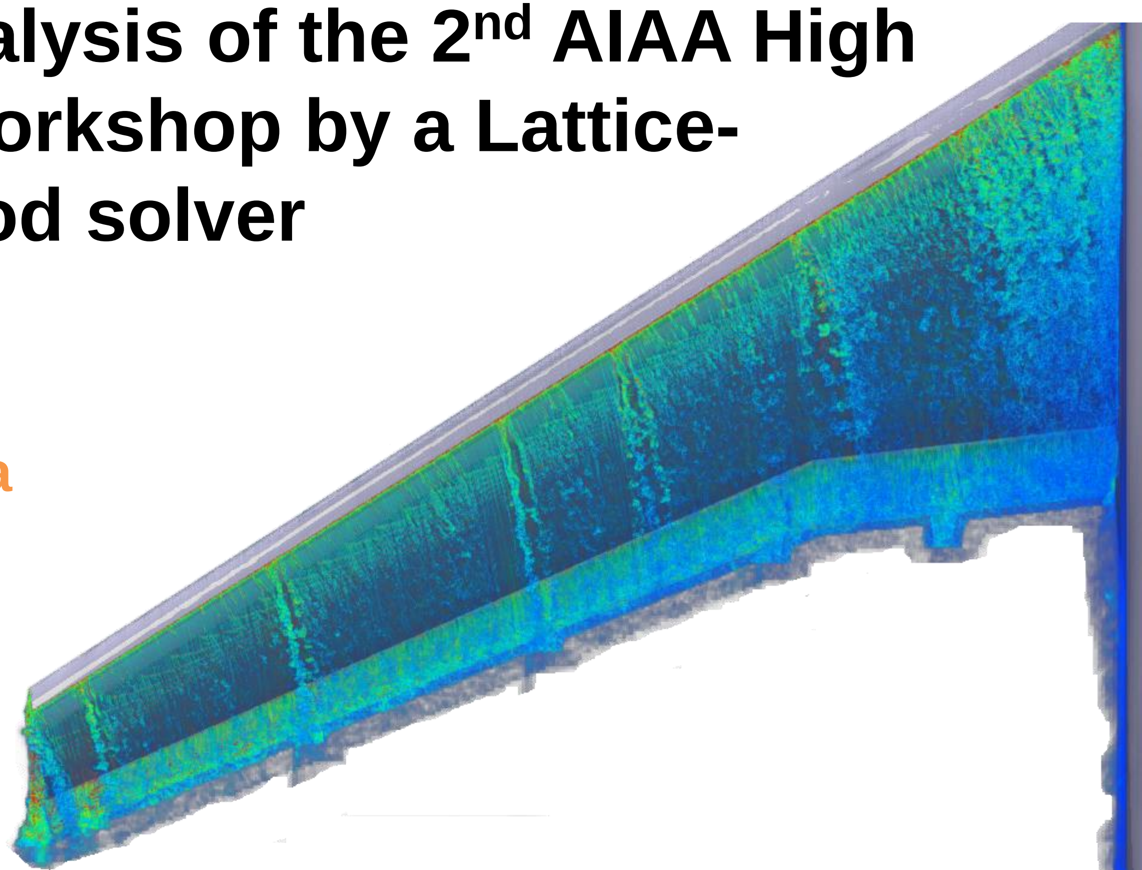
Aerodynamic analysis of the 2nd AIAA High Lift Prediction Workshop by a Lattice-Boltzmann Method solver

Ruddy Brionnaud
David M. Holman
Miguel Chavez Modena



18th June 2014

Outline

- XFlow CFD code
  - Numerical approach
  - Turbulence modelling
  - Spatial discretization
- 2nd HiLiftPW results
  - Simulations setup
  - Case 1: Convergence analysis
  - Case 3a: Low Reynolds number condition
  - Case 3b: High Reynolds number condition
  - Configurations comparison
- Conclusions

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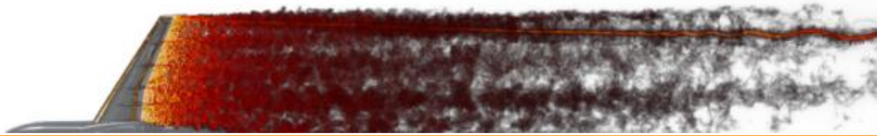

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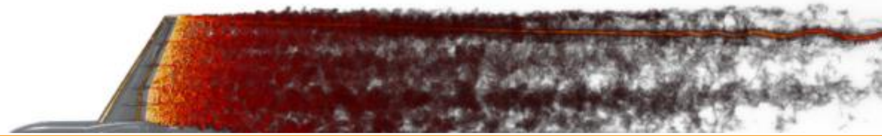
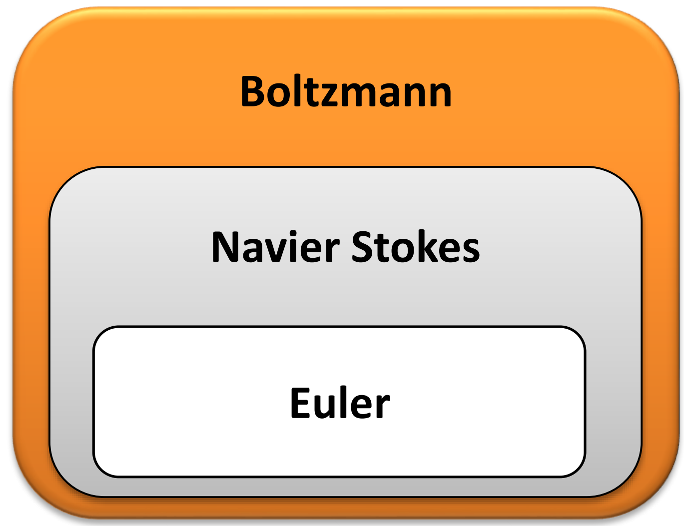


Numerical approach

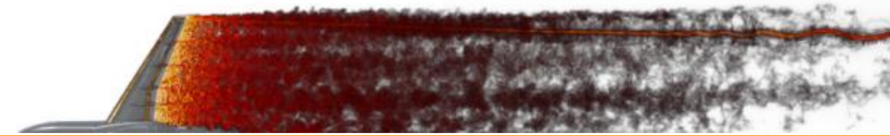
- **Lattice Boltzmann Method (LBM)**

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

$$\underbrace{\frac{Df}{Dt}}_{\text{Streaming}} = \underbrace{\Omega}_{\text{Collision}}$$



Reference: Nourgaliev, R.R., Dinh, T.N., Theofanous, T.G., and Joseph, D., "The lattice Boltzmann equation method: theoritical interpretation, numerics and implications," *International Journal of Multiphase Flow*, 29, 2003, 117-169



Numerical approach

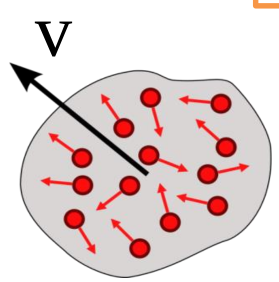
- **Lattice Boltzmann Method (LBM)**

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

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

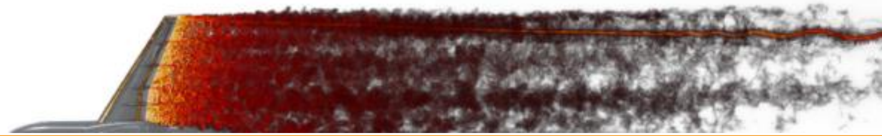
Probability Distribution Function (PDF)

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



f describes the distribution of particles that goes in directions *v*

Reference: Nourgaliev, R.R., Dinh, T.N., Theofanous, T.G., and Joseph, D., "The lattice Boltzmann equation method: theoritical interpretation, numerics and implications," *International Journal of Multiphase Flow*, 29, 2003, 117-169



Numerical approach

- **Lattice Boltzmann Method (LBM)**

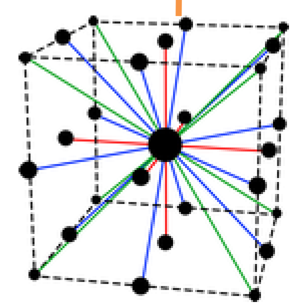
→ Particle-based Lagrangian discretization
→ Boltzmann transport equation
→ **Mesoscopic scale: macroscopic variables**

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

Statistical moments of PDFs

Order 0	Density	$\rho = \int f \, dv$
Order 1	Linear momentum	$\rho u = \int f v \, dv$

27 velocity directions



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Numerical approach

- **Lattice Boltzmann Method (LBM)**

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

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

Collision operator

Redistributes particles that arrive at the same time and position

Reference: Geier, M., Greiner, A., and Korvink, J., “A factorized central moment lattice Boltzmann method," *The European Physical Journal Special Topics*, Vol. 171, No. 1, 2009, pp. 55-61.

