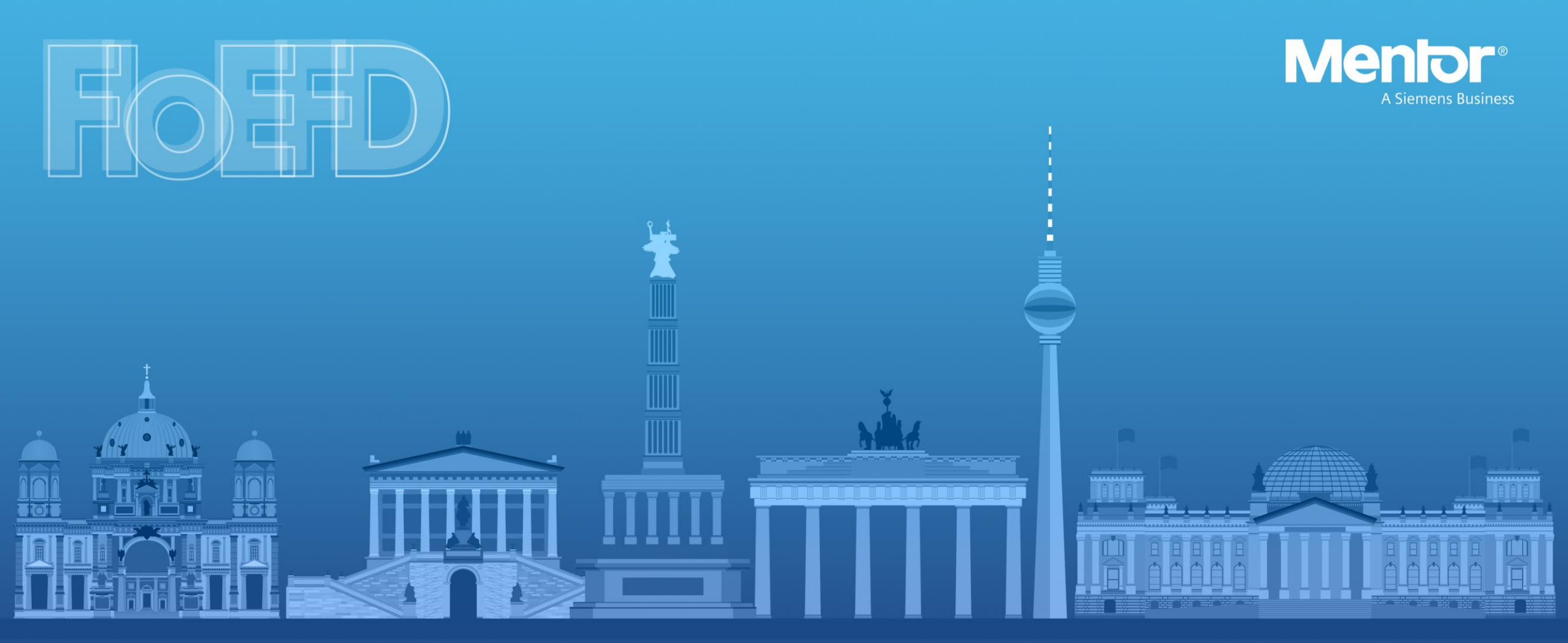


Expansion of FloEFD Possibilities Using „External Optimizer“ Option

Mechanical Analysis Division of Mentor Graphics

Vasiliy Platonovich
Gennady Dumnov

Calculations of separated objects behavior at high velocities

For many aerospace applications it is very important to know behavior of a body separated from vehicle moving with high velocity.

As a rule for such tasks typical aerodynamic time scale (τ_a) is much less typical ballistic time scale (τ_s). At that the task can be considered as quasi-stationary.

Currently the following procedure is used for estimation behavior of separated body:

- At different positions and angles of separated body the aerodynamic forces and torques are calculated.
- Using this data base, ballistic movement of the separated body is calculated.

Main idea of using FloEFD for Ballistic trajectory calculation

Main assumption $\tau_a << \tau_s$

If typical separation time scale (τ_s) is much more typical aerodynamic time scale (τ_a), aerodynamic and stage separation tasks can be separated.

The following procedure is realized with FloEFD:

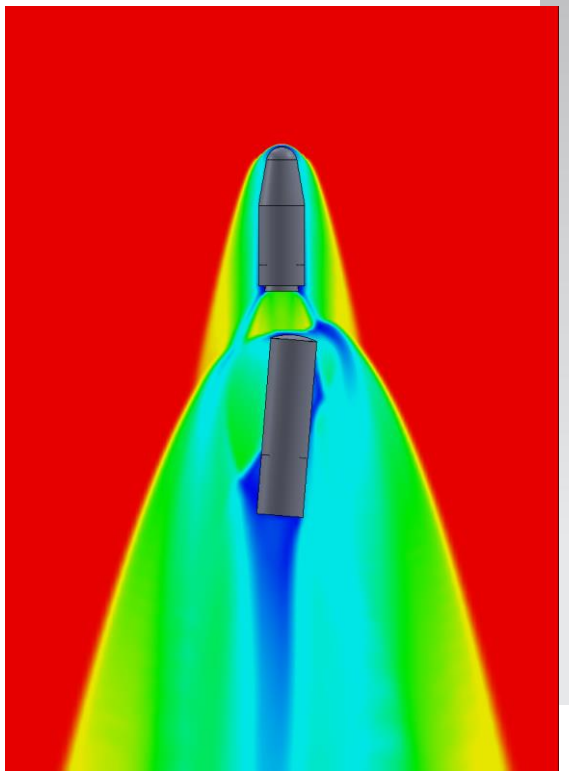
- Calculations of aerodynamic forces and torques at initial time (t=0) just before stages separation with FloEFD.
- Calculation ballistic equations with specified time step Δt.
- Remove separated stage in according with ballistics.
- Calculation of aerodynamic forces and torques at $t_{i+1}=t_i+\Delta t$ stages location with FloEFD.

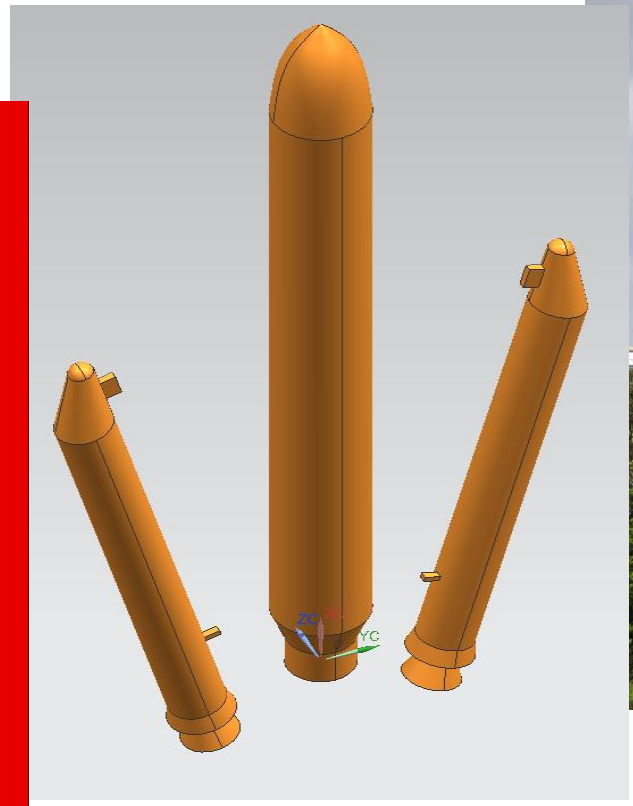
$$m\frac{d\vec{V}}{dt} = \vec{F}$$

$$I\frac{d\vec{\omega}}{dt} = \vec{M}$$

Ballistic Problems

- Aircraft trajectories calculation in accordance with aerodynamics forces
- Rocket stage separation
- Separation of solid body from the aircraft
- Cargo discharge
- So on …

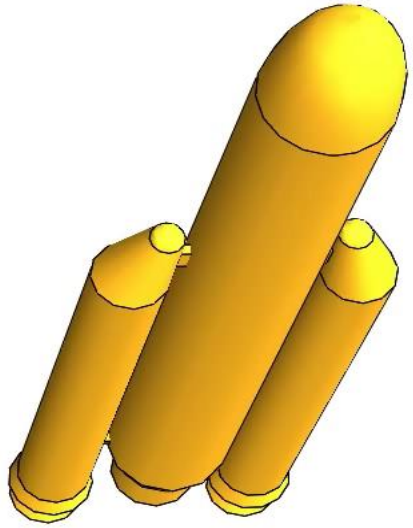




Ariane 5 - Task definition

Parameters just before separation: H=55 km, M=9.5
Rocket parameters:

- Main stage– D=5.4 m, L=50 m
- Solid rocket boosters– D=3.24 m, L=30 m



Goals:

- Plane trajectories of solid rocket boosters is the coordinate system of main stage
- Calculation of the ballistic equations
- Calculation of the series of quasi-stationary external fluid flow tasks in order to determine values of aerodynamic forces

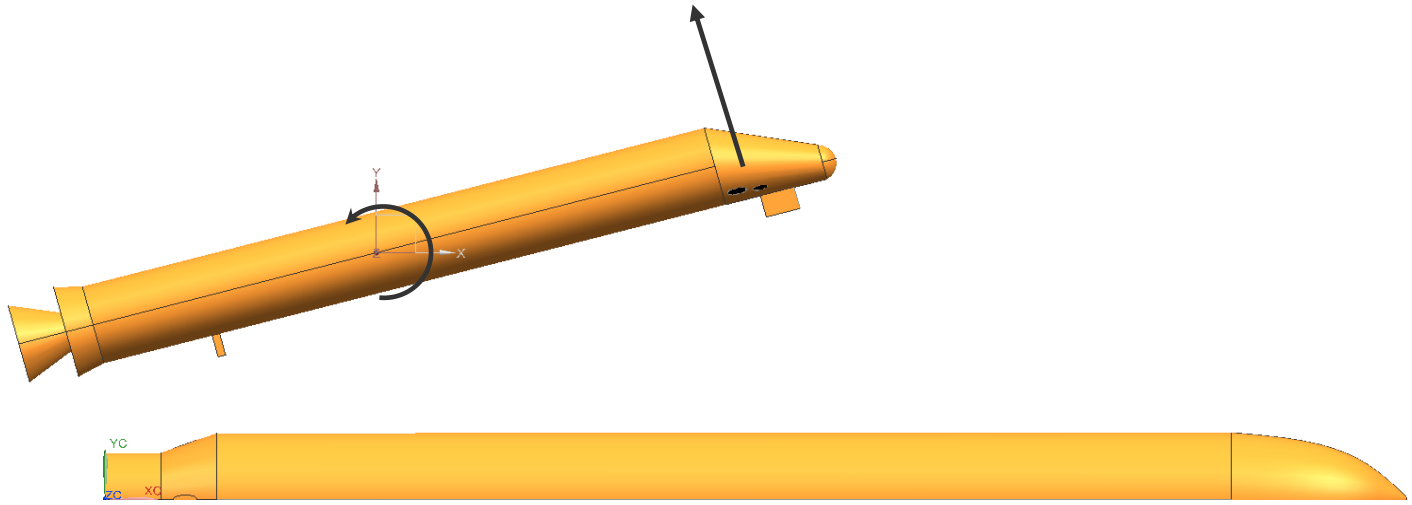
Plane ballistic equation

To estimate trajectory of the boosters following ballistic equations were used:

