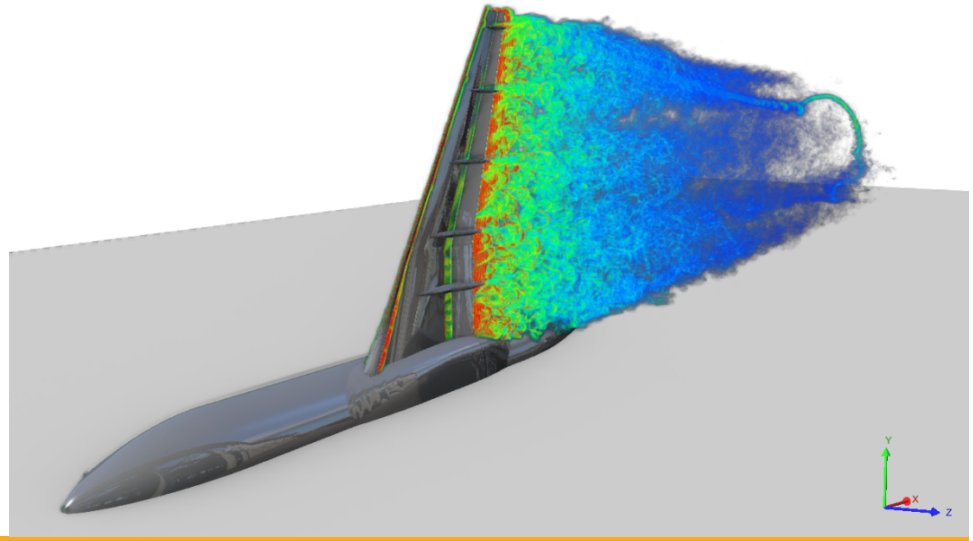
Lattice-Boltzmann Contribution the 2nd AIAA High Lift Prediction Workshop

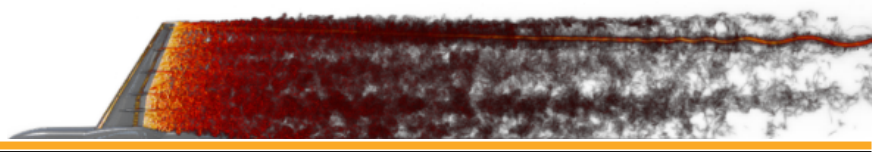
David M. Holman
Ruddy Brionnaud



23th June 2013

NEXT LIMIT TECHNOLOGIES

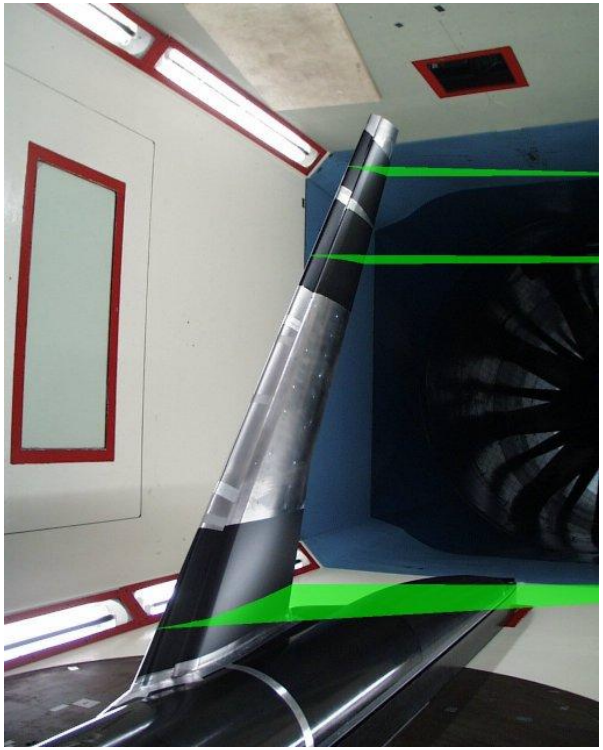
Outline



- **Motivation**
- **XFlow CFD code**
  - **Numerical approach**
  - Relevant sample cases
- 2nd HiLiftPW results
  - Case 1: Convergence analysis
  - Case 2a: Low Reynolds number condition
  - Case 2b: High Reynolds number condition
- Conclusions – Future work

Motivation

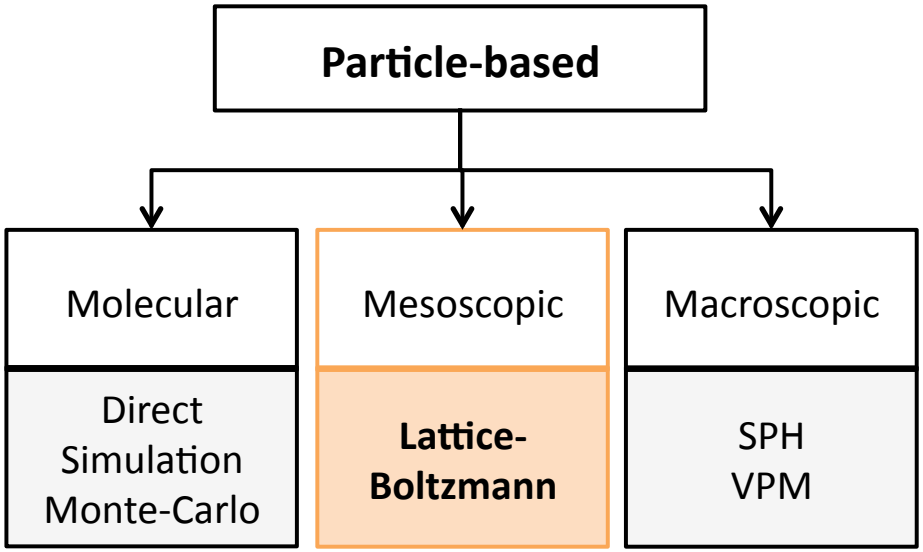
- Benchmark an accessible technology for **highly unsteady** flow simulation around **realistic aircraft** models
- **Assess** the **XFlow** ability to predict **stall** for **high-lift** landing or take-off configurations



Numerical approach

- **Lattice Boltzmann Method (LBM)**

  → Particle-based Lagrangian discretization
  → Mesoscopic scale



Numerical approach

- **Lattice Boltzmann Method (LBM)**

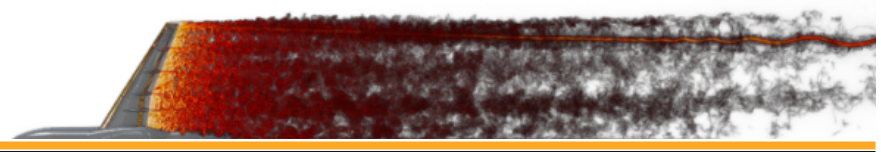
→ Particle-based Lagrangian discretization
→ Mesoscopic scale
→ **Boltzmann transport equation:**

$$\frac{Df}{Dt} = \Omega$$

Distribution function

$f = f(\mathbf{x}, \mathbf{v}, t)$

Density	$\rho = \int f \, dv$
Linear momentum	$\rho u = \int f v \, dv$



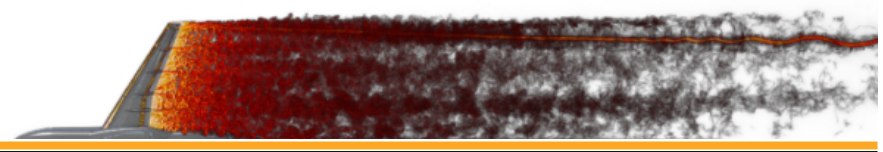
Numerical approach

- **Lattice Boltzmann Method (LBM)**

  → Particle-based Lagrangian discretization
  → Mesoscopic scale
  → **Boltzmann transport equation:**

$$\frac{\partial f_i}{\partial t} + e_i \cdot \nabla f_i = \Omega_\mathrm{i}$$

- f_i : particle distribution function in the direction *i*,
- $\boldsymbol{e}_i$ the discrete velocity in the direction *i*,
- Ω_i the collision operator.



Numerical approach

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  → Particle-based Lagrangian discretization
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  → **Boltzmann transport equation:**

$$\frac{\partial f_i}{\partial t} + e_i \cdot \nabla f_i = \Omega_i$$

Unique colission operator in **central moment space.**

$$\Omega_i^{\mathrm{MRT}} = M_{ij}^{-1} \hat{S}_{ij} (m_i^{\mathrm{eq}} - m_i)$$

- f_i : particle distribution function in the direction *i*,
- $\boldsymbol{e}_i$ the discrete velocity in the direction *i*,
- Ω_i the collision operator.

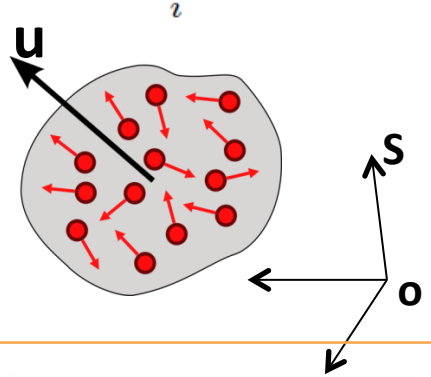
Numerical approach

- **Lattice Boltzmann Method (LBM)**

  → Particle-based Lagrangian discretization
  → Mesoscopic scale
  → Boltzmann transport equation
  → **Factorized Central Moment Lattice Boltzmann**

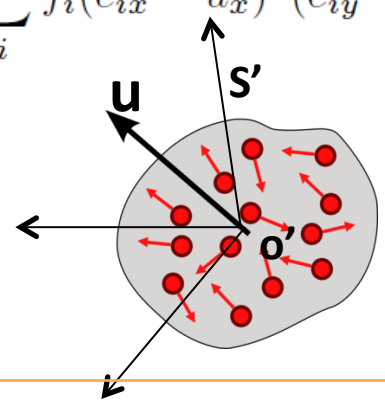
Raw moments

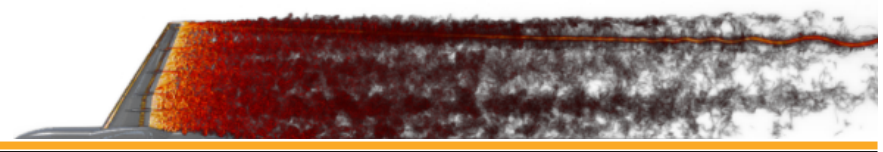
$$\mu x^k y^l z^m = \sum_i^N f_i e_{ix}^k e_{iy}^l e_{iz}^m$$



Central moments

$$\tilde{\mu} x^k y^l z^m = \sum_i^N f_i (e_{ix} - u_x)^k (e_{iy} - u_y)^l (e_{iz} - u_z)^m$$





Numerical approach

- **Lattice Boltzmann Method (LBM)**

  → Particle-based Lagrangian discretization
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  → **Factorized Central Moment Lattice Boltzmann**

Raw moments

$$\mu x^k y^l z^m = \sum_i^N f_i e_{ix}^k e_{iy}^l e_{iz}^m$$

- Stability issues at vanishing viscosity
- Lower Mach number limit
- Galilean invariance issues

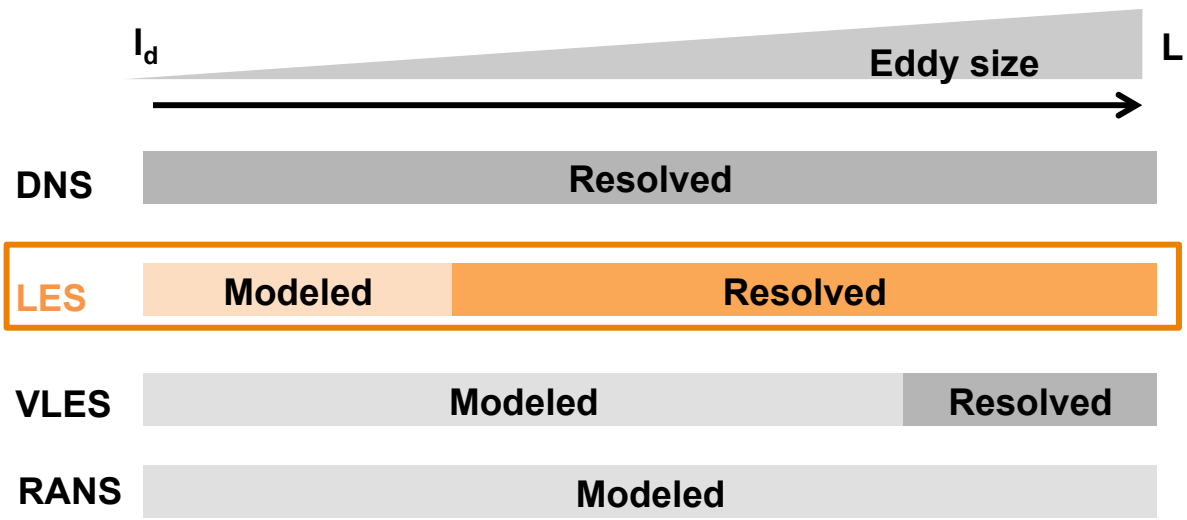
Central moments

$$\tilde{\mu} x^k y^l z^m = \sum_i^N f_i (e_{ix} - u_x)^k (e_{iy} - u_y)^l (e_{iz} - u_z)^m$$

- 4th order spatial discretization
- Higher accuracy
- Lower numerical dissipation
- Positive effective viscosity
- A-stable scheme

Turbulence modeling

- Wall-Modeled Large Eddie Simulation (**WMLES**)



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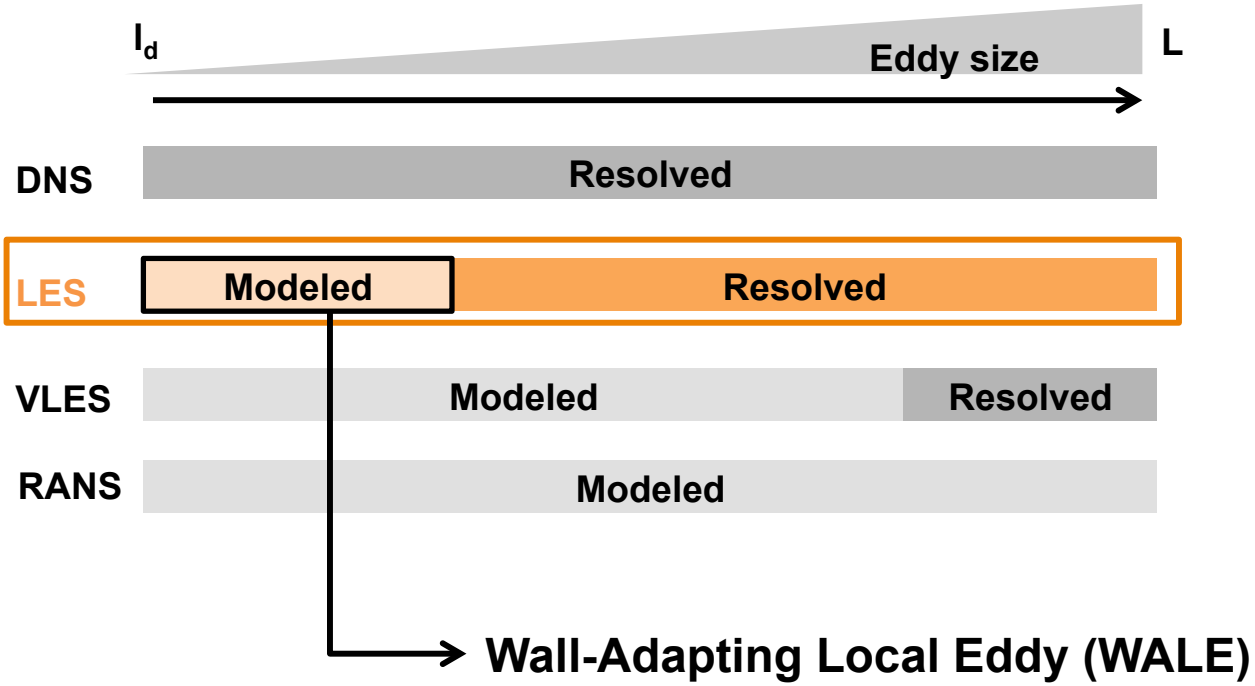
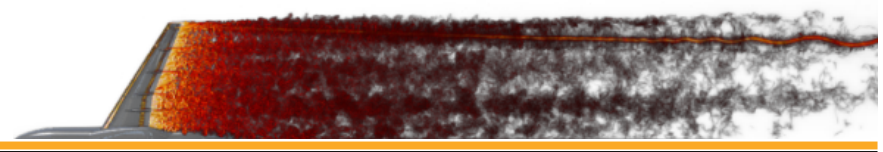


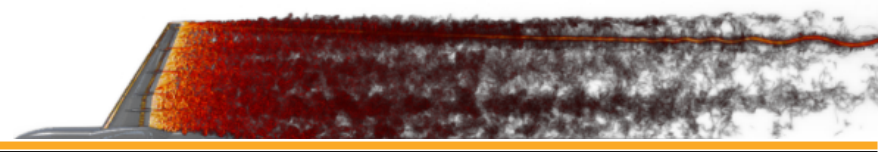


Turbulence modeling

- Wall-Modeled Large Eddie Simulation (**WMLES**)
  → Turbulent viscosity: Wall- Adapting Local Eddy (**WALE**) model

$$\nu_t = \Delta_f^2 \frac{\left(G^d_{\alpha\beta} G^d_{\alpha\beta}\right)^{\frac{3}{2}}}{\left(S_{\alpha\beta} S_{\alpha\beta}\right)^{\frac{5}{2}} + \left(G^d_{\alpha\beta} G^d_{\alpha\beta}\right)^{\frac{5}{4}}}$$

$$\begin{cases} S_{\alpha\beta} = \dfrac{g_{\alpha\beta} + g_{\beta\alpha}}{2} \\ G^d_{\alpha\beta} = \dfrac{1}{2}\left(g^2_{\alpha\beta} + g^2_{\beta\alpha}\right) - \dfrac{1}{3}\delta_{\alpha\beta} g^2_{\gamma\gamma} \\ g_{\alpha\beta} = \dfrac{\partial u_\alpha}{\partial x_\beta} \end{cases}$$



Turbulence modeling

- Generalized law of the wall

$$\frac{U}{u_c} = \frac{U_1 + U_2}{u_c} = \frac{u_\tau}{u_c}\frac{U_1}{u_\tau} + \frac{u_p}{u_c}\frac{U_2}{u_p}$$

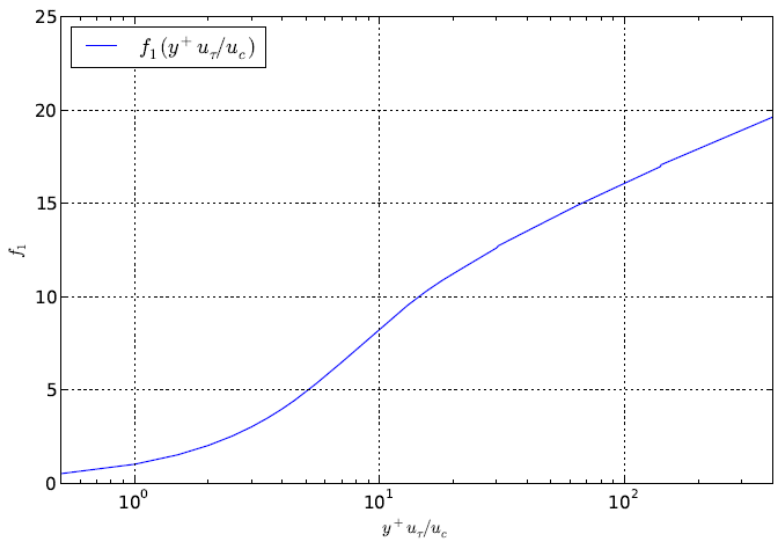
$$= \frac{\tau_w}{\rho u_\tau^2}\frac{u_\tau}{u_c} f_1\left(y^+\frac{u_\tau}{u_c}\right) + \frac{\mathrm{d}p_w/\mathrm{d}x}{|\mathrm{d}p_w/\mathrm{d}x|}\frac{u_p}{u_c} f_2\left(y^+\frac{u_p}{u_c}\right)$$

