XFlow™
Meshless Particle-based CFD Code

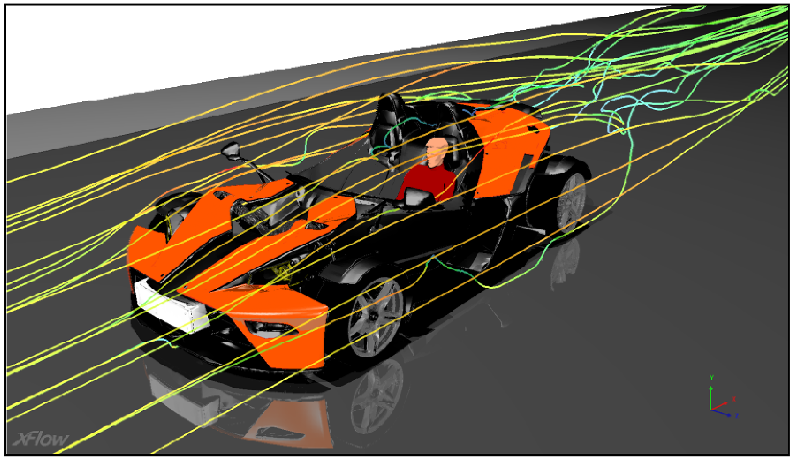
Presented By: Fausto Gill Di Vincenzo
24-05-2012

Topics

- XFlow Overview - Application fields & Theory
- GUI et Validation cases for external aerodynamics
- CFD Process approach - Mesh-based vs XFlow (Meshless)
- Wing case study - Static Aeroelasticity application
- UAV case study

XFlow™ Key Technology

- **XFlow** ™ developed by XFlow Technlogy™ - Division of Next Limit Technologies™
- **Next Limit Technology™** mission is to provide simulation technologies for a broad range of applications in Visualization, Science and Engineering
- **XFlow** ™ uses a proprietary, particle-based fully lagrangian, meshless approach which can easily predict Flow, Thermal and Acoustic behavior on complex geometric domain involving Moving Boundaries, Free Surface and Fluid-Structure Interaction (FSI)



- The **Particle-base Kinetic** algorithm resolves the Boltzmann (mesoscopic) and the compressible Navier-Stokes (macroscopic) equations - Specifically designed to perform fast with accessible hardware
- Complexity of surfaces is not a limiting factor

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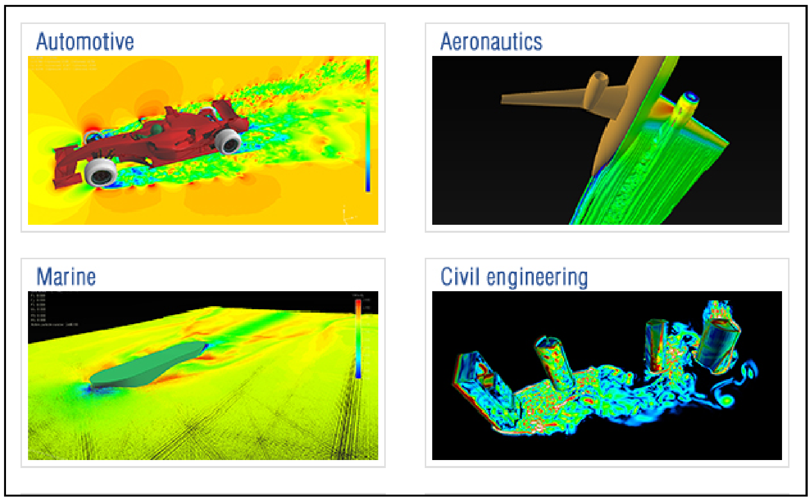
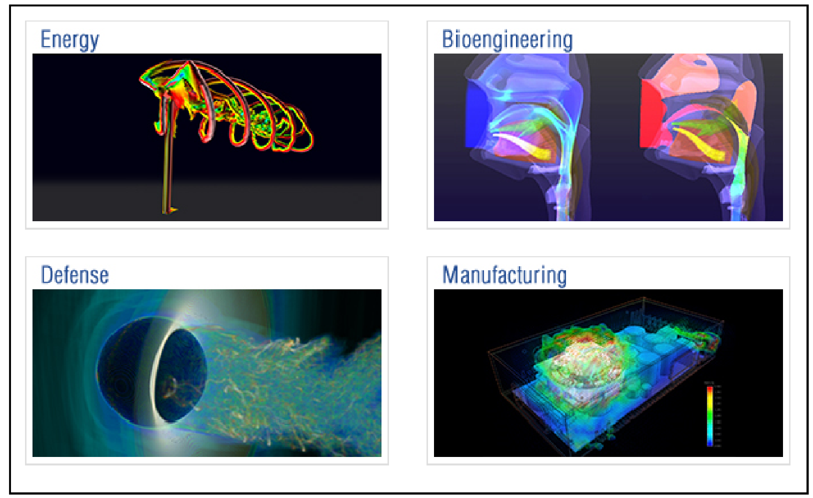
XFlow™ Applications

XFlow is a Particle-based CFD software able to solve complex **transient** fluid dynamics problems such as Aerodynamics, Aero-acoustic, Moving parts, Free surface flow including Fluid-Structures interaction





Analysis capabilities

- External and internal aerodynamics
- Free surface flows
- Thermal analysis: convection, radiation, conjugated heat transfer
- Flow through porous media
- Advanced modeling: moving parts, forced and constrained motion, contact

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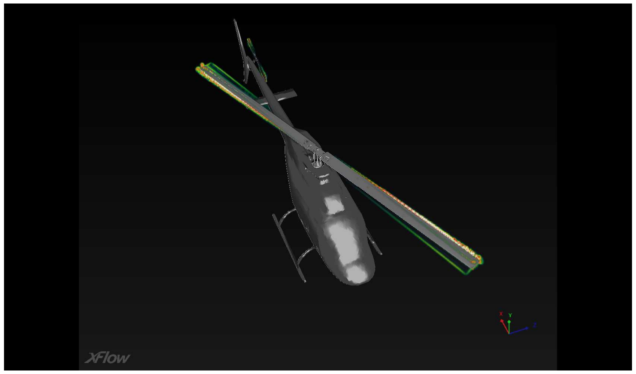
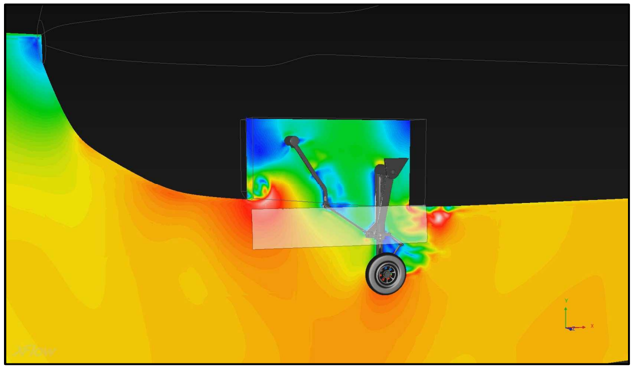
Xflow application fields

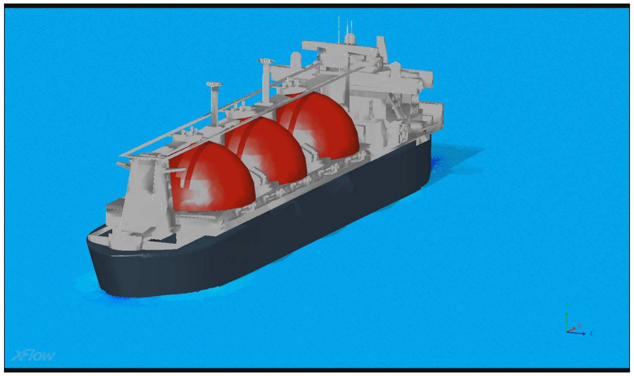
Helicopter - No moving Mesh



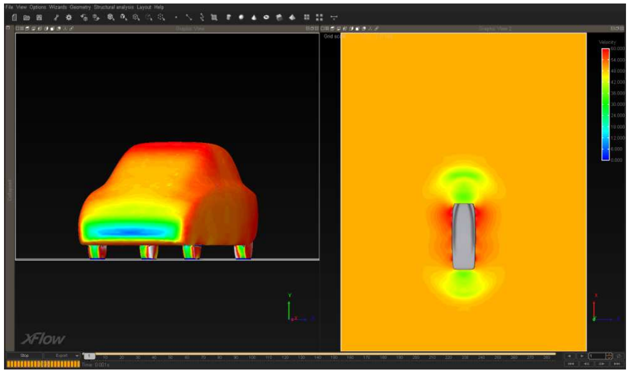
Landing gear - No moving Mesh

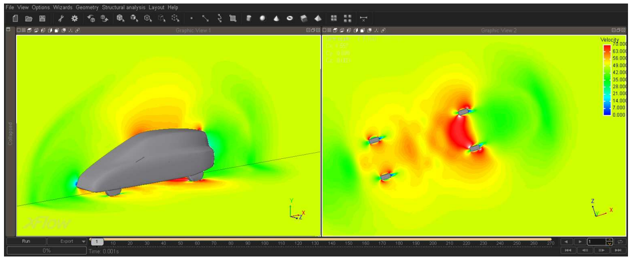


Free surface

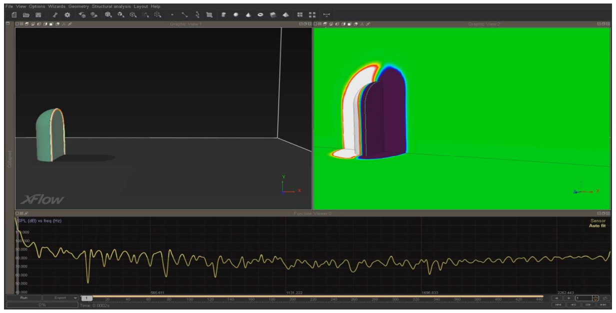


Automotive application





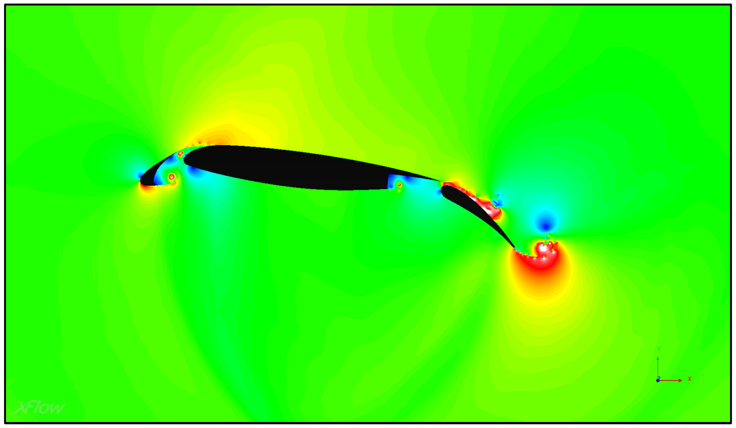
Acoustic



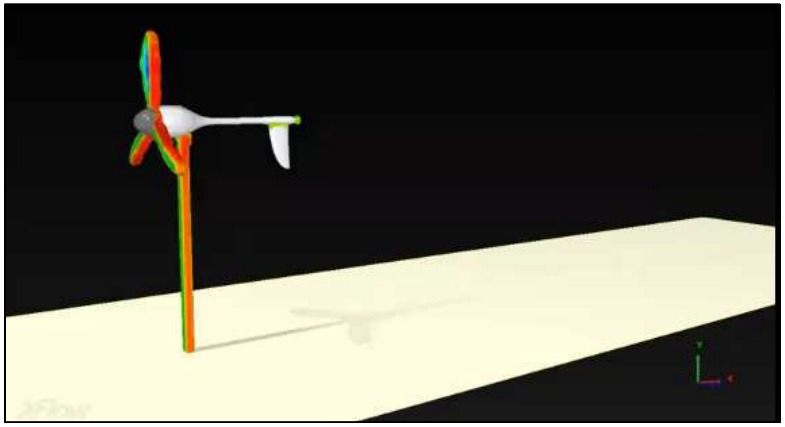
Xflow application fields

Aeronautic application - Surface Refinement

Boundary Layer modeling - High lift device



Wing turbine - Wake Refinement



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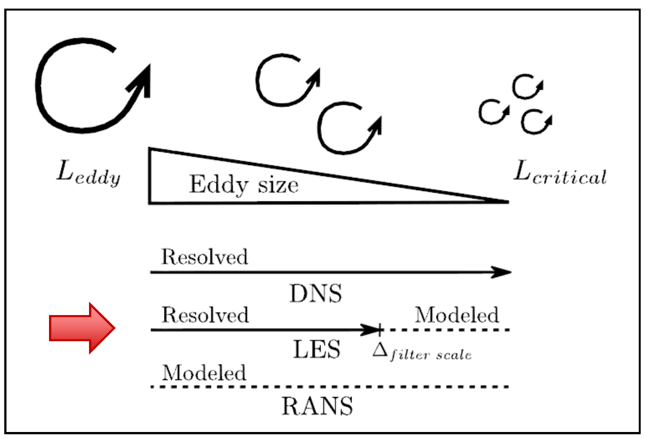
Large Eddy Simulation- Turbulence Modeling

Large **E**ddy **S**imulation (**LES**) originally implemented in the 1970s by atmospheric scientists to study the weather

- **Larger Scales of turbulence** carry the majority of the energy hence more important
- **Smaller Scales of turbulence** found to be more universal and extensively studied hence more easily modeled

LES directly **solves** large spatial scales while **modeling** the smaller scales

- **Sub-grid scale modeling** done by a low-pass filter applied to Navier-Stokes equation



- **D**irect **N**umerical **S**imulation (**DNS**) attempts to solve all time and scales - Computational unrealistic
- **R**eynolds **A**verage **N**avier**-S**tokes (**RANS**) splits variables into Time-Average "mean" part and Turbulent part - Not suitable for wake flows or flows with large separation when turbulence part could have the same order of the mean
- **L**arge **E**ddy **S**imulation is a method between **DNS** and **RANS** which filters of the N-S equation to separate scales to be modeled from those will be solved directly

- **XFlow LES** scheme - **W**all-**A**dapting **L**ocal **E**ddy-viscosity (**WALE**)

Good properties both near and far from the wall and with laminar and turbulent flow

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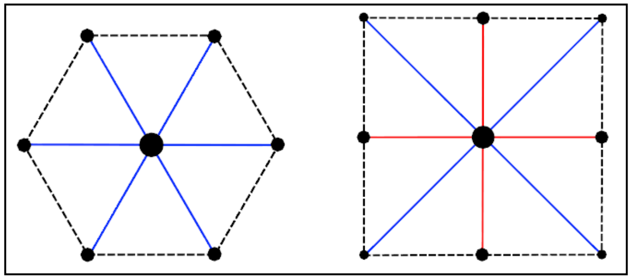
Lattice Boltzmann Method

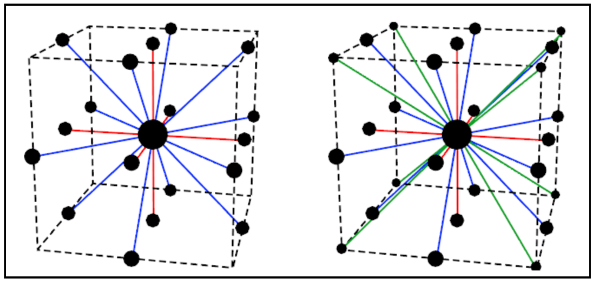
Lattice **B**oltzmann **M**ethod (**LBM**) is an extension of the **L**attice **G**as **A**utomata

- **LGA** schemes use discrete numbers to represent the state of the molecules
- **LBM** method makes use of **statistical distribution** functions with real variables preserving by construction the conservation of mass, linear momentum and energy
- **Chapman-Enskog** expansion shows that it is possible to design LGA schemes that recover the hydrodynamic macroscopic behavior at low Mach numbers
- From **Chapman-Enskog** & **Boltzmann's equation**
  Compressible Navier-Stokes equation is recovered
- **Boltzmann's Transport equation** identifies the **distribution function** f_i
  $f_i(r + c_i \Delta t, t + \Delta t) = f_i(r, t) + \Omega_i^B(f_1, ..., f_b)$ with the Collision operator $\Omega_i^B(f_1, ..., f_b)$
- **LBM** schemes classified by spatial dimension *d* and number of distribution function *b*
  DdQb

2D LBM schemes *D2Q7 - D2Q9*



3D LBM schemes *D3Q19 - D3Q27*



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- CFD Process approach - Mesh-based vs XFlow (Meshless)
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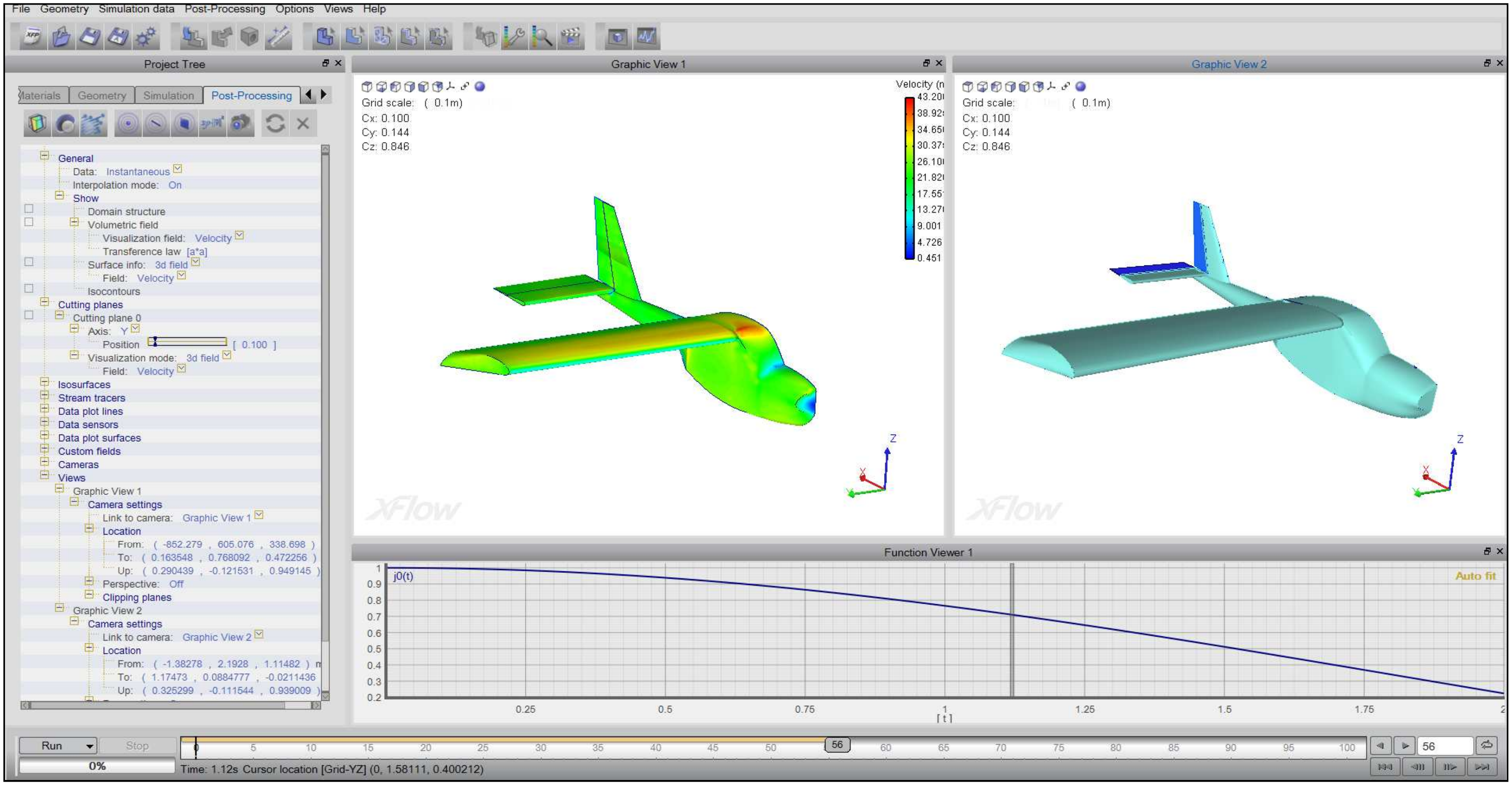
XFlow™ Interface