$$m\frac{d^2x}{dt^2} = F_x$$

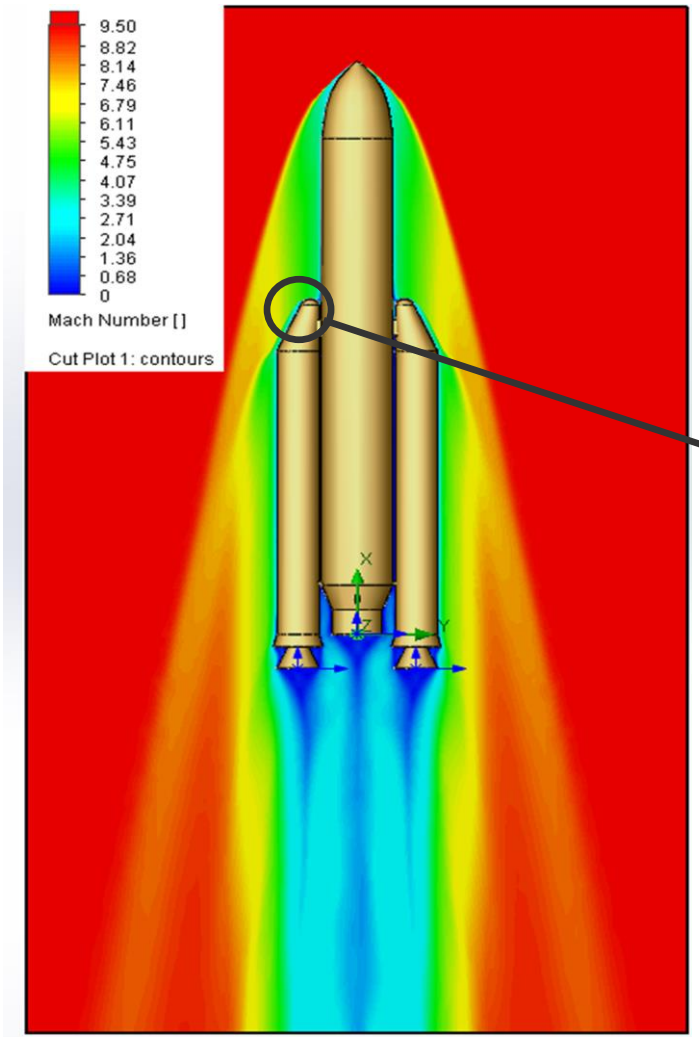
$$m\frac{d^2y}{dt^2} = F_y$$

$$I\frac{d^2\varphi}{dt^2} = M_z$$



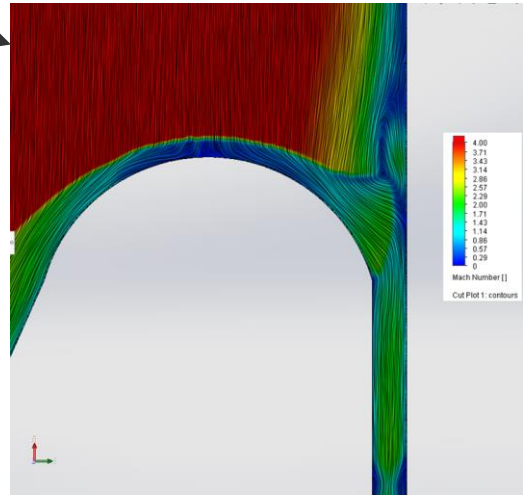
Fx, Fy and Mz – aerodynamics forces and torque, x, y and φ – coordinates and the angle of moving body to determine its position in plate trajectory, m – body mass, I – moment of inertia. Gravitational force should be taken into account in force calculation.

Main assumption

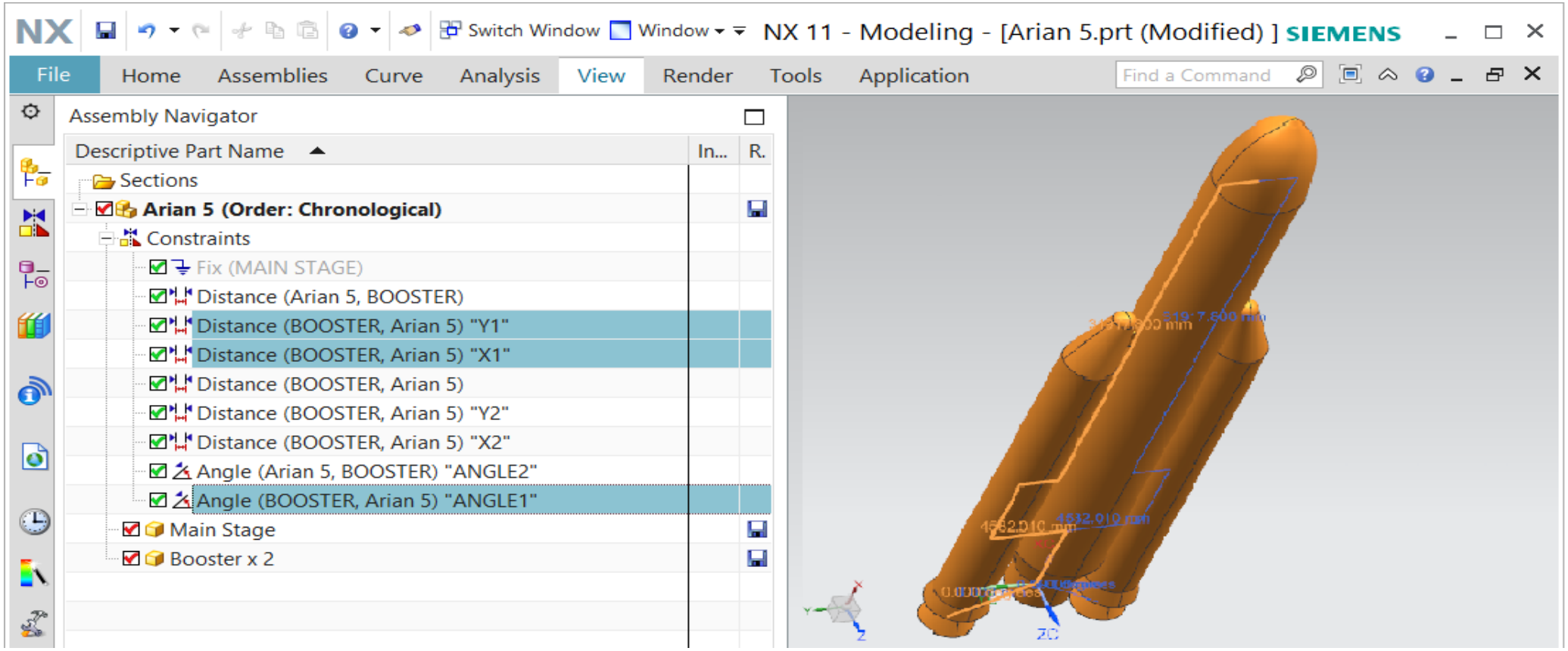


Main assumption is that typical separation time scale (τ_s) is much more typical aerodynamic time scale (τ_a), aerodynamic and stage separation tasks can be separated.

Rocket stage separation process satisfies this requirement.