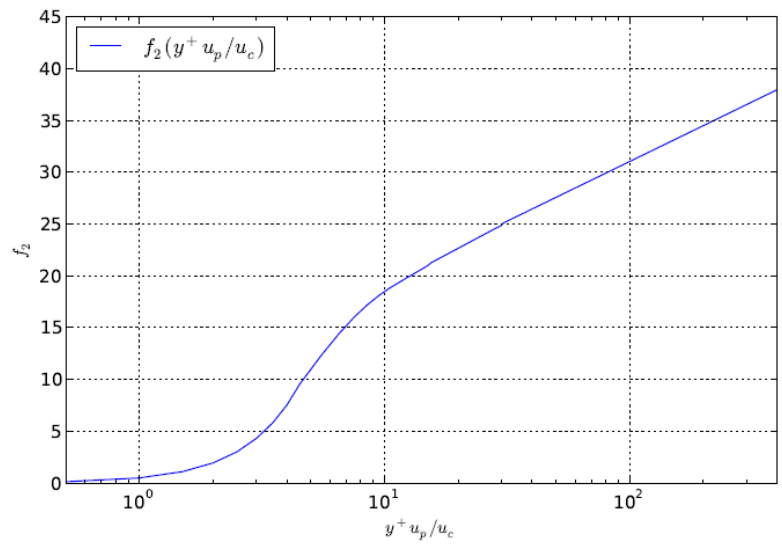
$$y^+ = \frac{u_c y}{\nu}$$

$$u_c = u_\tau + u_p$$

$$u_\tau = \sqrt{|\tau_w|/\rho}$$

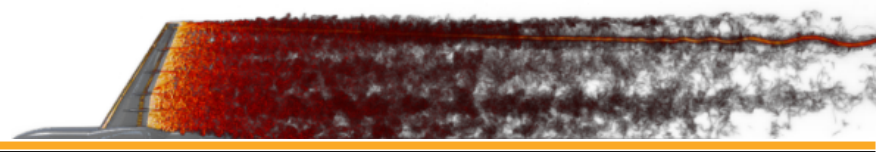
$$u_p = \left(\frac{\nu}{\rho}\left|\frac{\mathrm{d}p_w}{\mathrm{d}x}\right|\right)^{1/3}.$$





Spatial discretization

- **Lattice structure**
  1. **Complex Moving Boundaries**
  2. **Adaptative Refinement**



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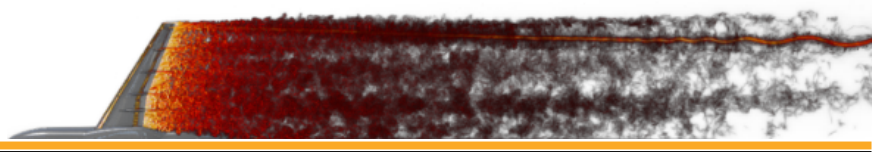
Turbulence modeling

- Wall-Modeled Large Eddie Simulation (**WMLES**)
  - → Turbulent viscosity: Wall- Adapting Local Eddy (**WALE**) model

Spatial discretization

- **Lattice structure**
  - → Moving boundaries
  - → Complex and crossing geometries
  - → Adaptative refinement
  - → Curvature refinement

Outline



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D-JET Flight test manoeuvres

Dynamic simulation of flight test manoeuvers

The D-JET is a five-seat single engine aircraft currently in flight test phase in Canada.

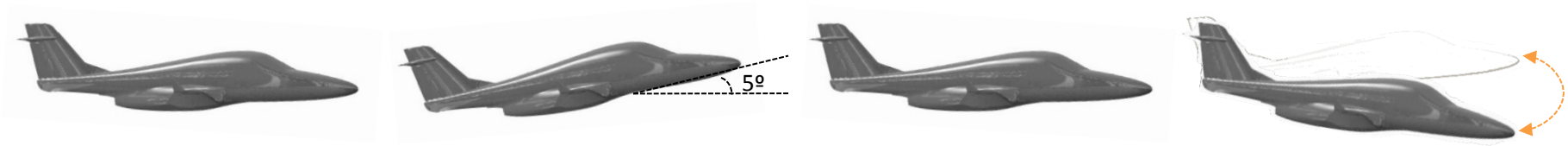
A realistic analysis of the airplane manoeuvrability involves the presence of moving parts, such as the deflection of the elevators, the ailerons, or the elevons.

Different flight test manoeuvres simulated with XFlow are shown and compared against flight test data

- Pitch capture
- Dutch roll
- Stall

Diamond AIRCRAFT

D-JET Flight test manoeuvres - Pitch



Trimmed conditions ⇨ Pitching up 5º (for 1-2 s) ⇨ Trimmed conditions ⇨ Pitch oscilation & damping

XFlow

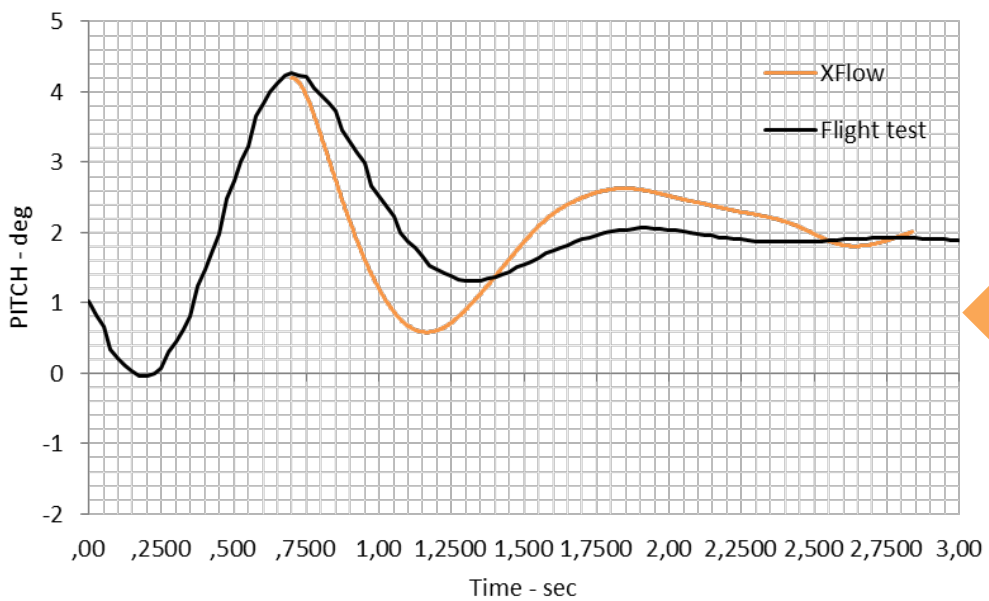
VIRTUAL WIND TUNNEL

Rigid body dynamics:

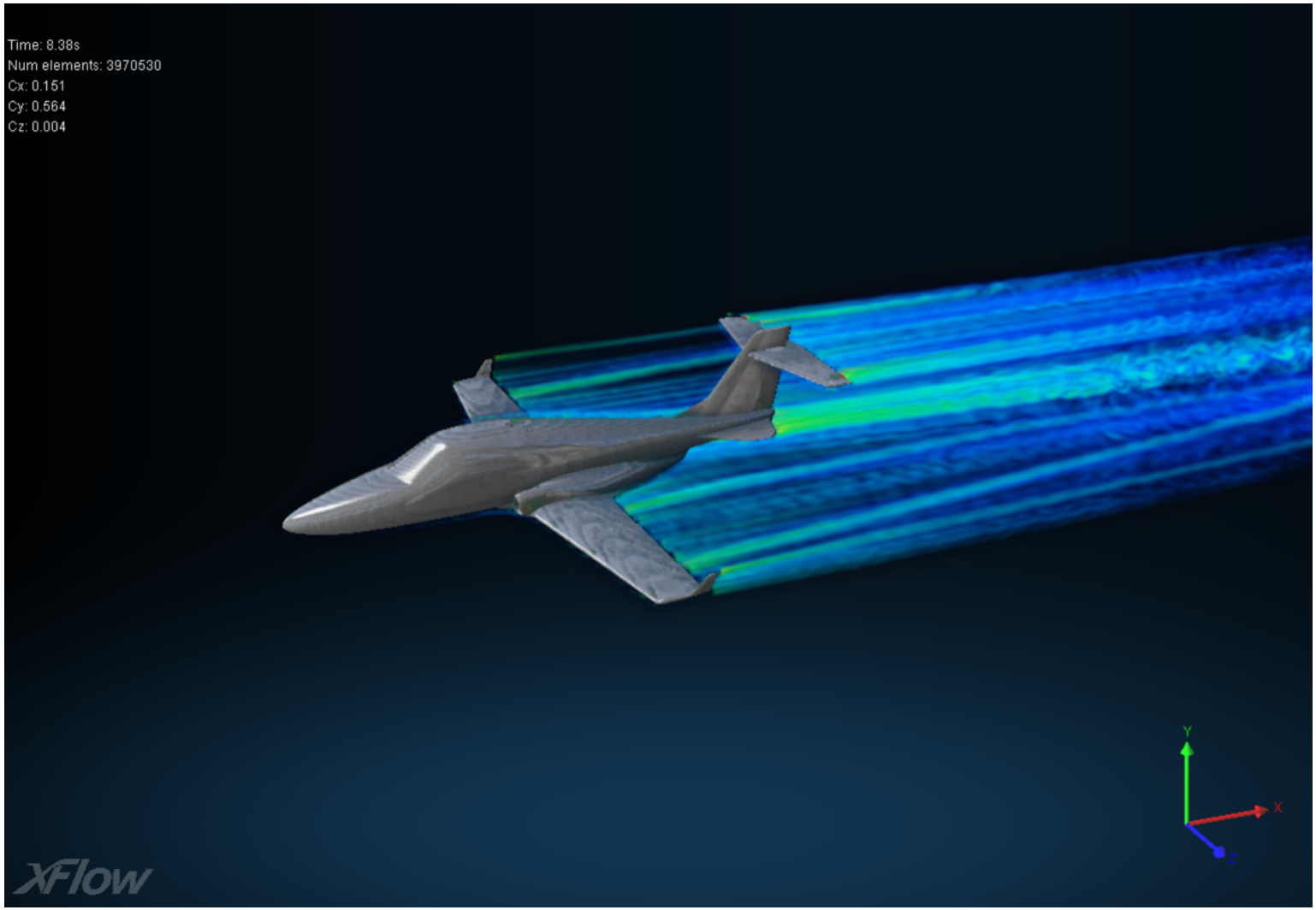
- 1 DoF – Pitch rotation

Initial conditions:

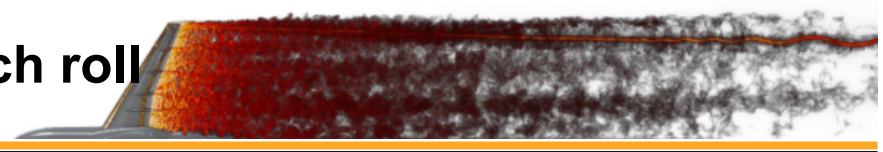
- Flight data @ 0.7s.



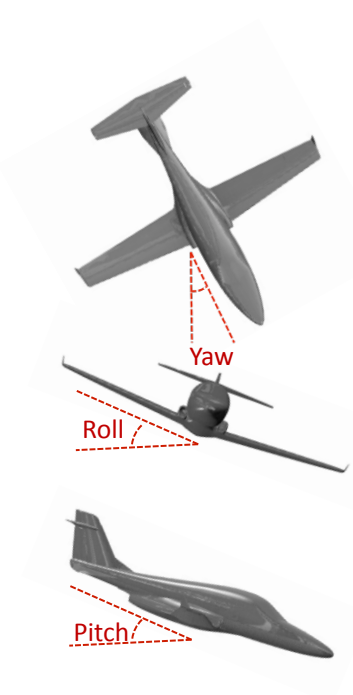
D-JET Flight test manoeuvres - Pitch

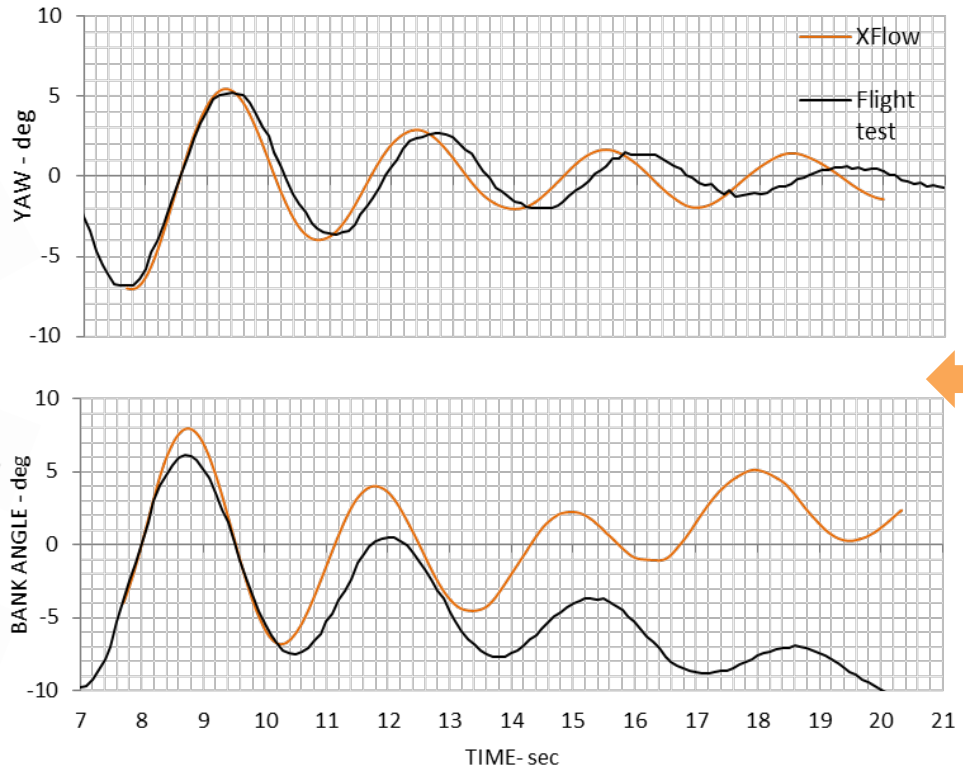


D-JET Flight test manoeuvres – Dutch roll



Trimmed conditions → Rudder excitation → Back-and-forth rolling and yawing motion



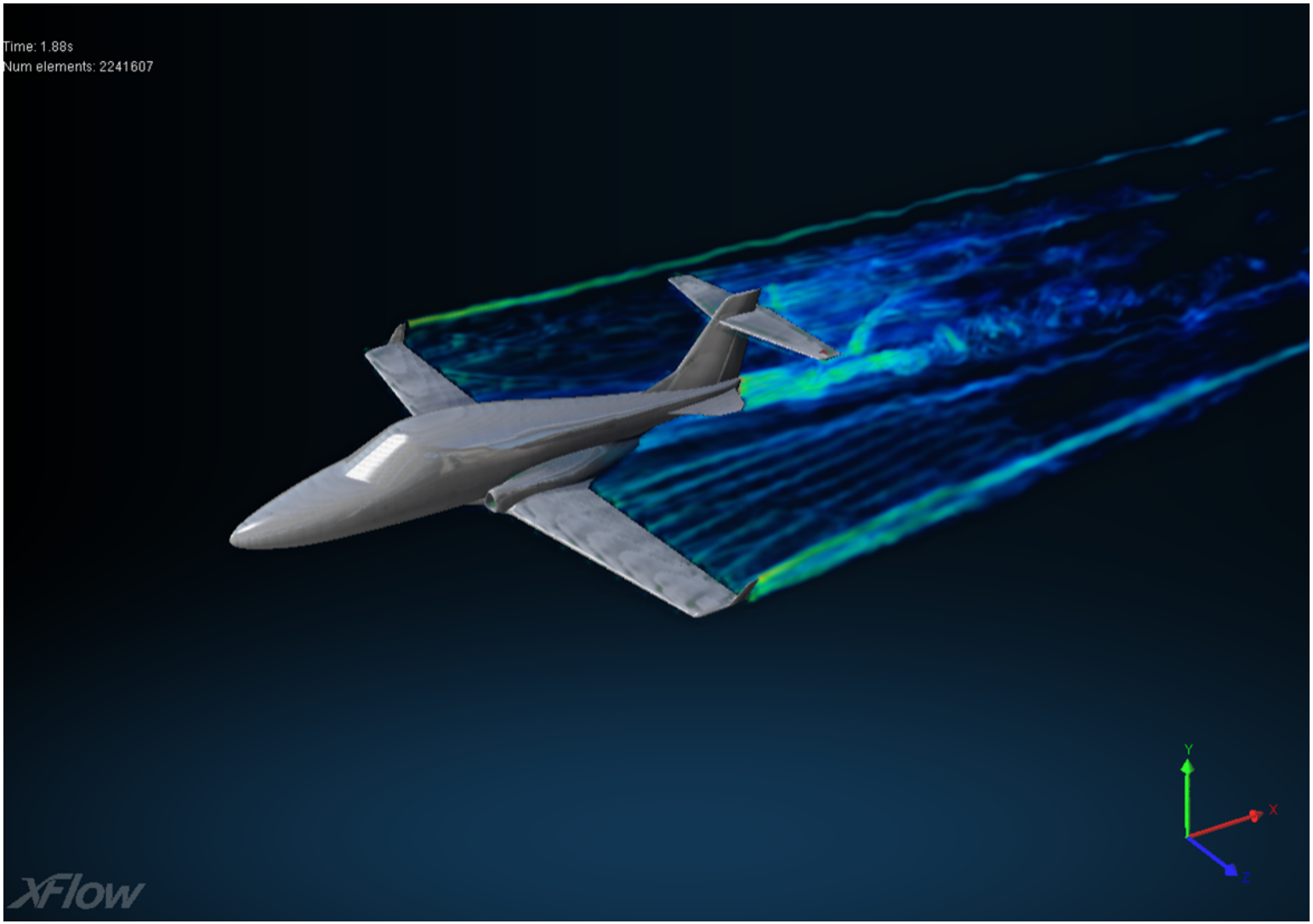


VIRTUAL WIND TUNNEL

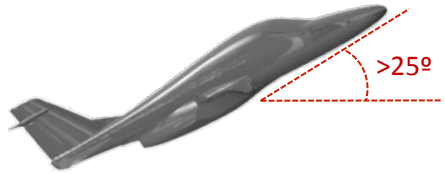
Rigid body – 3 DoF:
- Pitch rotation
- Yaw rotation
- Roll rotation

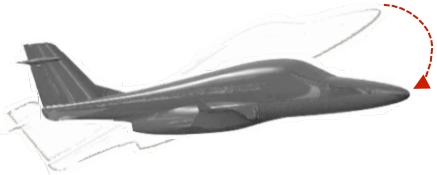
Initial conditions:
- Start time: 7.6 s
- Centered rudder

D-JET Flight test manoeuvres – Dutch roll



D-JET Flight test manoeuvres – Stall





Trimmed conditions

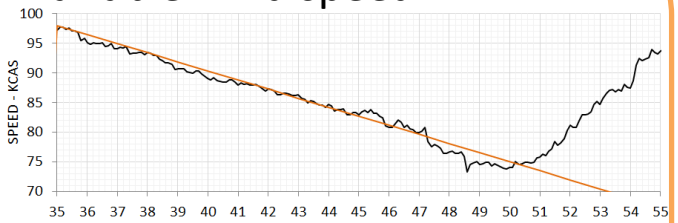
Stall:
Pitch > 25º

Close elevator:
Nose down

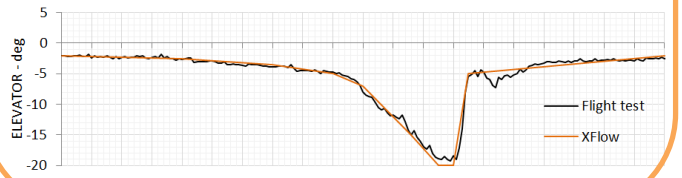
XFlow

VIRTUAL WIND TUNNEL

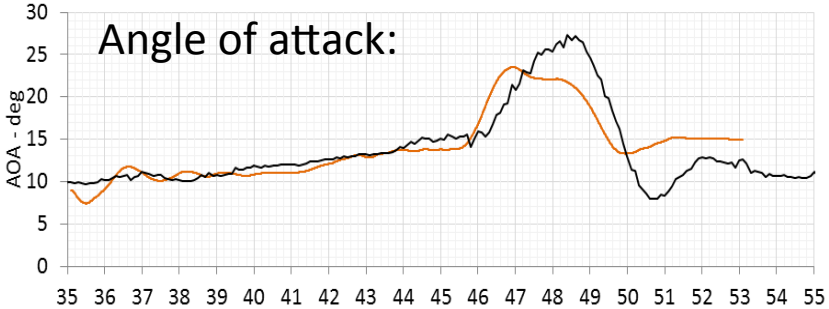
Variable wind speed:

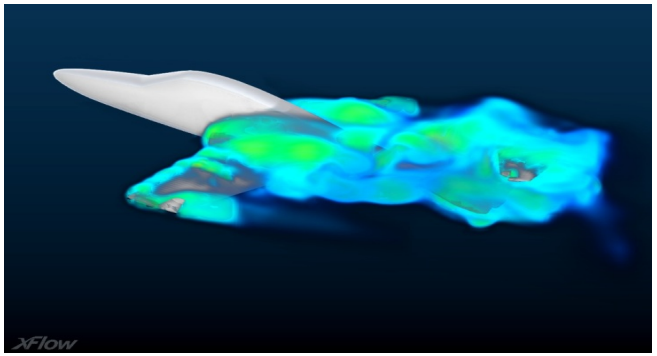


Elevator - Enforced movement:



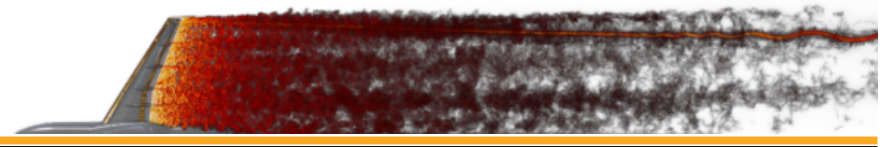
Angle of attack:



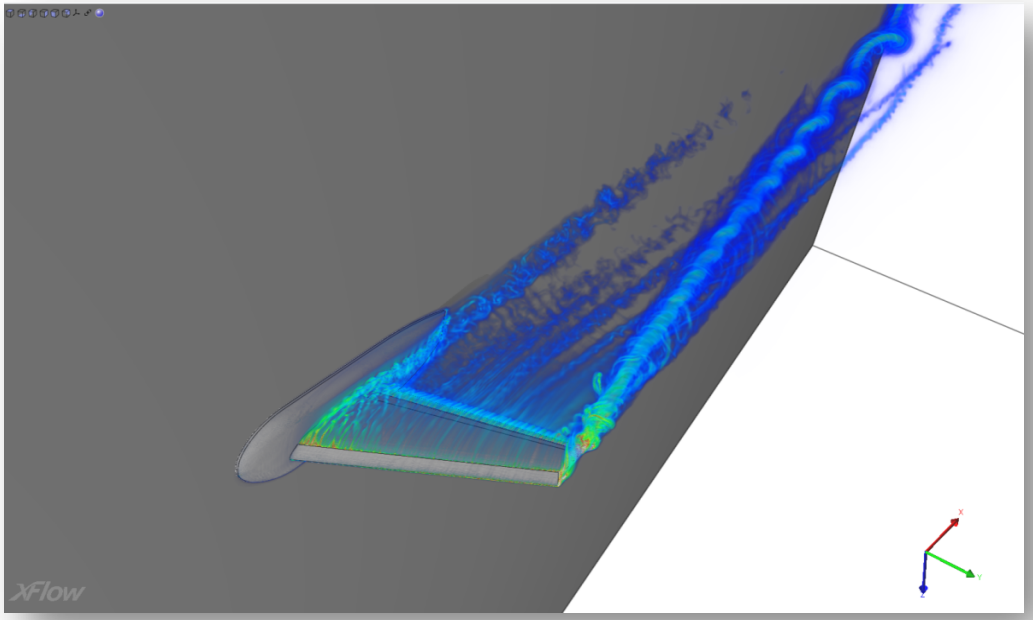


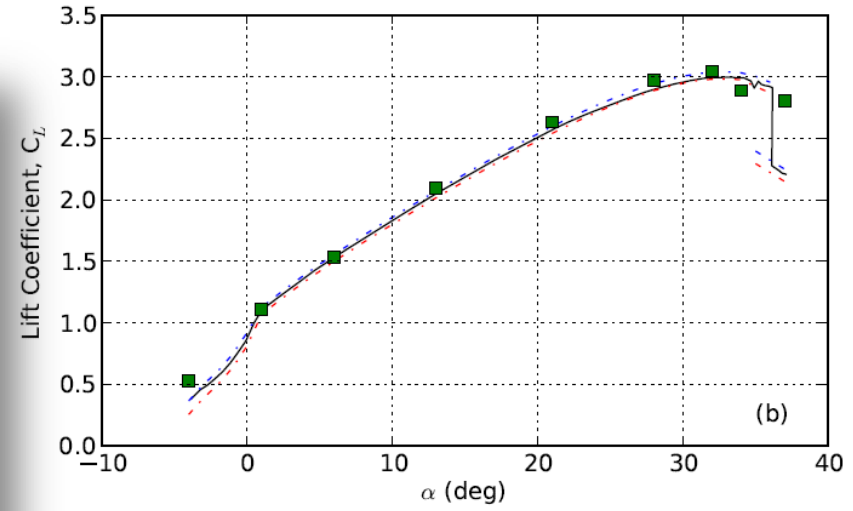
Stall manoeuvre at maximum angle of attack

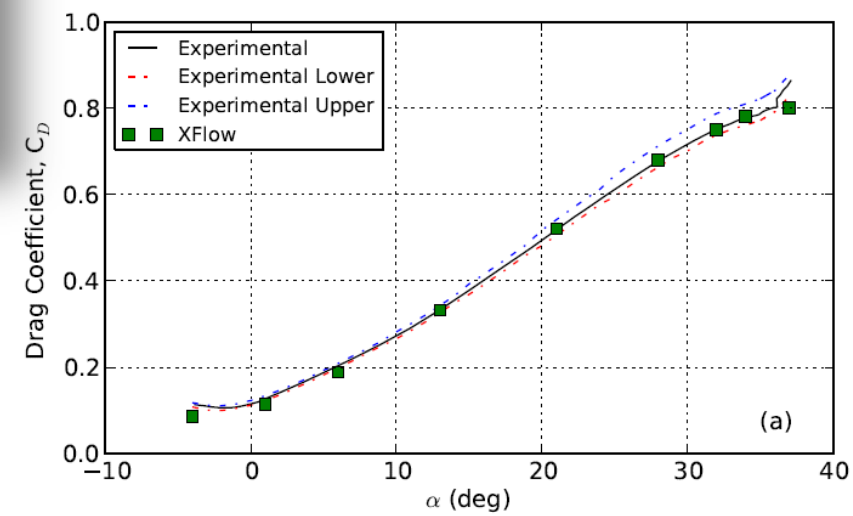
1st HiLiftPW Special Sessions



Standard Lift and Drag analysis







Preparation time

5 minutes

Computation time

Longest run ~36 hours on two processors (8 cores) and 25Million elements

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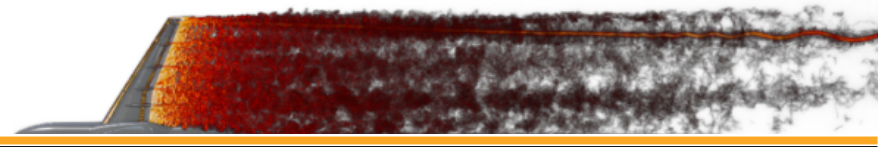
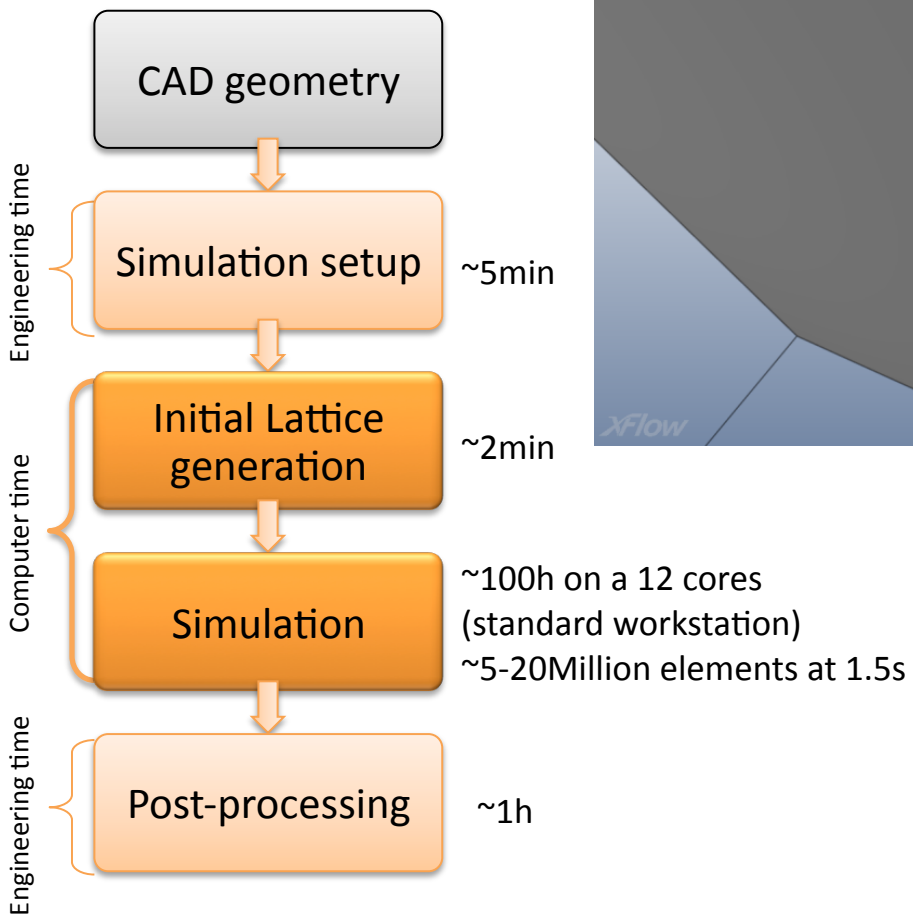
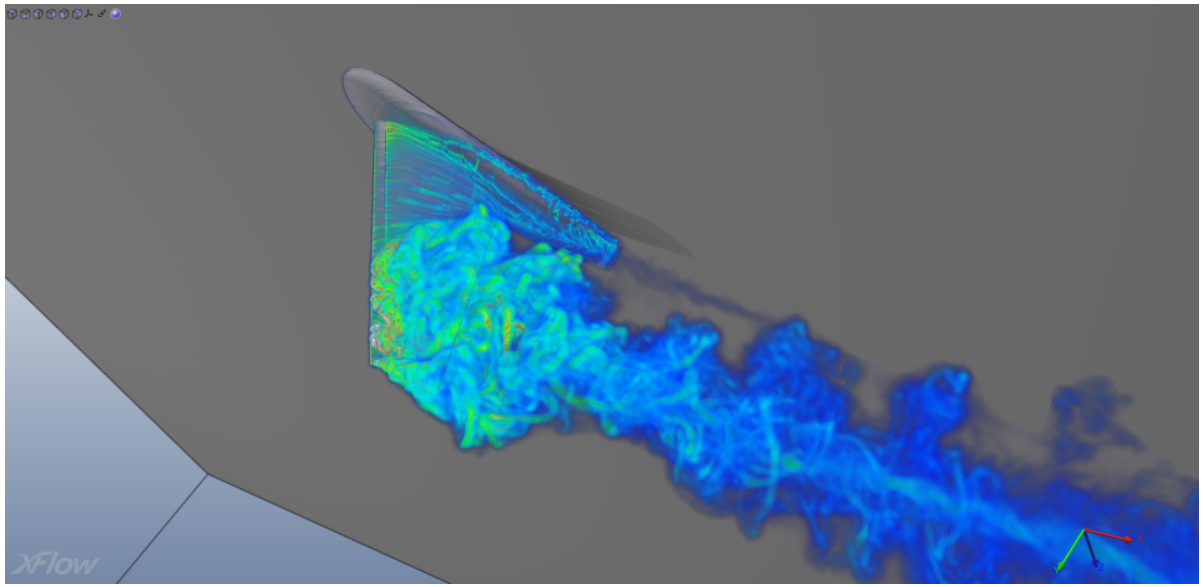
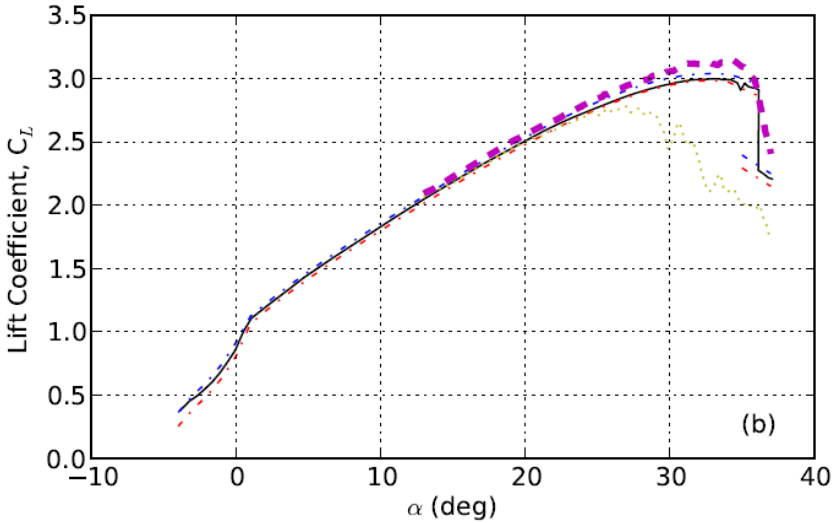


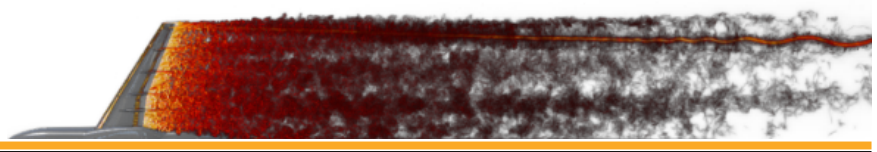
Polar Sweep







Outline



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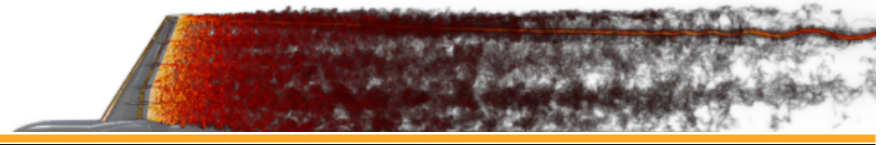
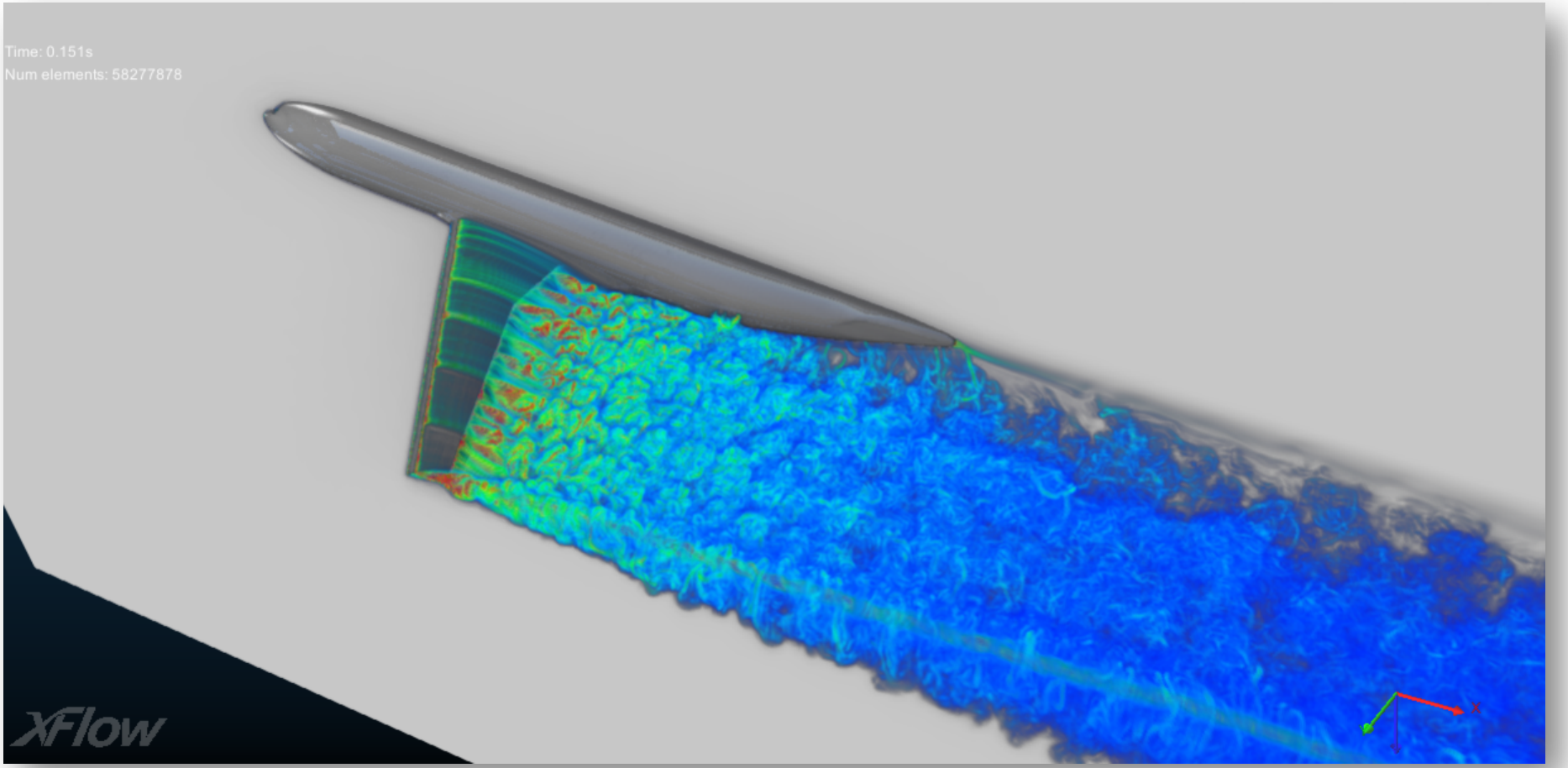
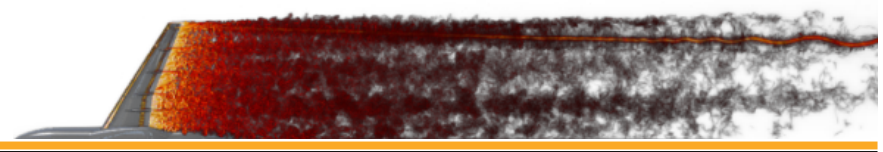
2nd HiLiftPW: Case 1