XFlow™ provides a unique GUI with pre-processor, solver and post-processor fully integrated in the same environment



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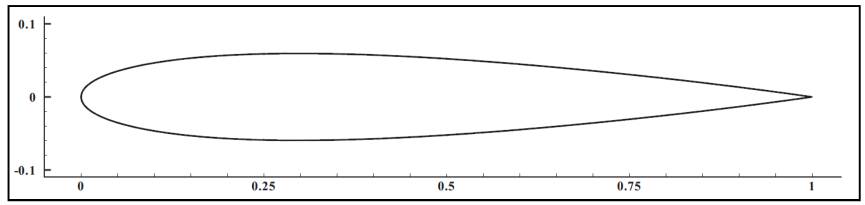
1st Validation Test Case

Two-Dimensional Simulation of Flow Past NACA-0012 Airfoil

- Simulation Conditions

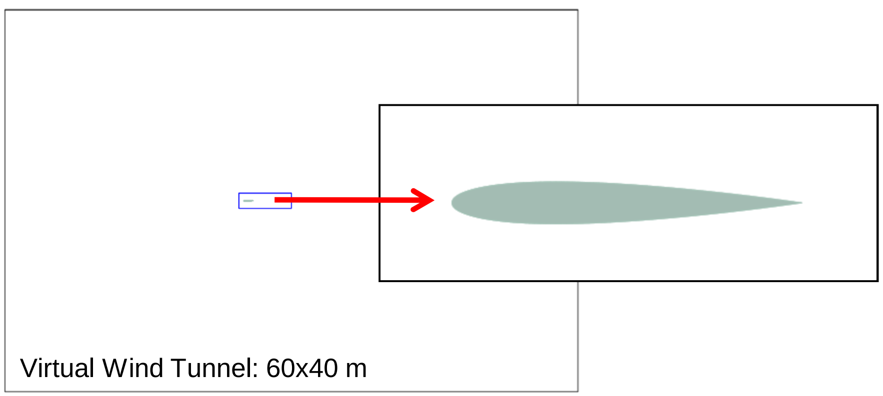
Free-stream velocity	v_{ref}	50 m s^{-1}
Density	ρ	1 kg m^{-3}
Dynamic viscosity	μ	0.1 Pa s
Chord length	L	1 m
Reynolds number	Re	500
Angle-of-attack	α	0 degree

NACA-0012 Airfoil

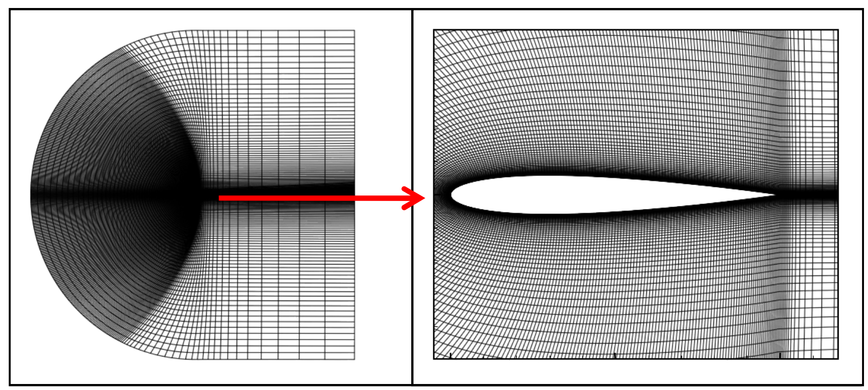


- XFlow - CFL3D Comparison

XFlow Wind Tunnel



CFL3D Domain & Mesh



Reference: David P. Lockard, Li-Shi Luo, Bart A. Singer, *Evaluation of the Lattice-Boltzmann Equation Solver PowerFLOW for Aerodynamic Applications*, October 2000.

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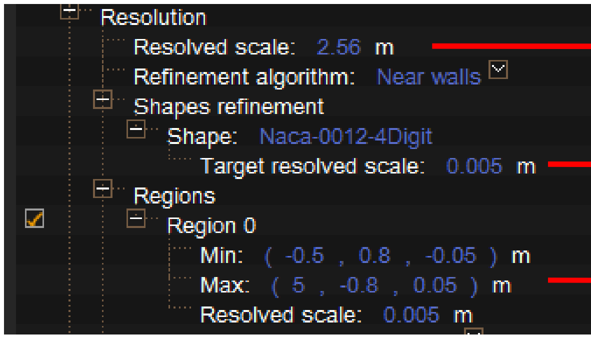
Resolution of the Solution

- Resolved scale set up to ensure the symmetry of the Flow

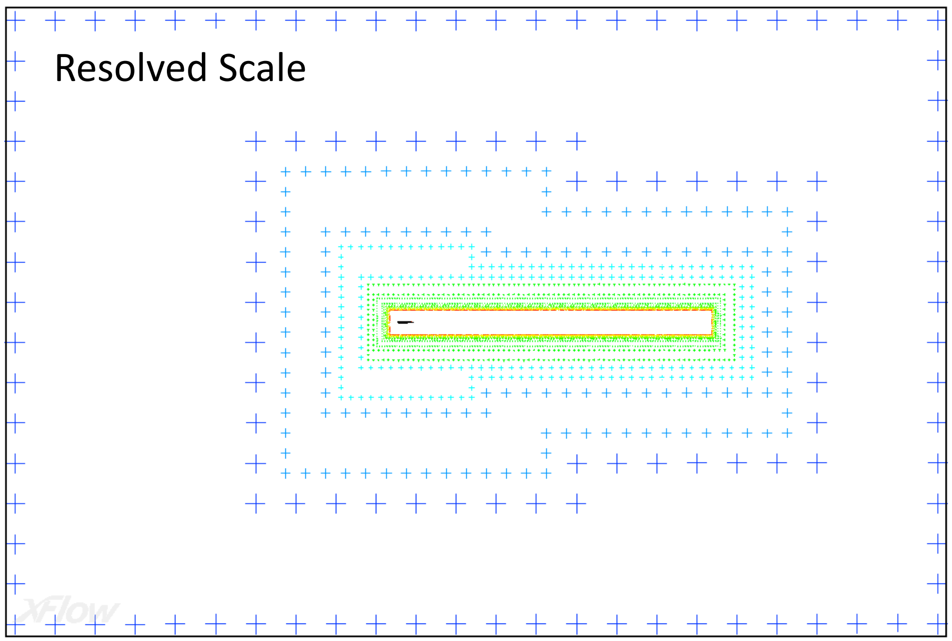


Resolved Scale

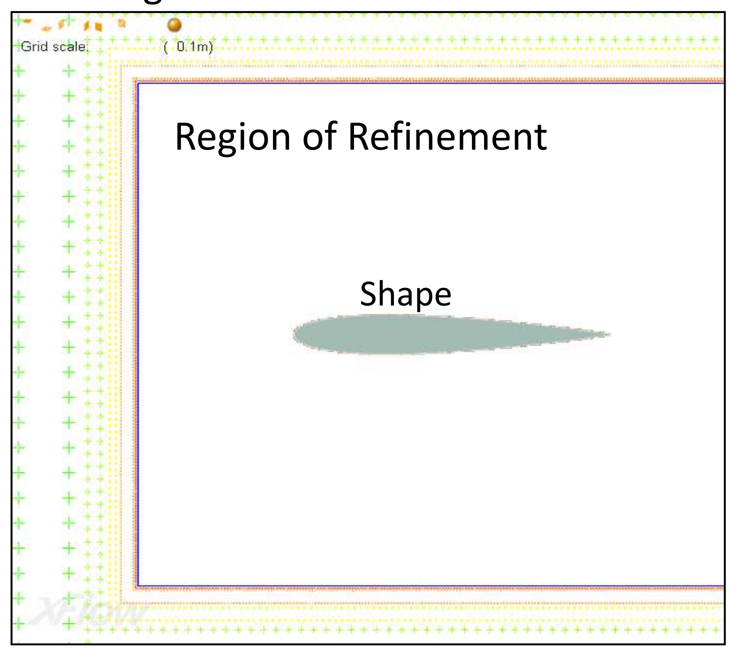
Target resolved Scale - Shape Naca 0012

Region of Refinement

Far field - 2.56m



Region of Refinement - 0.005m



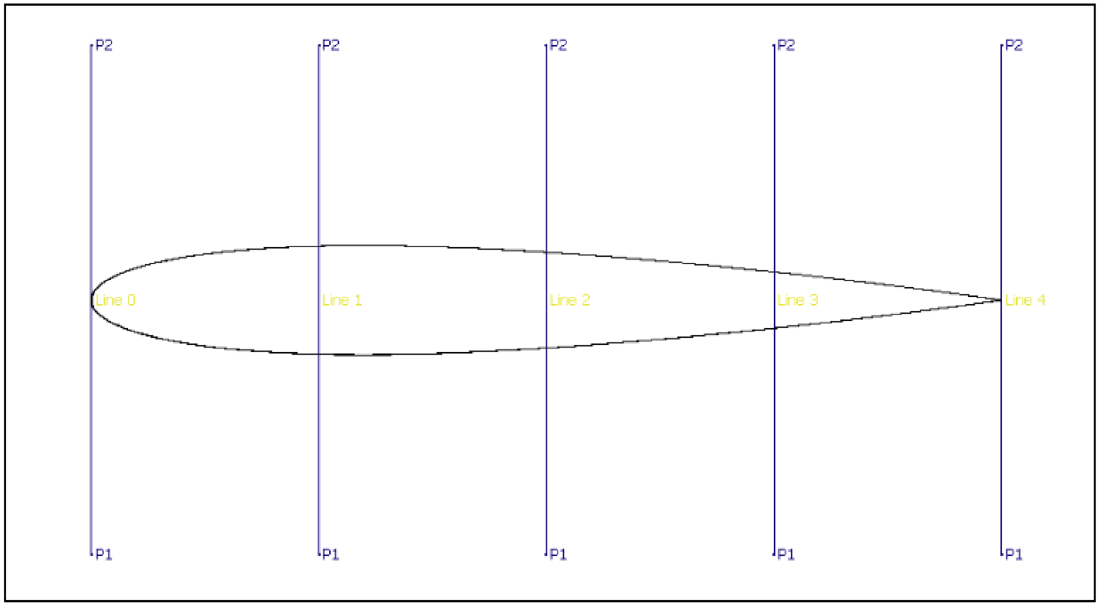
Post Processing of Results

Data plot lines: x/L = 0.0, 0.25, 0.5, 0.75 and 1.0

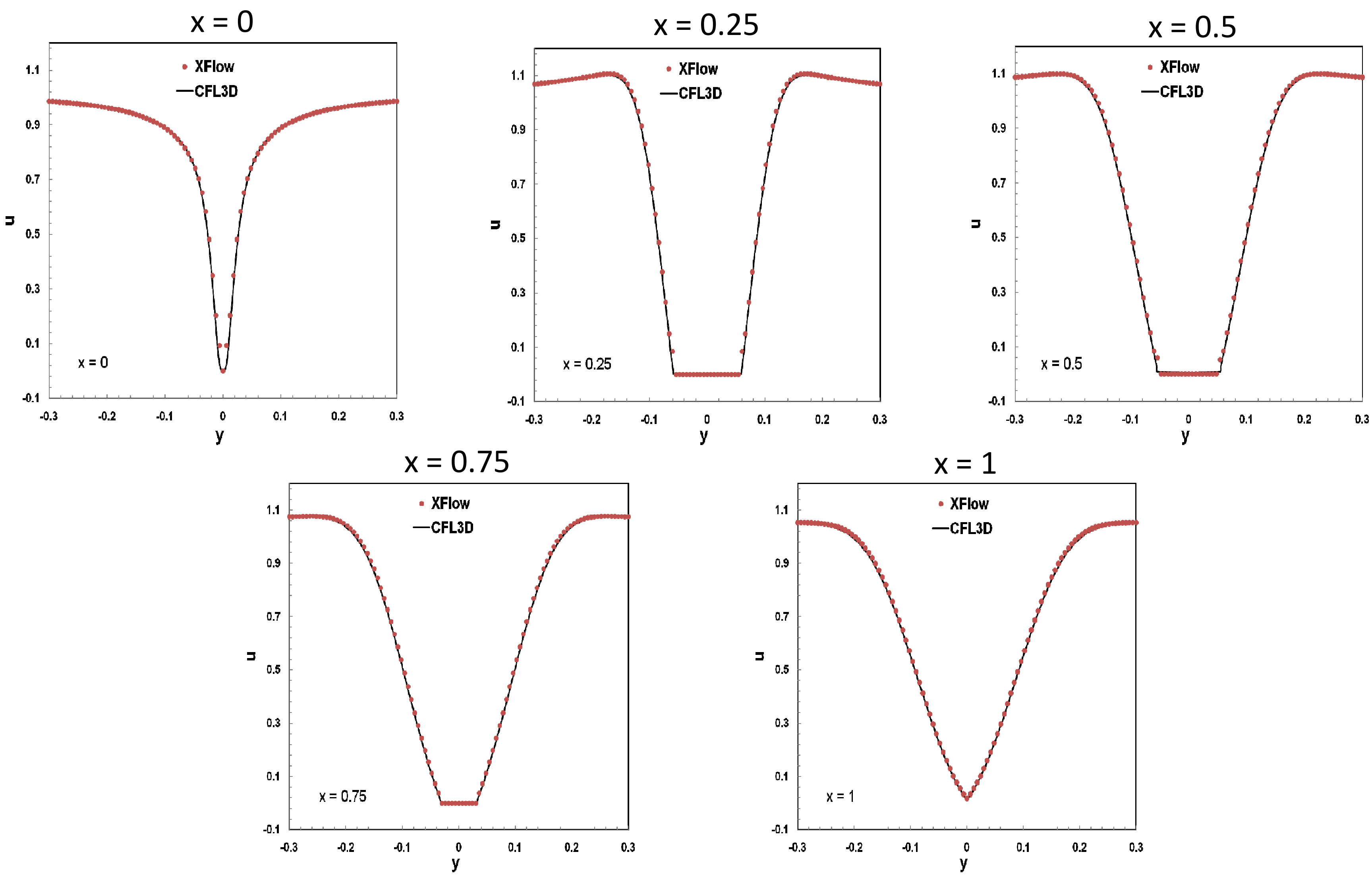
Results monitored:

- X Component of Velocity
- Y Component of Velocity
- Pressure Coefficient

Plot lines on shape



X - component of the Velocity along the Data Plot Lines



Courtesy of David P. Lockard and
the NASA Langley Research Center

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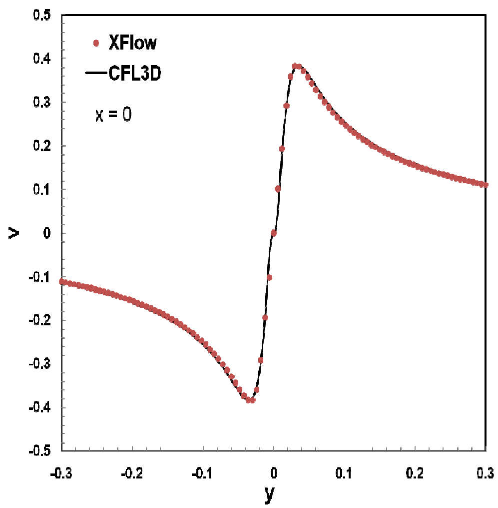
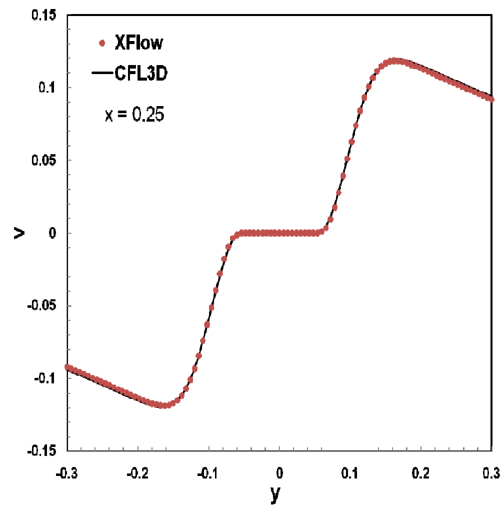
Y - component of the Velocity along the Data Plot Lines

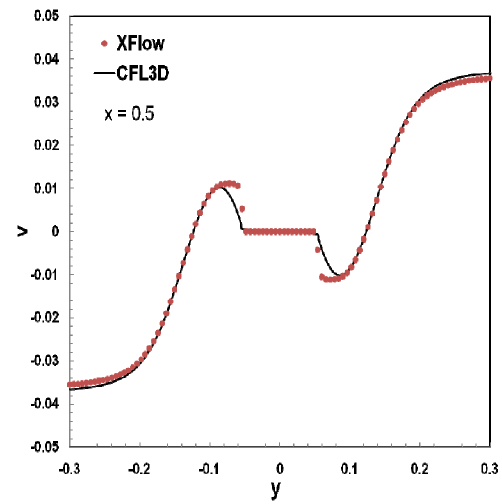
x = 0



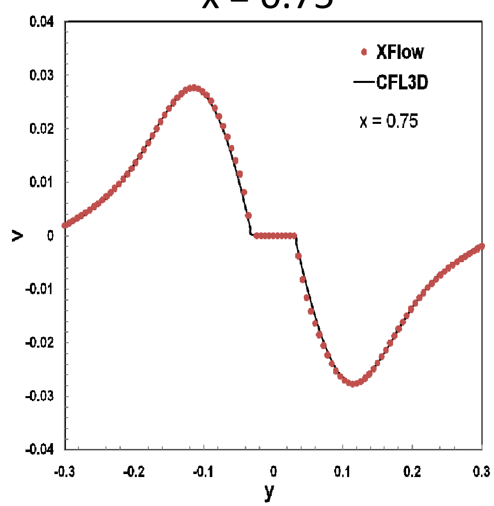
x = 0.25



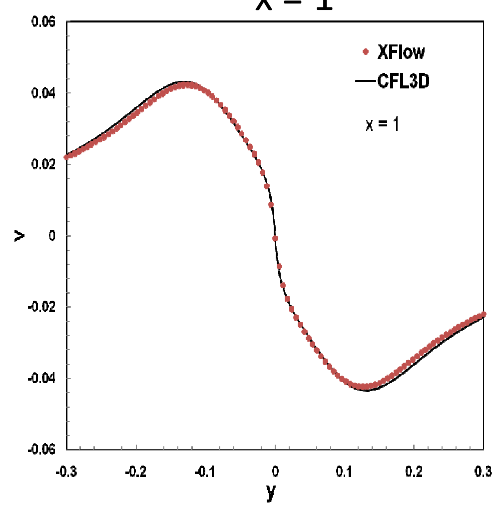
x = 0.5



x = 0.75



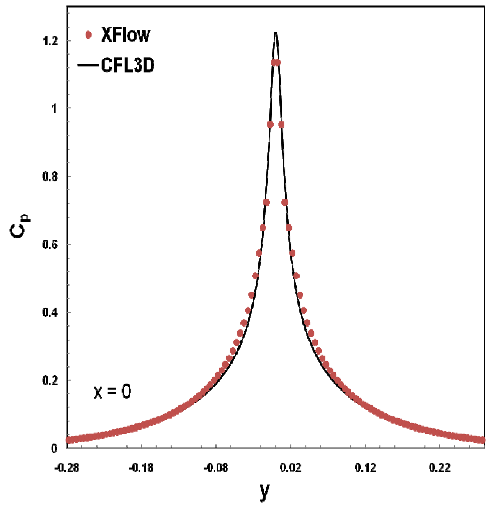
x = 1



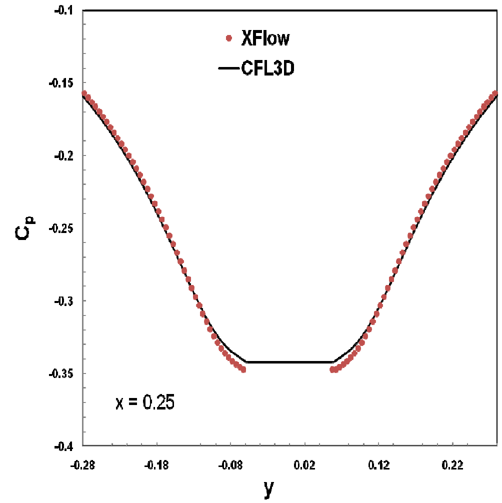
Courtesy of David P. Lockard and the NASA Langley Research Center