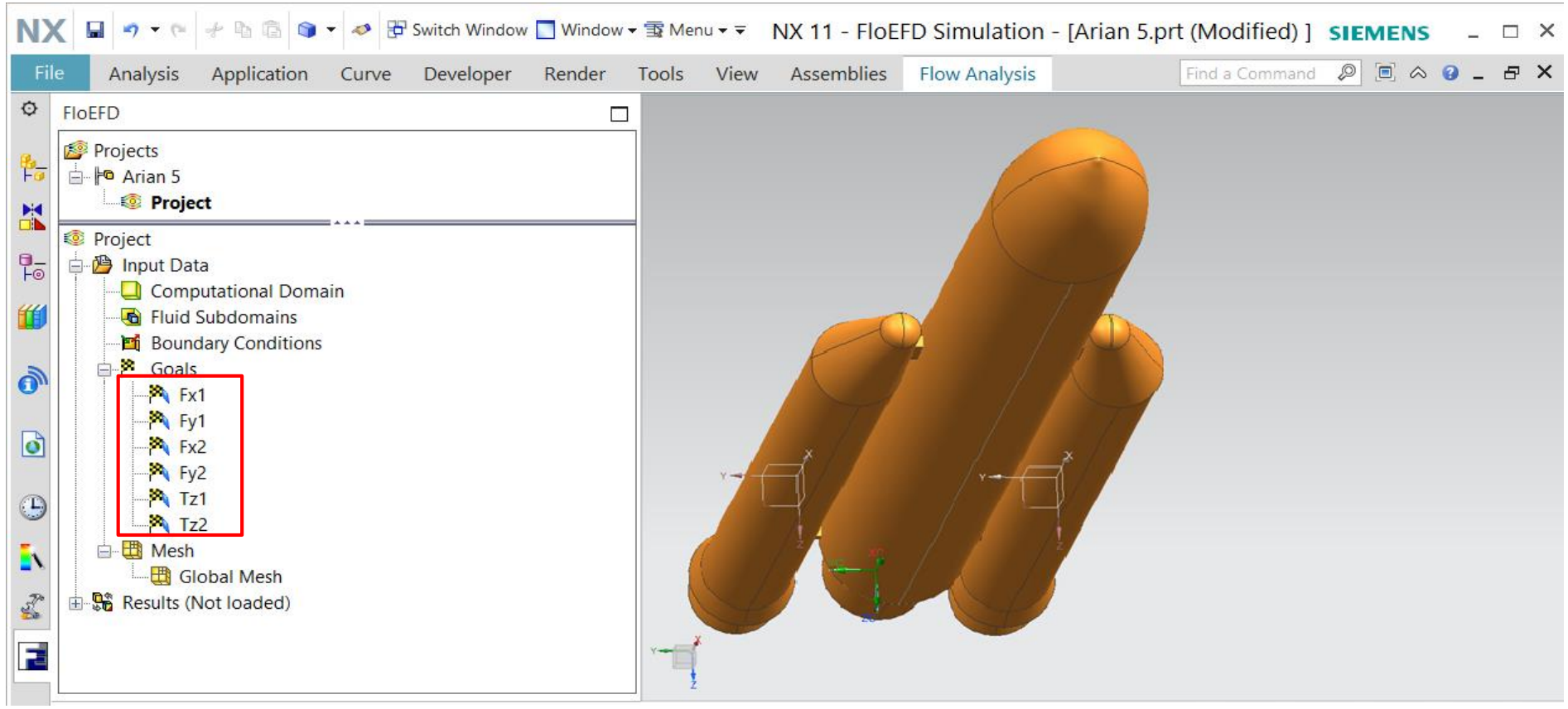


Ariane 5 - Solid rocket boosters handling



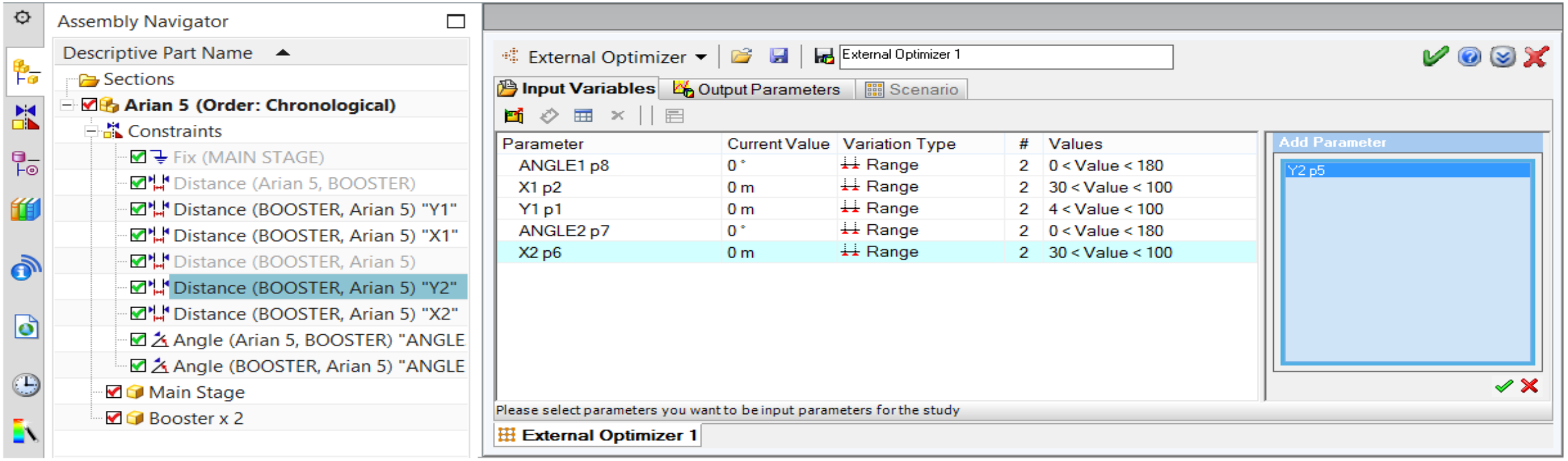
- Main rocket stage is fixed
- Boosters positions are determined with constrains: distances and angles

Ariane 5 - Aerodynamic forces measurement



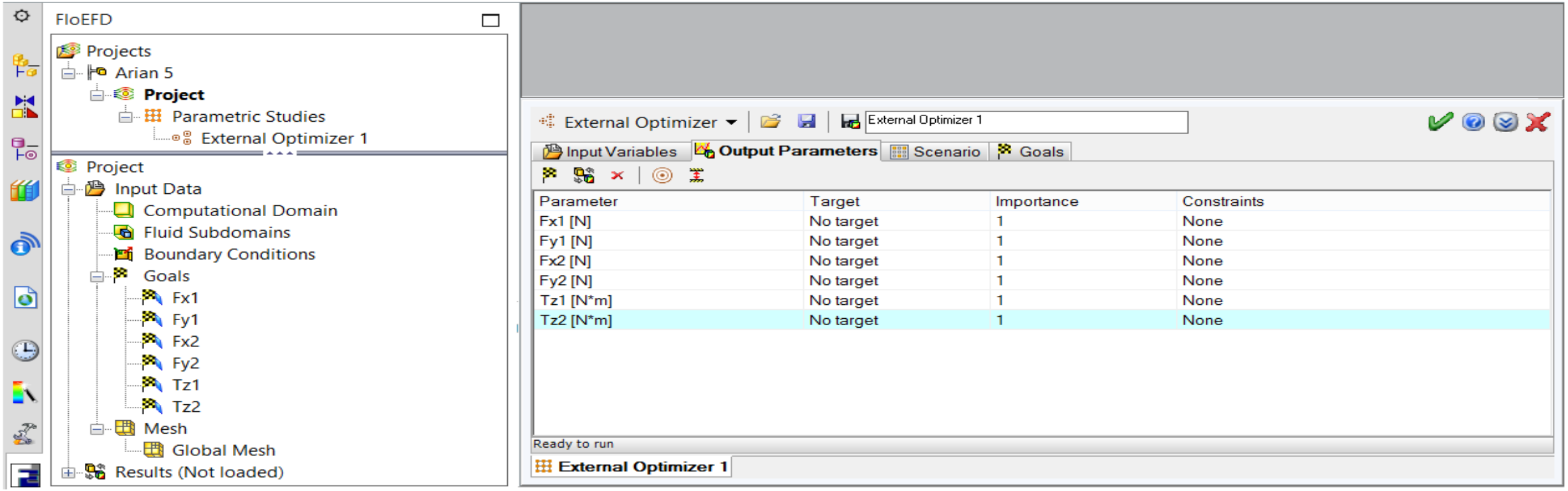
- Forces component are measured in coordinate system related with the main stage
- Torque values are on the axis of the coordinate system related with the boosters

Ariane 5 - Parametric Study. Input Variables



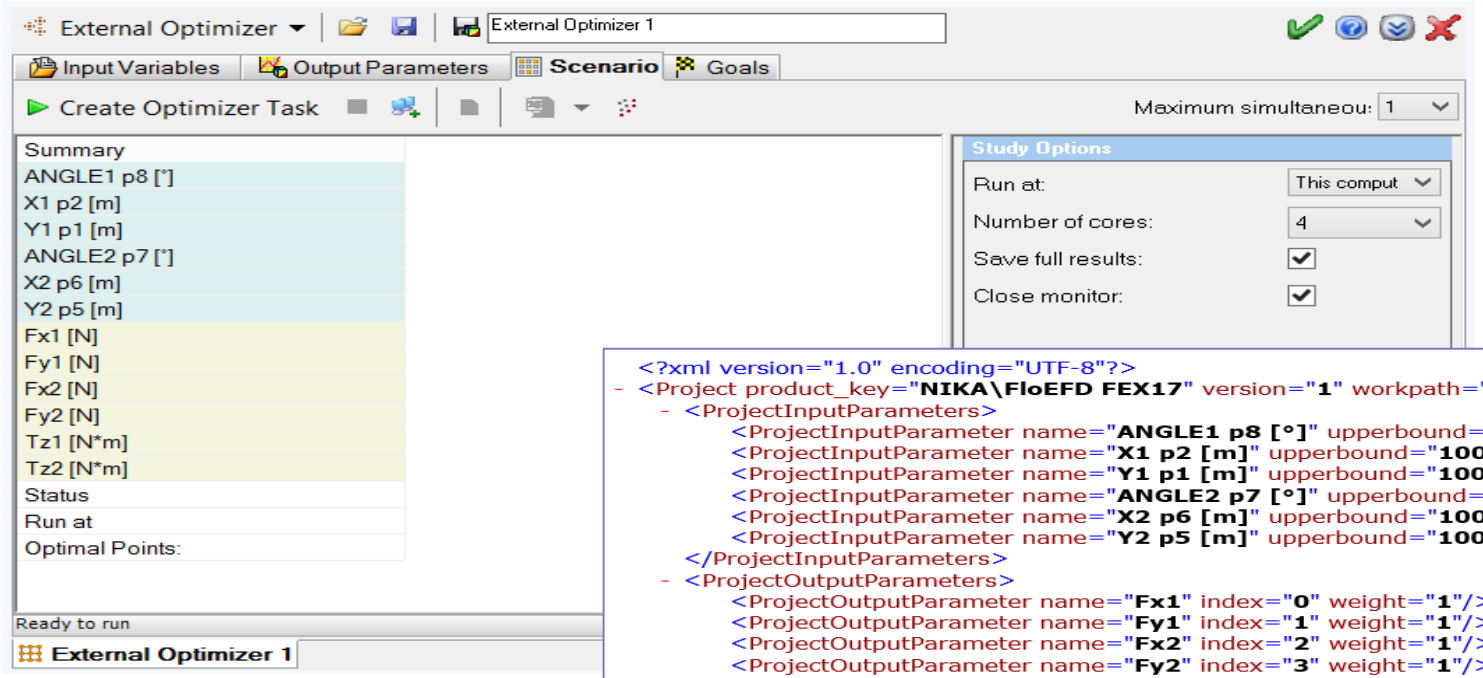
Parametric study allows to handle a FloEFD project parameters as well as a geometry constrains.
All necessary constrains are added on the Input Variable tab of the Parametric Study window.

Ariane 5 - Parametric Study. Output Parameters.



Output parameters supposed to be an objective function for the external optimizer but in this particular case output parameters are values of the aerodynamic forces. Force and torque goals are added in the Output Parameter tab of the Parametric Study window.