Numerical approach

- **Lattice Boltzmann Method (LBM)**

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

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

→ **Collision operator**

Redistributes particles that arrive at the same time and position

Unique XFlow collision operator in **central moments space**

→

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

Reference: Geier, M., Greiner, A., and Korvink, J., "A factorized central moment lattice Boltzmann method," *The European Physical Journal Special Topics*, Vol. 171, No. 1, 2009, pp. 55-61.

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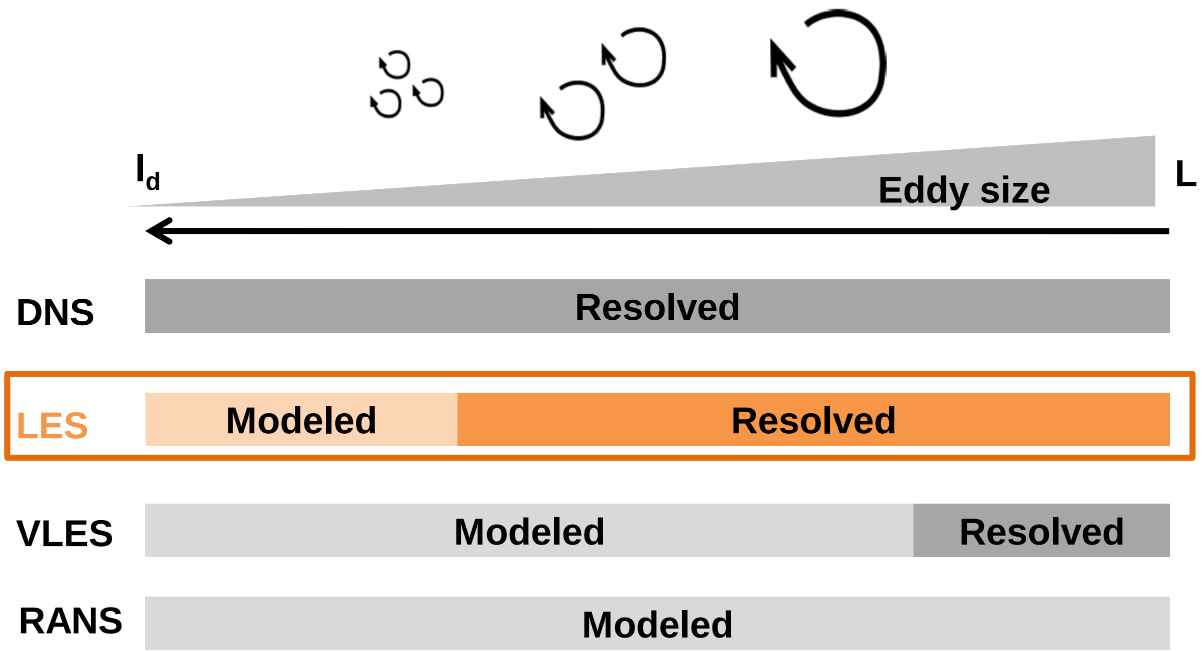
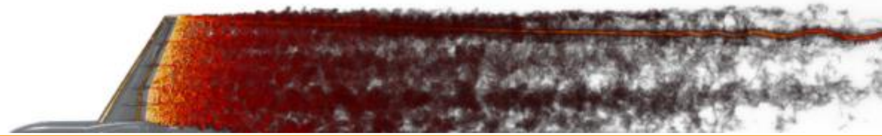
Turbulence modeling

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





Turbulence modeling

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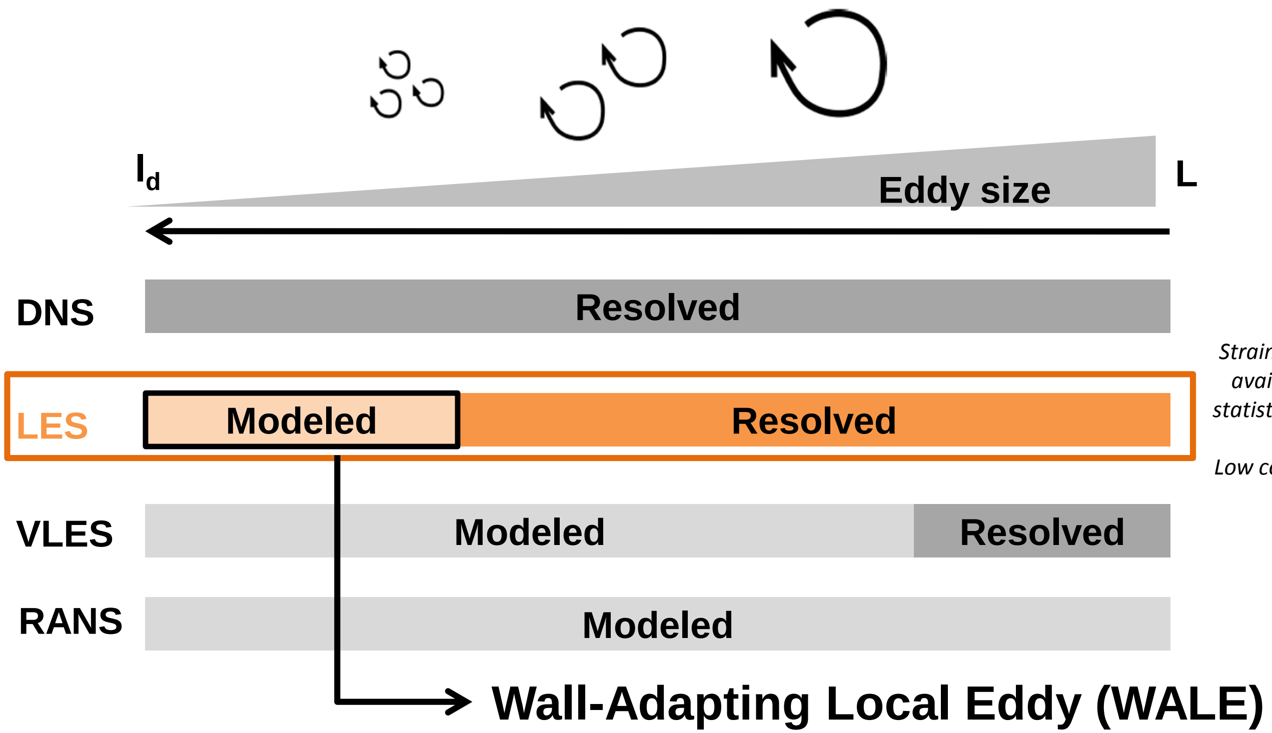


Strain rate tensor locally available as 2nd order statistical moment of PDF
=
Low computation cost for LBM!

Reference: Ducros, F., Nicoud, F. and Poinsot, T., "Wall-adapting local Eddy viscosity models for simulations in complex geometries," *Proceedings of 6th ICFD Conference on Numerical Methods for Fluid Dynamics*, 1998, pp. 293-299