Pressure Coefficient along the Data Plot Lines

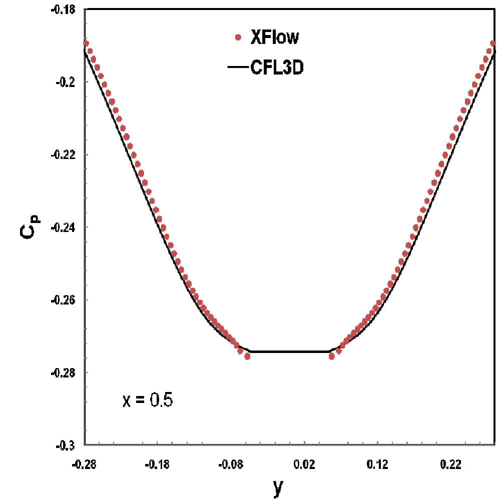
x = 0



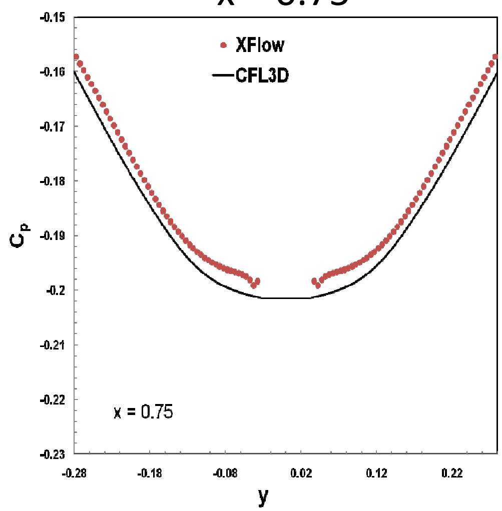
x = 0.25



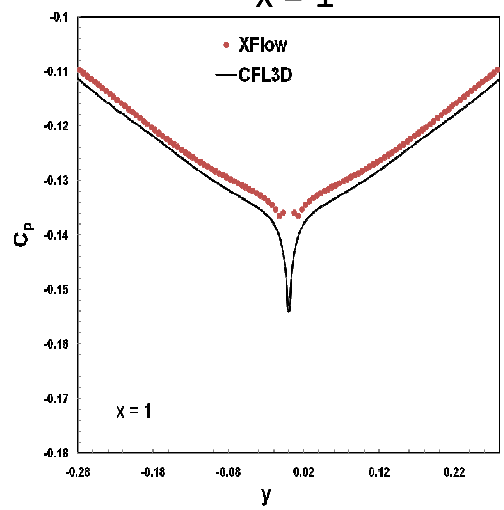
x = 0.5



x = 0.75



x = 1



Courtesy of David P. Lockard and the NASA Langley Research Center

Comparison of the Drag and Lift Coefficient

	XFlow	CFL3D	Objective	Relative Error to Objective
Cd	0.1705	0.1741	0.1741	-2.0678 %
Cl	1.0×10^{-13}	-0.538×10^{-5}	0	0 %

Results are in accordance with objective

Courtesy of David P. Lockard and
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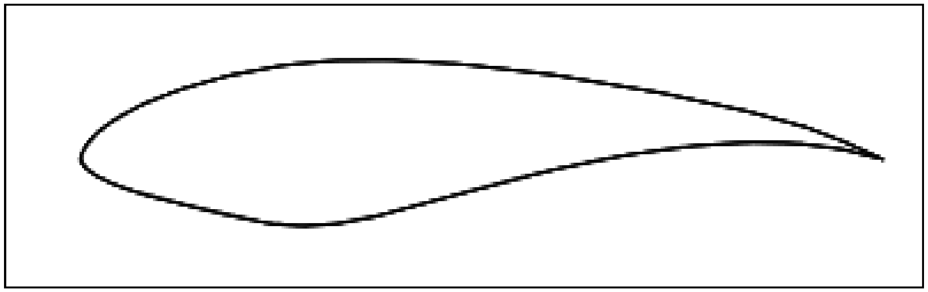
2nd Validation Test Case

Two-Dimensional Simulation of Flow Past S825 Airfoil

S825 Airfoil



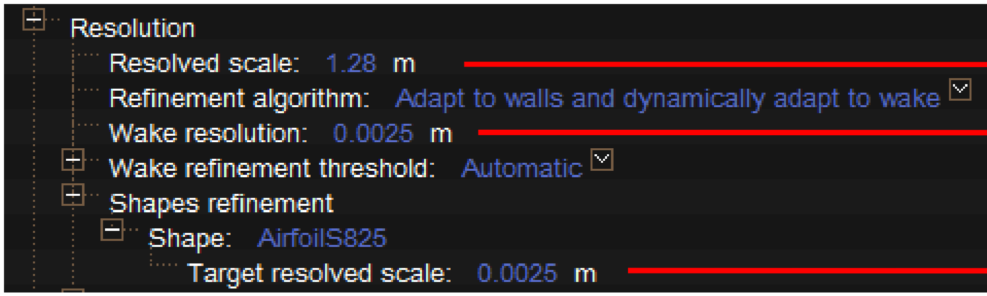
Flight condition

Angles of Attack	Mach Number	Reynolds Number	Reference Velocity
From -4 to 10º	0.1	2E+06	43.7493 m/s

Reference: D. Somers, *Design and Experimental Results for the S825 Airfoil; Period of Performance: 1998-1999*, tech. report, National Renewable Energy Laboratory, January 2005.

Resolution of the Solution

- Region of Dynamical Refinement scale: Wall and Wake



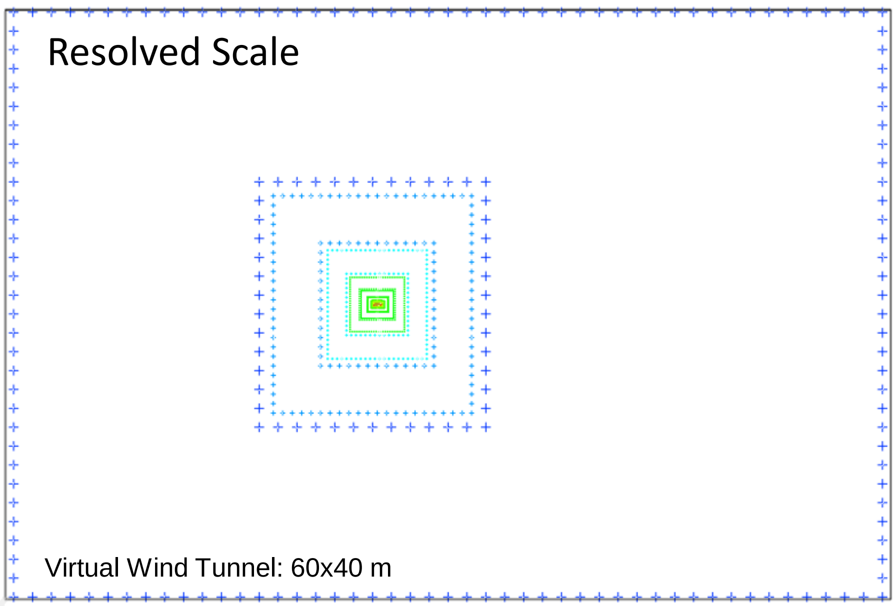
Resolved Scale

Dynamically Scale Adaption

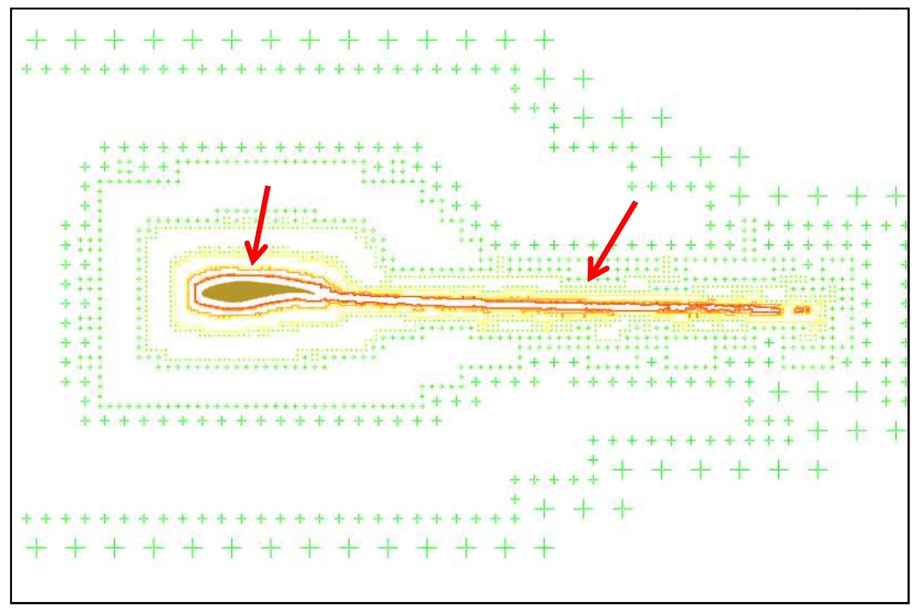
Wake Resolution

Target resolved Scale - AirfoilS825

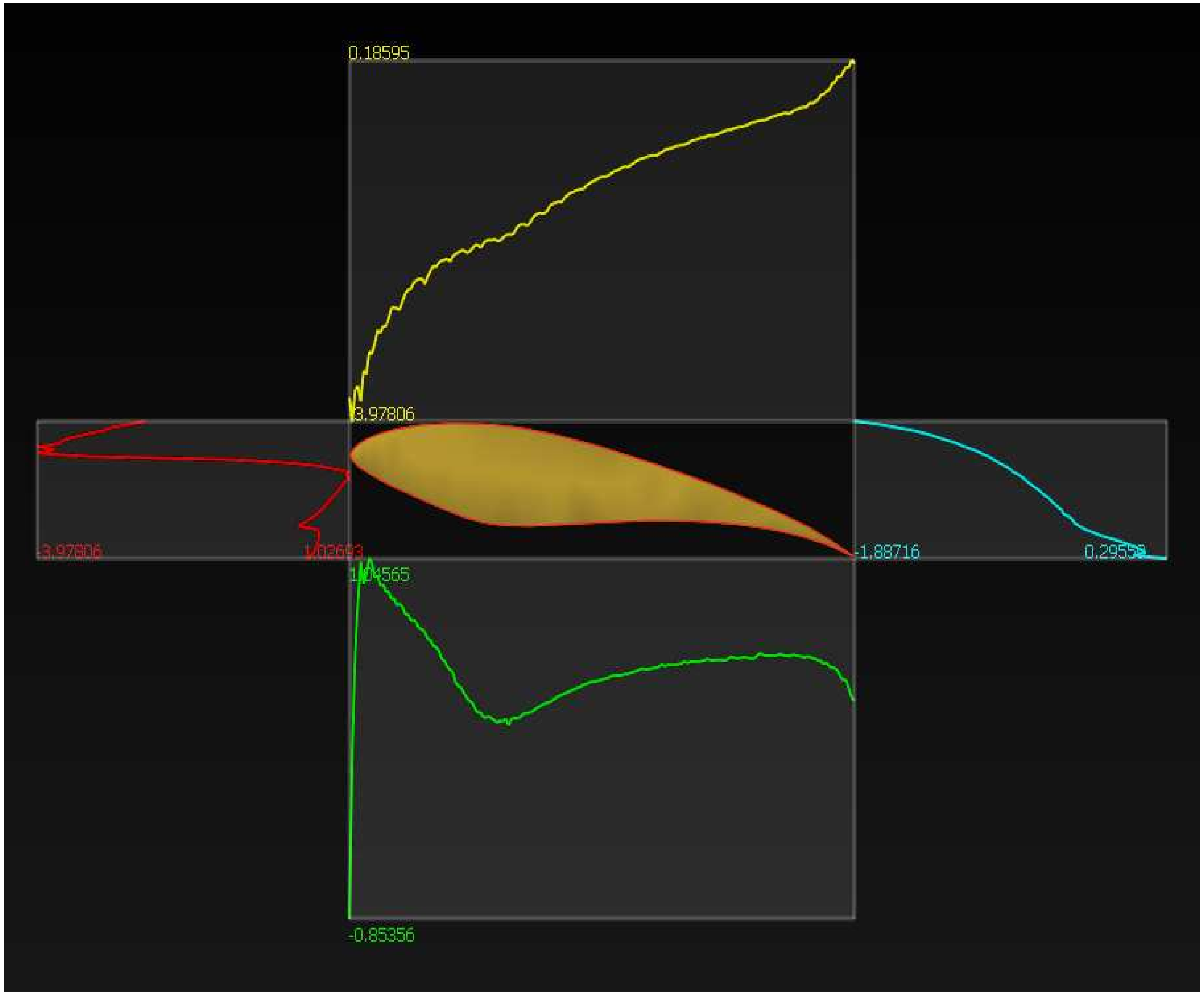
Far field - 1.28m



Wall & Wake Refinement - 0.0025m



Projection of the Pressure Coefficient



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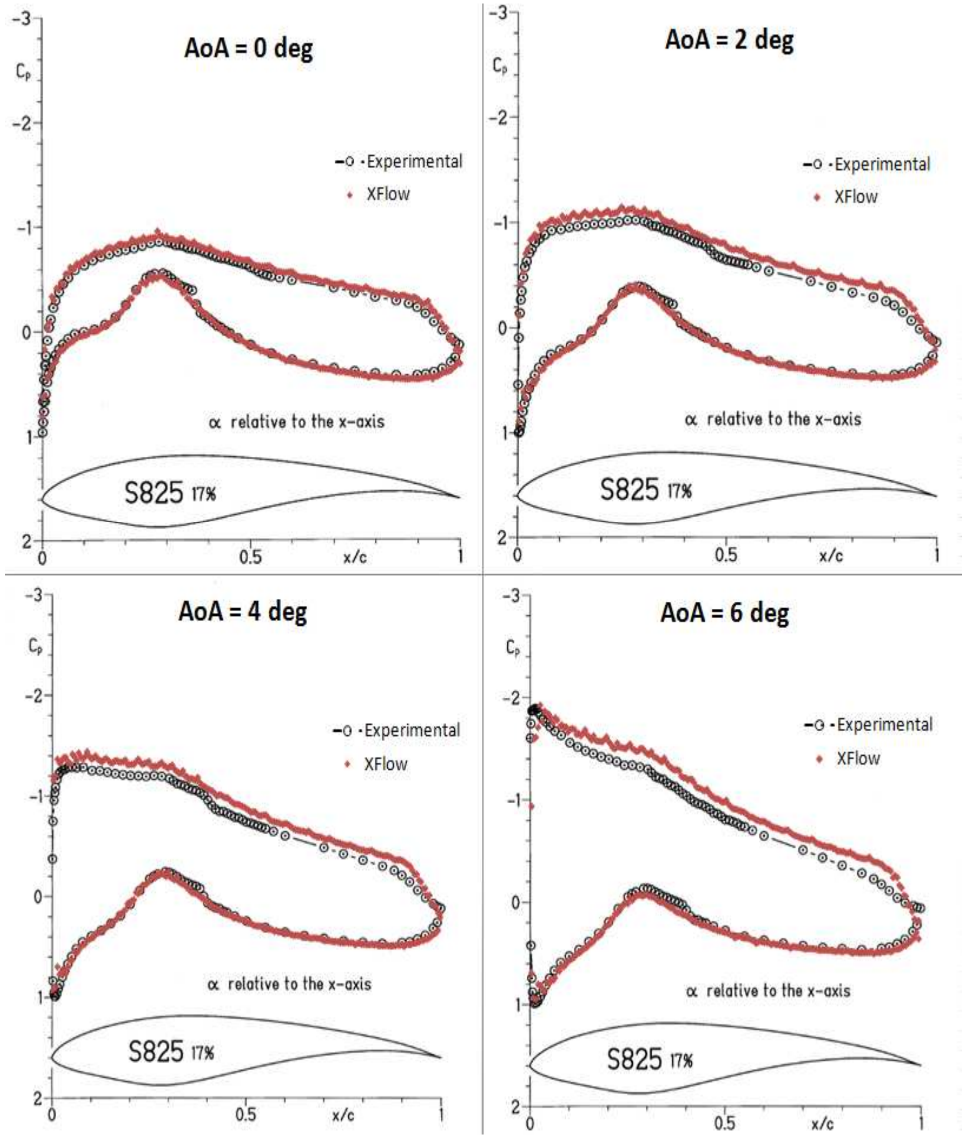
Pressure Coefficient for different AOA



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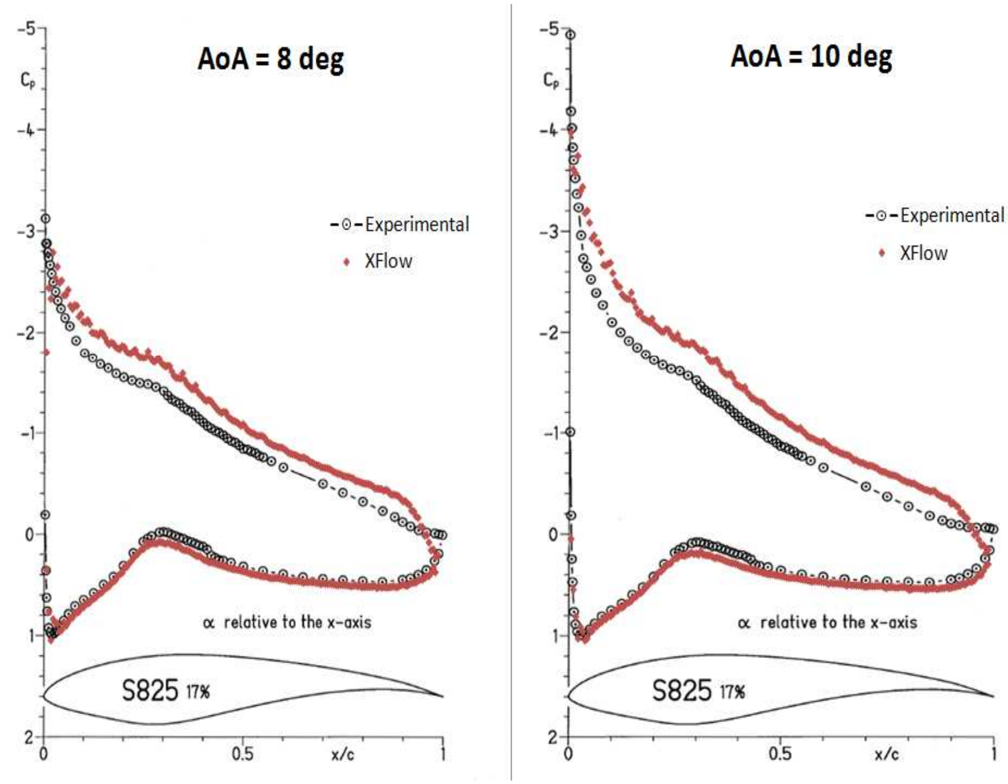
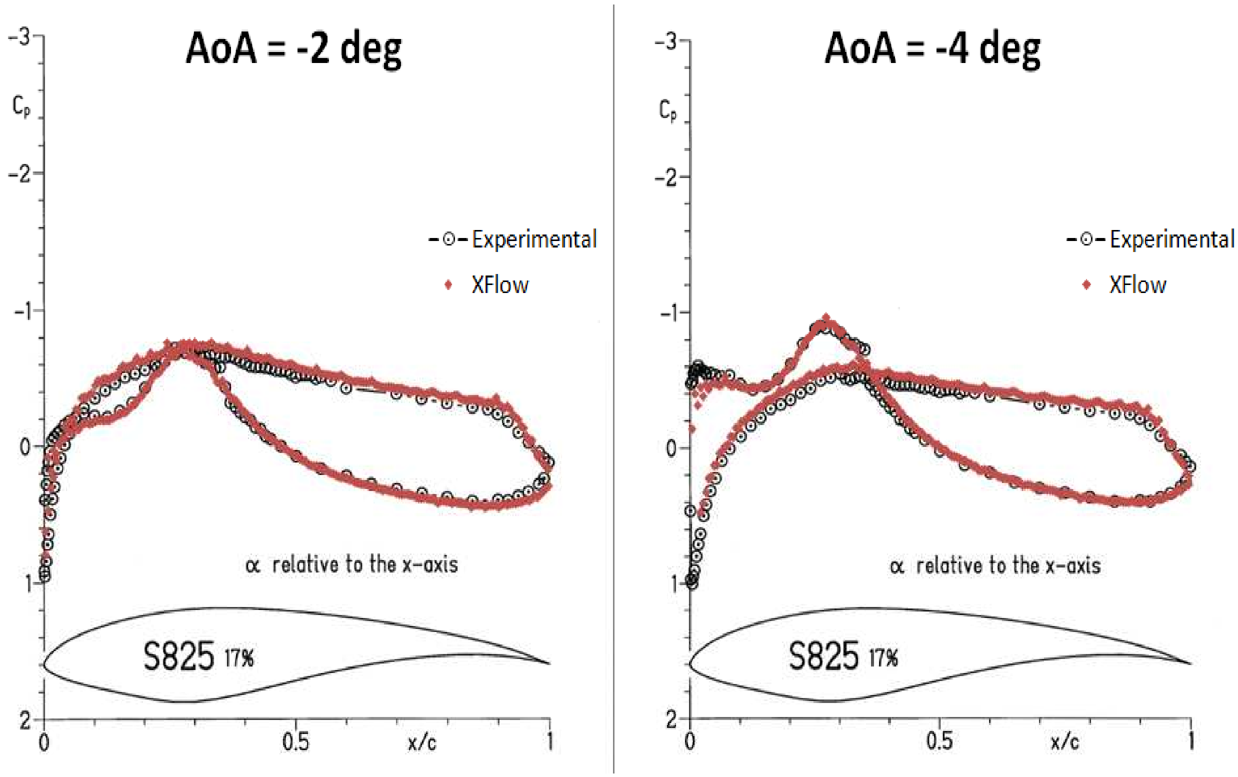
Pressure Coefficient for different AOA