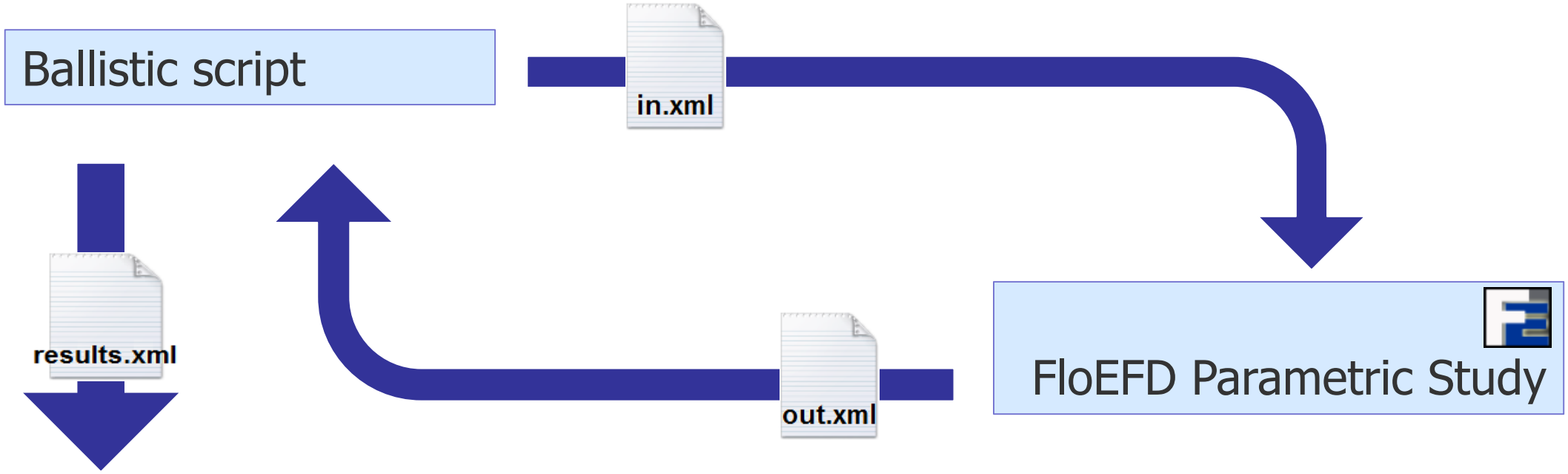
Ariane 5 - Parametric Study. The start button.




```
<?xml version="1.0" encoding="UTF-8"?>
- <Project product_key="NIKA\FloEFD FEX17" version="1" workpath="D:\Arian 5\1\Parametric Study 1" name="External Optimizer 1">
  - <ProjectInputParameters>
      <ProjectInputParameter name="ANGLE1 p8 [°]" upperbound="3.14159265358979" lowerbound="0" index="0"/>
      <ProjectInputParameter name="X1 p2 [m]" upperbound="100" lowerbound="30" index="1"/>
      <ProjectInputParameter name="Y1 p1 [m]" upperbound="100" lowerbound="4" index="2"/>
      <ProjectInputParameter name="ANGLE2 p7 [°]" upperbound="3.14159265358979" lowerbound="0" index="3"/>
      <ProjectInputParameter name="X2 p6 [m]" upperbound="100" lowerbound="30" index="4"/>
      <ProjectInputParameter name="Y2 p5 [m]" upperbound="100" lowerbound="4" index="5"/>
    </ProjectInputParameters>
  - <ProjectOutputParameters>
      <ProjectOutputParameter name="Fx1" index="0" weight="1"/>
      <ProjectOutputParameter name="Fy1" index="1" weight="1"/>
      <ProjectOutputParameter name="Fx2" index="2" weight="1"/>
      <ProjectOutputParameter name="Fy2" index="3" weight="1"/>
      <ProjectOutputParameter name="Tz1" index="4" weight="1"/>
      <ProjectOutputParameter name="Tz2" index="5" weight="1"/>
    </ProjectOutputParameters>
</Project>
```

Scenario tab is to manage the calculation process. In case of integration with an External Optimizer start button just creates the XML file with the task description.
Task. Xml is a file with input data for the external optimization program.

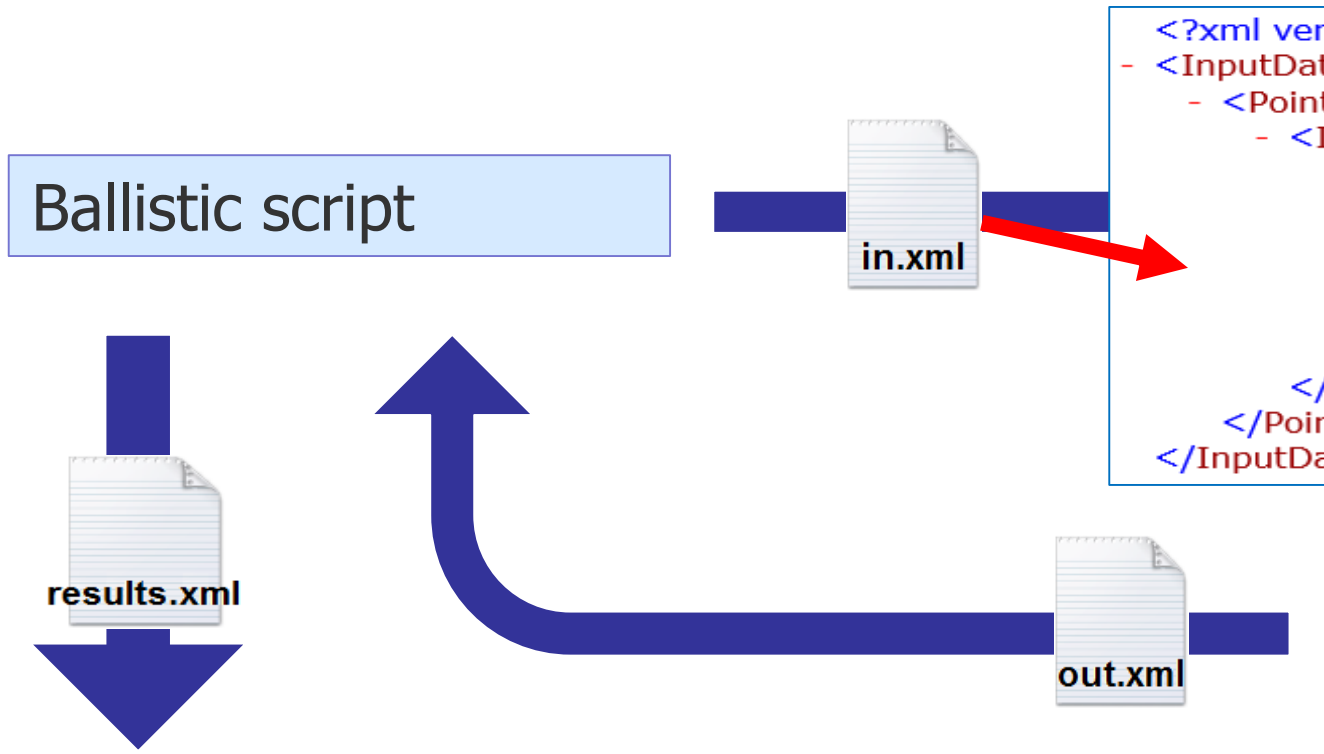
Ariane 5 - External script. Main cycle



Cycling calculation of each trajectory point controlled with users program. For this particular case Visual Basic script was developed. The script has to repeat the actions in the cycle:

- Creating in.xml file with the values of coordinates and angle of current booster position
- Starting of current position calculation and waiting of Out.xml file appearance
- Calculation of ballistic equation due to determination of the next position of the moving body

Ariane 5 - External script. Main cycle




```
<?xml version="1.0" encoding="UTF-8"?>
- <InputData>
  - <Point pointnum="1" index="0">
    - <InputParameters>
        <InputParameter index="0" value="0"/>
        <InputParameter index="1" value="31.91780"/>
        <InputParameter index="2" value="4.58201"/>
        <InputParameter index="3" value="0"/>
        <InputParameter index="4" value="31.91780"/>
        <InputParameter index="5" value="4.58201"/>
      </InputParameters>
    </Point>
  </InputData>
```

Cycling calculation of each trajectory point controlled with users program. For this particular case Visual Basic script was developed. The script has to repeat the actions in the cycle:

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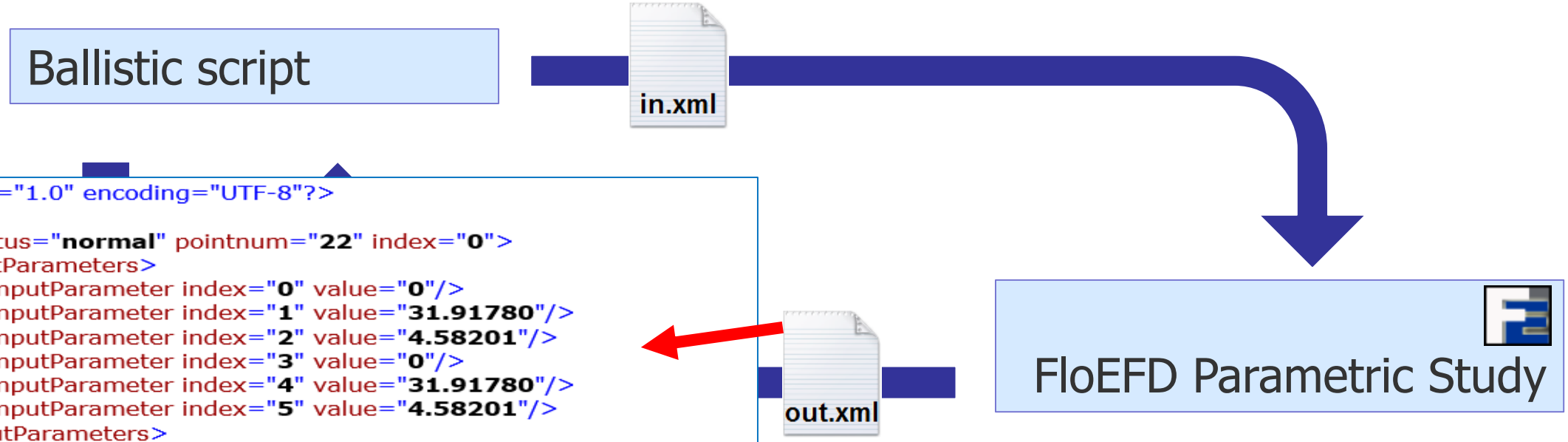
Ariane 5 - External script. Main cycle




```
<?xml version="1.0" encoding="UTF-8"?>
- <OutputData>
  - <Point status="normal" pointnum="22" index="0">
    - <InputParameters>
        <InputParameter index="0" value="0"/>
        <InputParameter index="1" value="31.91780"/>
        <InputParameter index="2" value="4.58201"/>
        <InputParameter index="3" value="0"/>
        <InputParameter index="4" value="31.91780"/>
        <InputParameter index="5" value="4.58201"/>
      </InputParameters>
    - <OutputParameters>
        <OutputParameter index="0" value="-1844.62333296517"/>
        <OutputParameter index="1" value="-1322.63067493238"/>
        <OutputParameter index="2" value="-17611.5373602153"/>
        <OutputParameter index="3" value="-1859.49628014235"/>
        <OutputParameter index="4" value="1314.01596482391"/>
        <OutputParameter index="5" value="17576.7690356027"/>
      </OutputParameters>
  </Point>
</OutputData>
```

n users program. For this particular case Visual Basic
in the cycle:
angle of current booster position
Out.xml file appearance
of the next position of the moving body

Ariane 5 - External script. In и Out

File with input data In.xml

```
<?xml version="1.0" encoding="UTF-8"?>
- <InputData>
  - <Point pointnum="1" index="0">
    - <InputParameters>
        <InputParameter index="0" value="0"/>
        <InputParameter index="1" value="31.91780"/>
        <InputParameter index="2" value="4.58201"/>
        <InputParameter index="3" value="0"/>
        <InputParameter index="4" value="31.91780"/>
        <InputParameter index="5" value="4.58201"/>
      </InputParameters>
    </Point>
</InputData>
```