DLR-F11 wake structure

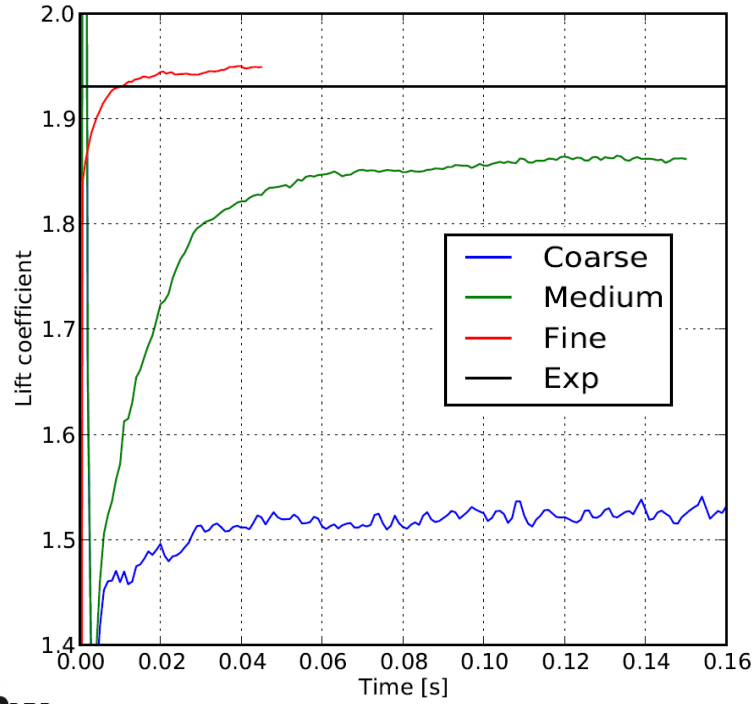
2nd HiLiftPW: Case 1

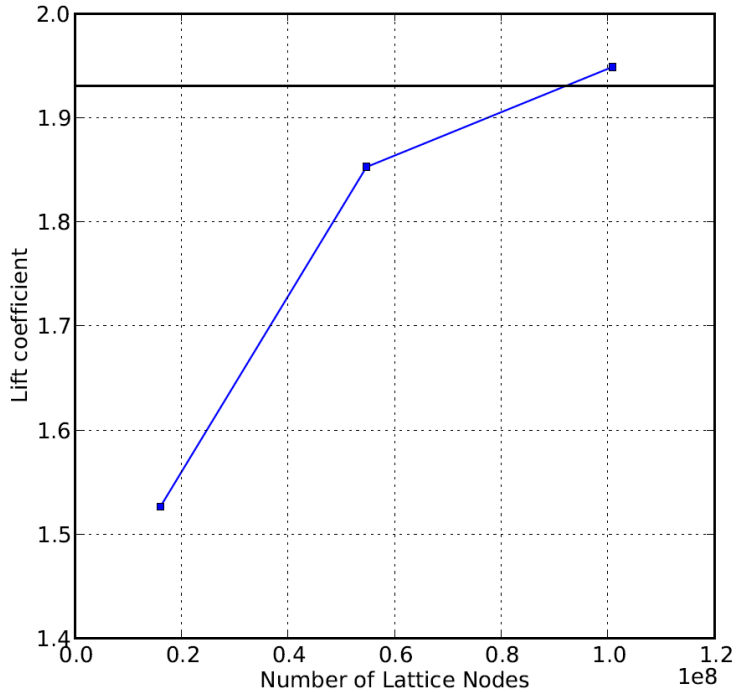


Convergence analysis

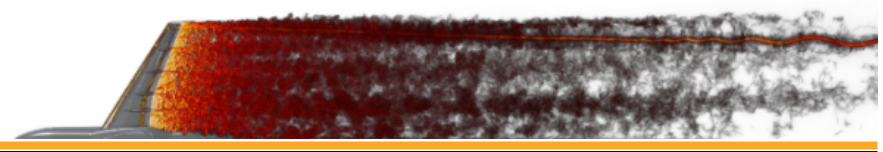
α = 7º

Lattice resolution	Elements	Sim. time	Hardware	Run time
Coarse = 2.5 mm	16,053,207	0.2 s	132 cores / 32GB RAM	6h
Medium = 1.25 mm	54,711,508	0.15 s	156 cores / 32GB RAM	24h
Fine = 0.9 mm	100,862,507	0.045 s	168 cores / 32GB RAM	19h





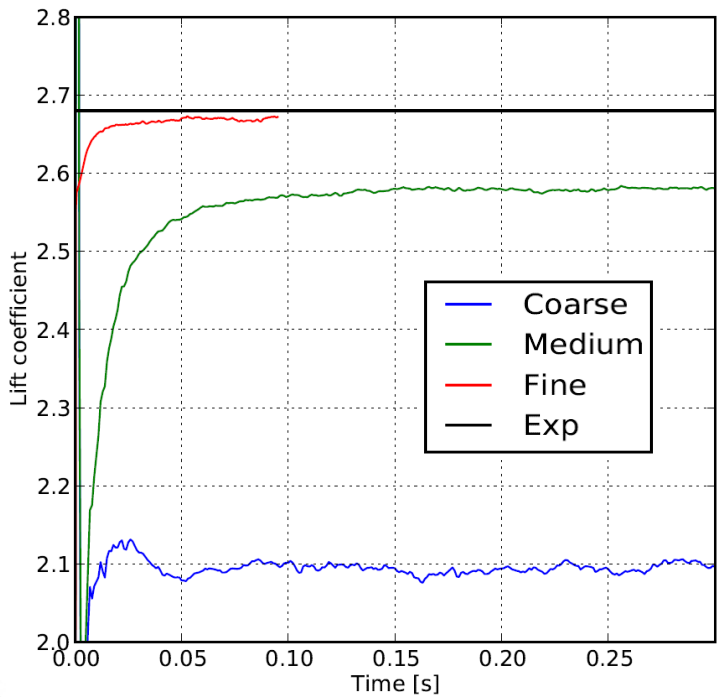
2nd HiLiftPW: Case 1

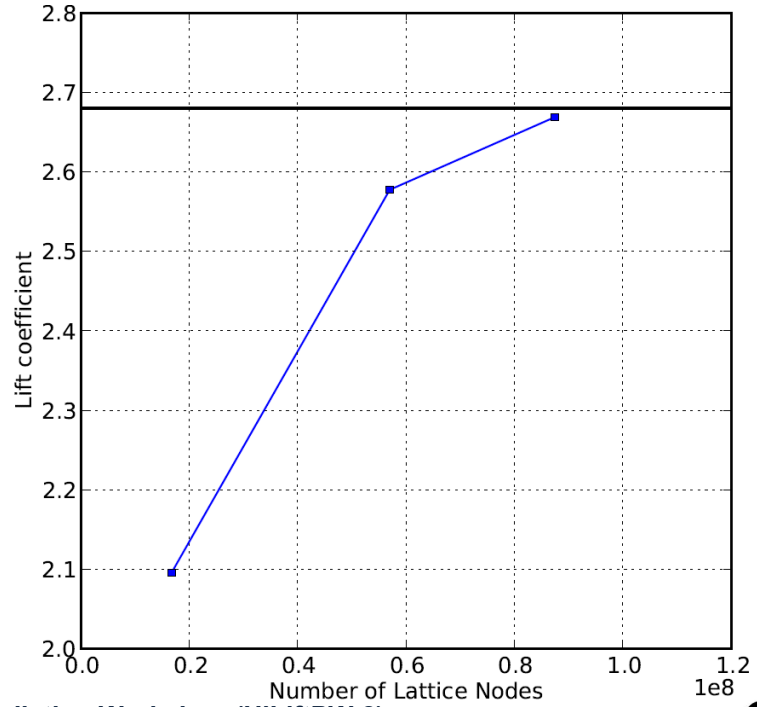


Convergence analysis

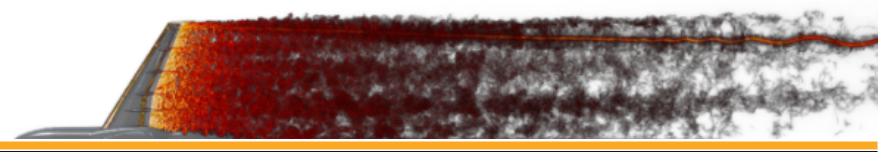
α = 16º

Lattice resolution	Elements	Sim. time	Hardware	Run time
Coarse = 2.5 mm	16,735,791	0.41 s	120 cores / 32GB RAM	14h
Medium = 1.25 mm	56,985,885	0.375 s	168 cores / 32GB RAM	67h
Fine = 1.0 mm	87,417,402	0.095 s	192 cores / 32GB RAM	23h