Pressure Coefficient for different AOA

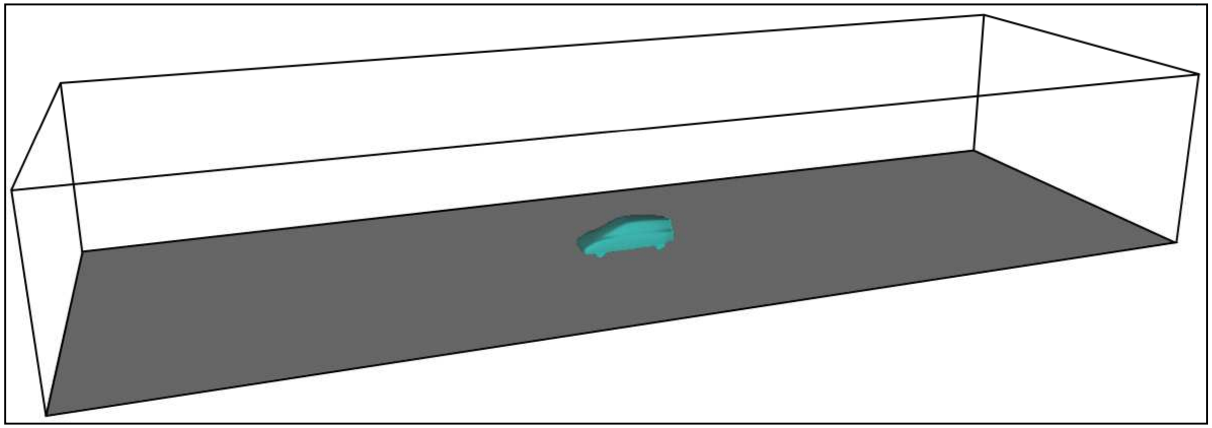


3th Validation Test Case

3D Simulation of Flow Past the ASMO model

- Flow velocity: V = 50 m/s
- Density: ρ = 1 Kg/m^{-3}
- Dynamic viscosity: μ = 1.5e-5 Pa·s

ASMO model

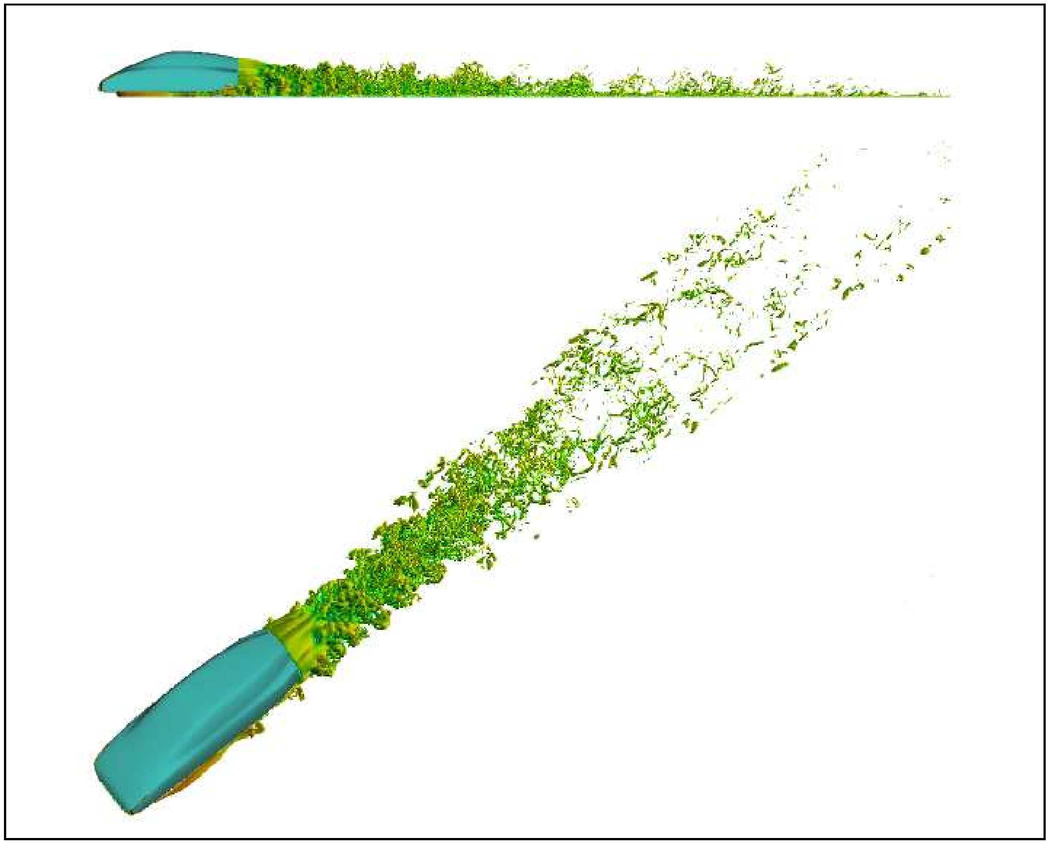


[1] G. Le Good and K. Garry. On the use of reference models in automotive aerodynamics. *SAE paper*, 2004-01-1308.

[2] S. Perzon and L. Davidson. On transient modeling of the flow around vehicles using the reynolds equations. In *ACFD 2000 Beijing*, pages 720–727, 2000.

Turbulent wake structure

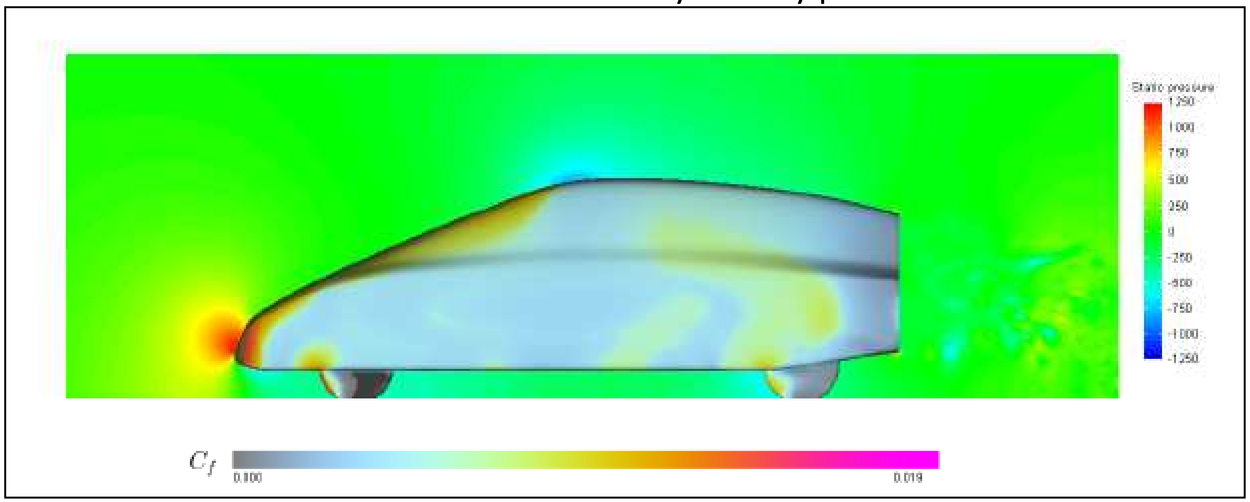
Isosurface of vorticity



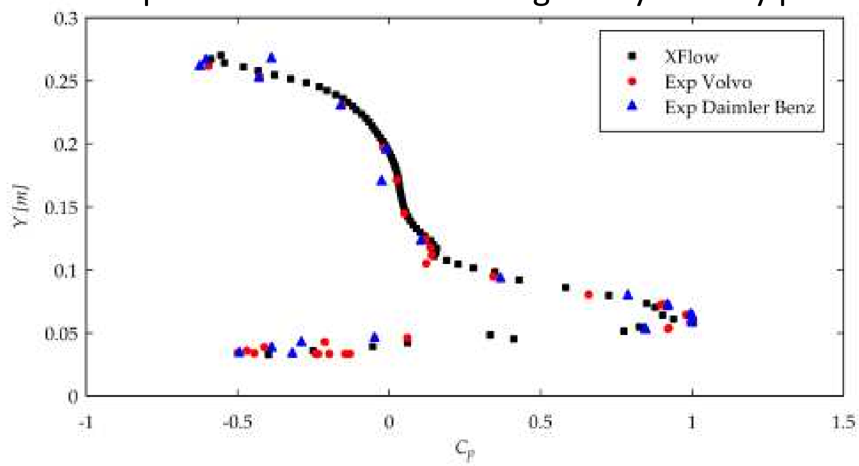
Pressure distribution along the symmetry plane

- Comparison with experimental data - Volvo and Daimler Benz

Pressure filed in the symmetry plane



Front pressure distribution along the symmetry plane



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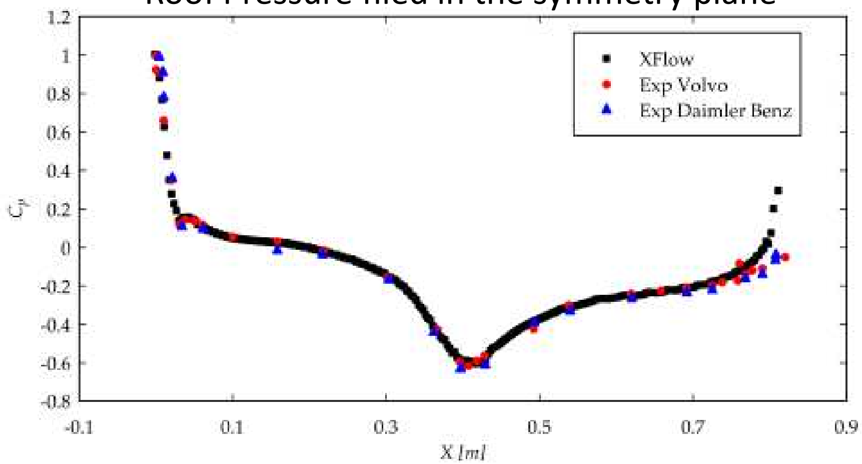
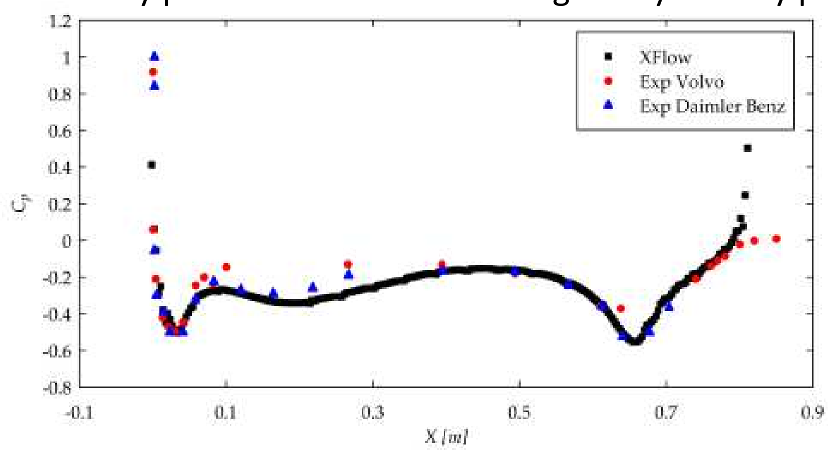
Pressure distribution along the symmetry plane

- Comparison with experimental data - Volvo and Daimler Benz

Roof Pressure filed in the symmetry plane



Underbody pressure distribution along the symmetry plane



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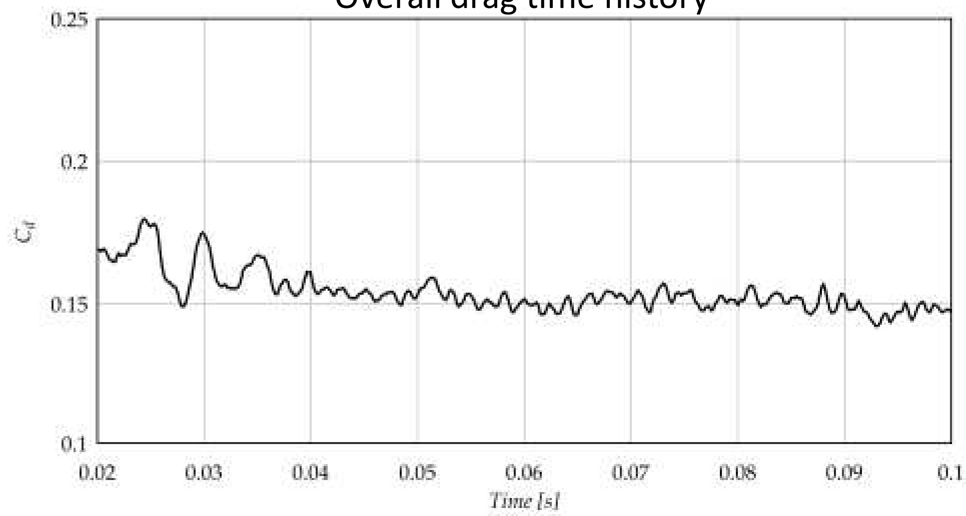
Drag estimation

- Comparison with experimental data - Volvo and Daimler Benz

Overall drag time history



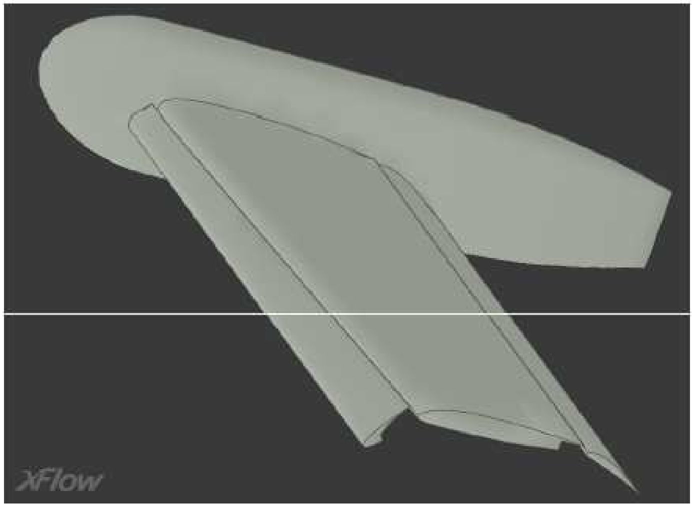
Comparison with experiments - Drug

XFlow	0.151
Experiments Volvo	0.158
Experiments Daimler Benz	0.153

4th High lift prediction

3D Simulation of Flow Past a wing with model with flap and slat

Wing geometry



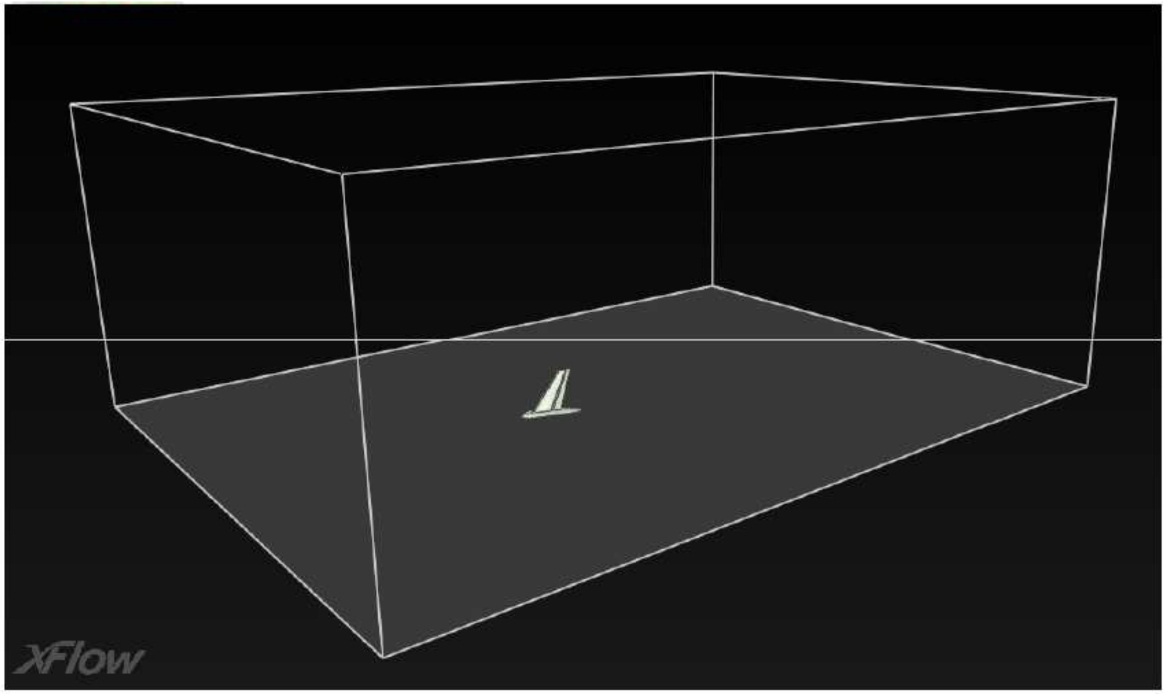
Angles of Attack	Mach Number	Reynolds Number	Mean Aerodynamic Chord	Surface Reference
From -4 to 37º	0.2	4.3E+06	1.0067 m	2.04647631 m

Christopher Rumsey, NASA Langley Research Center, *The 1st AIAA CFD High Lift Prediction Workshop (HiLiftPW-1)*, http://hiliftpw.larc.nasa.gov/index-workshop1.html.