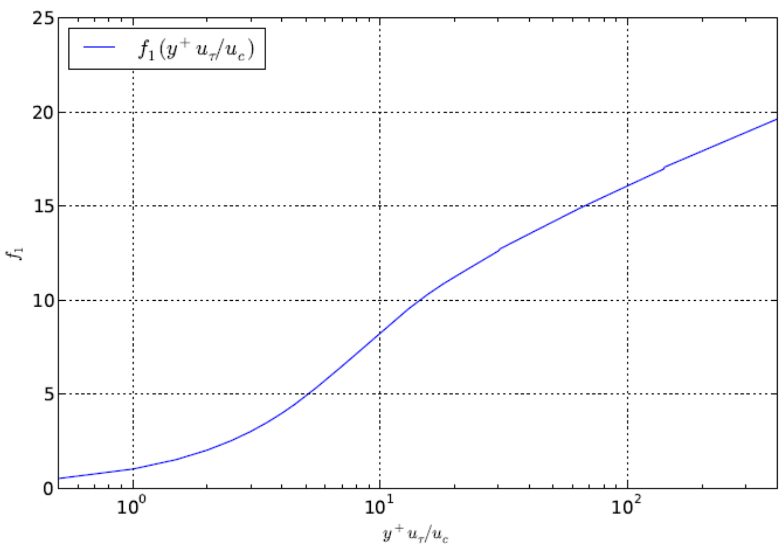
Turbulence modeling

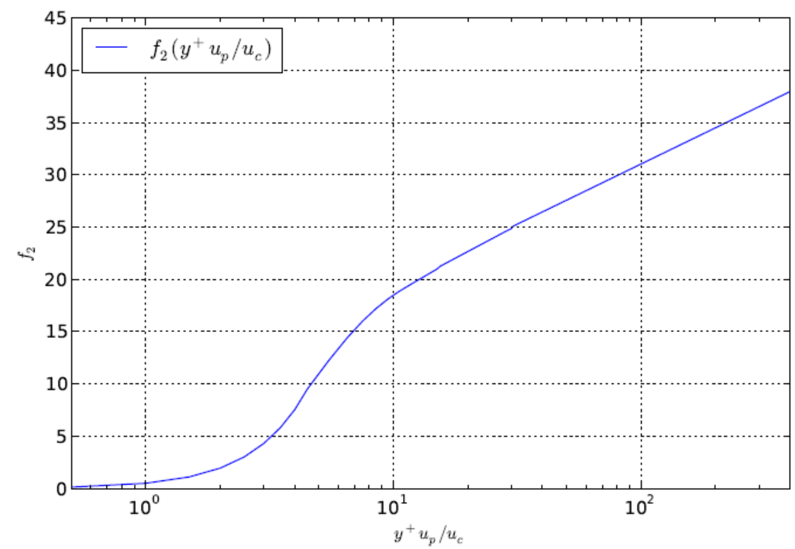
- Generalized law of the wall

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

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

$$\begin{aligned} y^+ &= \frac{u_c y}{\nu} \\ u_c &= u_\tau + u_p \\ u_\tau &= \sqrt{|\tau_w|/\rho} \\ u_p &= \left(\frac{\nu}{\rho}\left|\frac{\mathrm{d}p_w}{\mathrm{d}x}\right|\right)^{1/3}. \end{aligned}$$





Reference: Shih, T., Povinelli, L., Liu, N., Potapczuk, M., and Lumley, J., "A generalized wall function," *NASA Technical Report*, July 1999

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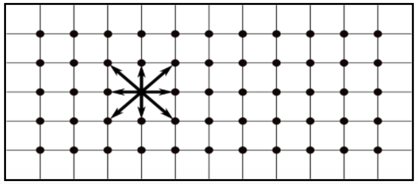
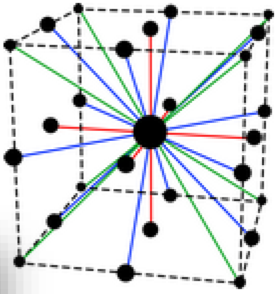
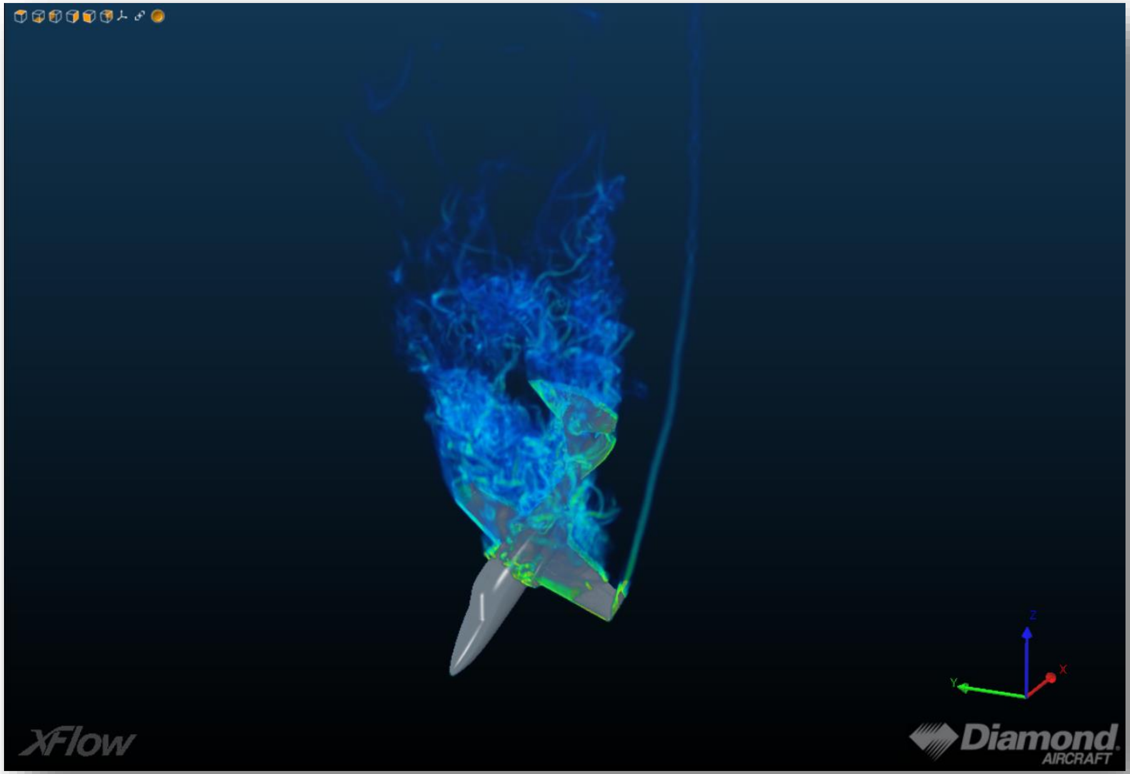
Spatial discretization

- **Lattice structure**
  1. **Complex Moving Boundaries**

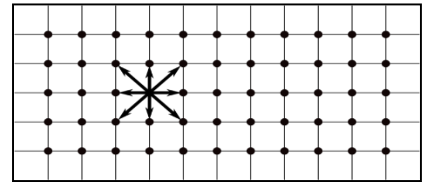


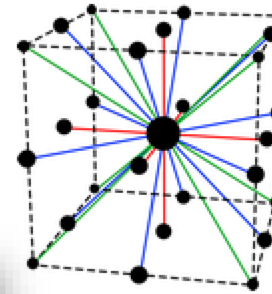


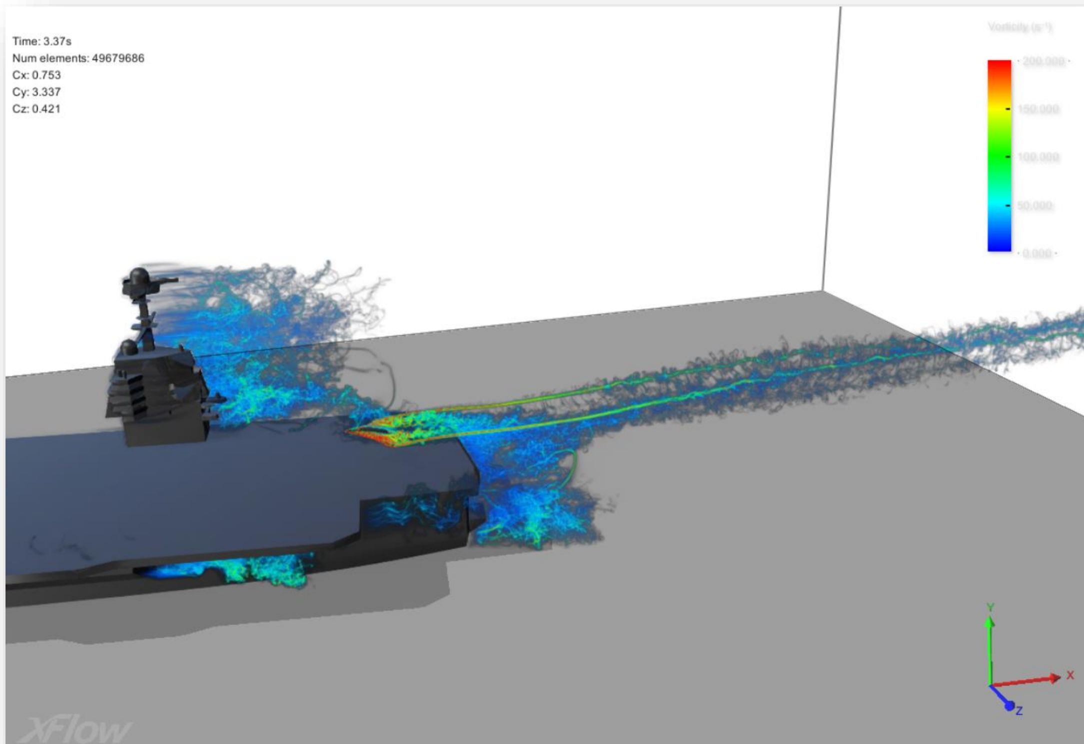


Spatial discretization

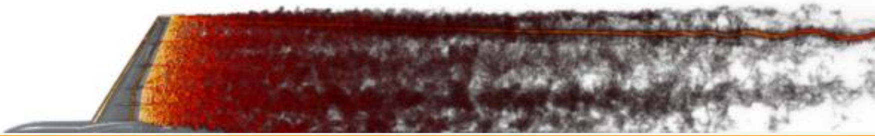
- **Lattice structure**
  1. **Complex Moving Boundaries**
  2. **Adaptative Refinement**