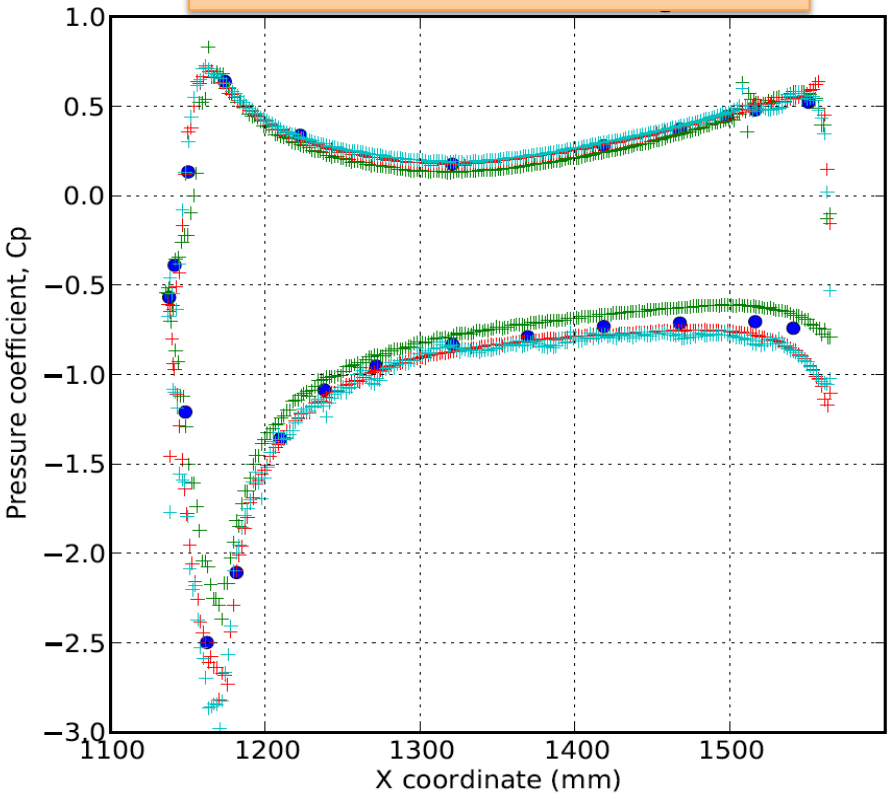


2nd HiLiftPW: Case 1

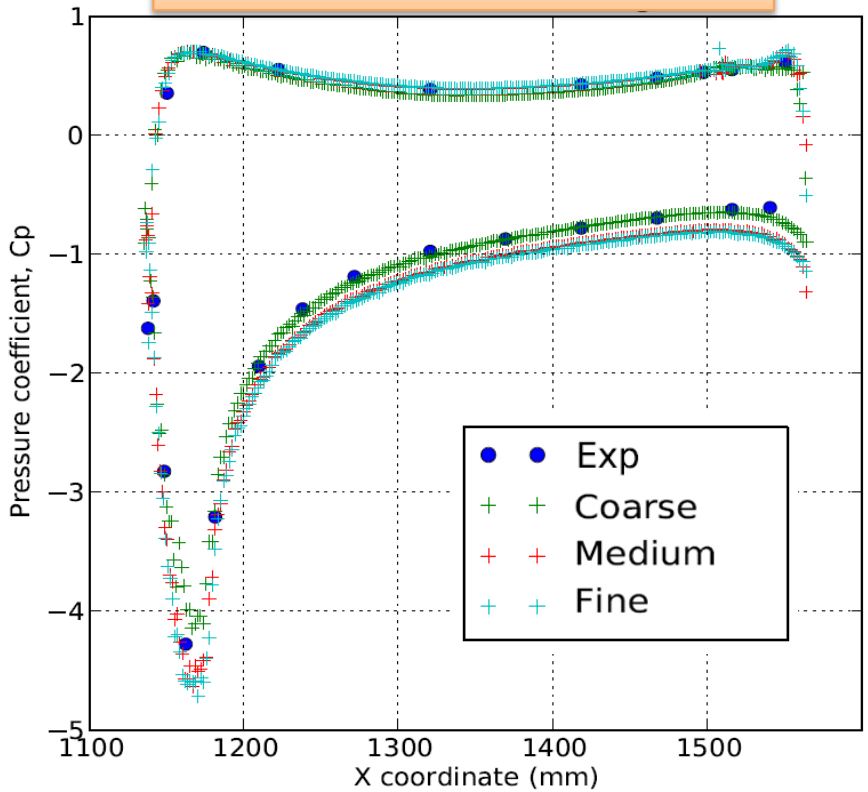


Convergence analysis – Cp distribution - Main wing element @ P01

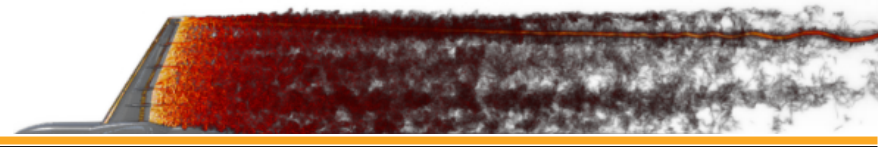
α = 7º



α = 16º

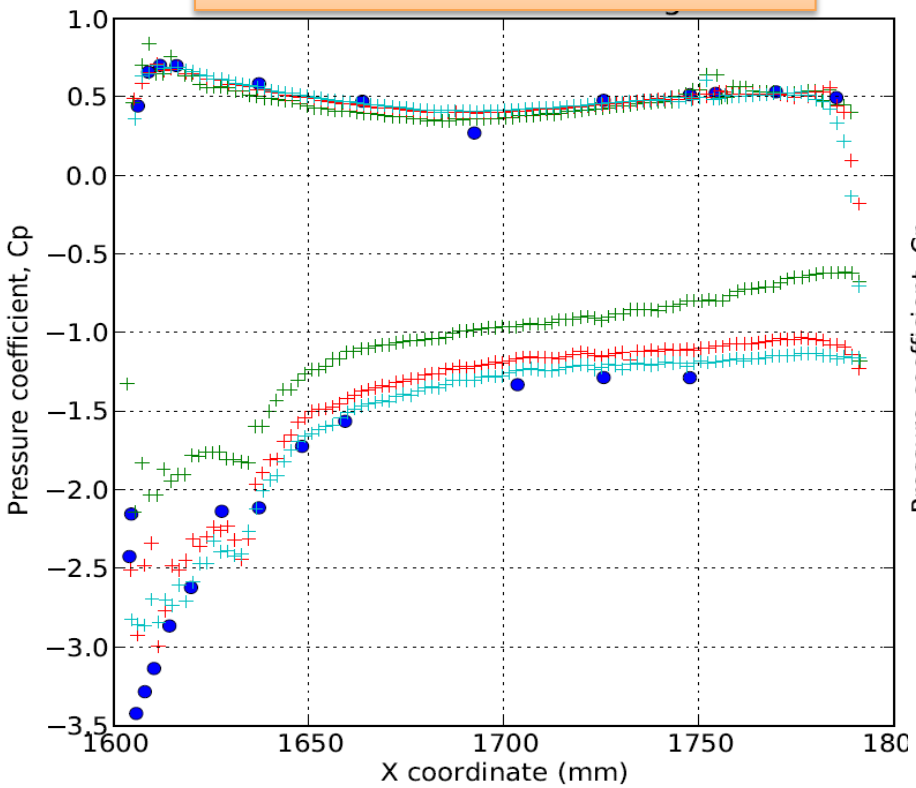


2nd HiLiftPW: Case 1

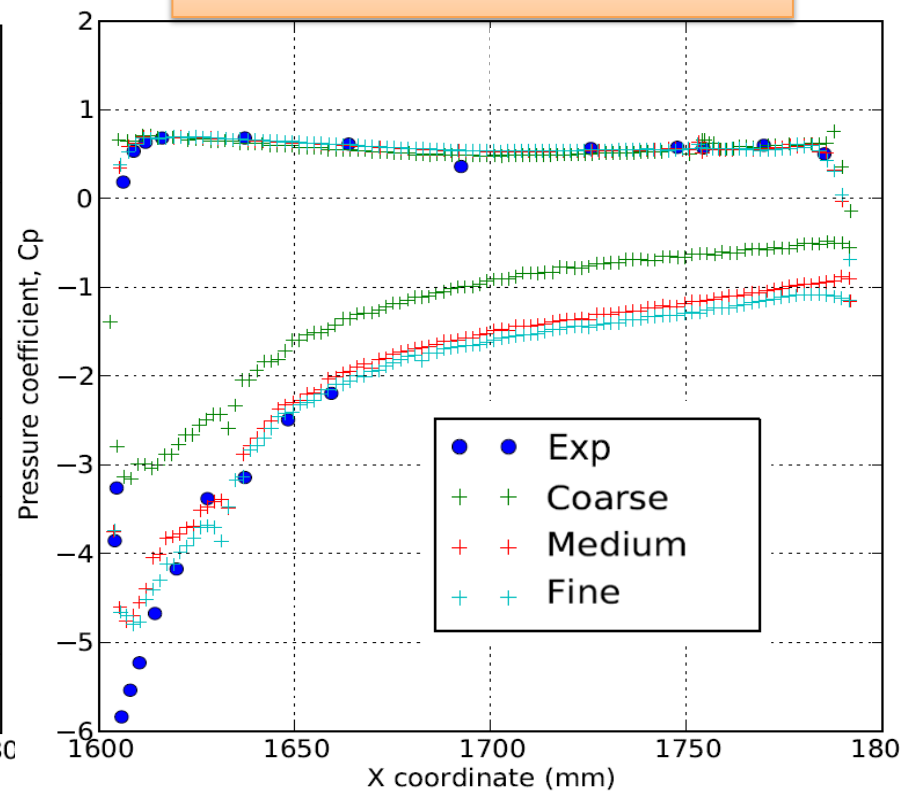


Convergence analysis – Cp distribution - Main wing element @ P06

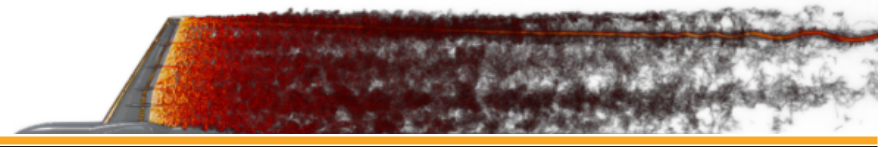
α = 7º



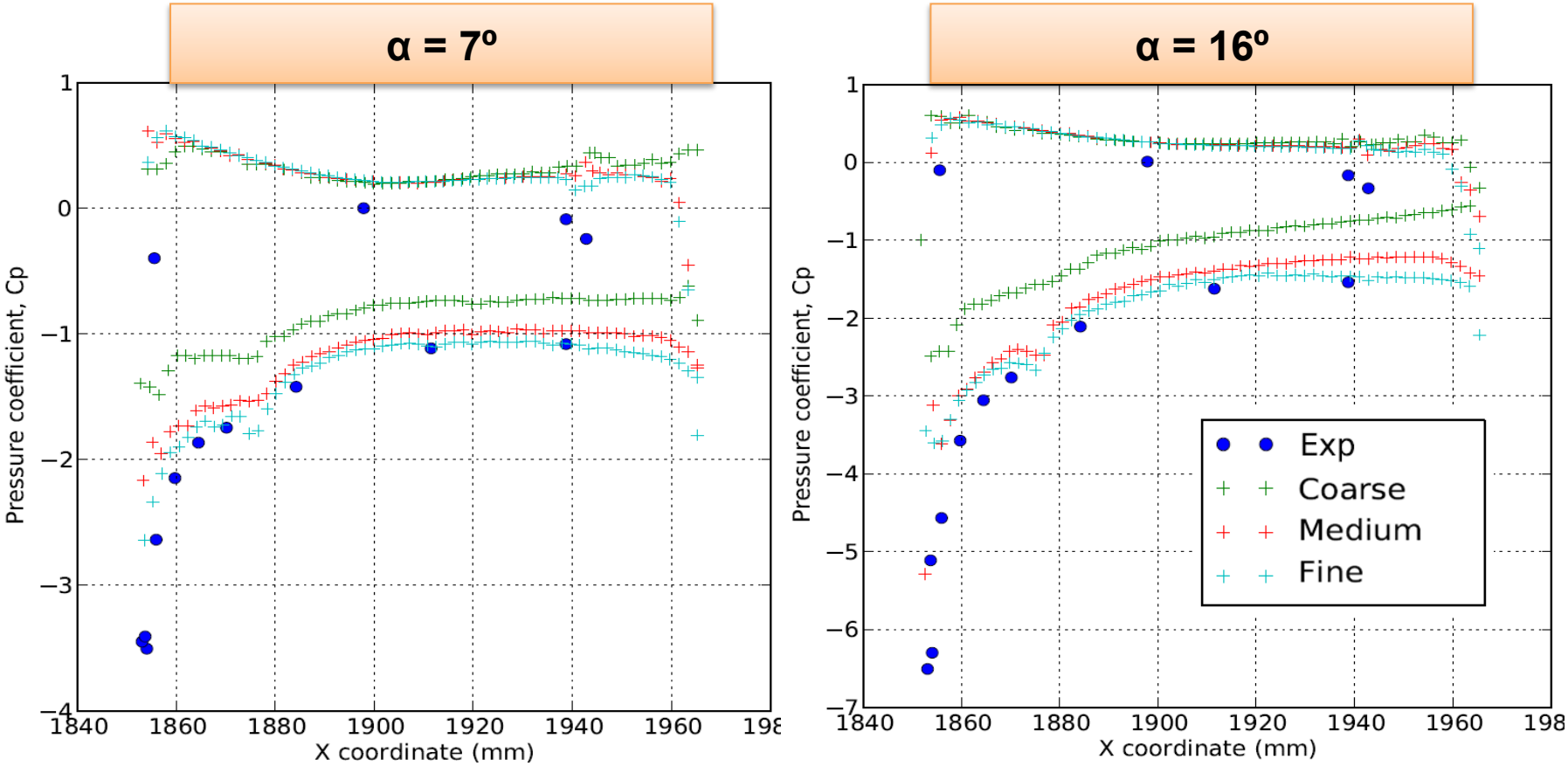
α = 16º



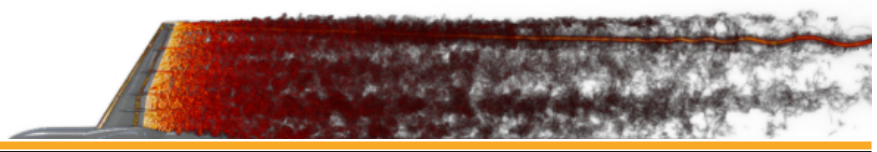
2nd HiLiftPW: Case 1



Convergence analysis – Cp distribution - Main wing element @ P11

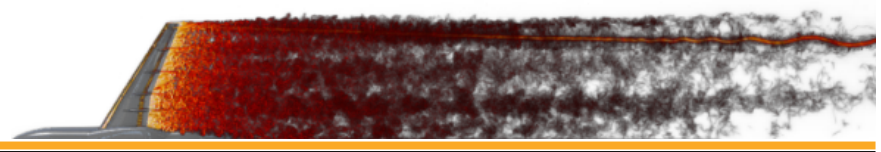


Outline



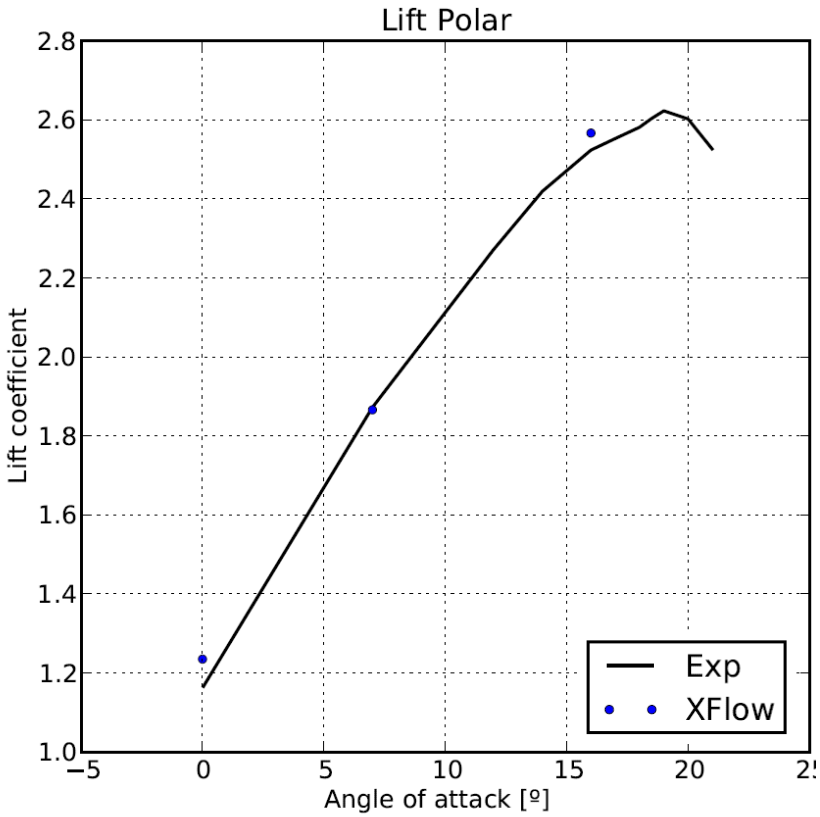
- Motivation
- XFlow CFD code
  - Numerical approach
  - Relevant sample cases
- **2nd HiLiftPW results**
  - Case 1: Convergence analysis
  - **Case 2a: Low Reynolds number condition**
  - Case 2b: High Reynolds number condition
- Conclusions – Future work

2nd HiLiftPW: Case 2 (Re=1.35e6)

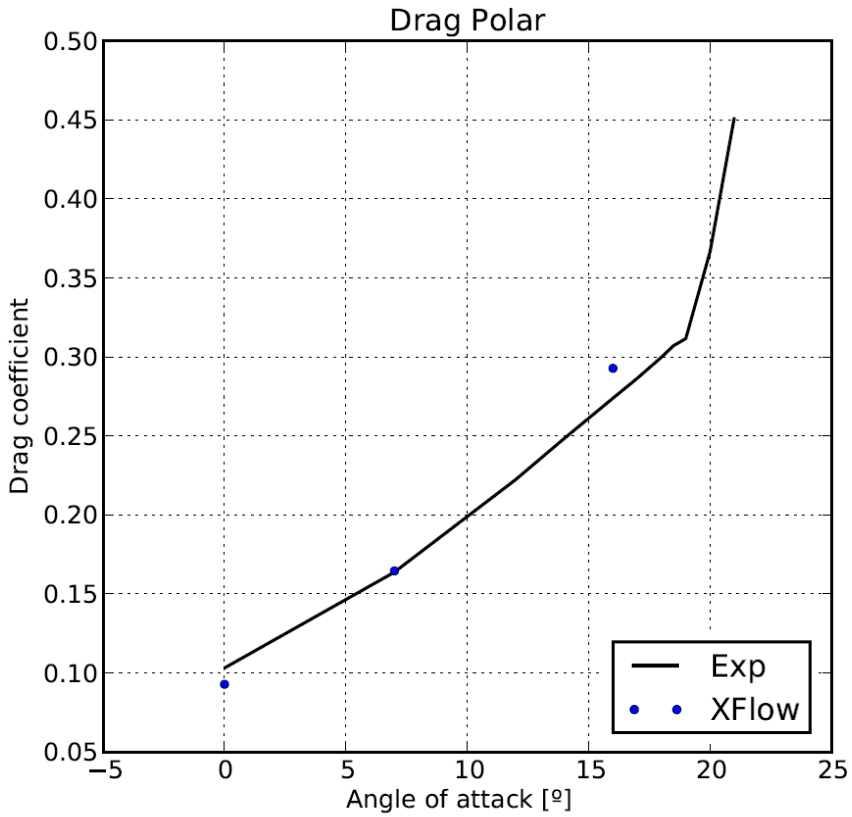


Low Reynolds number condition – Lift and Drag curves

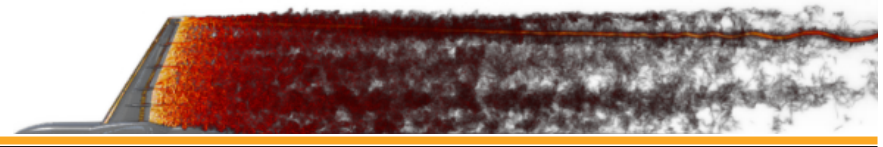
LIFT



DRAG

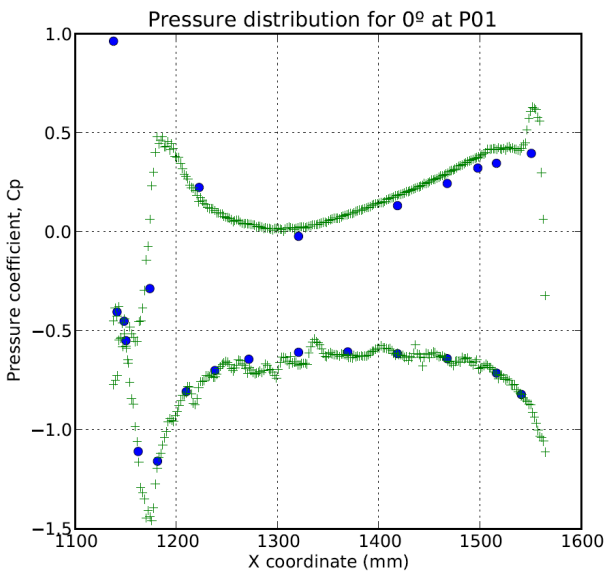


2nd HiLiftPW: Case 2 (Re=1.35e6)

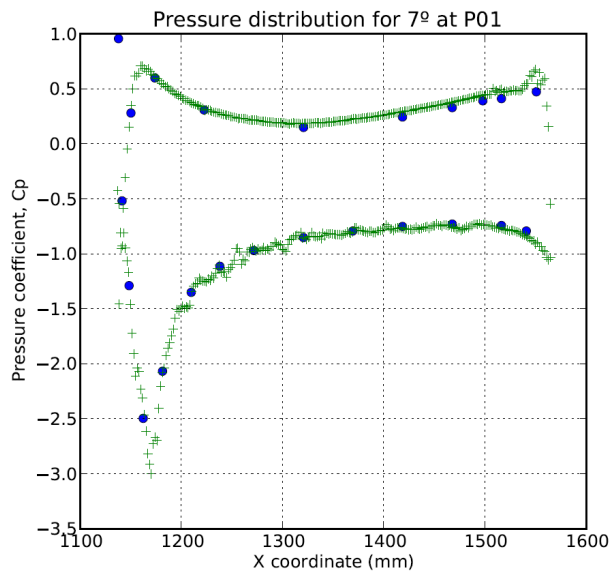


Low Reynolds number – Cp distribution - Main wing element @ P01

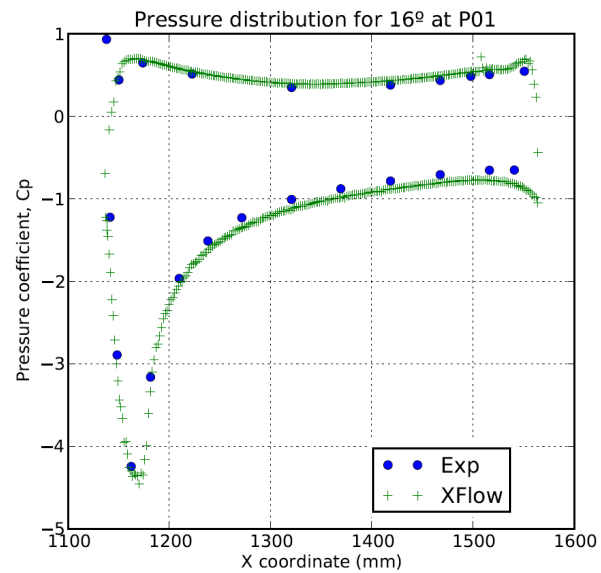
α = 0º



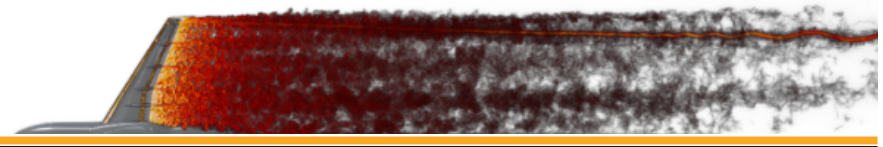
α = 7º



α = 16º

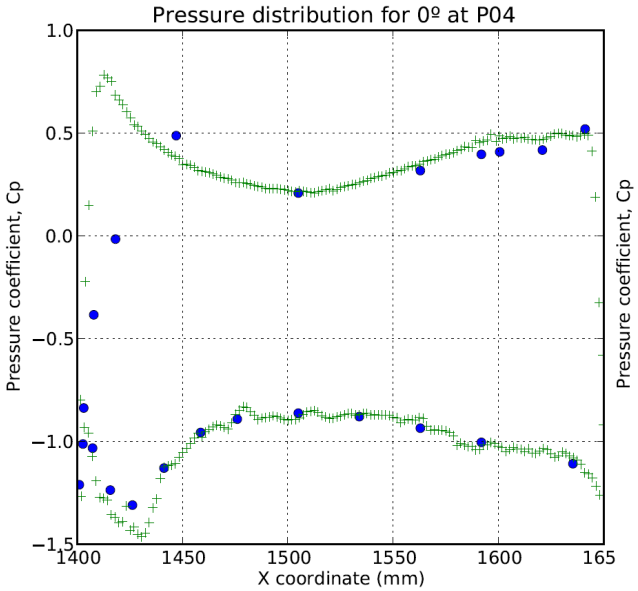


2nd HiLiftPW: Case 2 (Re=1.35e6)

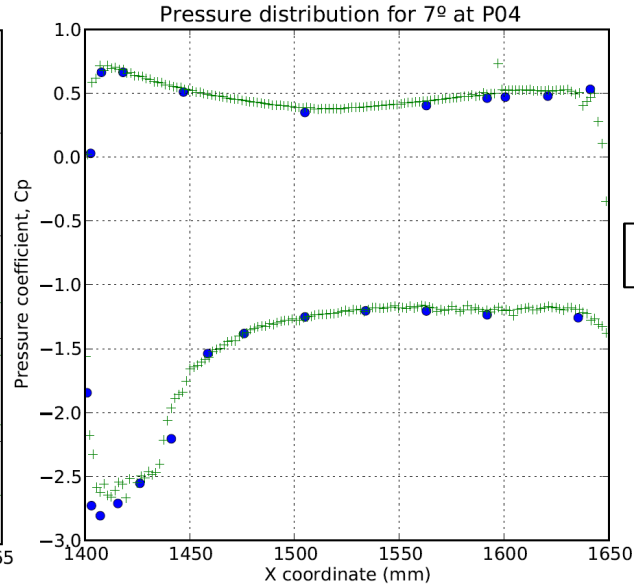


Low Reynolds number – Cp distribution - Main wing element @ P04

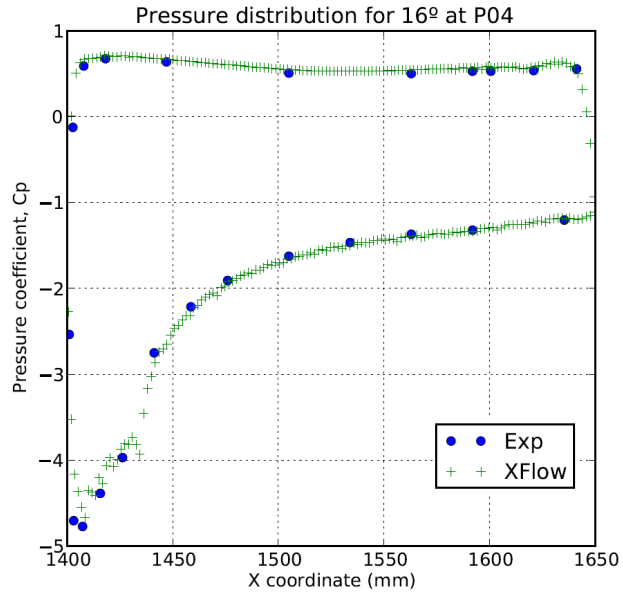
α = 0º



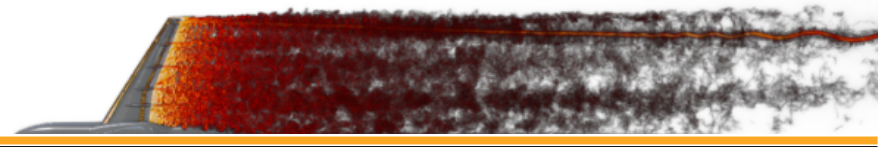
α = 7º



α = 16º

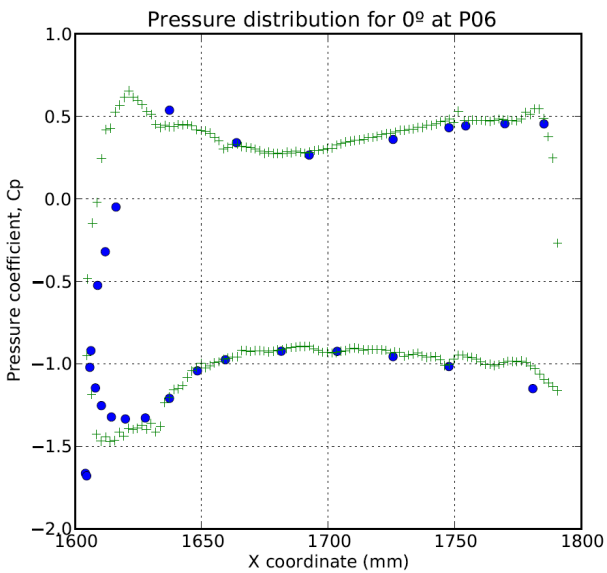


2nd HiLiftPW: Case 2 (Re=1.35e6)

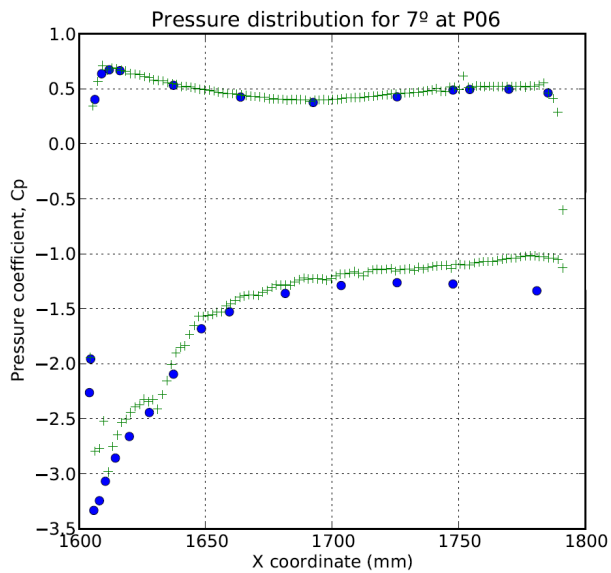


Low Reynolds number – Cp distribution - Main wing element @ P06

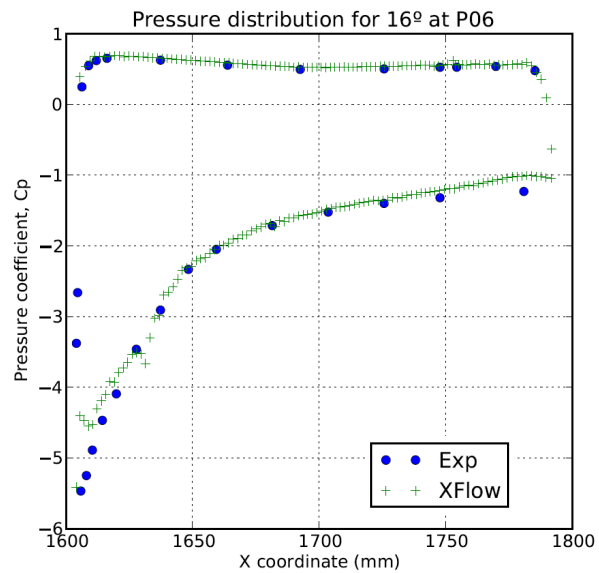
α = 0º



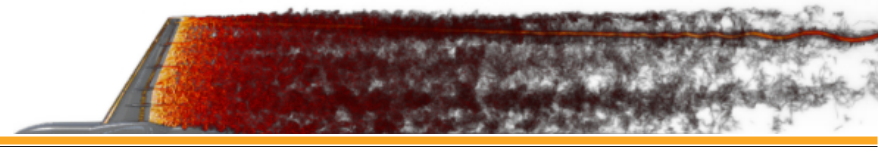
α = 7º



α = 16º

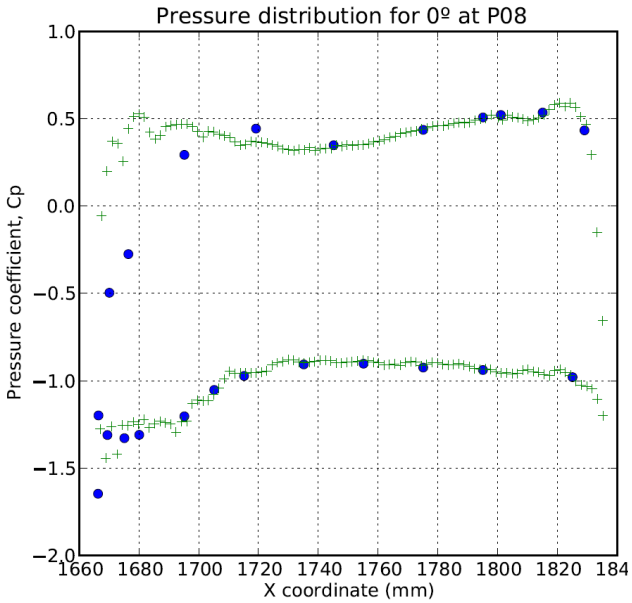


2nd HiLiftPW: Case 2 (Re=1.35e6)