4^{th} High lift prediction

- Wind Tunnel definition - 40 x 15 x 30 m
- Ground wall effect enabled

Virtual wind tunnel

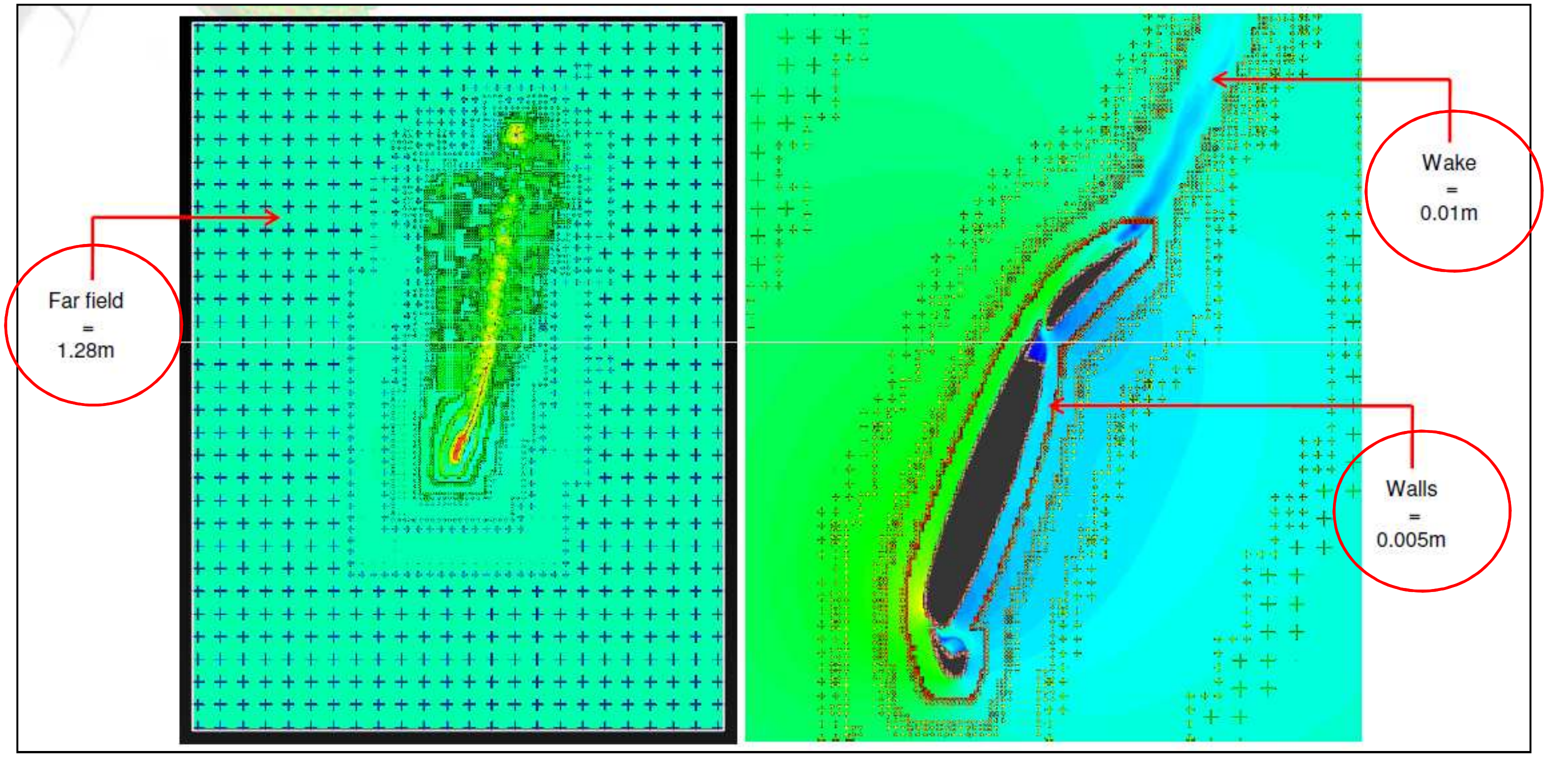


4th High lift prediction

Resolved scaled definition with adaptive refinement - Wall and Wake

- Resolved scale (far field): 1.28 m
- Target scale for wake : 0.01 m s
- Target scale for wall : 0.005 m

Resolved scale resolution

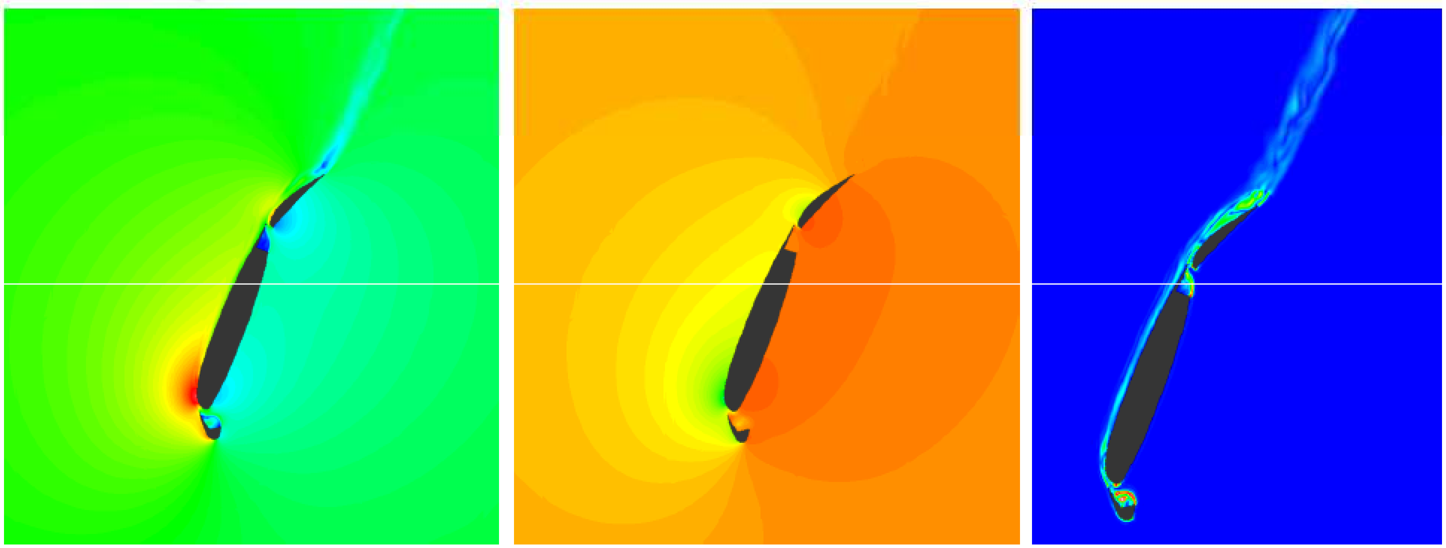


Results overview

Velocity - Static pressure - Vorticity visualization

- AOA: 13 degrees
- Simulation time: 0.26 s

Contours of wing section

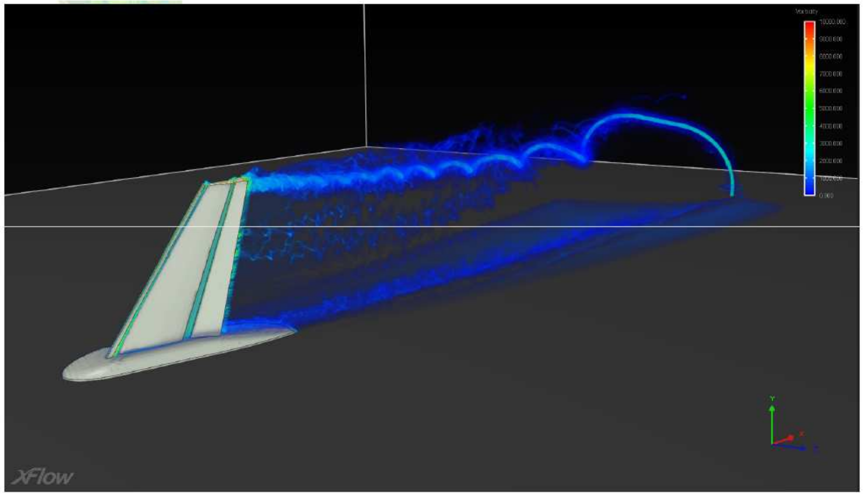


Velocity
Static Pressure
Vorticity

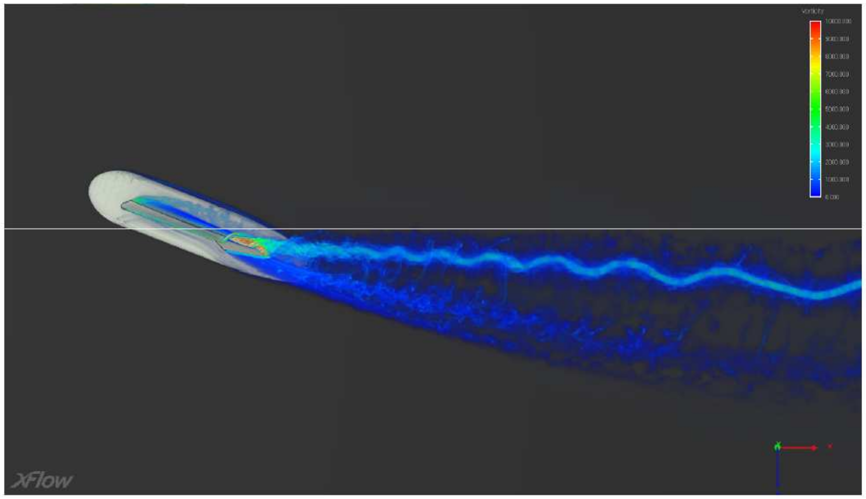
Vorticity

- AOA: 13 degrees
- Simulation time: 0.26 s

Volumetric Rendering of Vorticity - Ortho view



Volumetric Rendering of Vorticity - Top view



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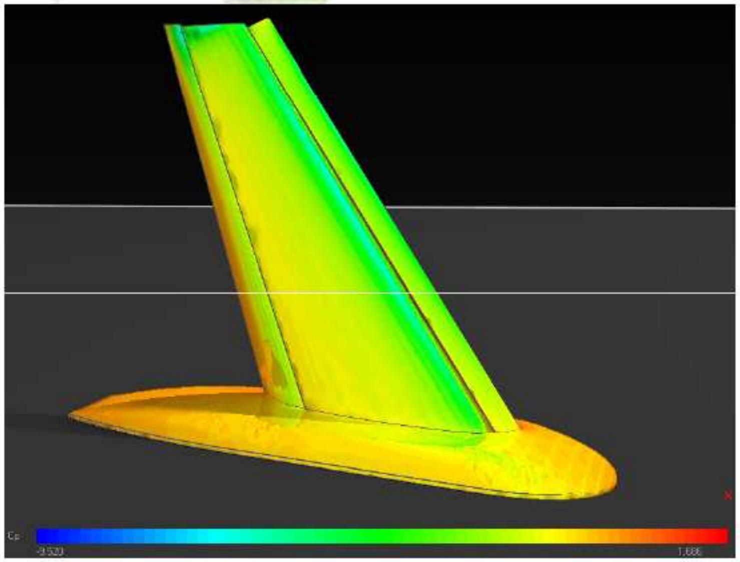
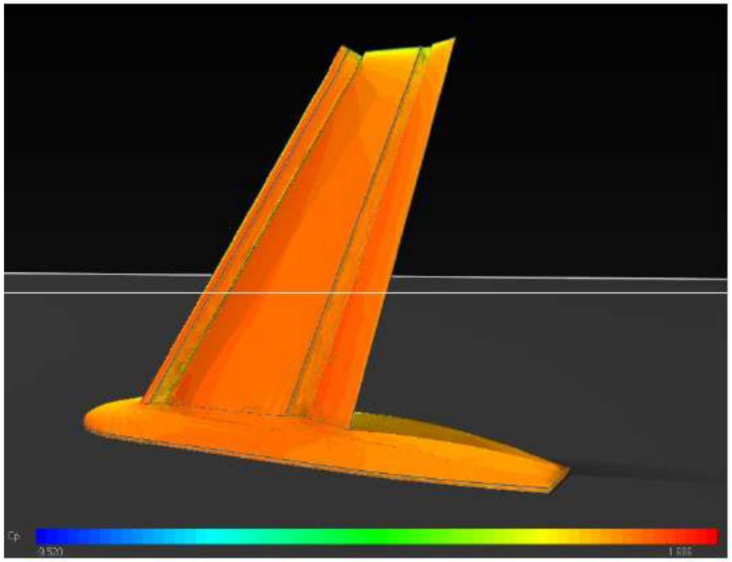
Pressure distribution

- AOA: 13 degrees
- Simulation time: 0.26 s

Static pressure - "Pressure" side



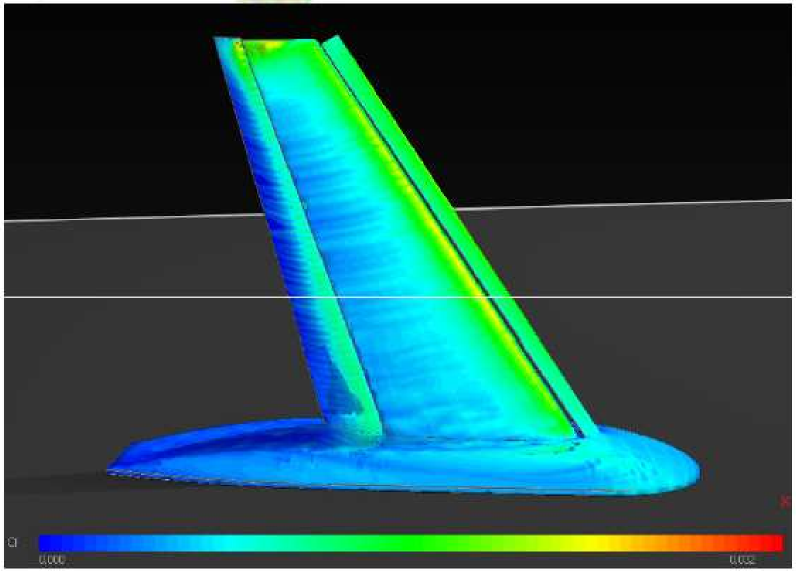
Volumetric Rendering of Vorticity – "Suction side"



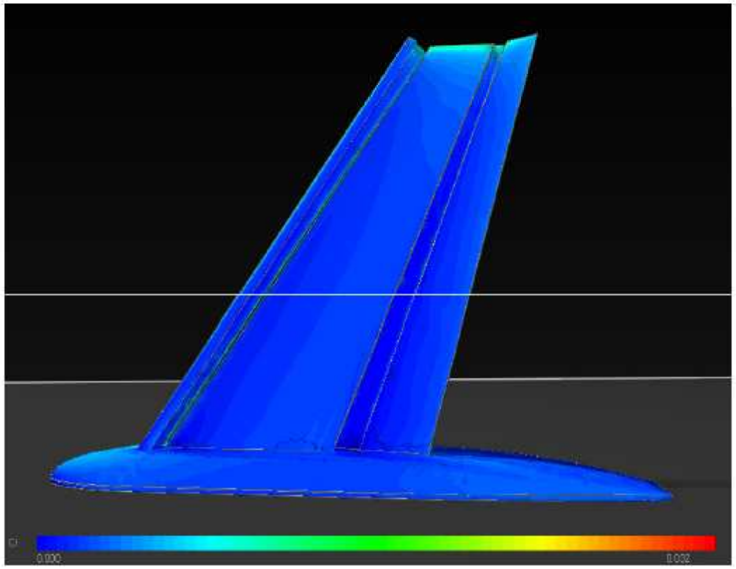
Friction coefficient distribution

- AOA: 13 degrees
- Simulation time: 0.26 s

Friction coefficient - “Pressure” side



Volumetric Rendering of Vorticity - “Suction side”



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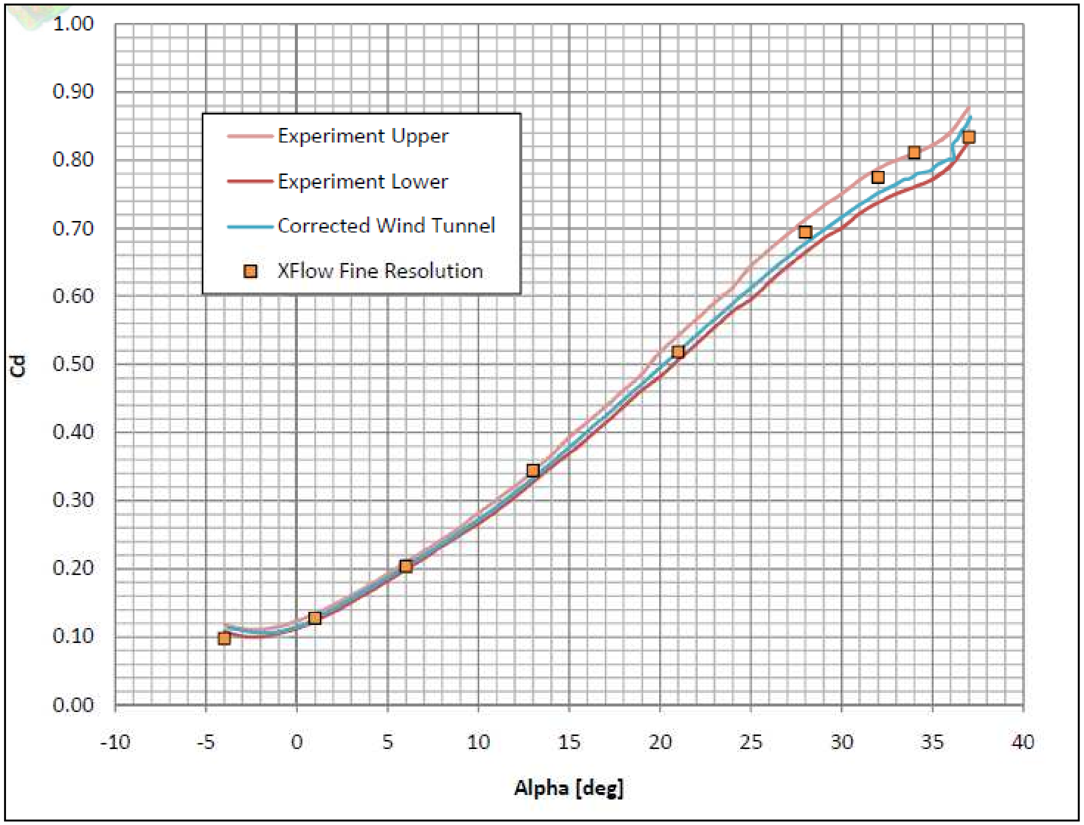
Drag coefficient distribution