Outline



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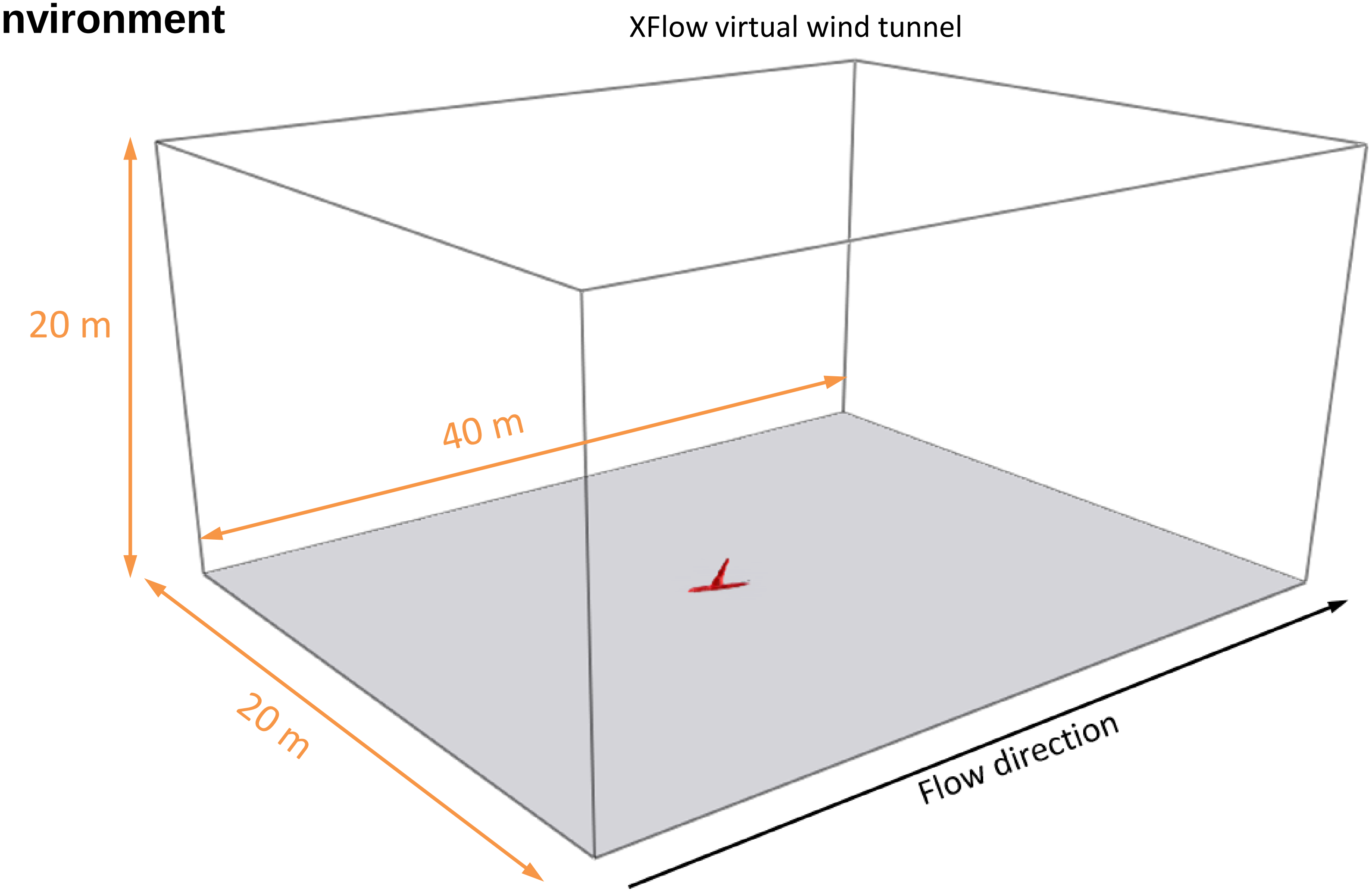
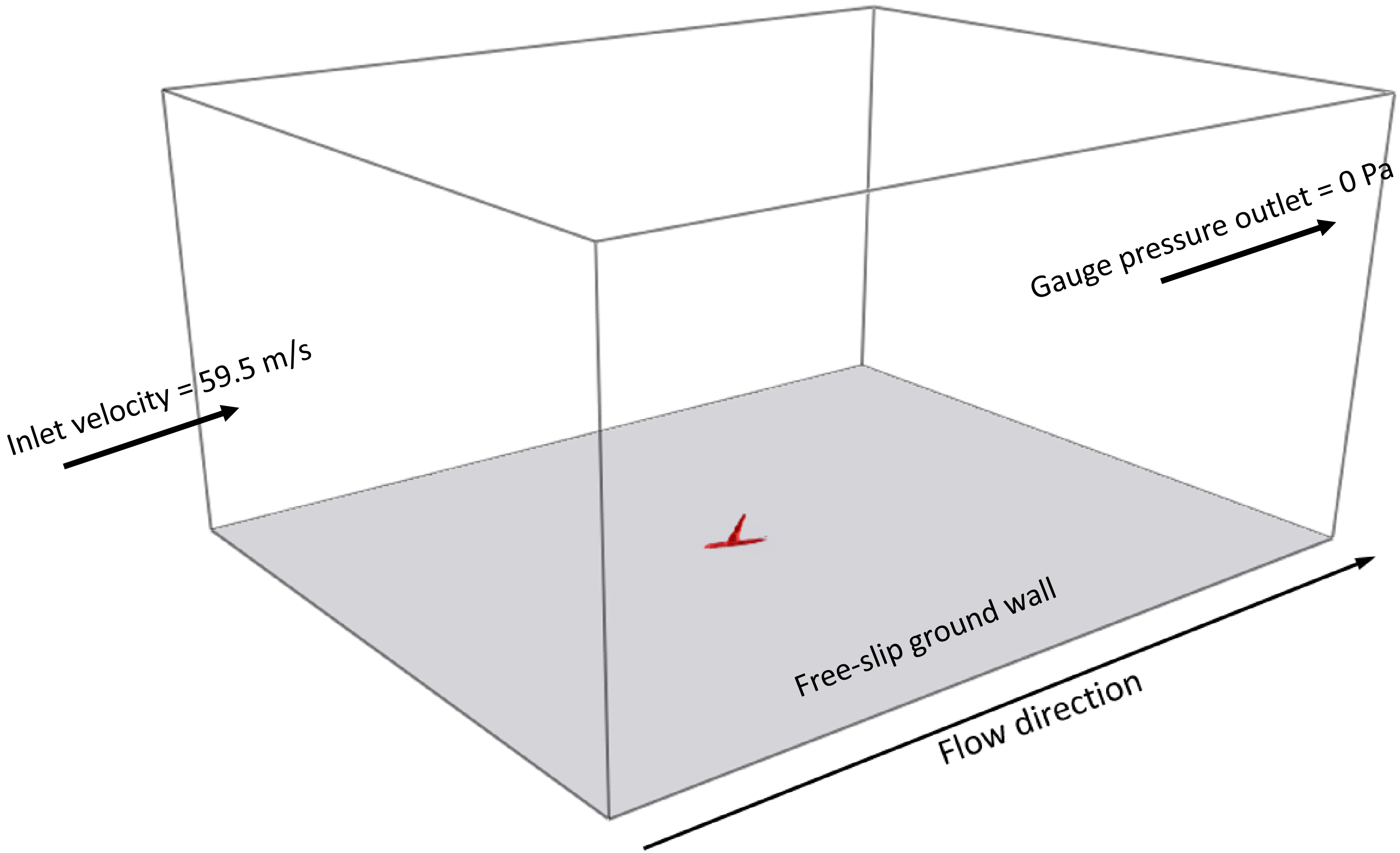
2nd HiLiftPW: Simulation setup