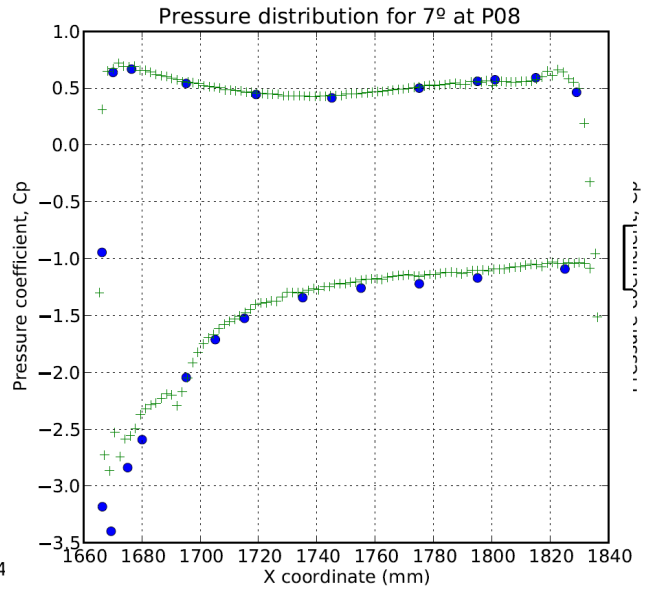


Low Reynolds number – Cp distribution - Main wing element @ P08

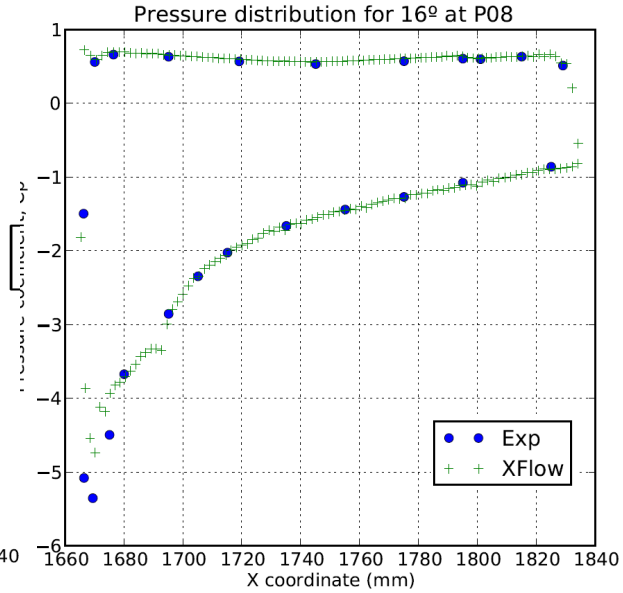
α = 0º



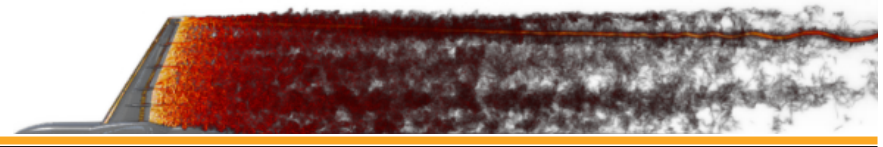
α = 7º



α = 16º

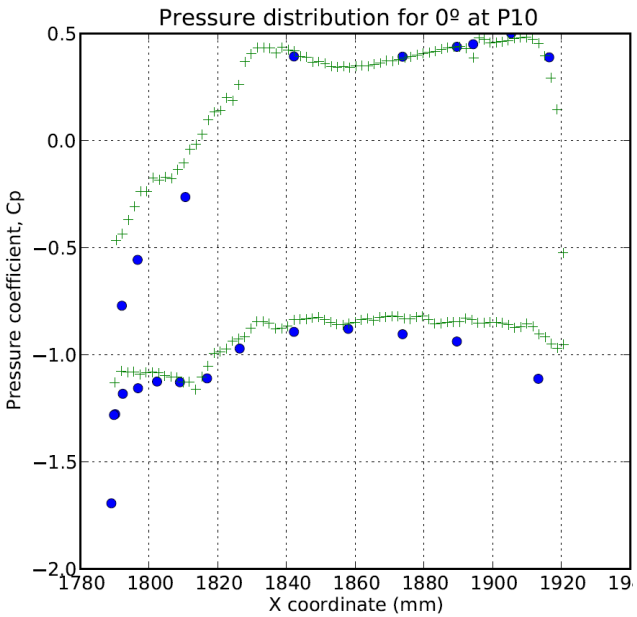


2nd HiLiftPW: Case 2 (Re=1.35e6)

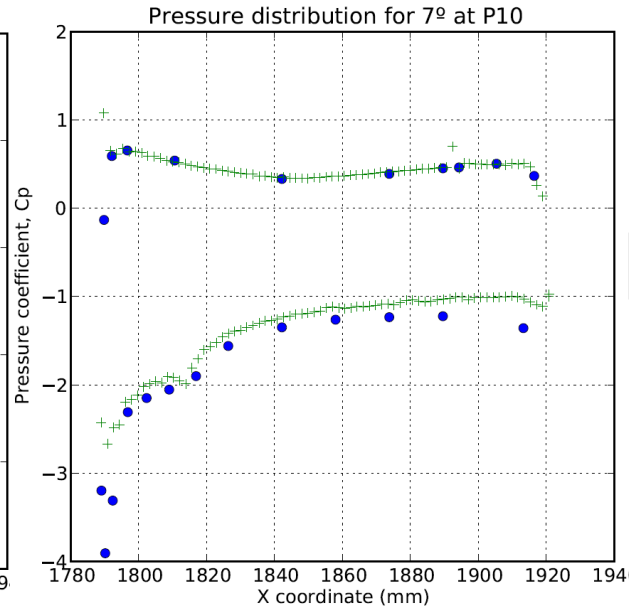


Low Reynolds number – Cp distribution - Main wing element @ P10

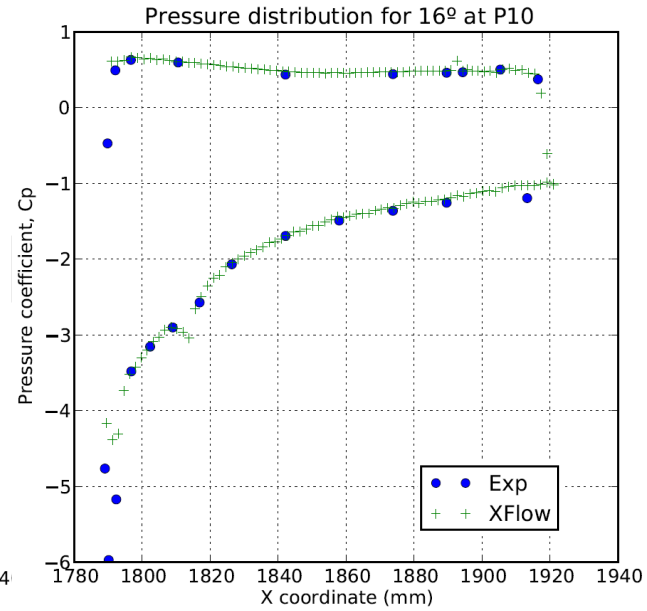
α = 0º



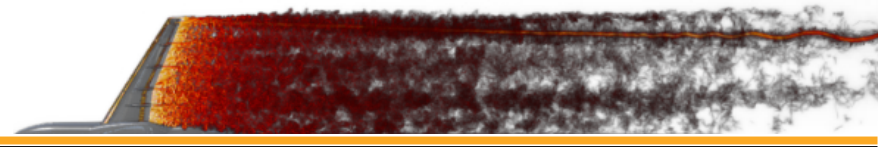
α = 7º



α = 16º

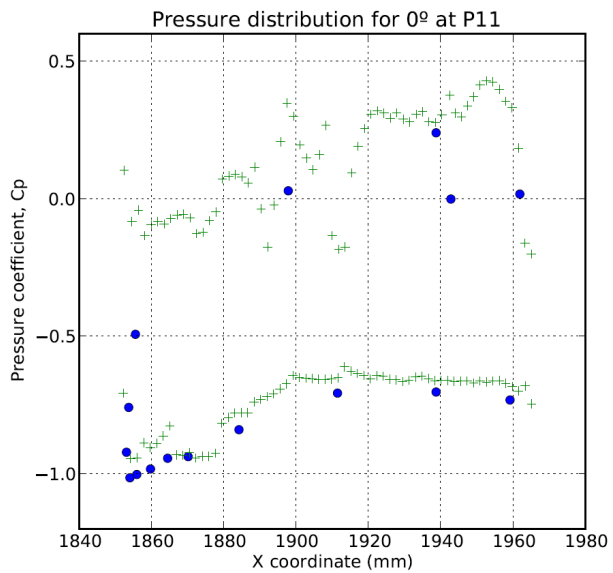


2nd HiLiftPW: Case 2 (Re=1.35e6)

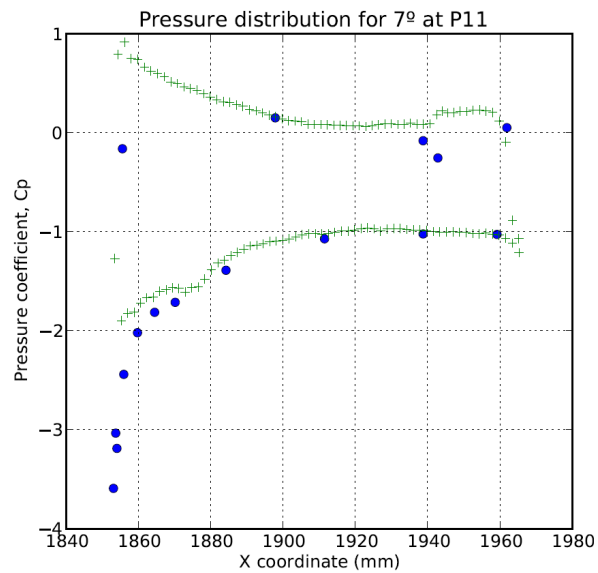


Low Reynolds number – Cp distribution - Main wing element @ P11

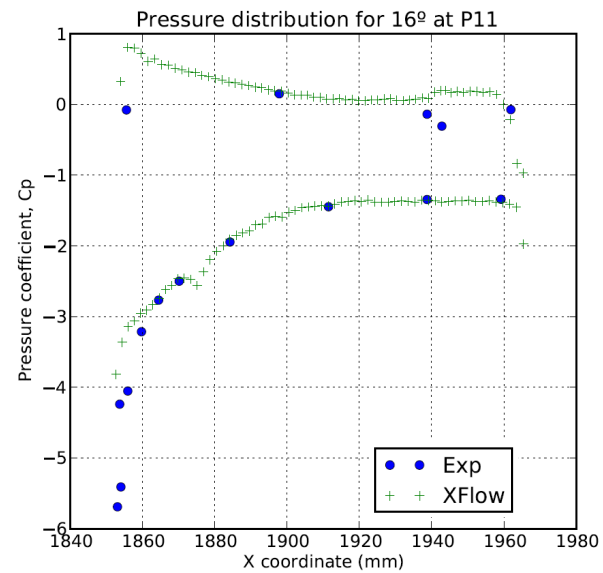
α = 0º



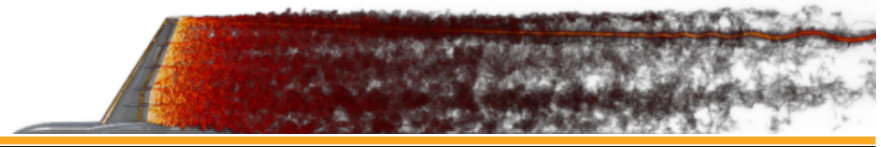
α = 7º

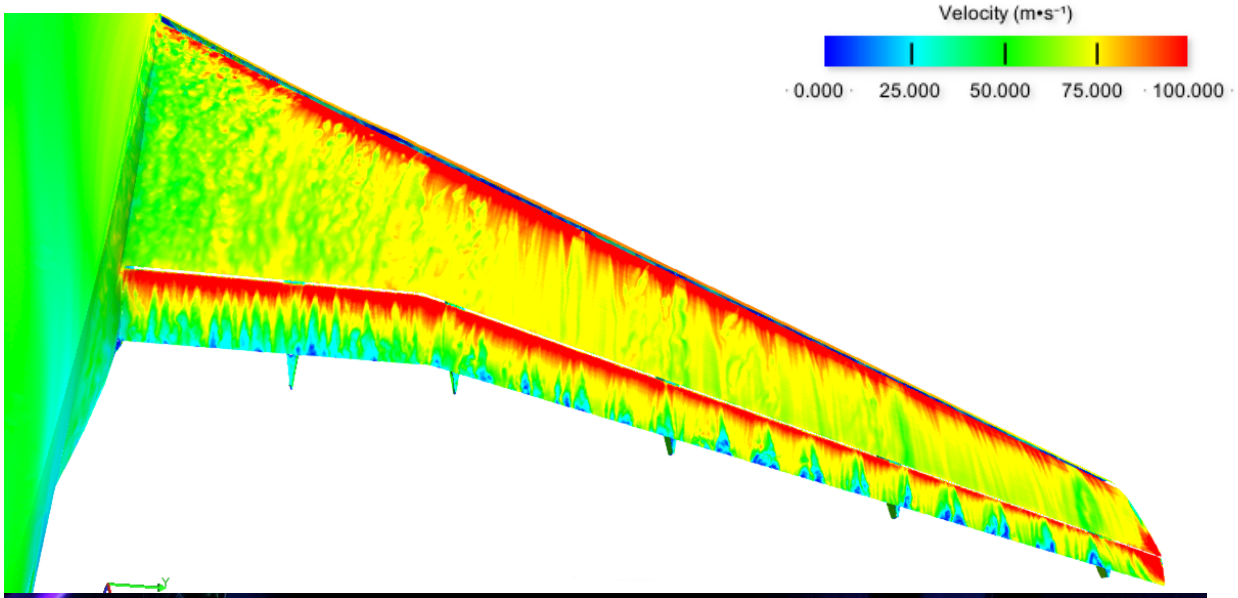


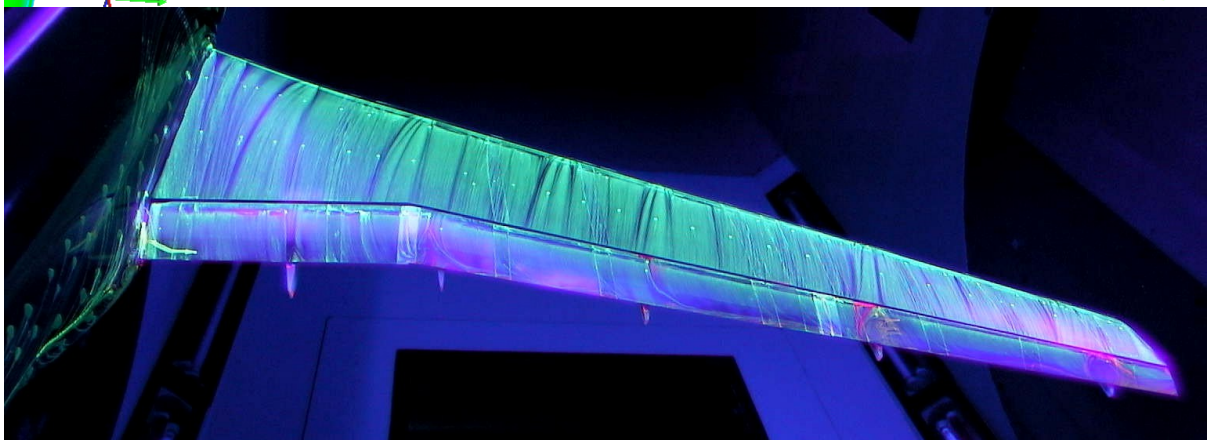
α = 16º



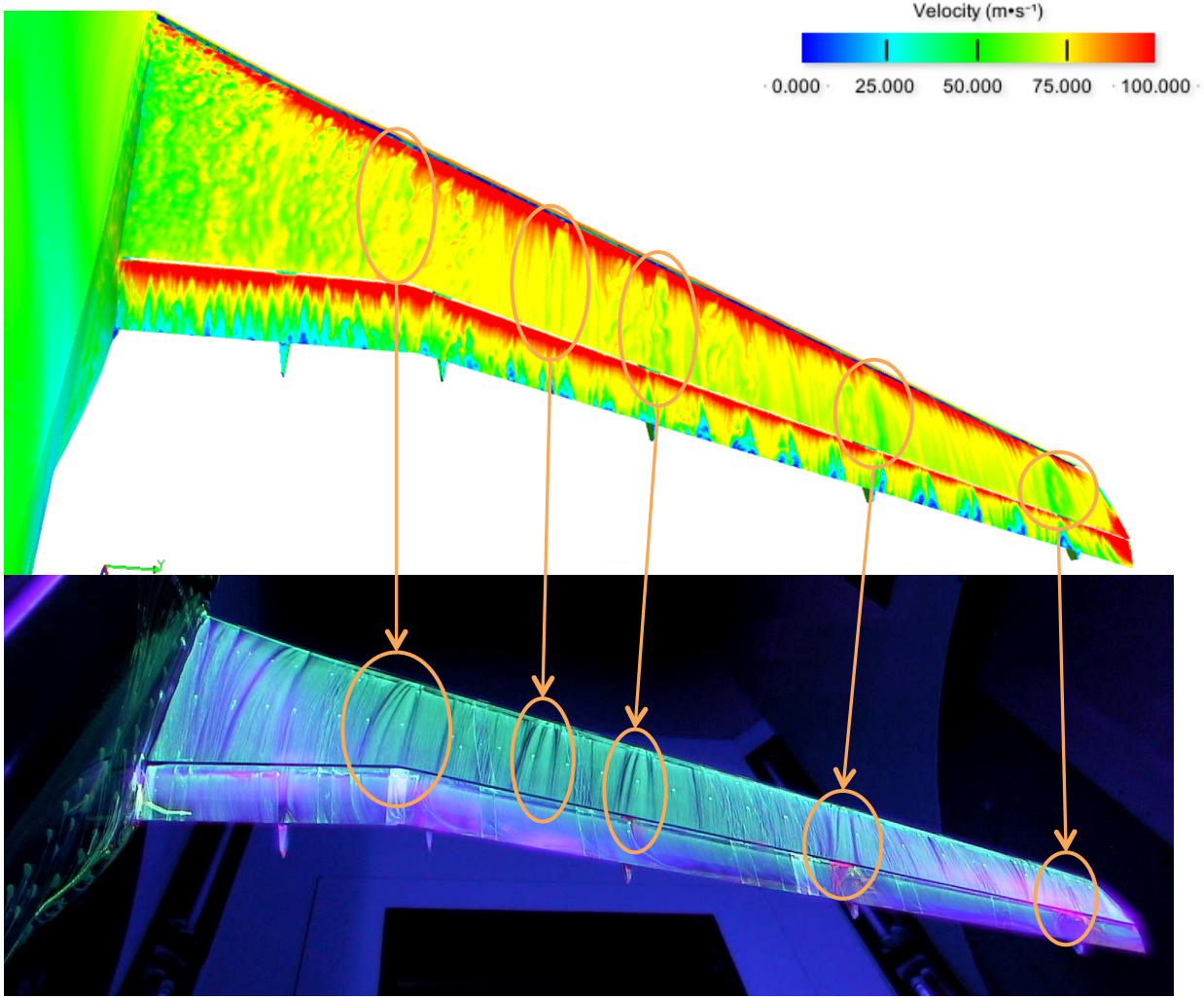
2nd HiLiftPW: Case 2 (Re=1.35e6)