- Comparison with experiments - NASA Langley Research Center

Drag coefficient vs Alpha



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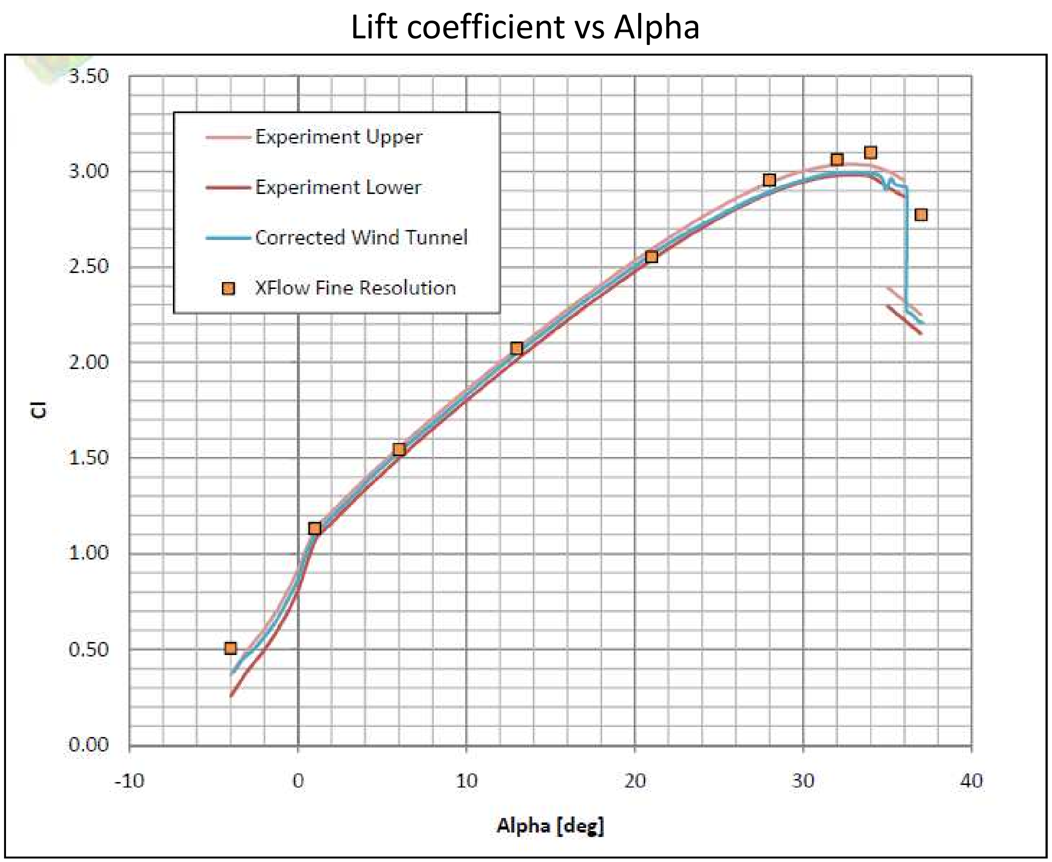
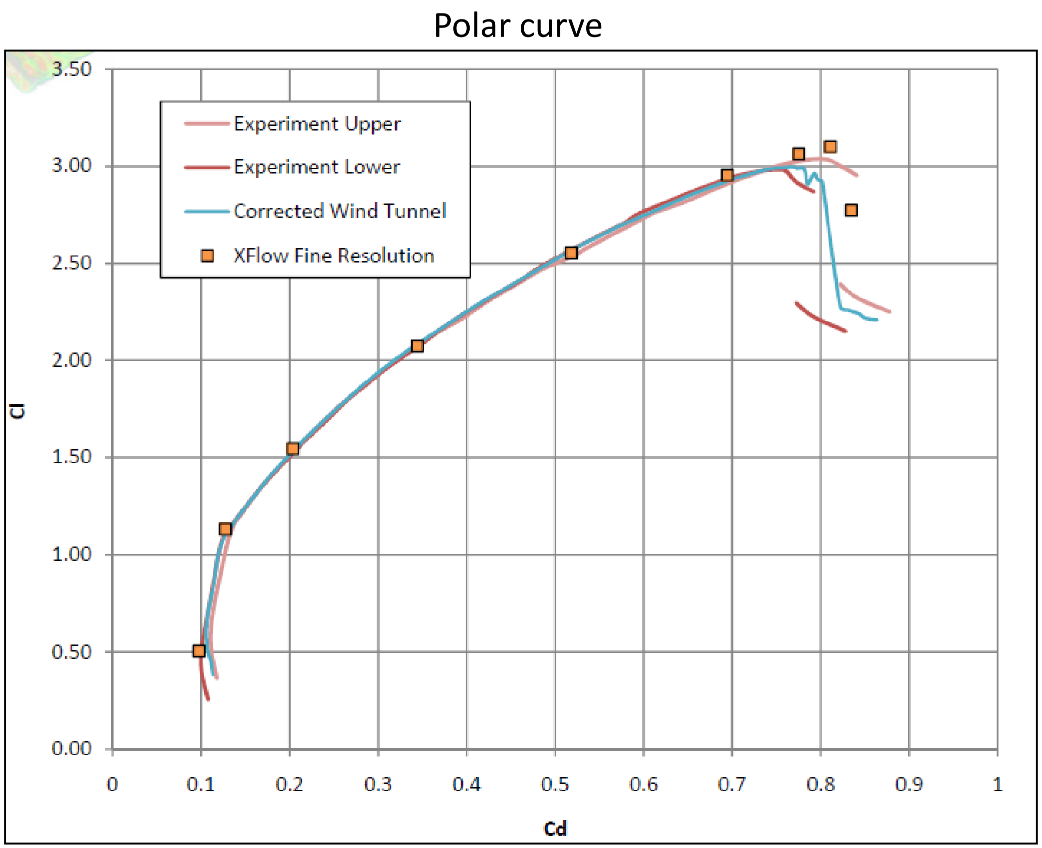
Lift coefficient distribution

- Comparison with experiments - NASA Langley Research Center



Polar curve evaluation

- Comparison with experiments - NASA Langley Research Center



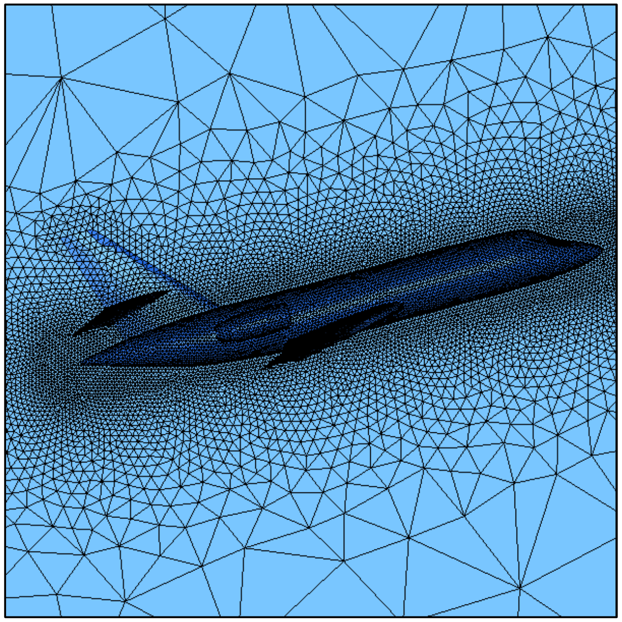
Topics

- XFlow Overview - Application fields & Theory
- GUI et Validation Cases for External Aerodynamics
- CFD Process approach - Mesh-based vs XFlow (Meshless)
- Wing case study - Static Aeroelastic application
- UAV case study

Traditional Mesh-based CFD codes

- Domain to be solved is divided into finite control volumes - Mesh
- The reliability of the solution highly depends on the quality of the mesh - Mesh Sensitivity
- Several solver parameters for turbulence model affect the solution stability - Convergence criteria
- Parallel process computing - CPU resources

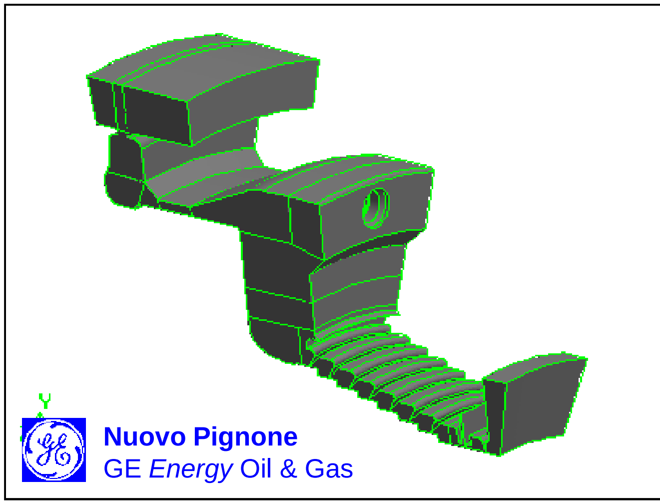
Mesh



Several engineering time needs to be spent

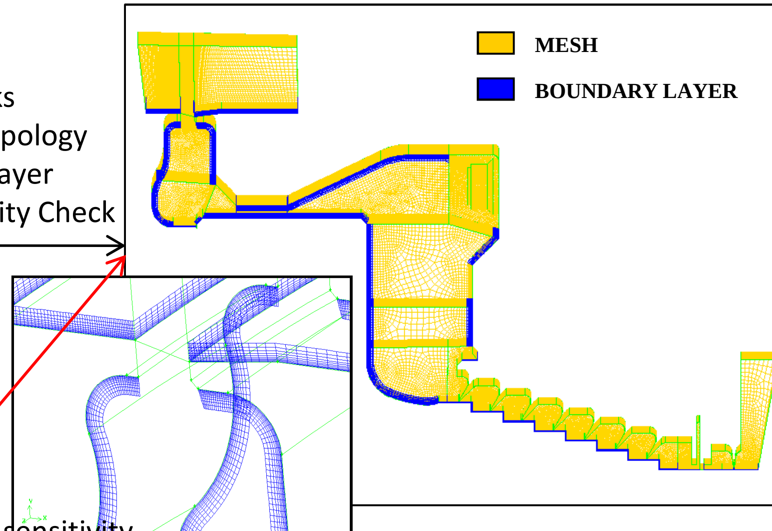
Traditional Mesh-based process analysis

CAD Model



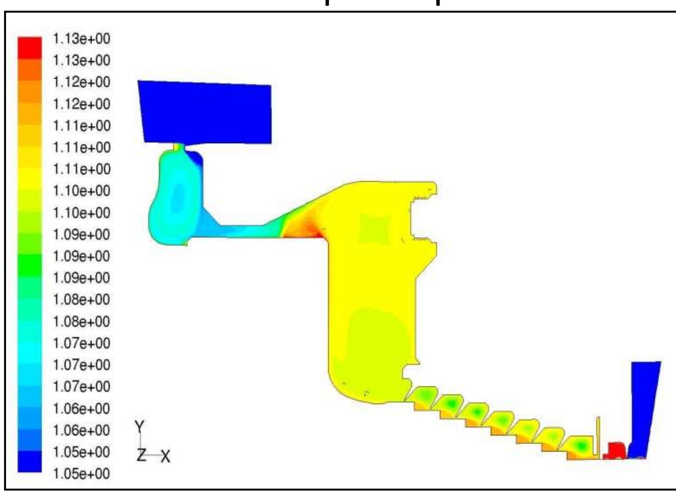
- Multi blocks
- Element topology
- Boundary layer
- Mesh Quality Check

GRID Generation



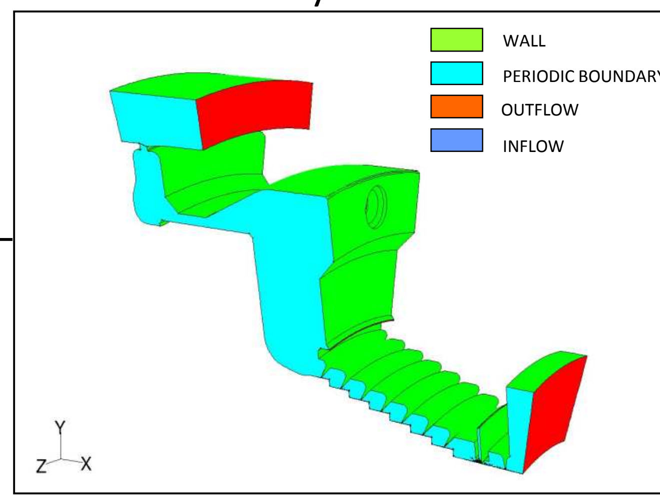
Mesh sensitivity

Results - Exp Comparison



- Solver
- Turbulence Model
- Check Residual
- Convergence
- Parallelization

Boundary conditions

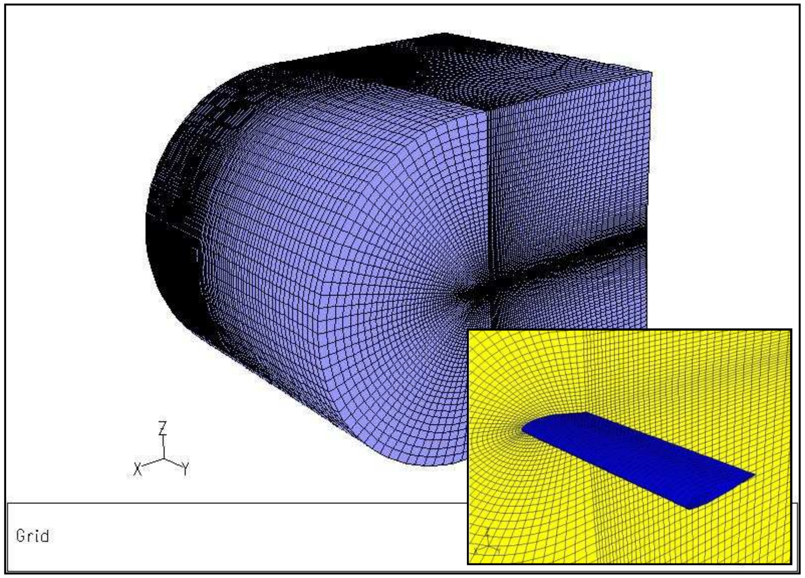


More than 1 year of work

Motivation for modeling with XFlow

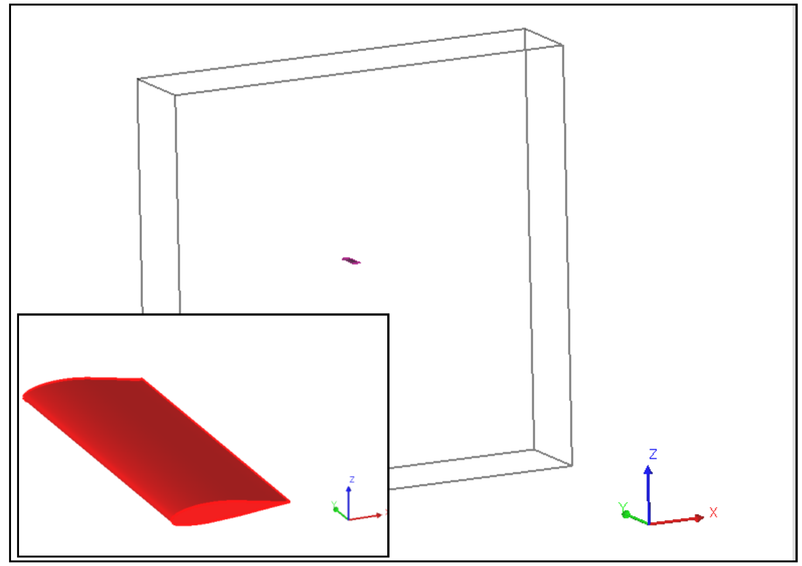
Particle-based Kinetic Approach - Lagrangian Formulation with LES Turbulence Model

Mesh-based - 3D Wing model



Meshless ➡

XFlow - 3D Wing model



- CAD import
- Mesh generation (Multiblocks, Boundary Layer, Topology)
- Convergence criteria (Residual check for Energy, Momentum, Mass)
- Turbulence parameters (RANS k-ε)
- Mesh Sensitivity → Remeshing

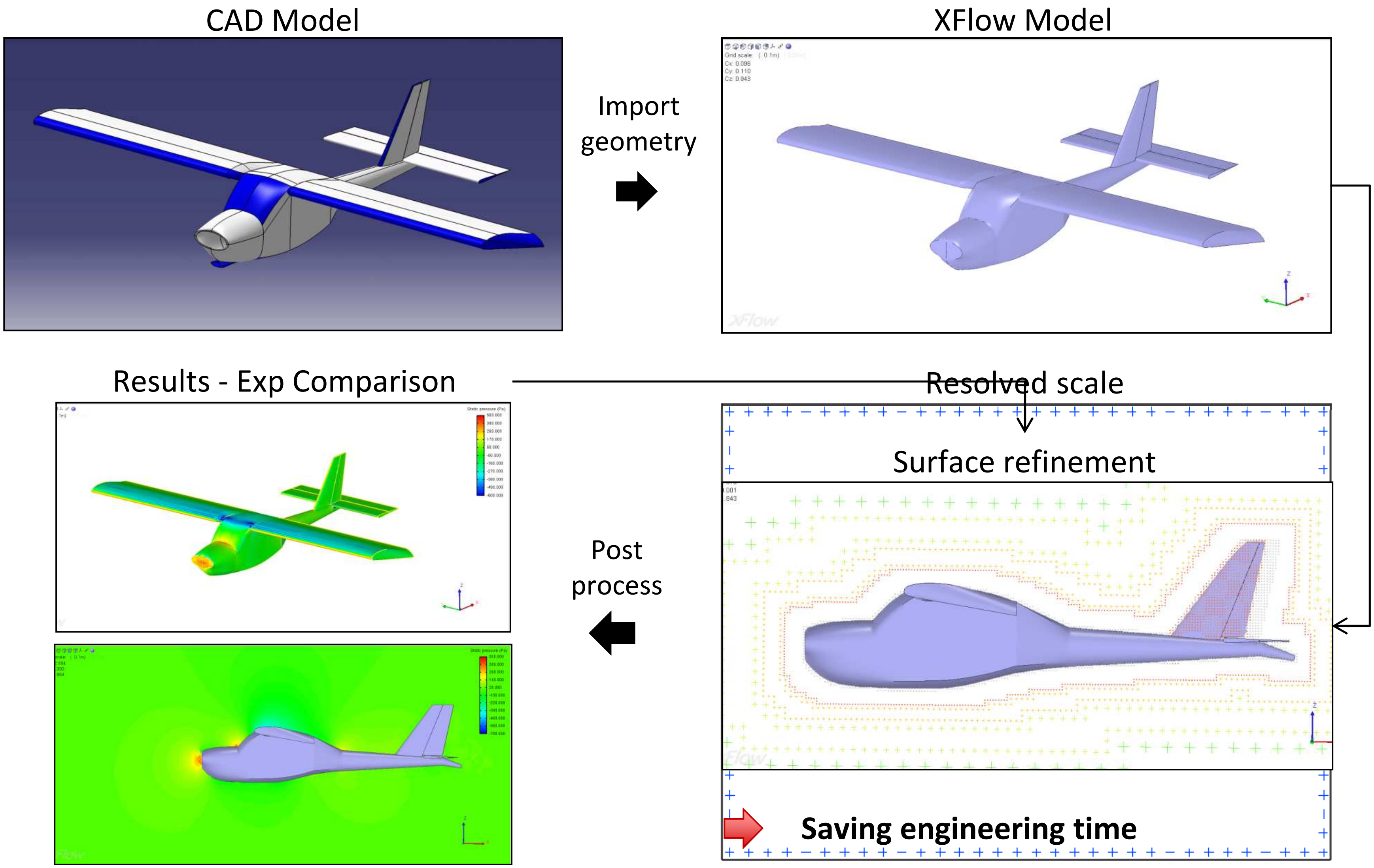
- CAD import
- Resolved scale (Automatic shapes and wake refinement)

➡ No more Mesh needed

➡ Easy to use

➡ Fast Pre-design purpose

XFlow - Overview process analysis



Topics

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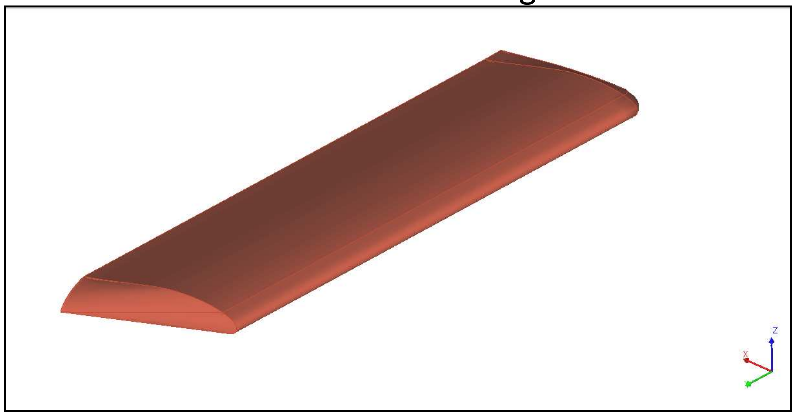
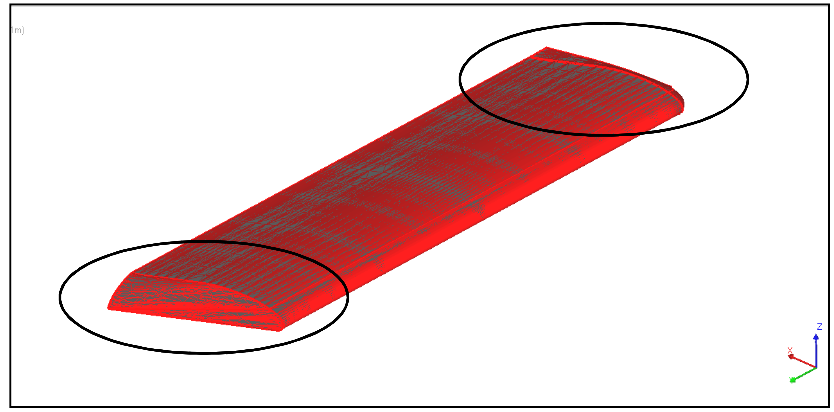
- Wing case study - Static Aeroelastic application
- UAV case study

Geometry tessellation - “Mesh”

CAD Model - Wing



Geometry tessellation

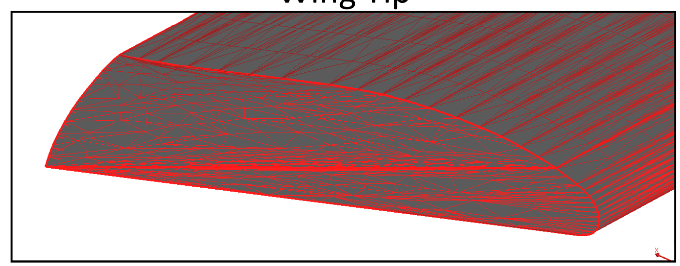


- Geometry is automatically tessellated by Xflow into an irregular “triangular Mesh” (Vertex, Polygons)
- All surface entities (Cp, Velocity, Pressure etc) to be exported are extrapolated from particles to vertex