Environment

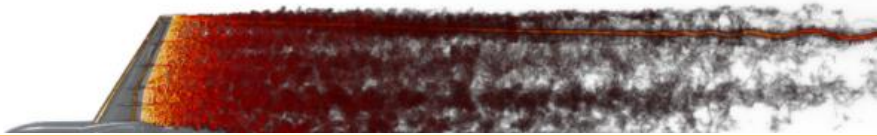


2nd HiLiftPW: Simulation setup

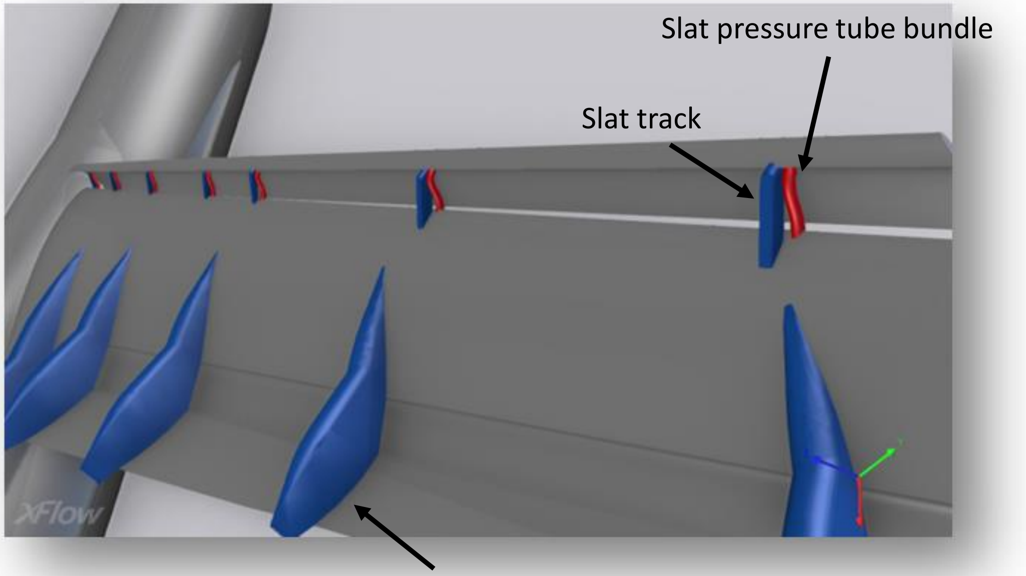
Boundary conditions



2nd HiLiftPW: Simulation setup



Configurations



Case 1: “Config. 2”

Case 3: “Config. 5”

2nd HiLiftPW: Simulation setup

HPC resources

Teide-HPC	CeSViMa
1052 nodes	44 nodes
Intel Xeon E5-2670 – 8 cores @2.60 GHz	2x Intel Xeon E5-2670 – 8 cores @2.60 GHz
32 GB DDR-3 RAM	64 GB DDR-3 RAM
Infiniband QDR 4x to 40Gb/s	Infiniband QDR 4x to 40Gb/s

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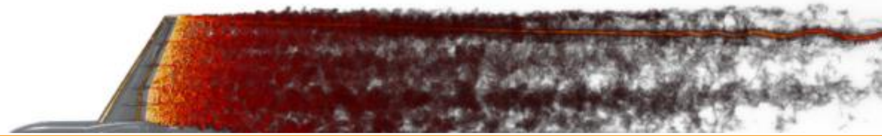
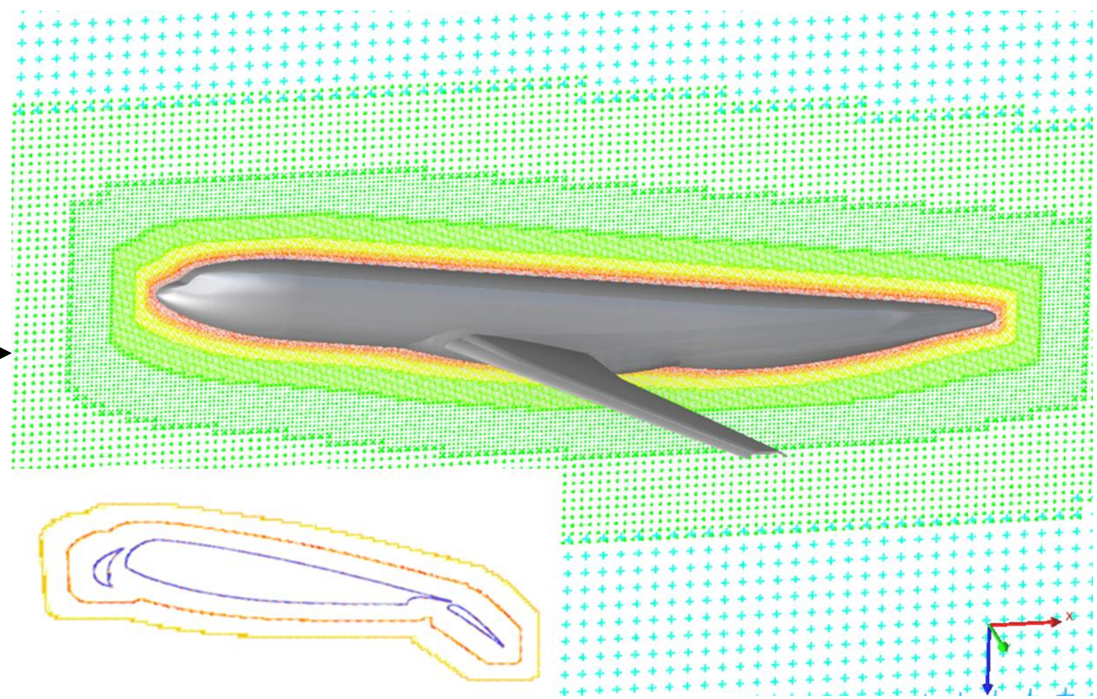


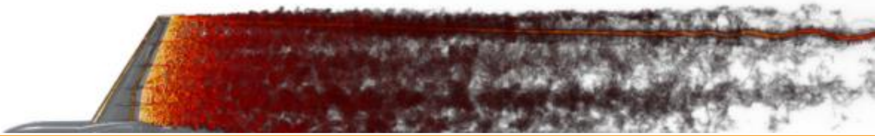
Global convergence

α = 16º

Lattice resolution	# Elements	Sim. time	Comp. time	Cores
Coarse = 4 mm	9,200,000	0.1 s	1 h	160
Medium = 2 mm	25,900,000	0.1 s	5.2 h	160
Fine = 1 mm	87,400,000	0.1 s	33.8 h	160