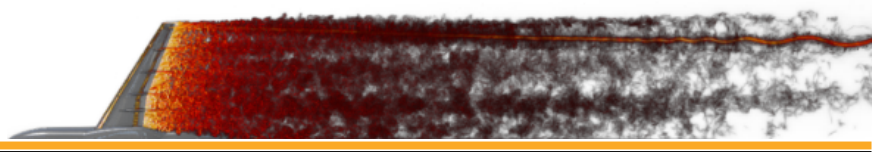




2nd HiLiftPW: Case 2 (Re=1.35e6)



Outline



- Motivation
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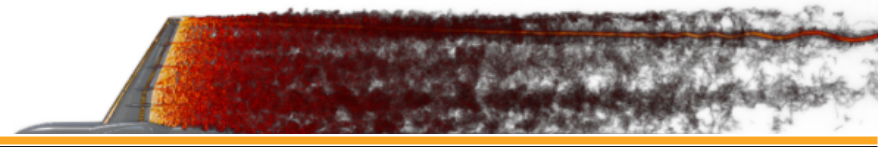
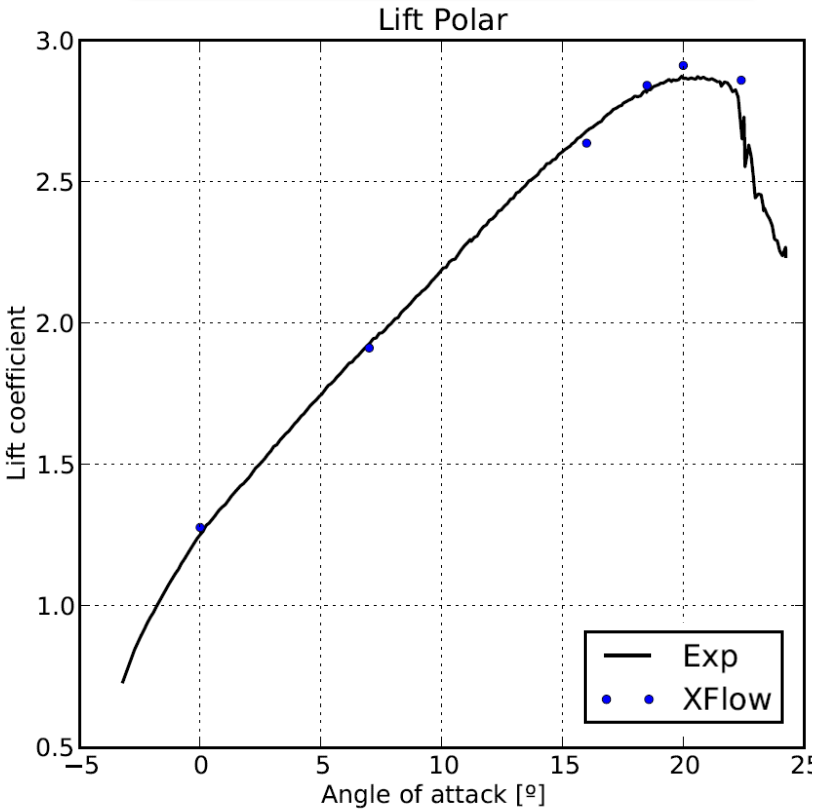
2nd HiLiftPW: Case 2 (Re=15.1 e6)

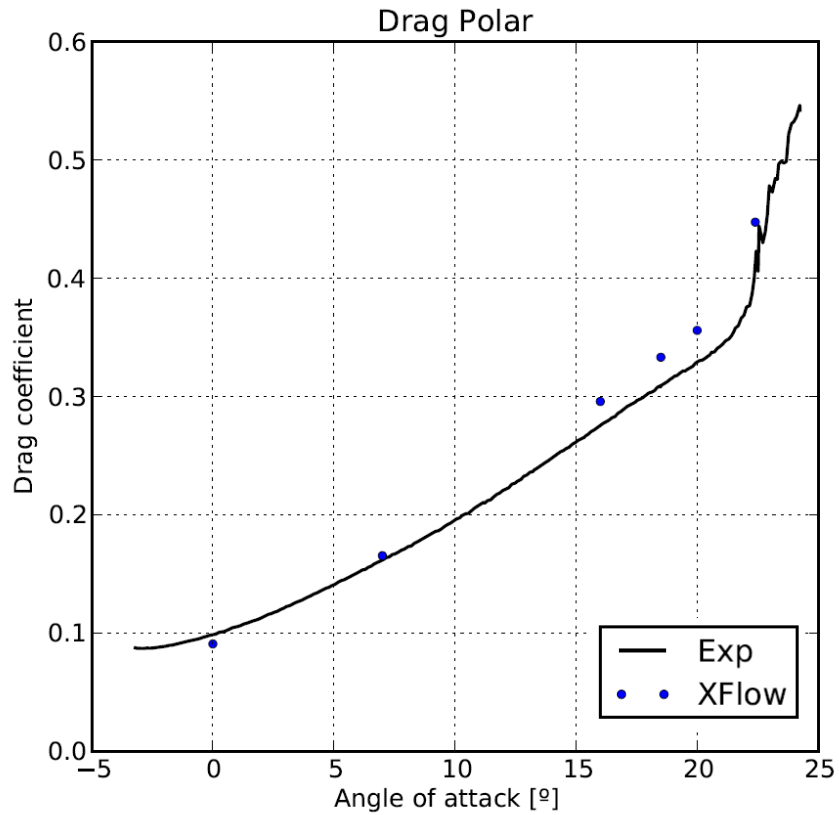


High Reynolds number condition – Lift and Drag curves

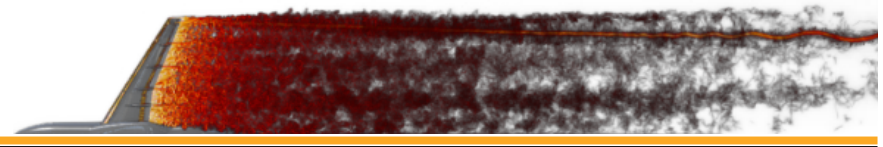
LIFT



DRAG

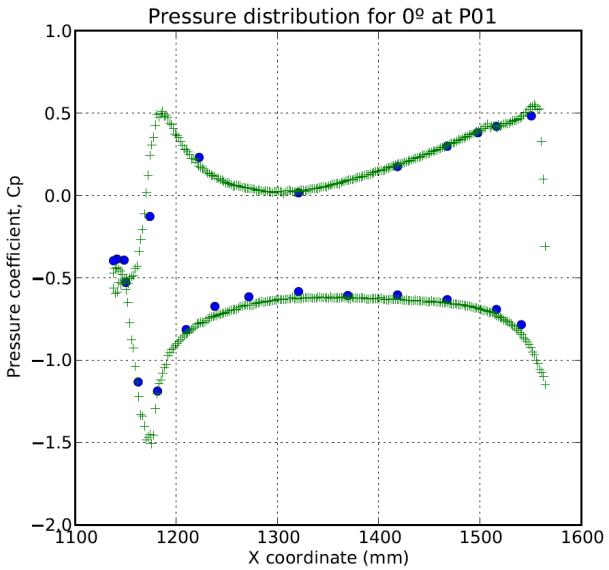


2nd HiLiftPW: Case 2 (Re=15.1 e6)

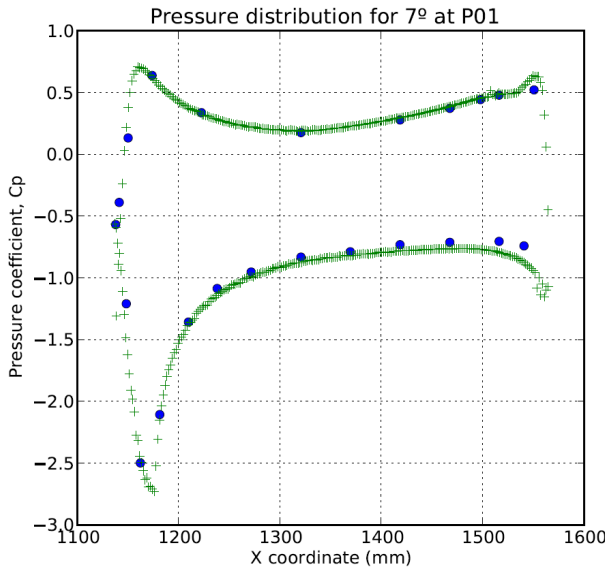


High Reynolds number – Cp distribution - Main wing element @ P01

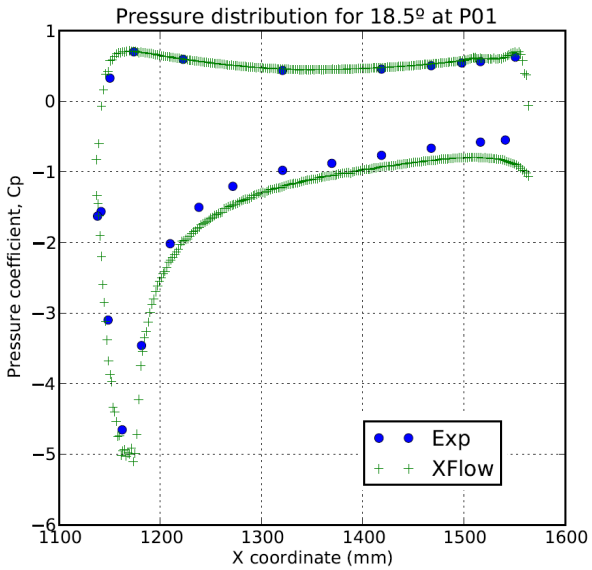
α = 0º



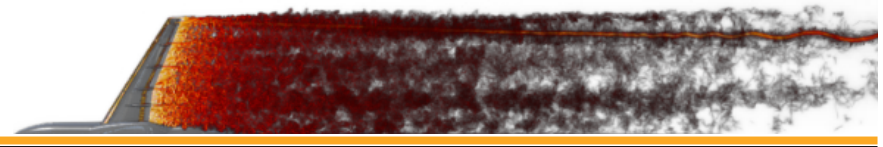
α = 7º



α = 18.5º

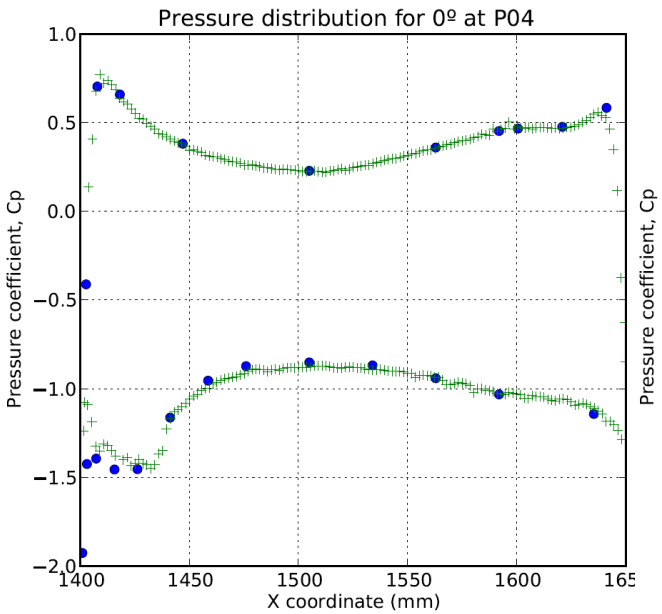


2nd HiLiftPW: Case 2 (Re=15.1 e6)

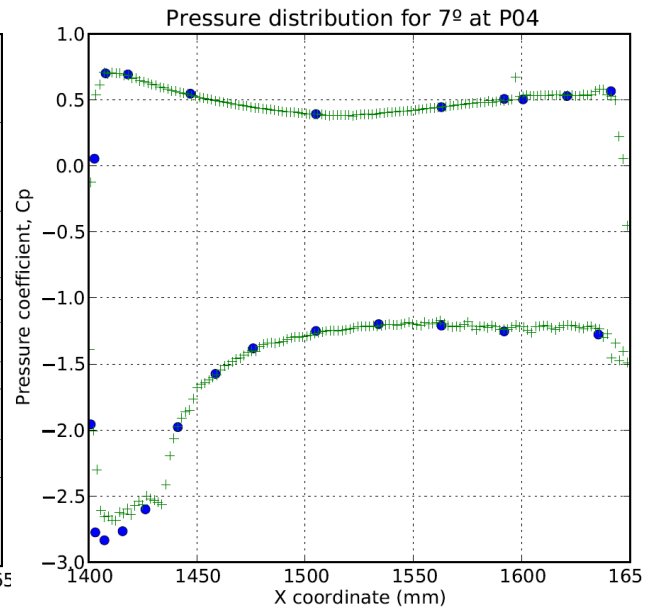


High Reynolds number – Cp distribution - Main wing element @ P04

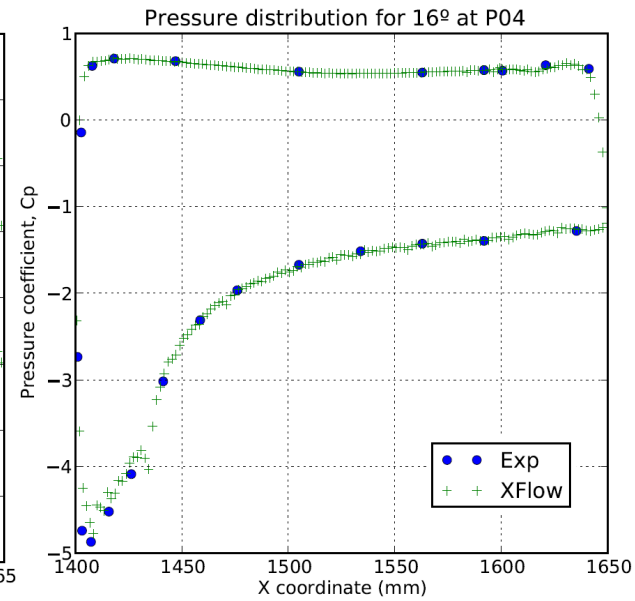
α = 0º



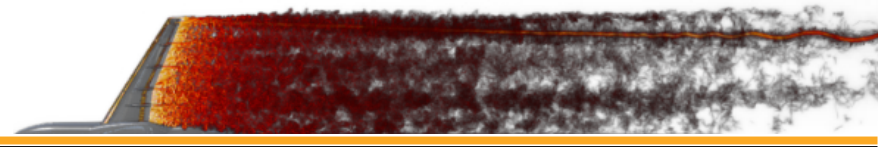
α = 7º



α = 16º

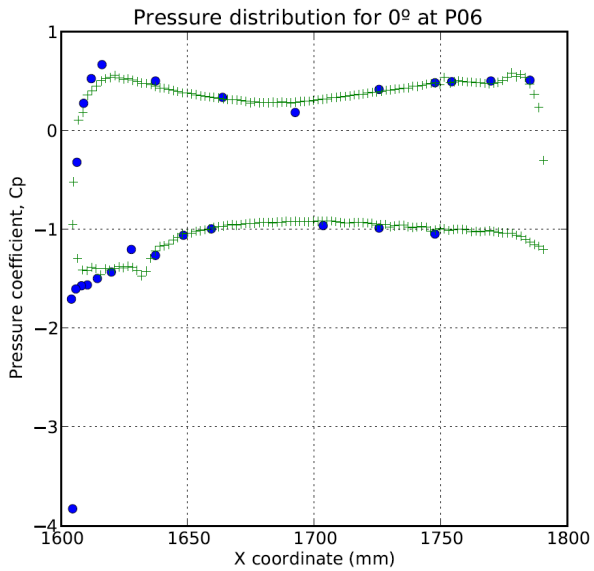


2nd HiLiftPW: Case 2 (Re=15.1 e6)

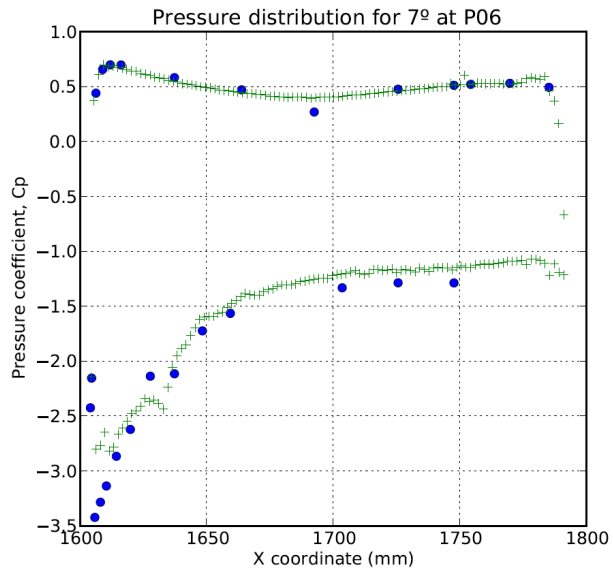


High Reynolds number – Cp distribution - Main wing element @ P06

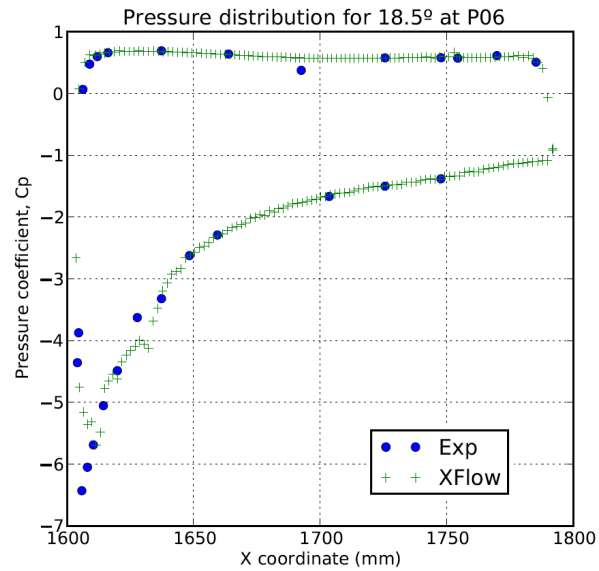
α = 0º



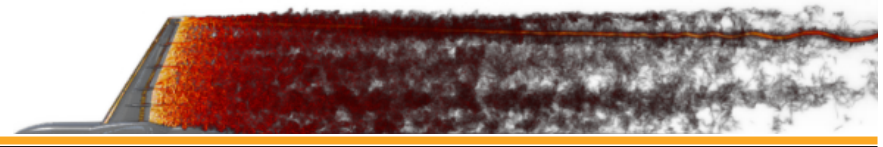
α = 7º



α = 18.5º

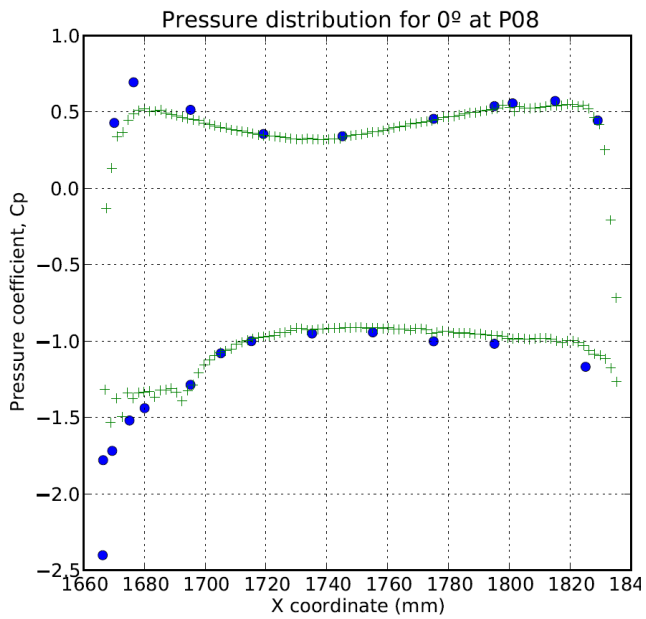


2nd HiLiftPW: Case 2 (Re=15.1 e6)



