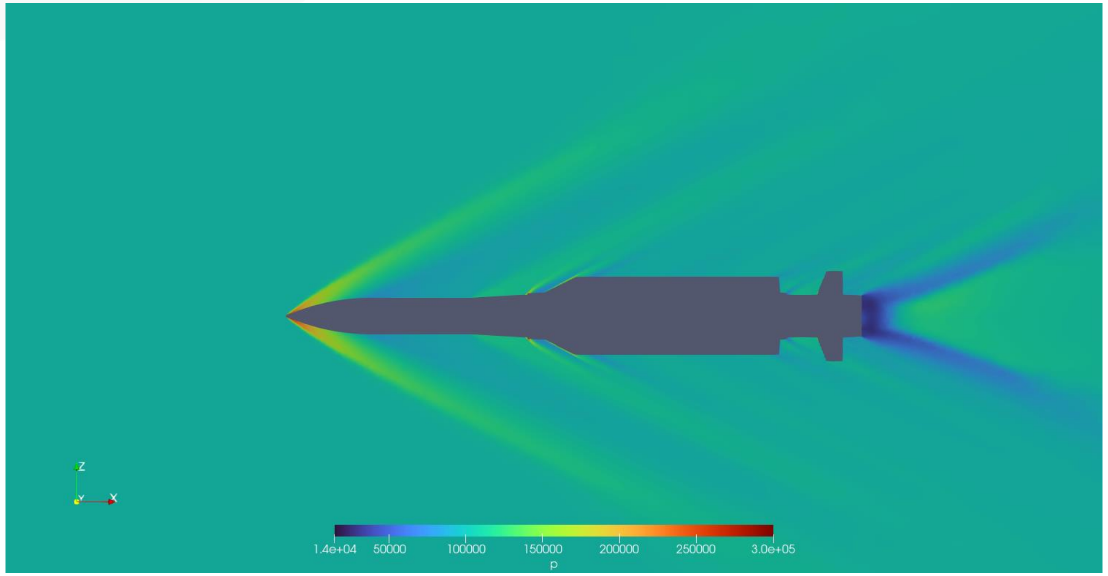
Benchmark Test

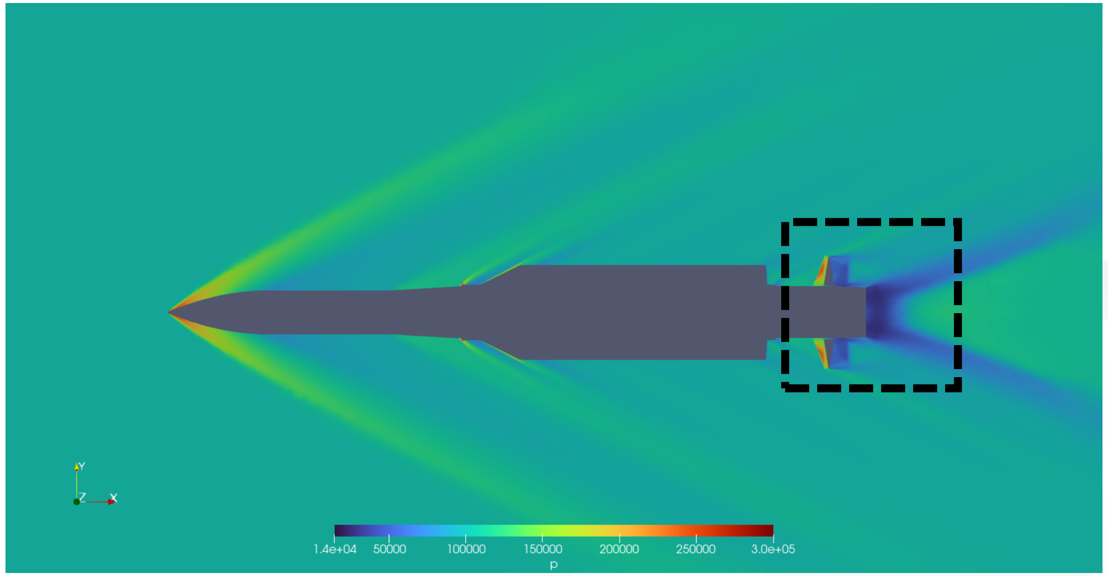
○ **Case 3 (NASA TM 2005)**

- Shock wave and wake flow are captured clearly by the use of the refinement regions
- Flow field around gap is shown physically





AoA = 0.85° (X – Z Plane)



AoA = 0.85° (X – Y Plane)

Conclusion

○ **Automated Aerodynamic Process**

- Developed to be applicable for arbitrary missile configuration
- Composed of geometry, mesh, flow analysis and post-processing modules
- Use open-source software in all modules
  - ✓ OpenCASCADE, Salome, OpenFOAM, ParaView
- Minimize user intervention using defined parameters
- Perform bechmarktest with 3 different missile configurations

Thank you for attention