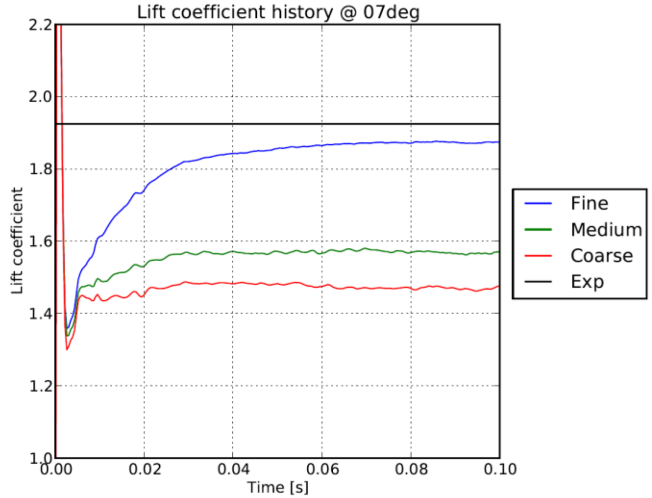


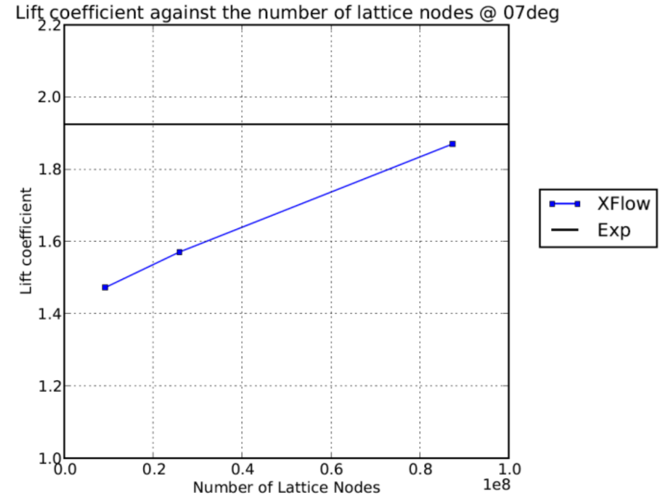
2nd HiLiftPW: Case 1



Global convergence

α = 7º





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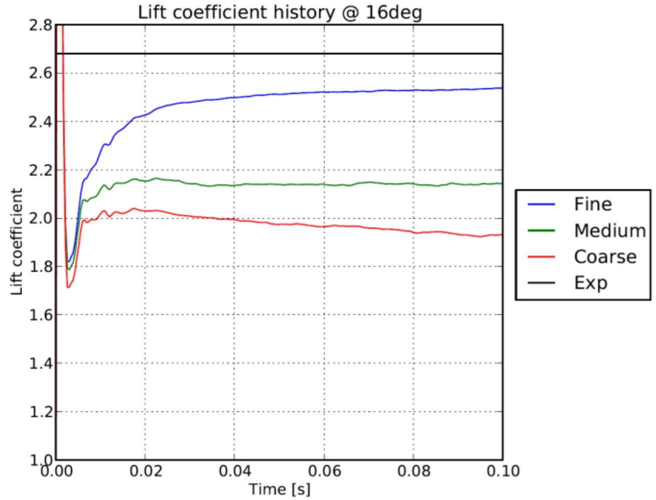
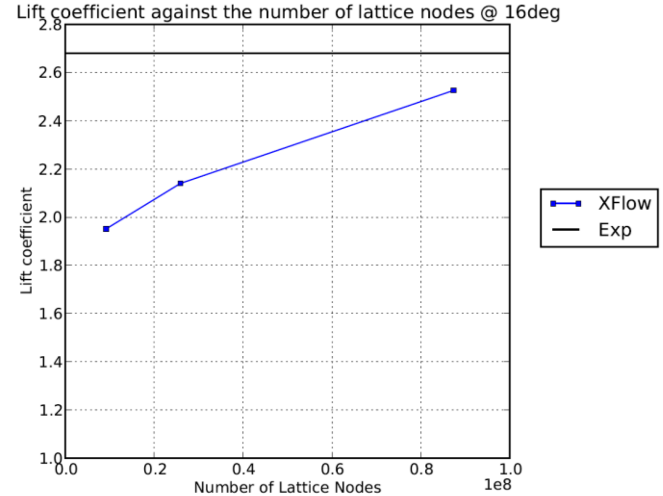
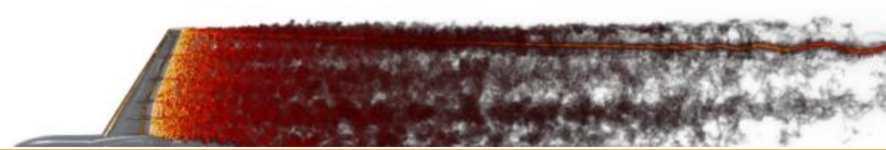




2nd HiLiftPW: Case 1



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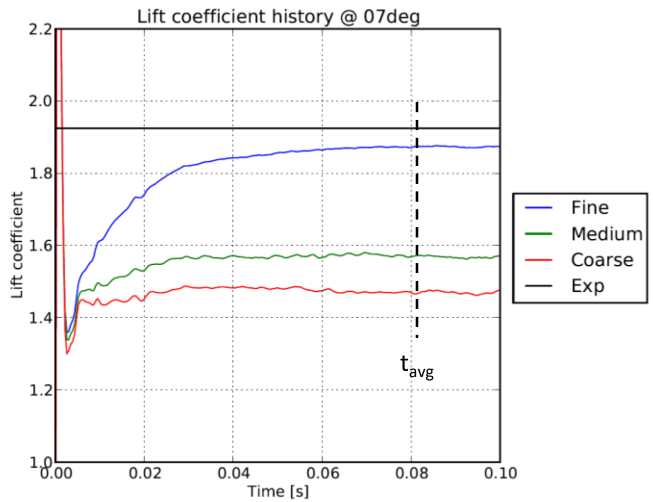

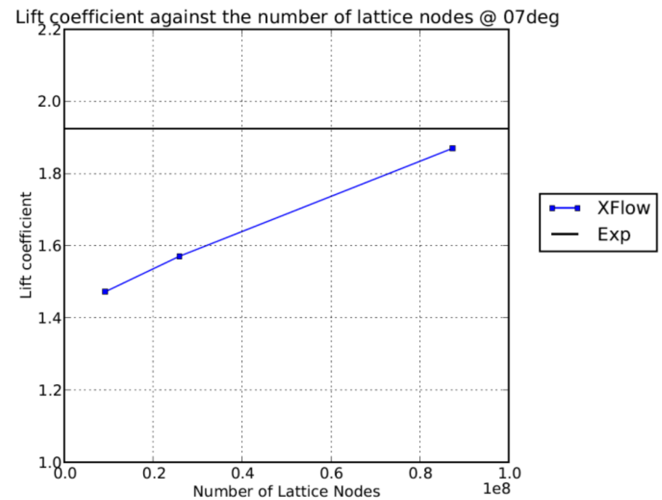

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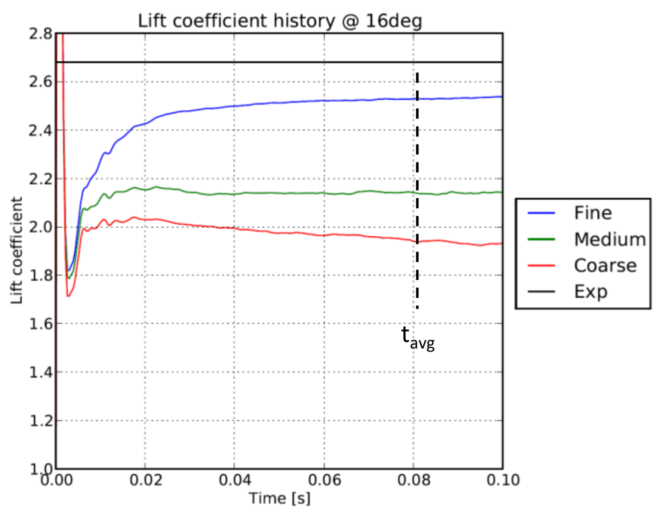

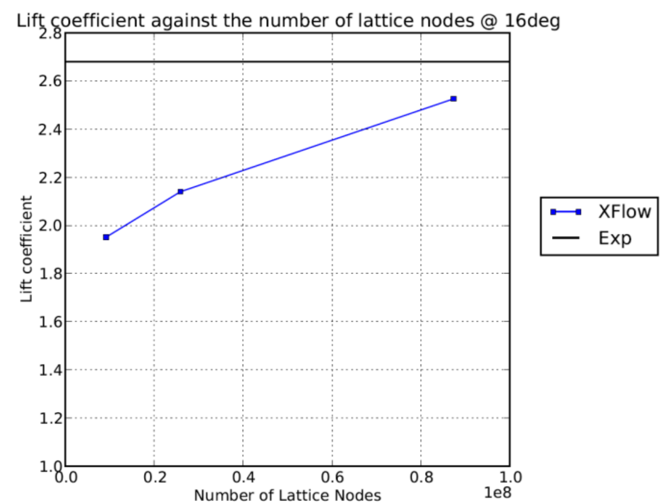

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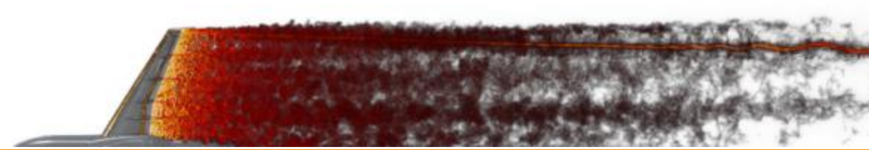