High Reynolds number – Cp distribution - Main wing element @ P08

α = 0º



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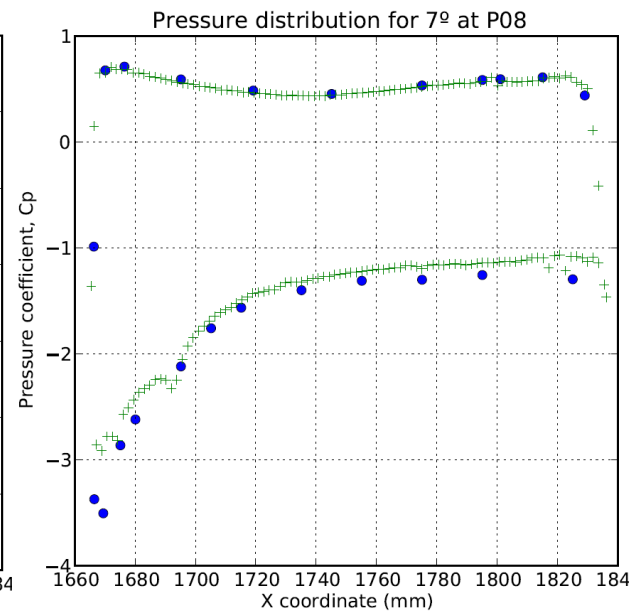

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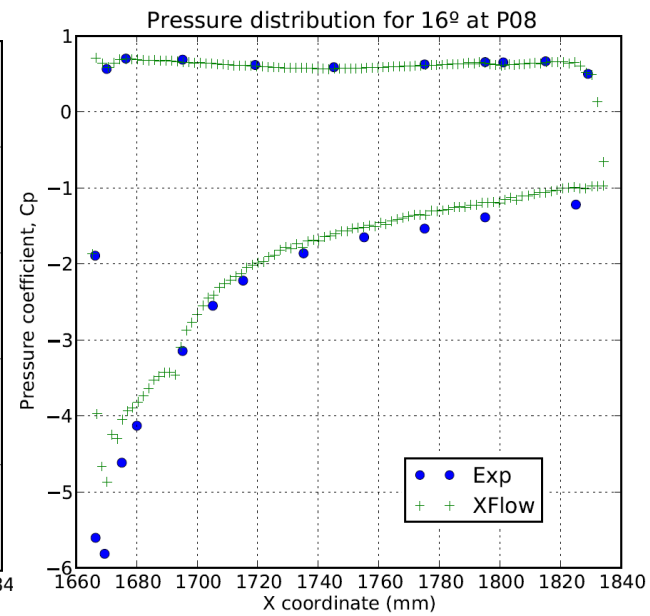
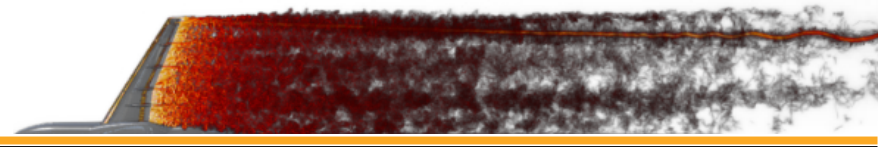
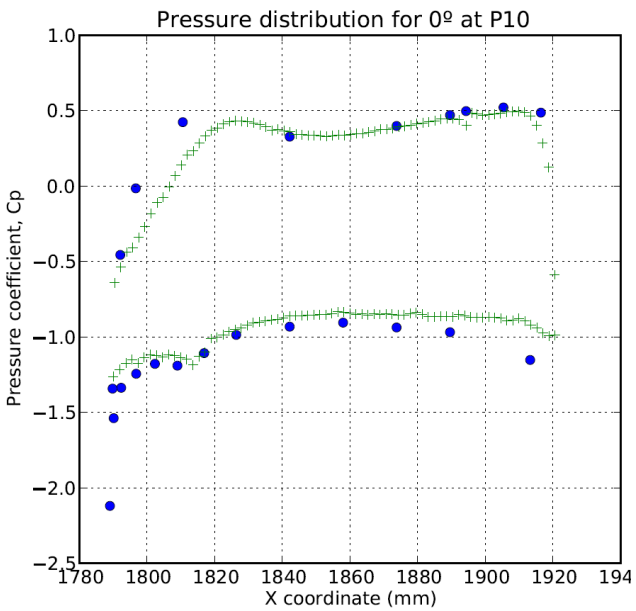


2nd HiLiftPW: Case 2 (Re=15.1 e6)



High Reynolds number – Cp distribution - Main wing element @ P10

α = 0º



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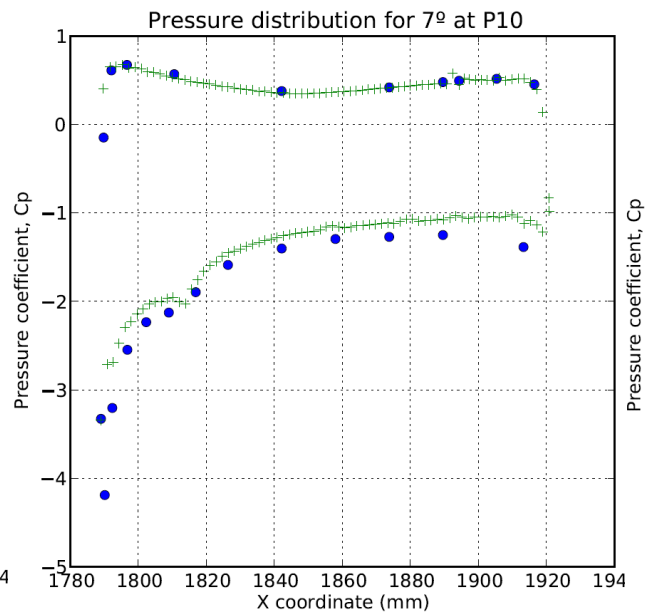
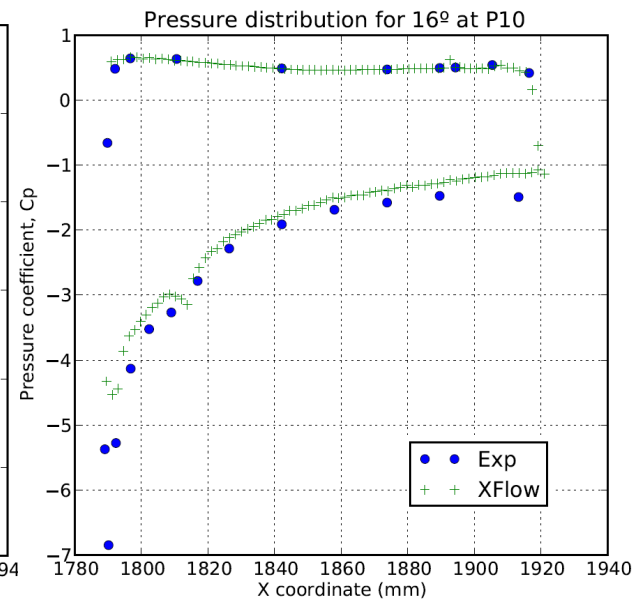
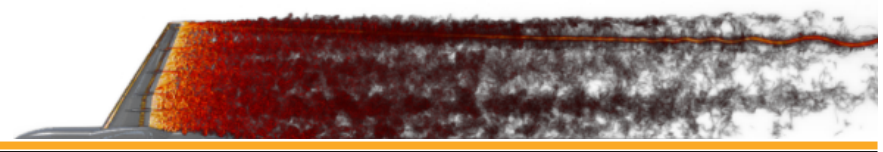


α = 16º

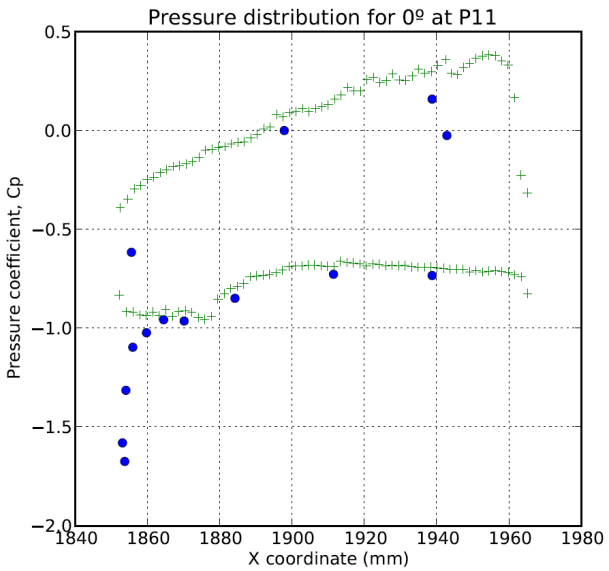


2nd HiLiftPW: Case 2 (Re=15.1 e6)

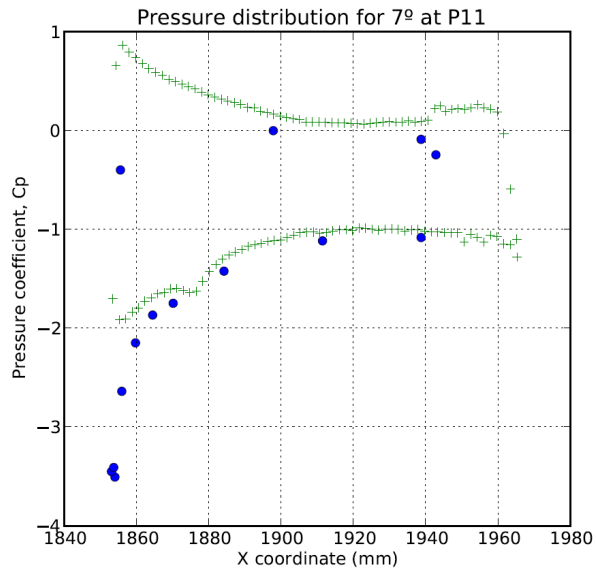


High Reynolds number – Cp distribution - Main wing element @ P11

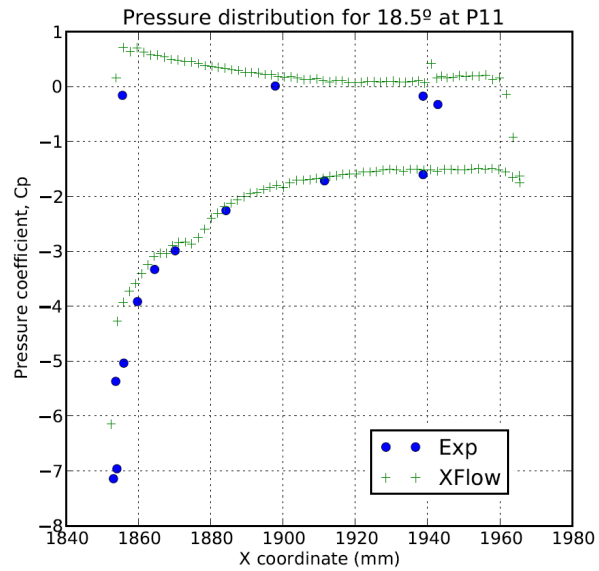
α = 0º



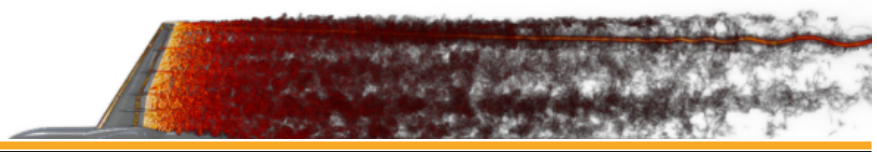
α = 7º



α = 18.5º

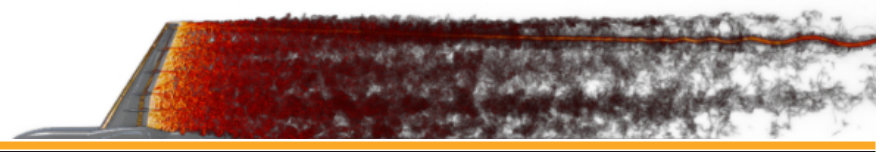


Outline

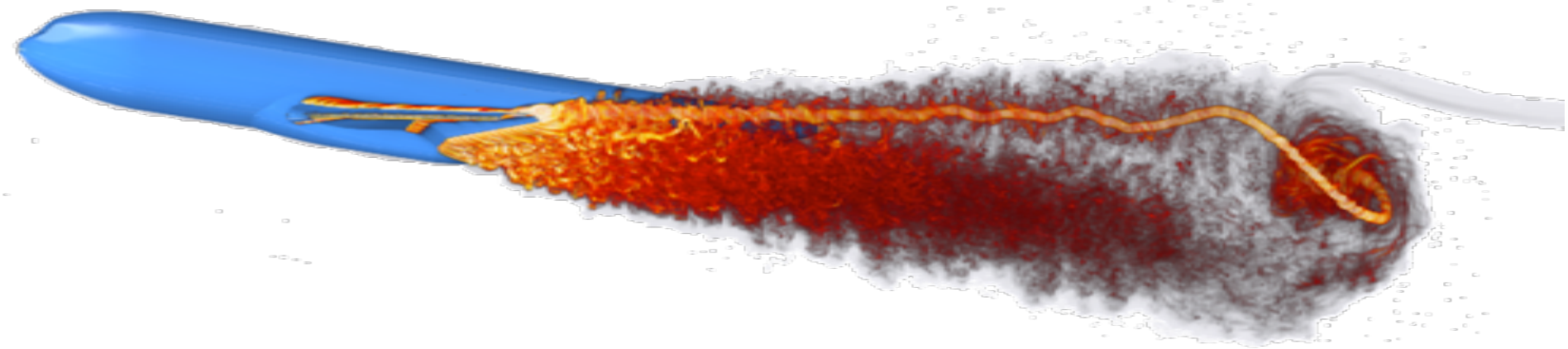


- Motivation
- XFlow CFD code
  - Numerical approach
  - Relevant sample cases
- 2nd HiLiftPW results
  - Case 1: Convergence analysis
  - Case 2a: Low Reynolds number condition
  - Case 2b: High Reynolds number condition
- **Conclusions – Future work**

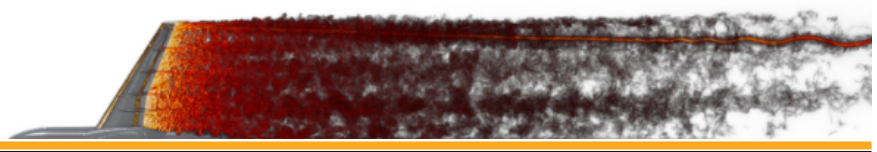
Conclusions



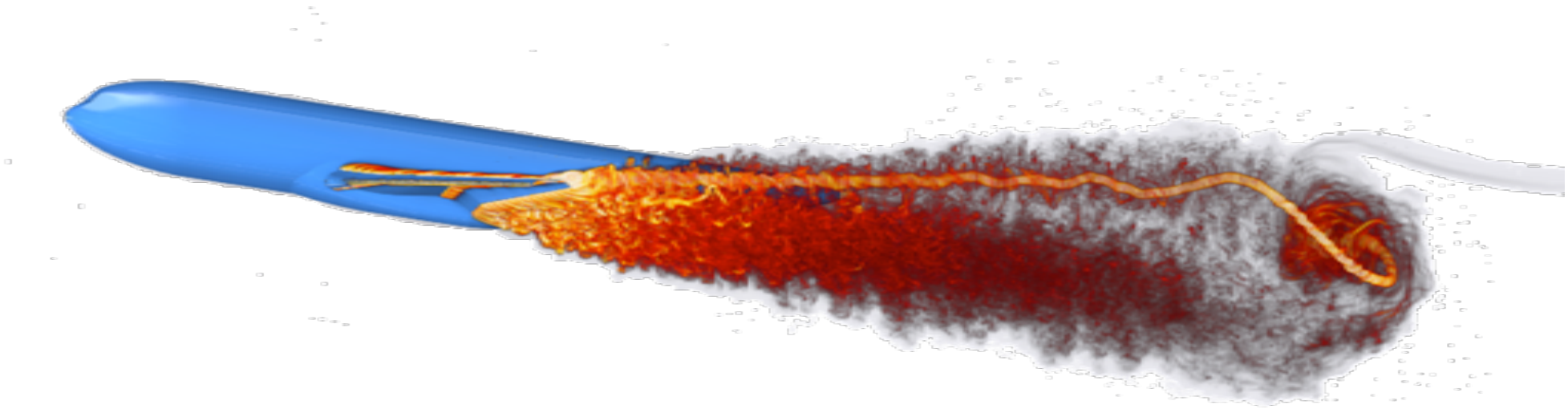
- **Complex unsteady aerodynamics** simulations are conducted with **XFlow** in a **straightforward** way for different aircraft geometries, showing a **good level of correlation** with wind-tunnel data
- Results for the **HiLiftPW-2** are in **good agreement** with experimental data
- The **CFD setup** is **short and easy** being the technology applicable even at early design stage



Future work



- Case 3 analysis
- Comparison against PIV data
- **AIAA Summer 2014 HiLiftPW-2 Special Sessions Paper**



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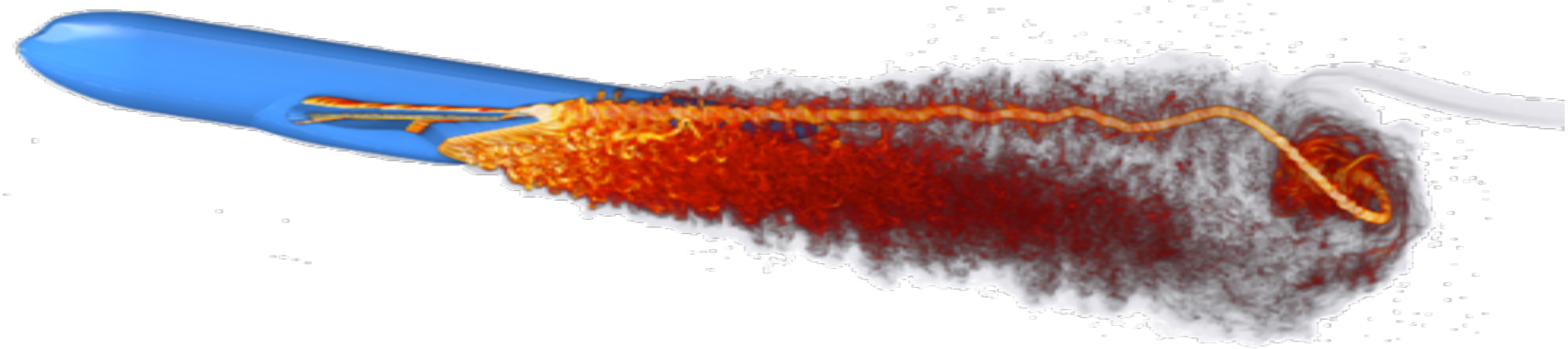

Thank you for your attention!

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