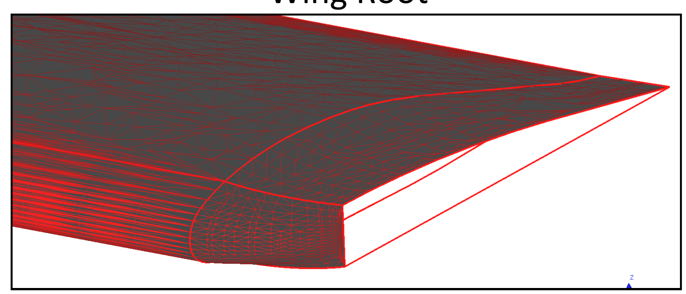
```
Wing


x y z Cp
0.751150 1.325000 0.157787 0.170765
0.751150 1.315000 0.157787 0.188369
0.751150 1.305000 0.157787 0.213254
0.751150 1.295000 0.157787 0.222032
```

Wing Tip



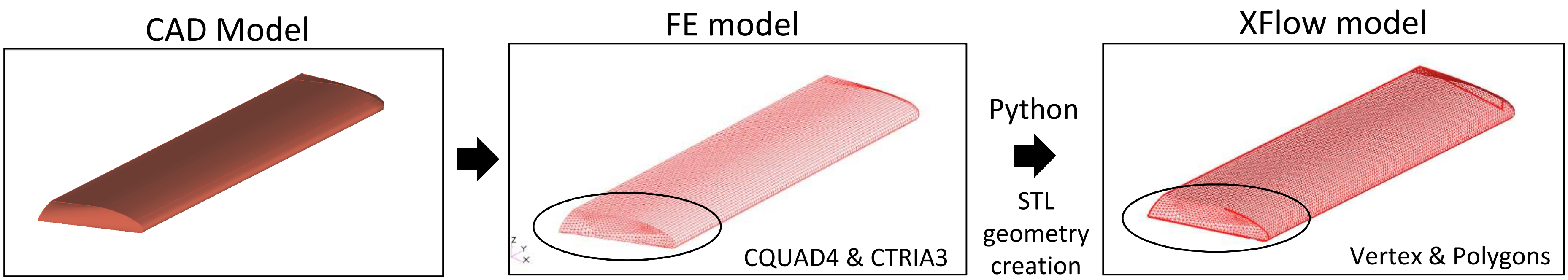
Wing Root



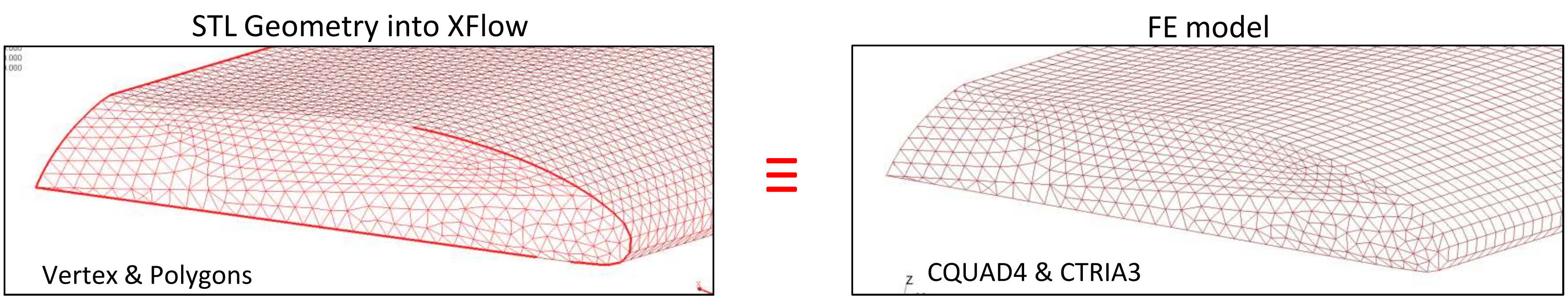
➡ Pressure data difficult to be processed (Nastran purpouse)

➡ STL geometry creation “ad hoc”.. FE model + python algorithm..

“Regular” STL Geometry creation via FEM



- SimXpert or Patran to create the FE model from CAD
- CQUAD4 & CTRIA3 converted into a regular “**triangular mesh**” (Vertex & Polygons) by python code - STL geometry format
- Vertex positions ≡ Nodes positions (ID vertex ≠ID node)



Aerodynamic Pressure data can now be properly managed (all vertex positions are known)

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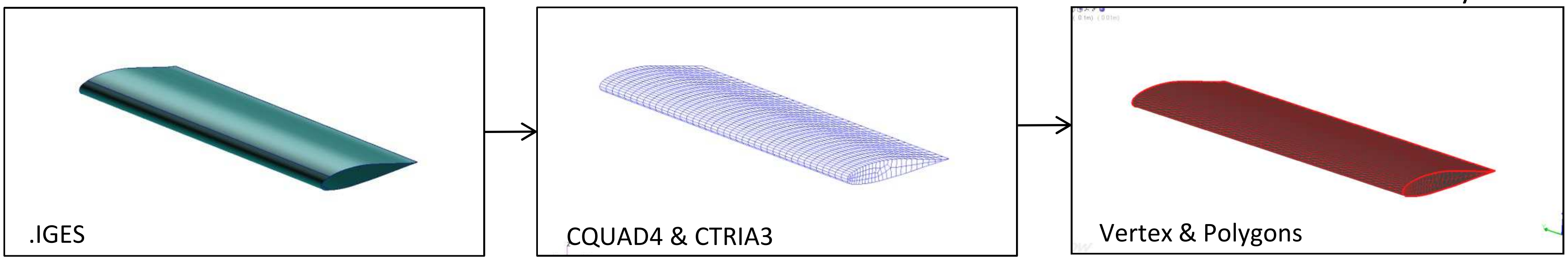
Wing case study

Three-Dimensional Simulation of Flow around an UAV Wing

- STL Geometry creation

CAD Model — FE Model — XFlow - STL Geometry

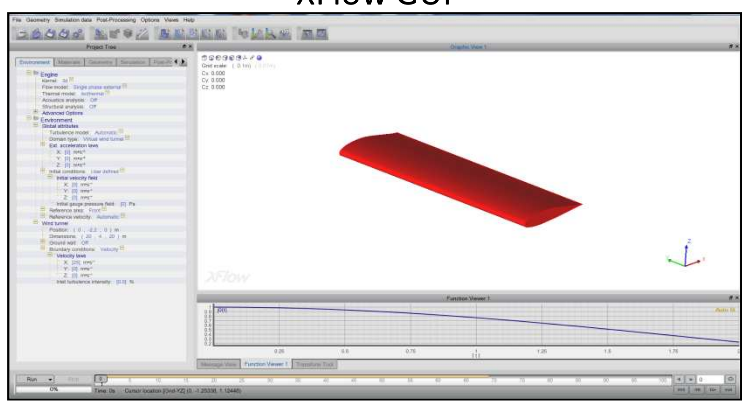


➡ From CAD to FE Model (CQUAD4 & CTRIA3) via SimXpert or Patran

➡ From FEM to STL Geometry (Vertex & Polygons) and Aero Mesh (AEGRID..)

- Simulation Conditions
  - Free-stream velocity *Vref* = 25m/s
  - Density ρ = 1.225 Kg m-3
  - Dynamic viscosity μ =0.1 Pa s
  - Chord lenght L = 0.402 m
  - AOA [0 ÷ 8]

XFlow GUI



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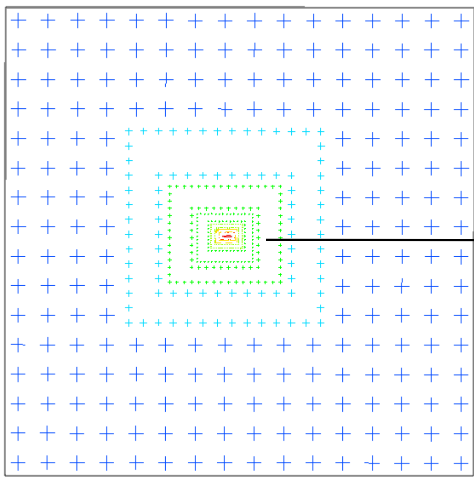
Wing case study

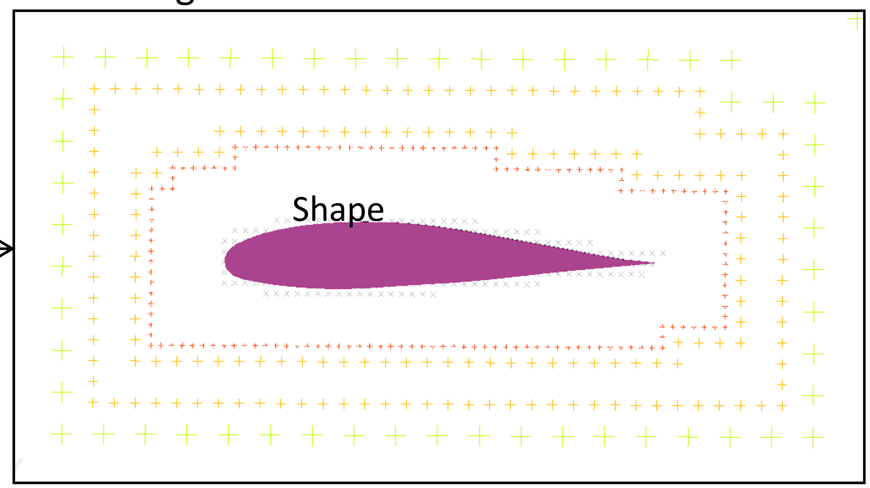
Three-Dimensional Simulation of Flow around an UAV Wing

- Resolved Scale
  - Far field - 1.26 m
  - Target resolved scale Wing - 0.005 m

Far field - 2.56m



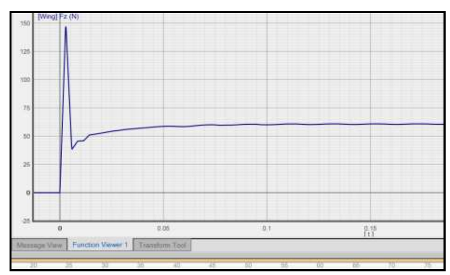
Region of Refinement - 0.005m



Run simulation..

Stability parameter

Function viewer- Fz



Get results

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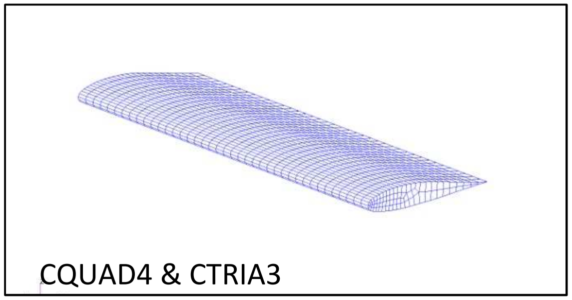
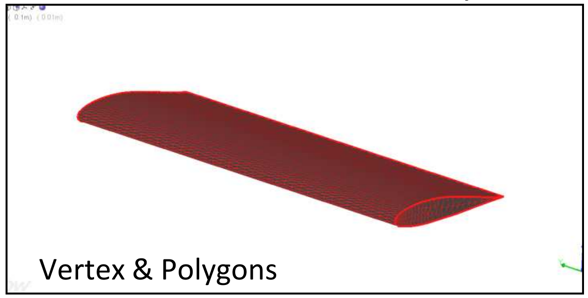
From XFlow to Nastran - Static Aeroelasticity

AOA = 0°

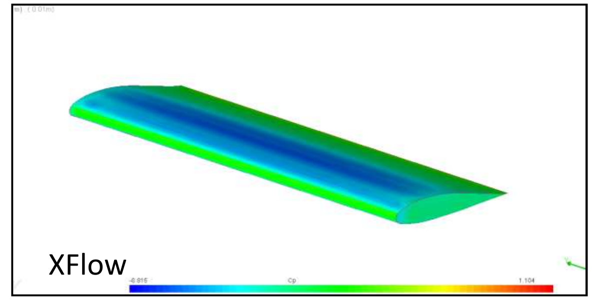
FE Model



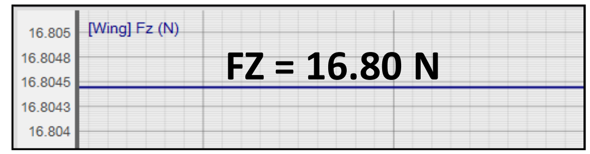
XFlow - STL Geometry



XFlow - Pressure Coefficient field

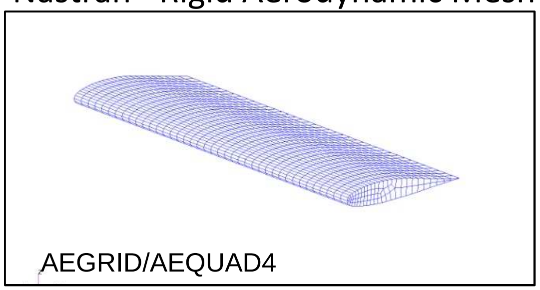


XFlow – Force in Z direction

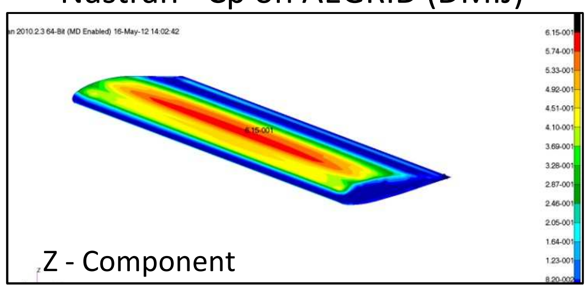


- From CAD to FE Model (CQUAD4 & CTRIA3) via SimXpert or Patran
- From FEM to STL Geometry (Vertex & Polygons) and Aero Mesh (AEGRID..)
- CFD simulation and Cp field extraction from Xflow on Vertex
- From XFlow Cp to DMIJ (Nastran “aero nodal” Cp) - Python code
- Aerodynamic Monitor point to check the mapped Aerodynamic load

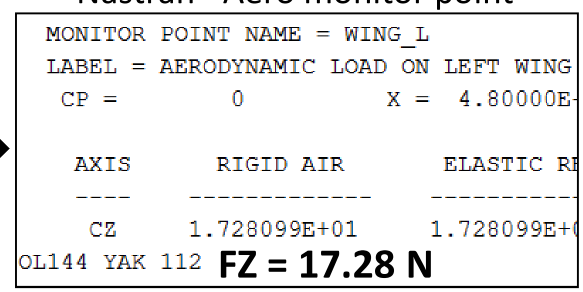
Nastran - Rigid Aerodynamic Mesh



Nastran - Cp on AEGRID (DMIJ)



Nastran - Aero monitor point



- Aerodynamic pressure is quite well mapped on the Aerodynamic Mesh..
- To be improved by increasing Resolved Scale and Geometry quality

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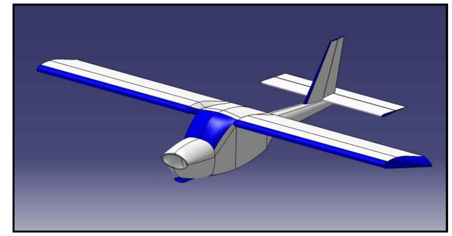
From XFlow to Nastran - Static Aeroelasticity

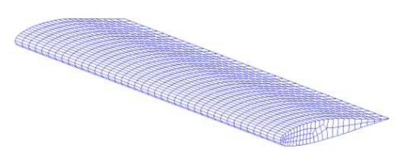
Longitudinal Trim Sol144

- UAV Flight condition
  - Air flowing over the Left Wing of the UAV
  - Freestreem velocity is 25 m/s
  - AOA [0°÷ 8°]



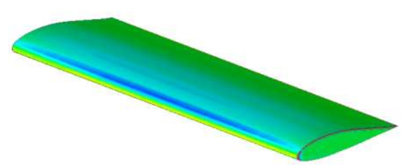
XFlow

"Aerodynamic Mesh"



Aerodynamic Mesh

Static Pressure Field on the Wing



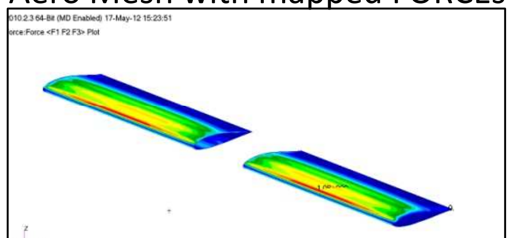
CFD Results

NASTRAN

AEPRESS

DMIJ

Aero Mesh with mapped FORCEs

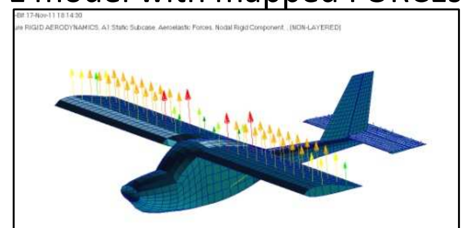


Fringe of Nodal forces

SPLINE 6/7

Load Mapping

FE model with mapped FORCEs

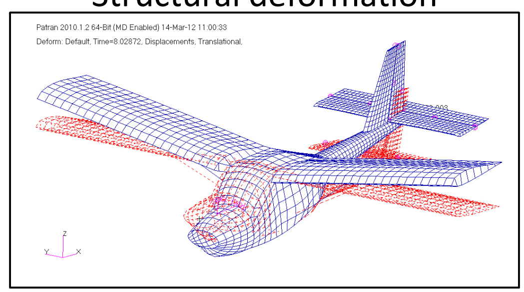


Structural Model

Trim condition obtained by using CFD pressure distribution

$\alpha \approx 4.31°$ $\delta_E \approx 0.8°$

Structural deformation



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Topics

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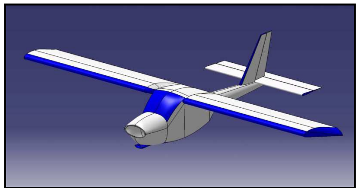
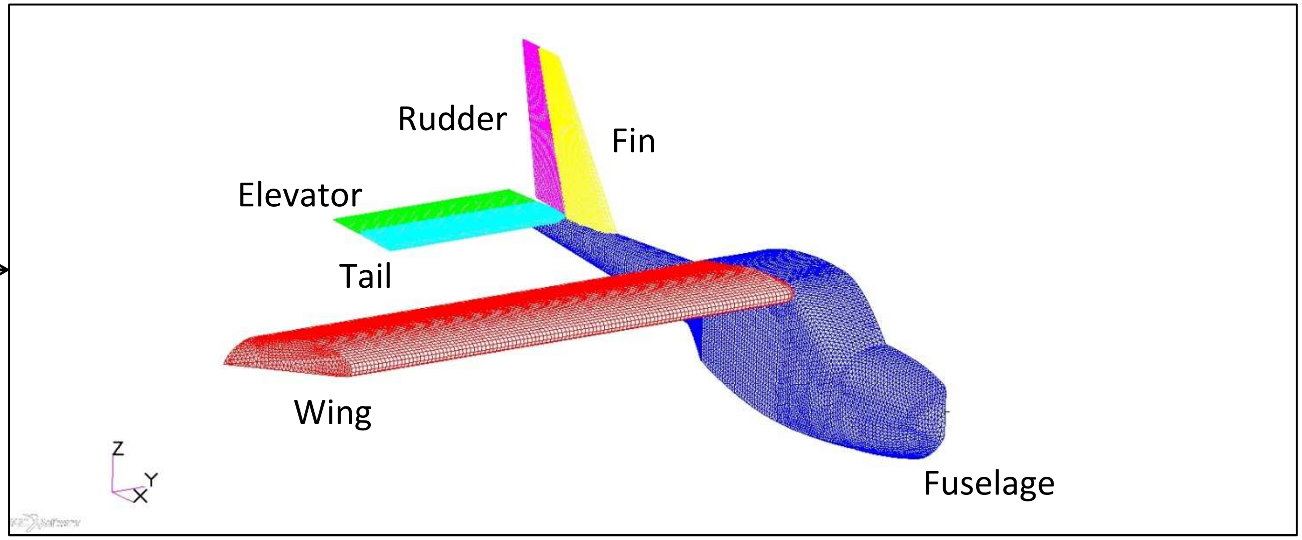
- CFD Process approach - Mesh-based vs XFlow (Meshless)
- Wing case study
- UAV case study