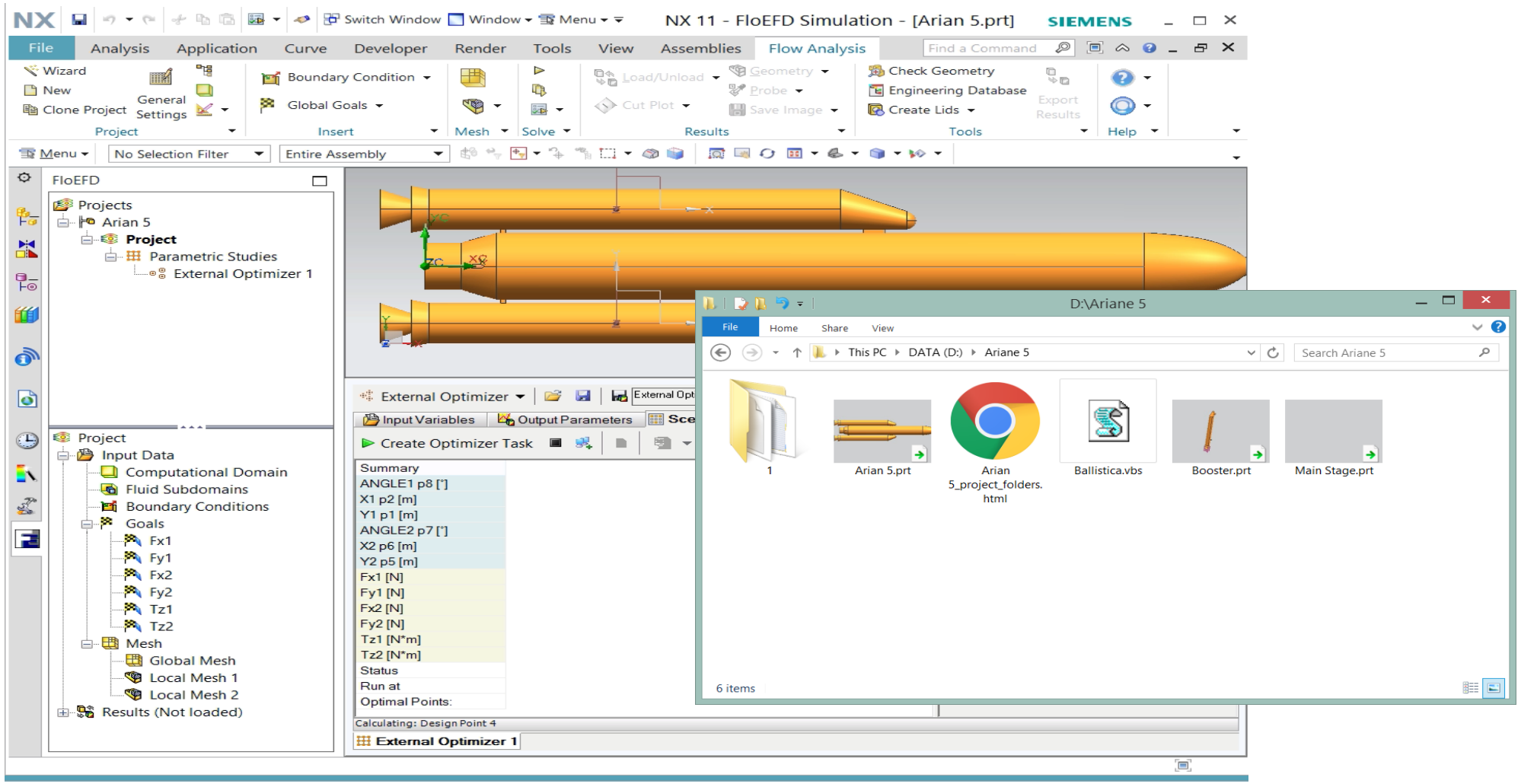
File with output dataOut.xml

```
<?xml version="1.0" encoding="UTF-8"?>
- <OutputData>
  - <Point status="normal" pointnum="22" index="0">
    - <InputParameters>
        <InputParameter index="0" value="0"/>
        <InputParameter index="1" value="31.91780"/>
        <InputParameter index="2" value="4.58201"/>
        <InputParameter index="3" value="0"/>
        <InputParameter index="4" value="31.91780"/>
        <InputParameter index="5" value="4.58201"/>
      </InputParameters>
    - <OutputParameters>
        <OutputParameter index="0" value="-1844.62333296517"/>
        <OutputParameter index="1" value="-1322.63067493238"/>
        <OutputParameter index="2" value="-17611.5373602153"/>
        <OutputParameter index="3" value="-1859.49628014235"/>
        <OutputParameter index="4" value="1314.01596482391"/>
        <OutputParameter index="5" value="17576.7690356027"/>
      </OutputParameters>
    </Point>
</OutputData>
```

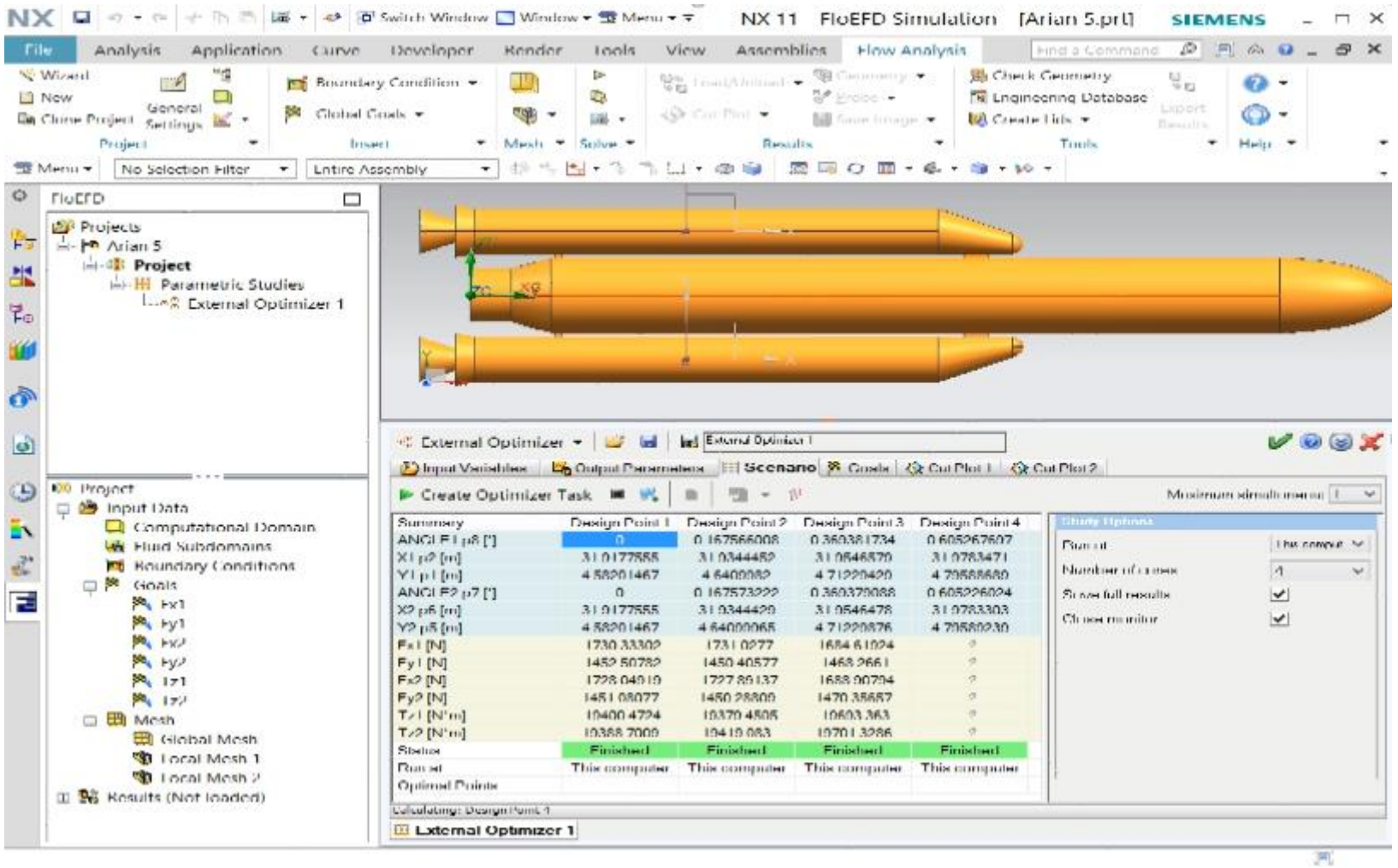
Ariane 5 - External script

```
'   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
'                              Initial parameters
I = 3740000
Mass = 39300
dt = 0.2
Fi = 0
X = 31.91775553
Y = 4.582014666
Vx = 0 : Vy = 0 : W = 0 : j = 0
'   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
'                              Main cycle
While (Abs(X) <= 70) And (Y <= 30)
    X0 = X : Y0 = Y : Fi0 = Fi : Vx0 = Vx : Vy0 = Vy : W0 = W
    Set t_in=fso.CreateTextFile(TaskPath & "in.xml", true)
    t_in.WriteLine ("<?xml version=""1.0"" encoding=""utf-8"" ?>") : t_in.WriteLine ("<InputData>")
    t_in.WriteLine ("<Point index="""& 0 &""" pointnum=""" & j & """>") : t_in.WriteLine ("<InputParameters>")
    t_in.WriteLine ("<InputParameter index=""0"" value="""& X & """/>") : t_in.WriteLine ("<InputParameter index=""1"" value="""& Y & """ />")
    t_in.WriteLine ("<InputParameter index=""2"" value="""& Fi & """ />") : t_in.WriteLine ("</InputParameters>")
    t_in.WriteLine ("</Point>") : t_in.WriteLine ("</InputData>")
    t_in.Close ()
'   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
'                              Runing the calculation of current position
    WshShell.Run PathEXE & " """ & TaskPath & "task.xml"" " & "-start -wait",1, True
    j = j + 1
    While Not fso.FileExists(TaskPath & "out.xml")
        WScript.Sleep 10000
    Wend
'   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
'                              Parsing of the resulting out.xml
    ValueOut = ""
    objXML.load(TaskPath & "out.xml")
    Set ParametersOuts = objXML.documentElement.childNodes
    For Each ParameterOut In ParametersOuts
        Set OutParams = ParameterOut.childNodes
        For Each Param In OutParams
            If Param.nodename = "OutputParameters" Then
                Set OPs = Param.childNodes
                For Each OP In OPs : Value0 = OP.getAttribute ("value") : ValueOut = ValueOut & "|" & Value0 : Next
            End If
        Next
    Next
    OutputValue = Split (ValueOut,"|")
    ForceX = OutputValue(1) : ForceY = OutputValue(2) : TorqueZ = OutputValue(3)
'   .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .  .
'                              Ballistic Equations
    Vx = Vx0 + (Fg-ForceX/Mass)*dt
    Vy = Vy0 + (ForceY + F1)/Mass*dt
    W = W0 + dt*(TorqueZ + M1)/I
    X = X0 + dt*(Vx + Vx0)/2
    Y = Y0 + dt*(Vy + Vy0)/2
    Fi = Fi0 + dt*(W + W0)/2
Wend
```