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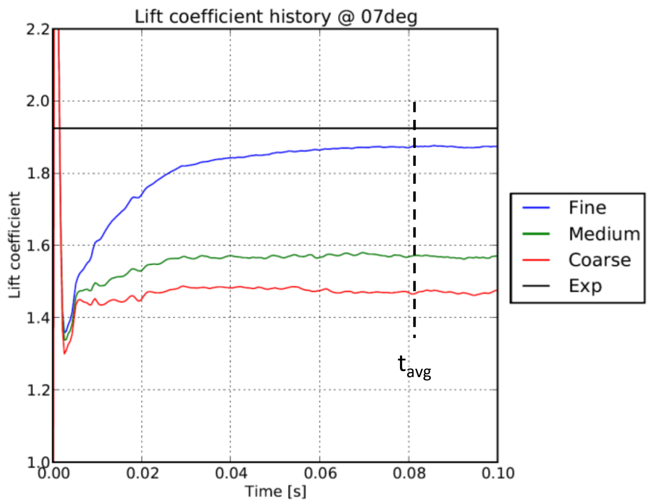

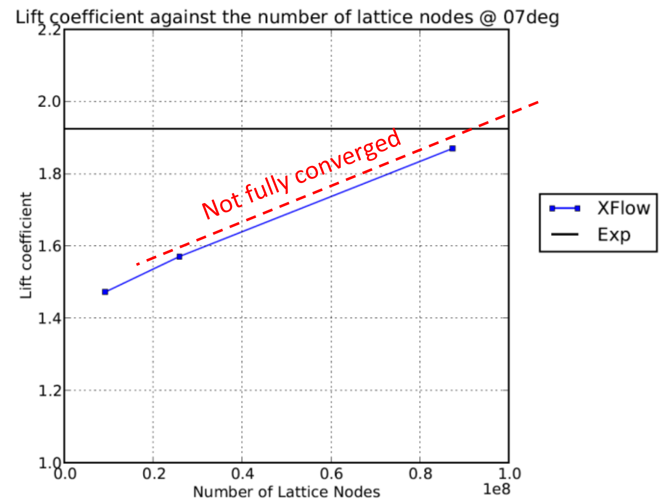

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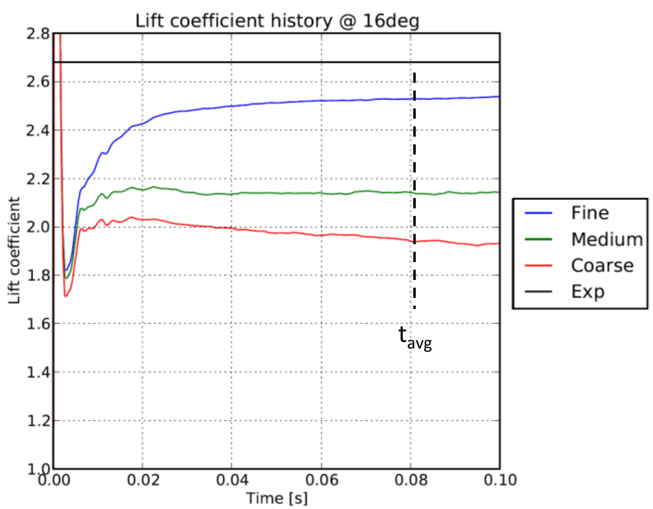
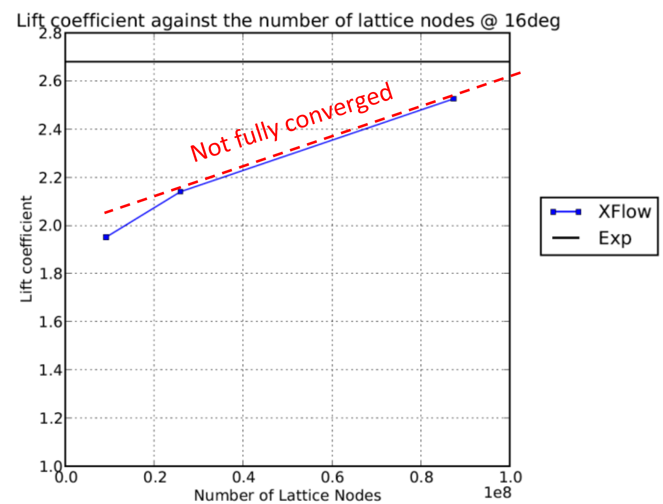


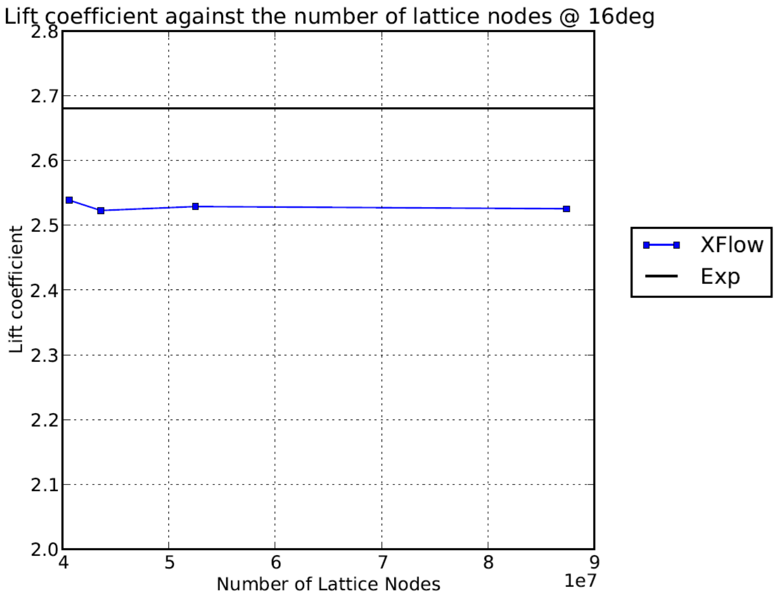


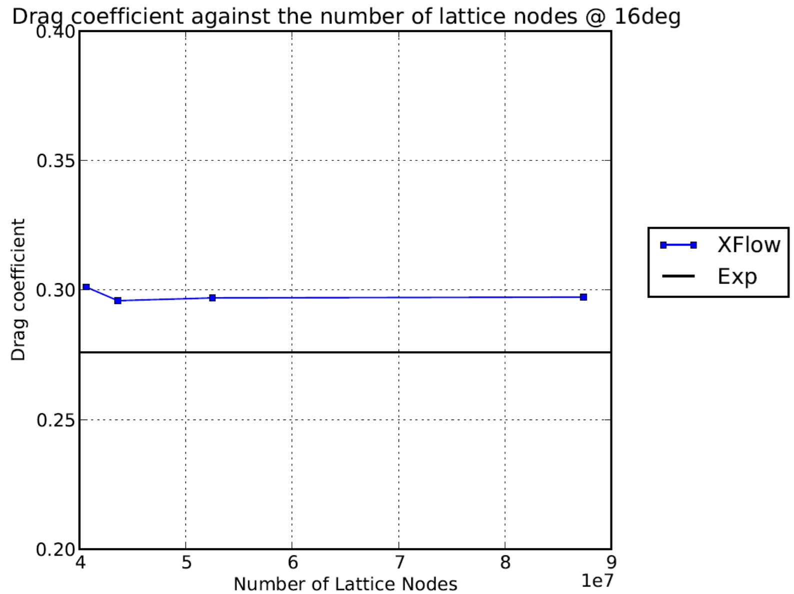
2nd HiLiftPW: Case 1

Fuselage convergence

α = 16º

	Fuselage	Wing	# Elements	Sim. time	Comp. time	Cores
Extra-Coarse	8 mm	1 mm	40,600,000	0.1 s	15.8 h	160
Coarse	4 mm	1 mm	43,600,000	0.1 s	17.6 h	160
Medium	2 mm	1 mm	52,500,000	0.1 s	29.0 h	160
Fine	1 mm	1 mm	87,400,000	0.1 s	33.8 h	160