UAV - Geometry creation via FEM



FE model - Half geometry



FE model is divided into 6 different parts to be properly used into Xflow

FE model (CQUAD4 & CTRIA3)

- Fuselage.bdf
- Wing.bdf
- Tail.bdf
- Elevator.bdf
- Fin.bdf
- Rudder.bdf

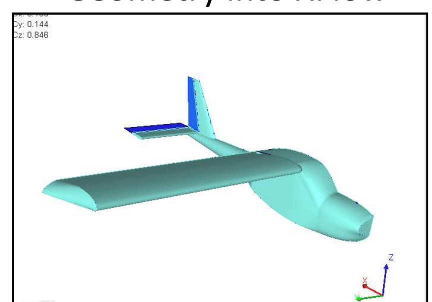
Python code

STL Geometry (Vertex & Polygons)

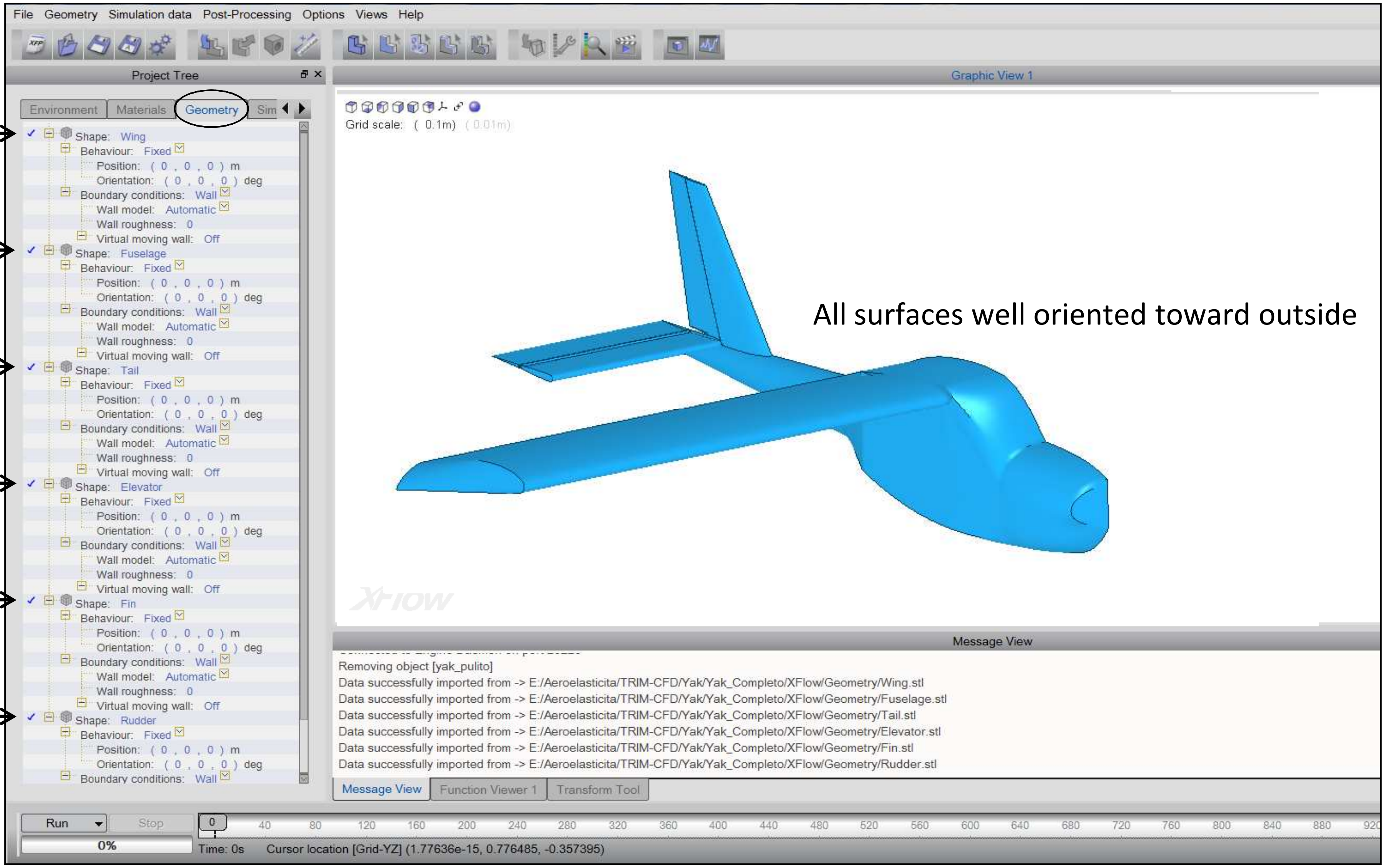
- Fuselage.stl
- Wing.stl
- Tail.stl
- Elevator.stl
- Fin.stl
- Rudder.stl

Six different components

Geometry into XFlow



UAV - Import geometry



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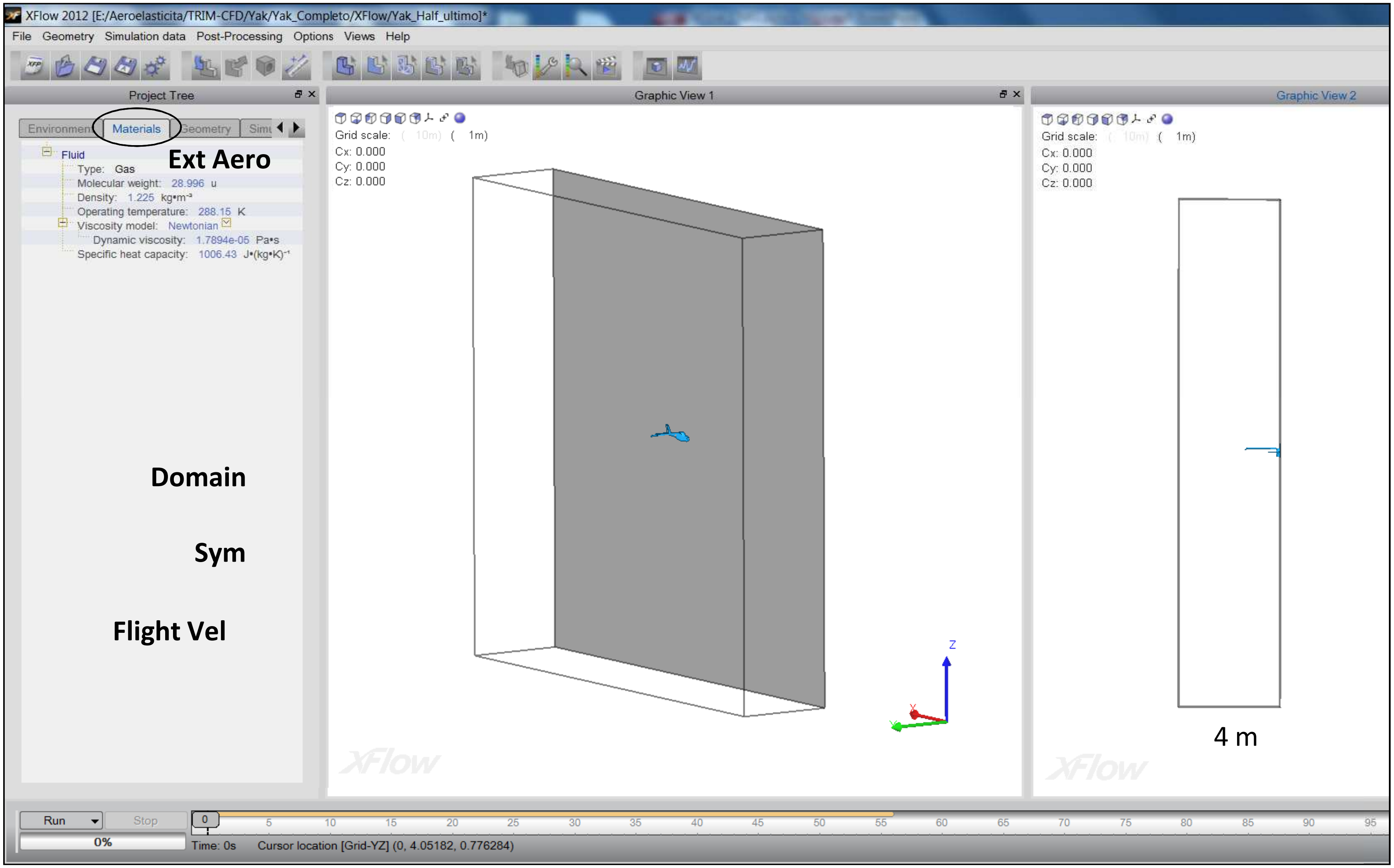
UAV - Environment set up



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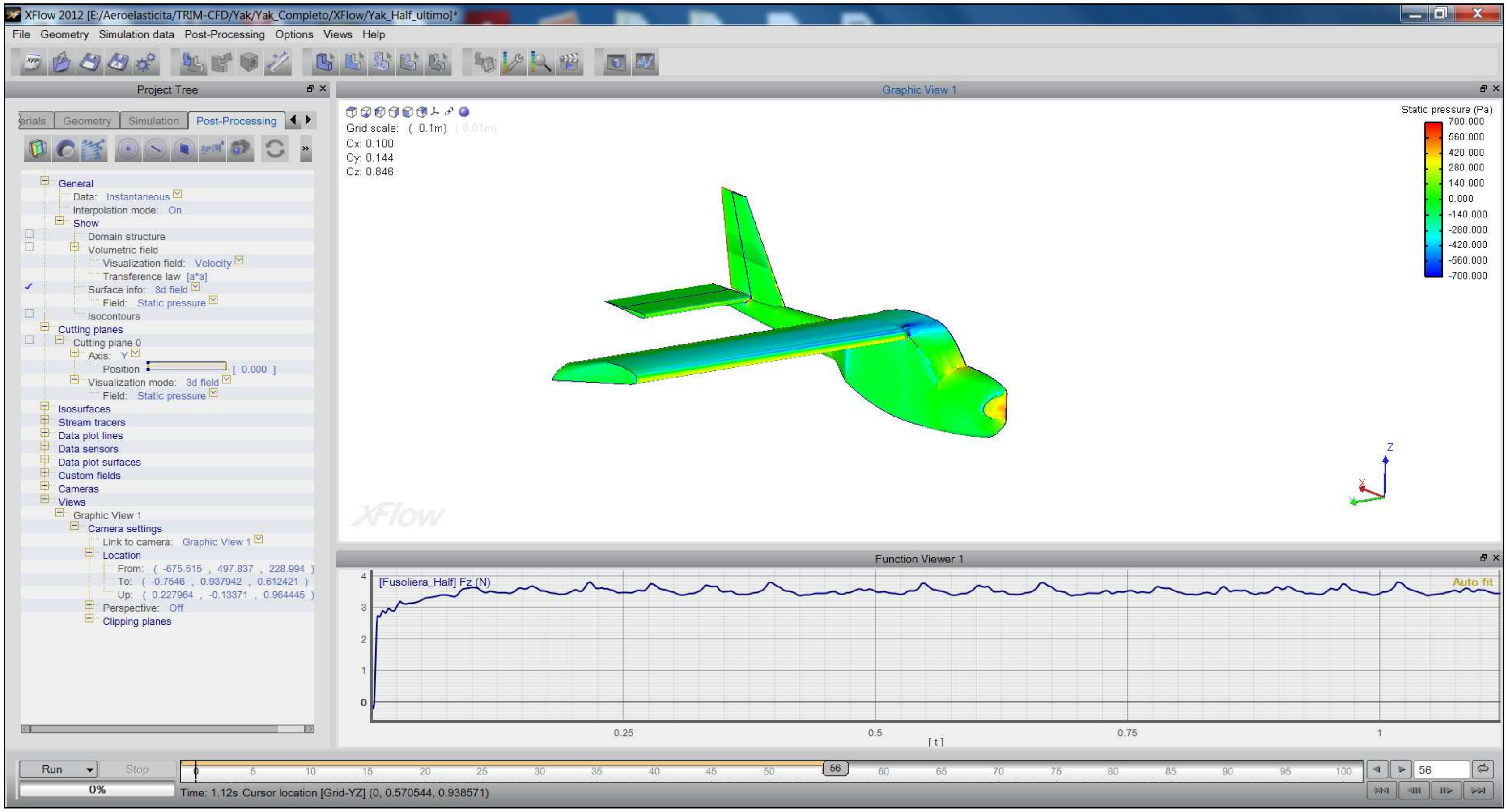
UAV - Post processing

Static pressure distribution



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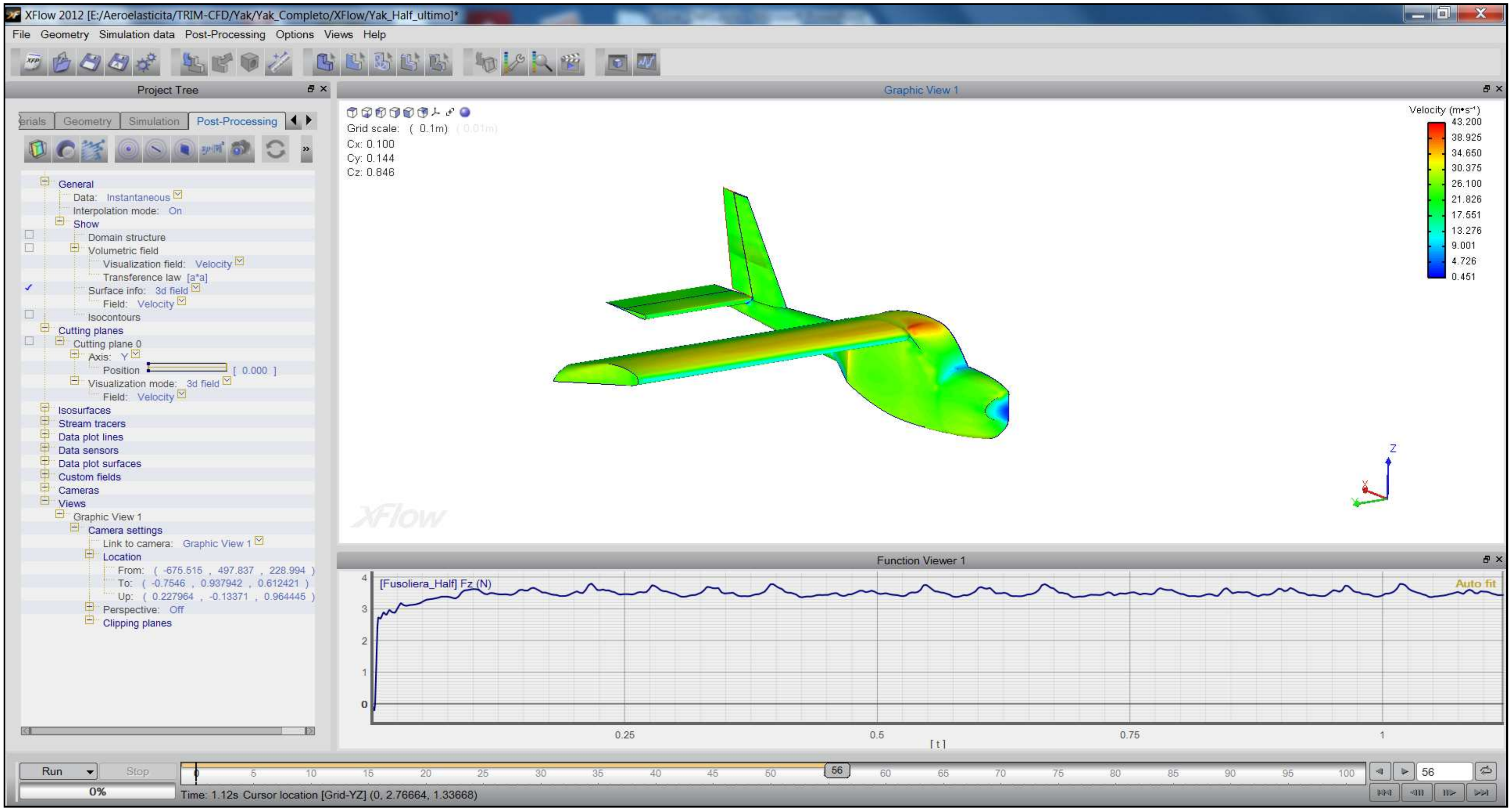
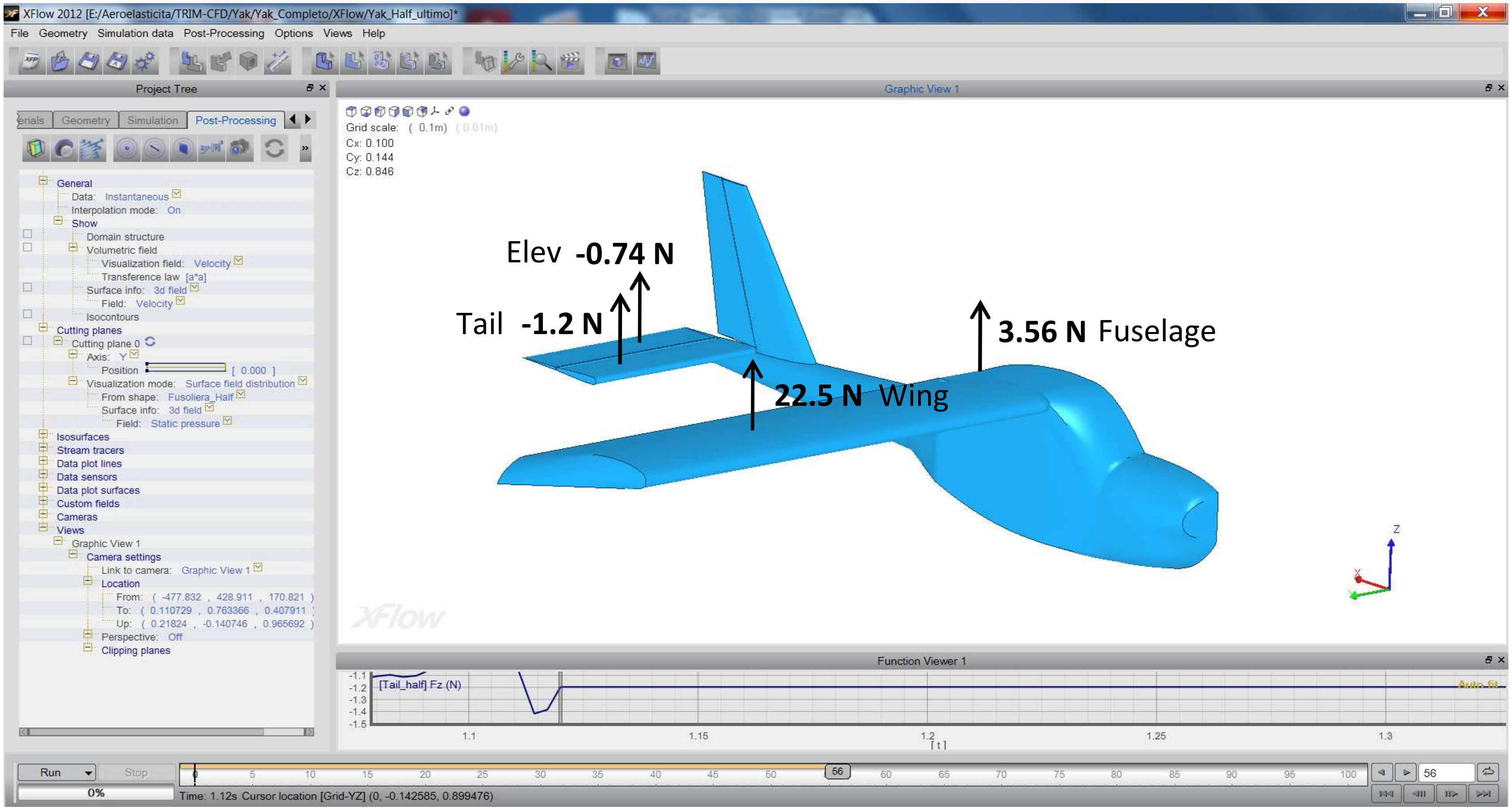
UAV - Post processing

Velocity distribution



UAV - Post processing

Overall Load distribution - Z Component



Future Static Aeroelasticity application

All components could be taken into account for Static Aeroelastic Analysis..

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Thanks!