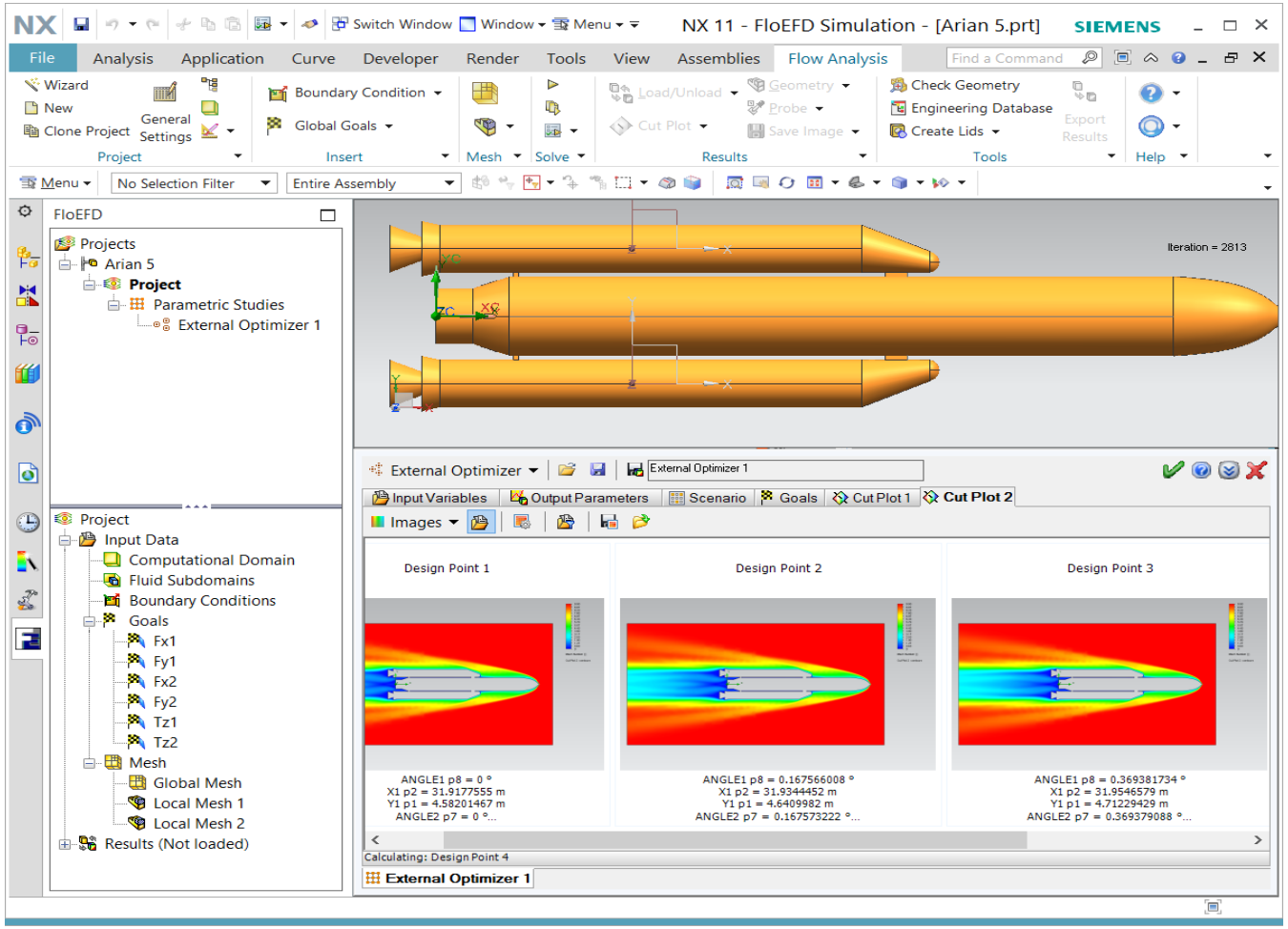
Ariane 5 - Parametric Study. Cycling process



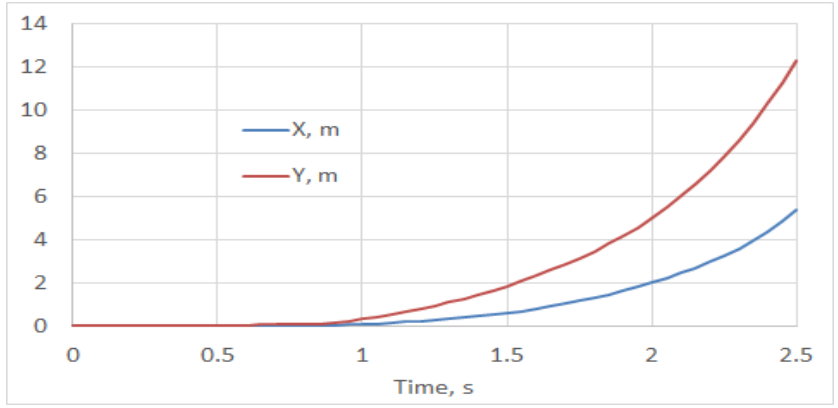
Ariane 5 - Parametric Study. Cycling process

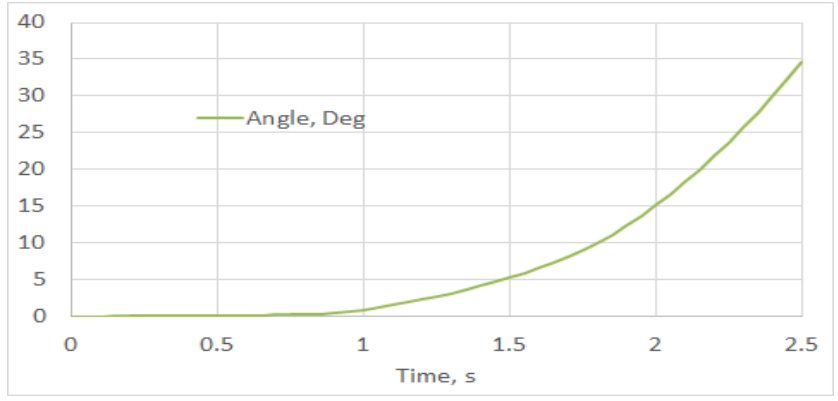


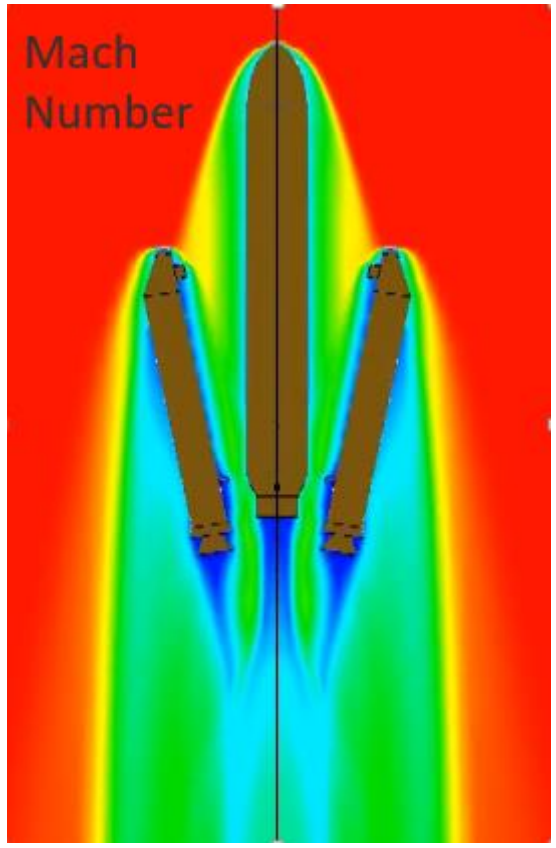
Ariane 5 - Parametric Study. Cycling process

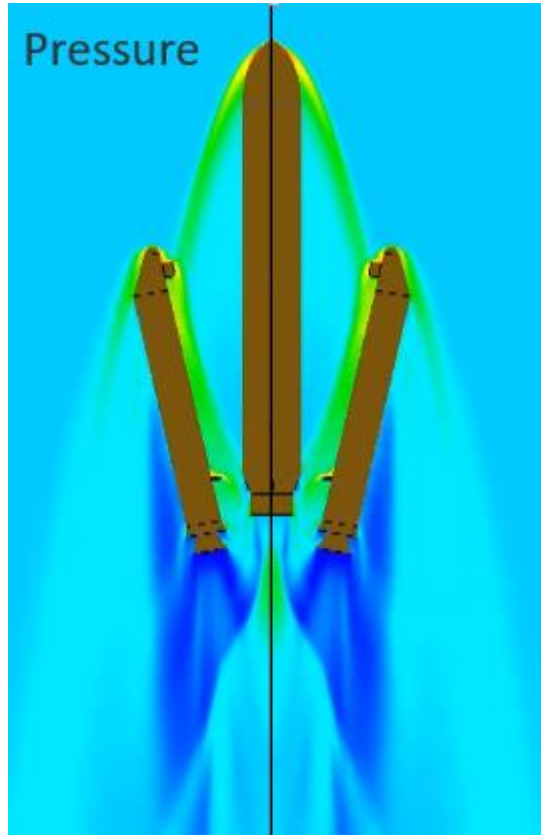


Ariane 5 - Results





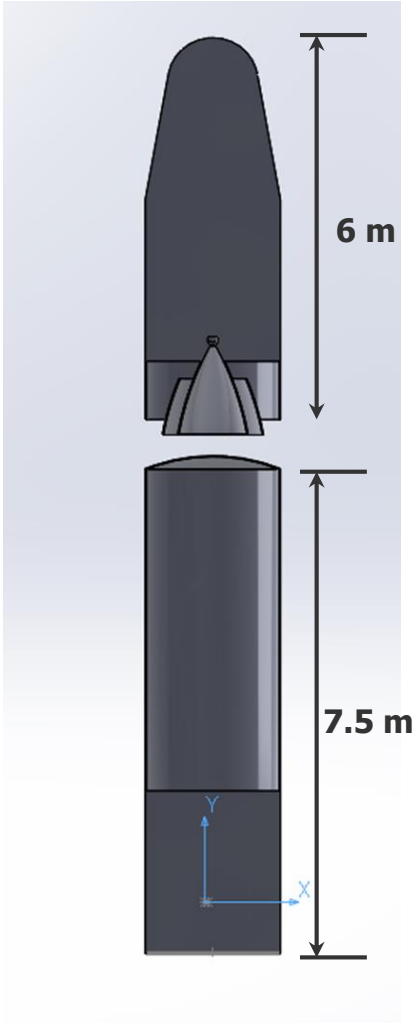




Results of solid rocket booster trajectory calculation:

- coordinate chart and angle chart VS time
- Mach number and pressure fields

"Hot" rocket stage separation



Parameters just before separation: H=55 km, M=9.5
Parameters of separated stage: D=2 m, m_2=2160 kg, I_{2z}=3770 kg*m2
Parameters in engine combustion chamber: P=70 bar, T=3500 K
Nozzle expansion area ratio: ε_{a1}=137 , M_{a1}=4.94
ε_{a2}=292 , M_{a2}=5.46

Ballistic equations:

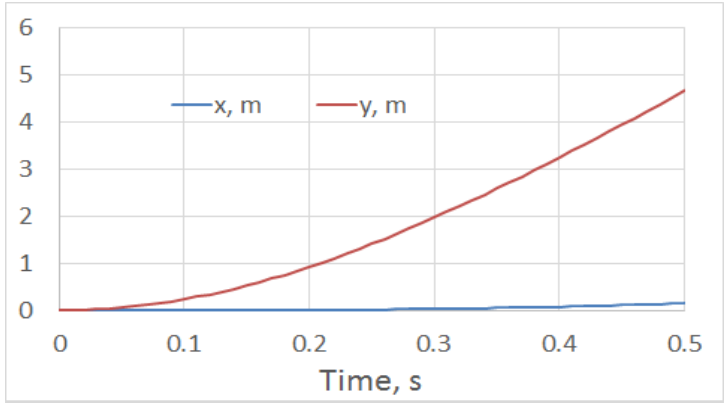
$$m_2 \frac{d\overrightarrow{V_2}}{dt} = \overrightarrow{F_{2a}} + \overrightarrow{F_{2g}} \qquad \frac{d\overrightarrow{r_2}}{dt} = \overrightarrow{V_2}$$

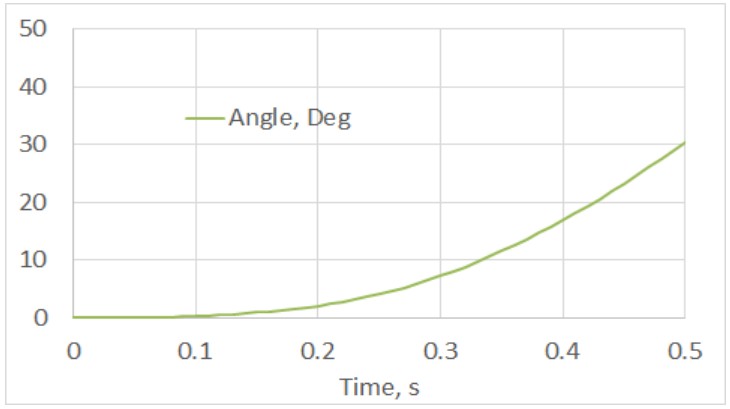
$$I_{2z} \frac{d\omega_{2z}}{dt} = M_{2z} \qquad \frac{d\varphi_z}{dt} = \omega_z$$

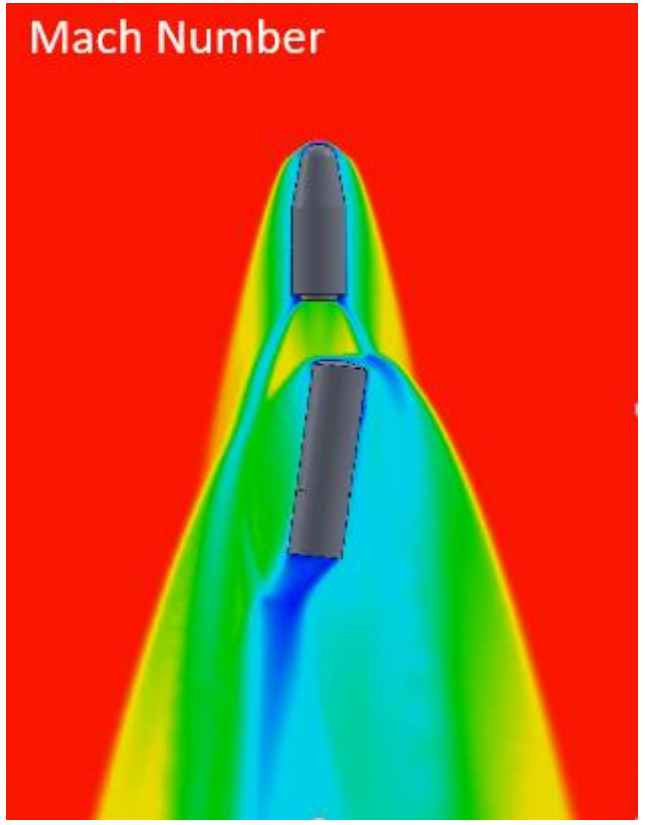
Typical time scales estimations

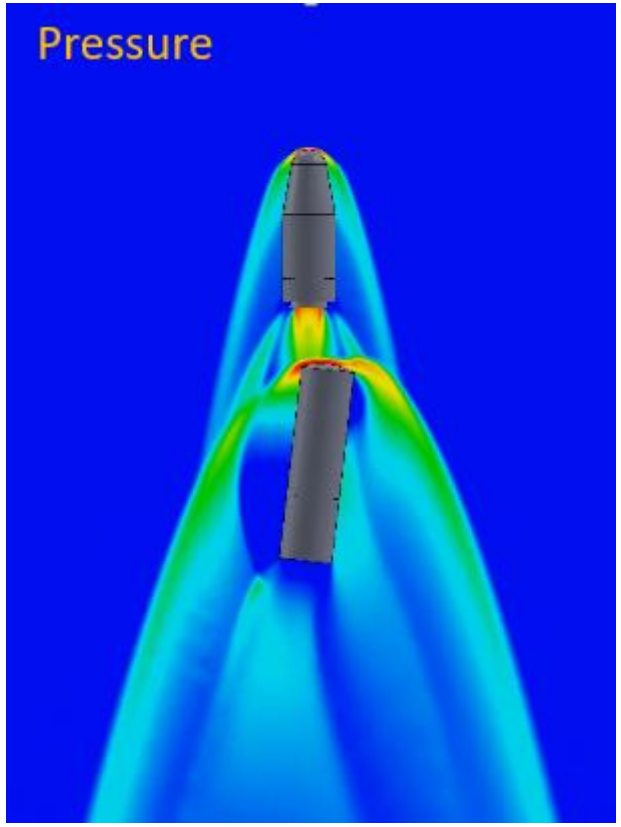
$\tau_a \sim L^*/V \sim 7e\text{-}4$ s,
$\tau_s \sim (2*m*L^*/(S*Po'))^{1/2} \sim 0.2$ s $\Rightarrow$
$\tau_a << \tau_s$

"Hot" rocket stage separation - Results









Results of rocket stage separation trajectory calculation:

- coordinate chart and angle chart VS time
- Mach number and pressure fields

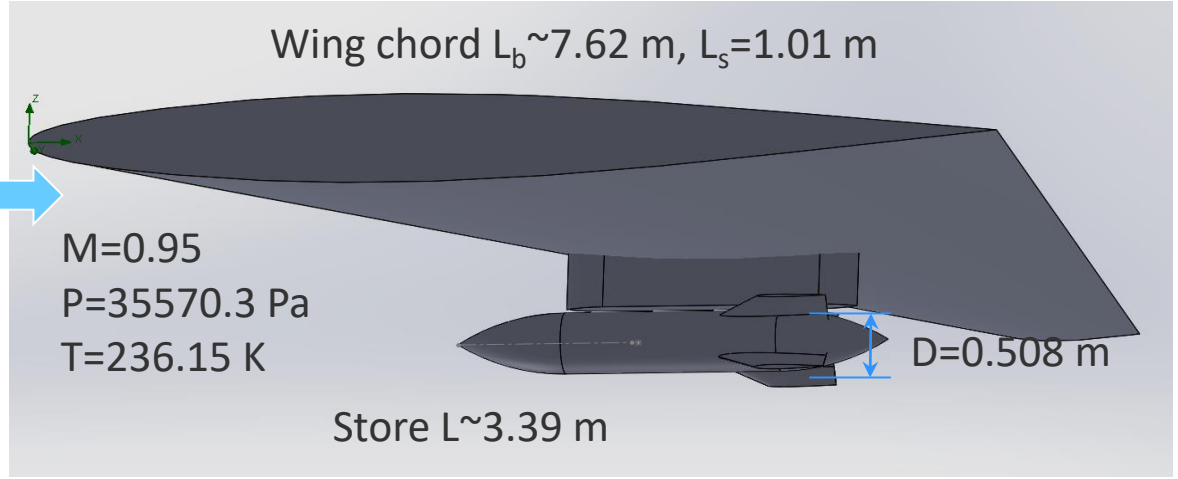
Separation of solid body from the aircraft

Approach accuracy is verified by the results comparison with the data from the article:

Thoms, R.D. and Jordan, J.K., "Investigation of Multiple-Body Trajectory Prediction Using Time-Accurate Computational Fluid Dynamics", AIAA Paper 95-1870, June, 1995

Model was considered in 3D

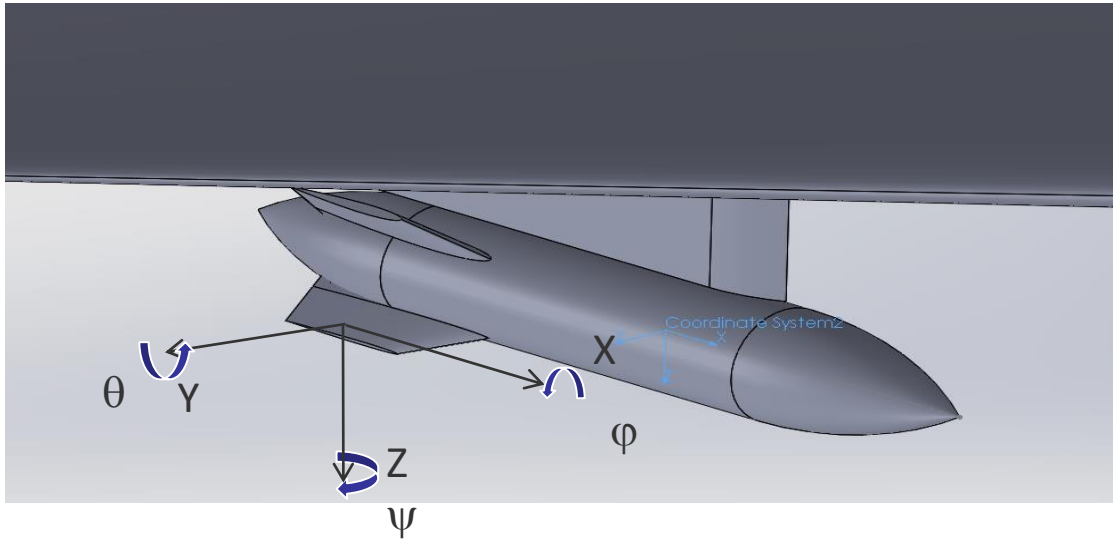
Separation is started at altitude of H=8 000 m



Ballistic Equations for 3D task

To estimate store position change the following ballistic equations were used:

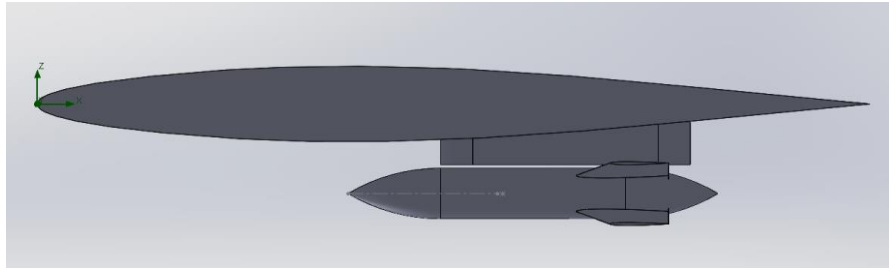
$$m\frac{d^2x}{dt^2} = F_x$$
$$m\frac{d^2y}{dt^2} = F_y$$
$$m\frac{d^2z}{dt^2} = F_z + F_g$$
$$I_x\frac{d^2\varphi}{dt^2} = M_x$$
$$I_y\frac{d^2\theta}{dt^2} + \frac{d\varphi}{dt}\frac{d\psi}{dt}(I_x - I_z) = M_y$$
$$I_z\frac{d^2\theta}{dt^2} + \frac{d\varphi}{dt}\frac{d\theta}{dt}(I_y - I_x) = M_y$$



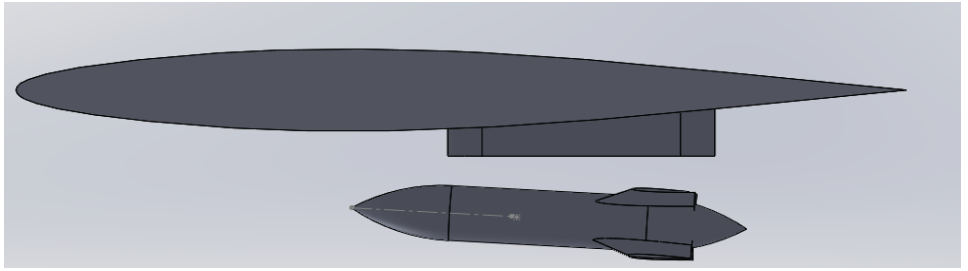
Mass = 907.1525 kg
I_X = 27.11644 kg*m2
I_Y = 488.0959 kg*m2
I_Z = 488.0959 kg*m^2

Separation of solid body from the aircraft

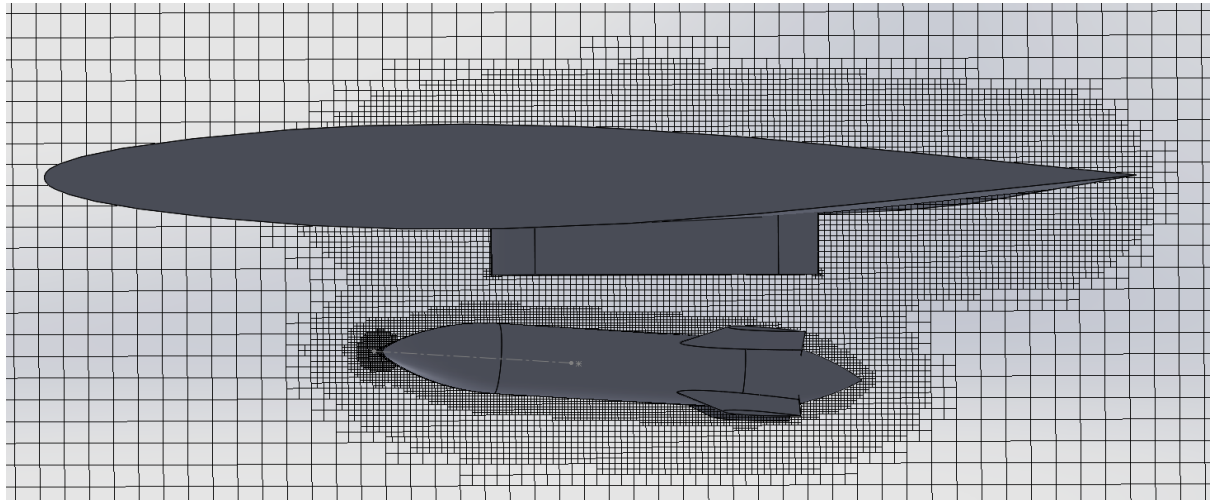
T=0 s



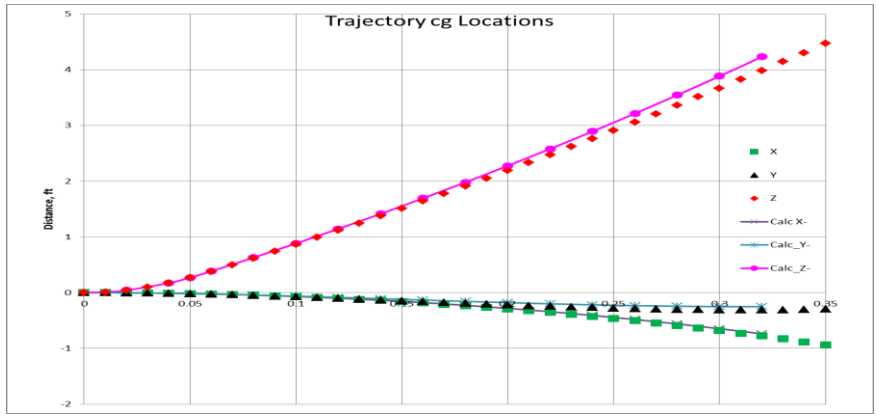
T=0.1 s



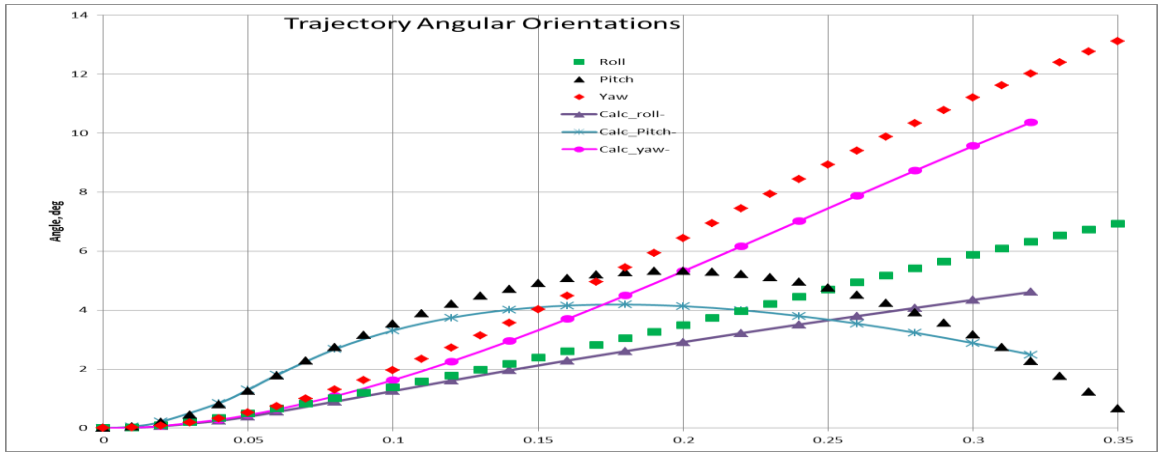
T=0.32 s



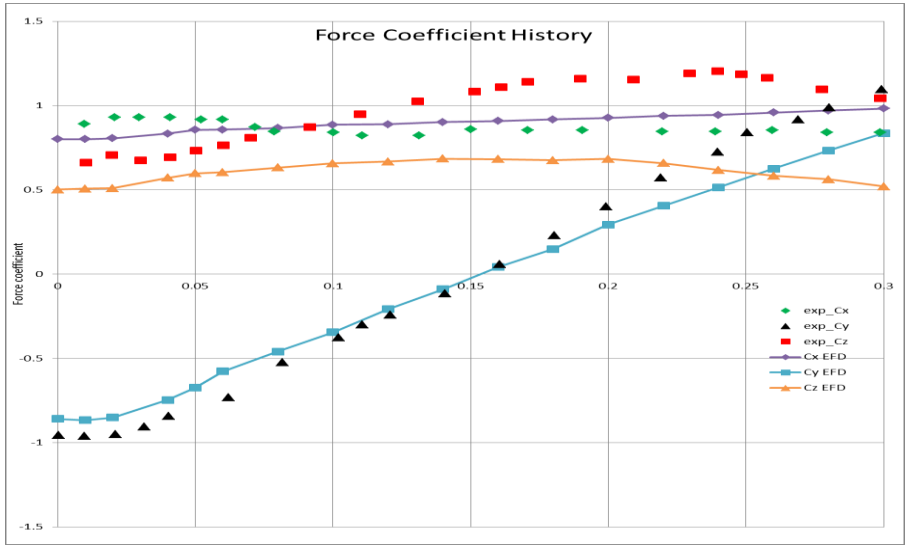
Body separation - Results comparison

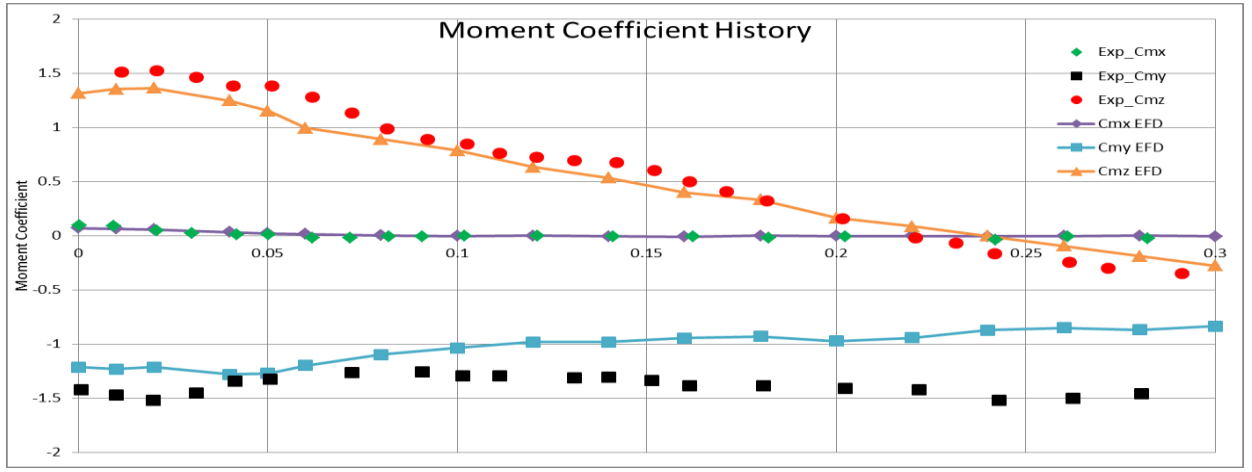


Store Mass center displacement vs time



Store angular turn regarding mass center vs time





Body separation - Results