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Fuselage convergence

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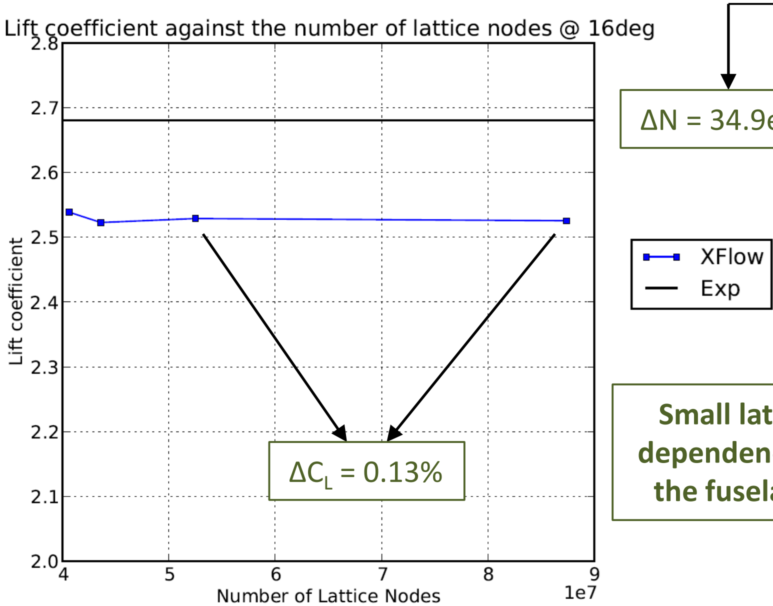
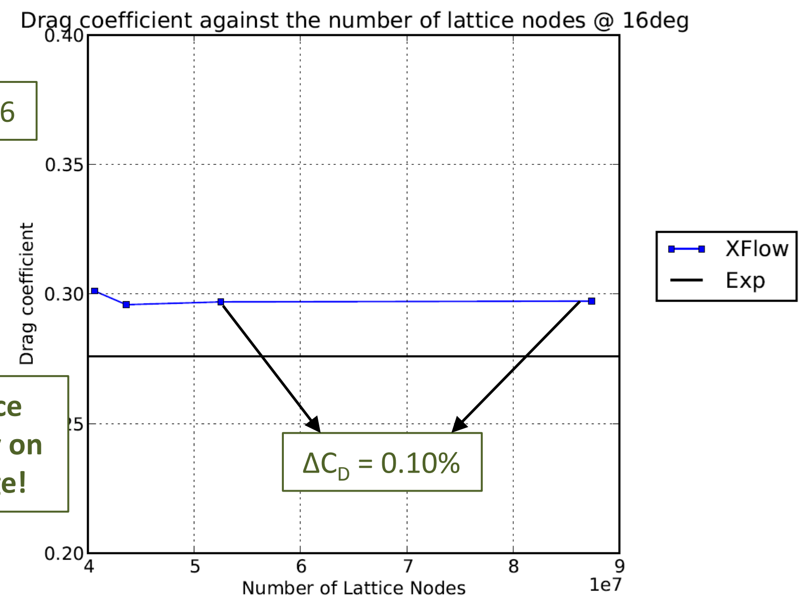


ΔN = 34.9e+6

Small lattice dependency on the fuselage!



2nd HiLiftPW: Case 1

Global convergence

α = 16º

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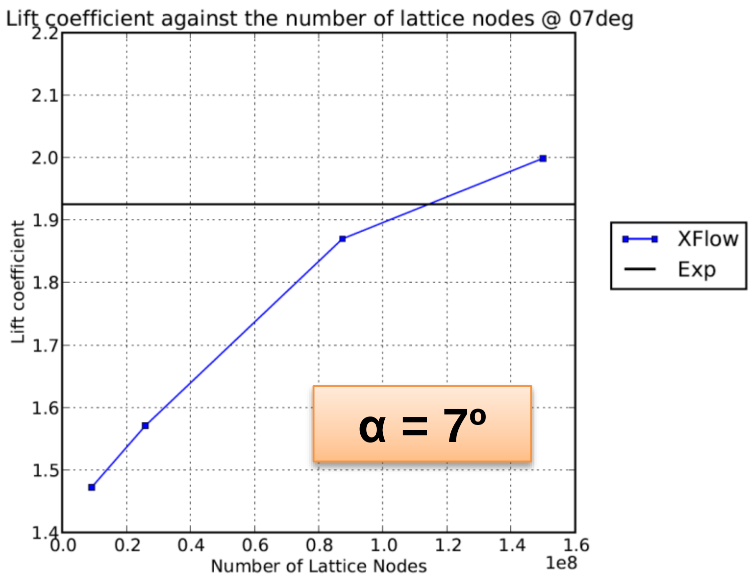
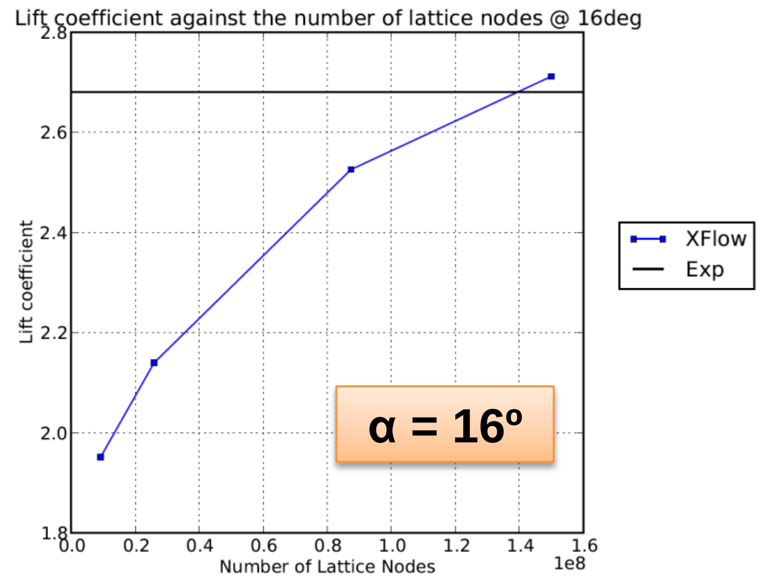
Medium	2 mm	2 mm	52,500,000	0.1 s	5.2 h	160
Fine	1 mm	1 mm	87,400,000	0.1 s	33.8 h	160
Extra-Fine	0.5 mm	2 mm	150,000,000	0.1 s	84 h	256





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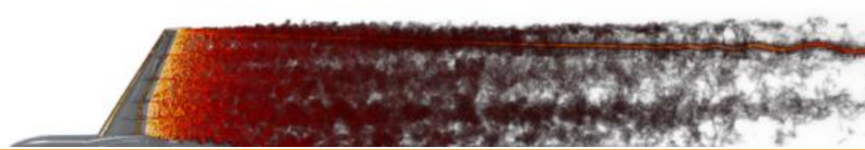

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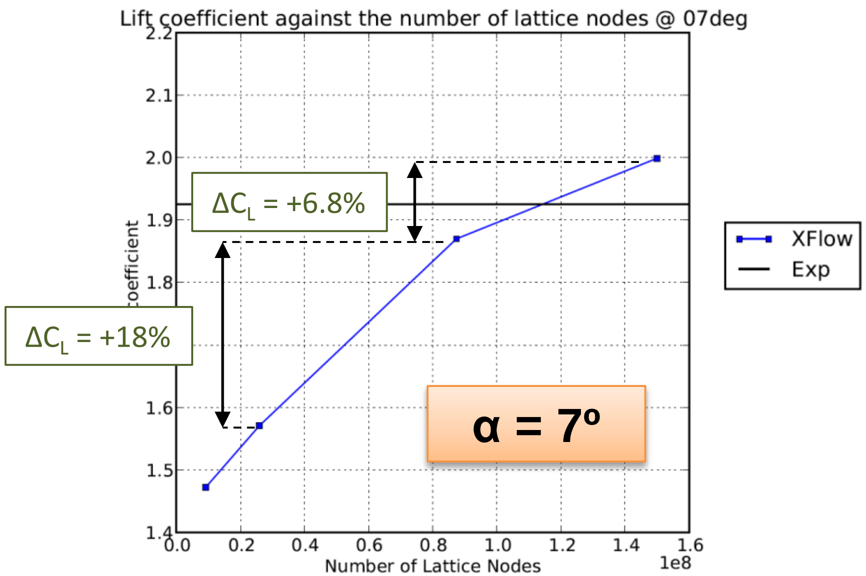
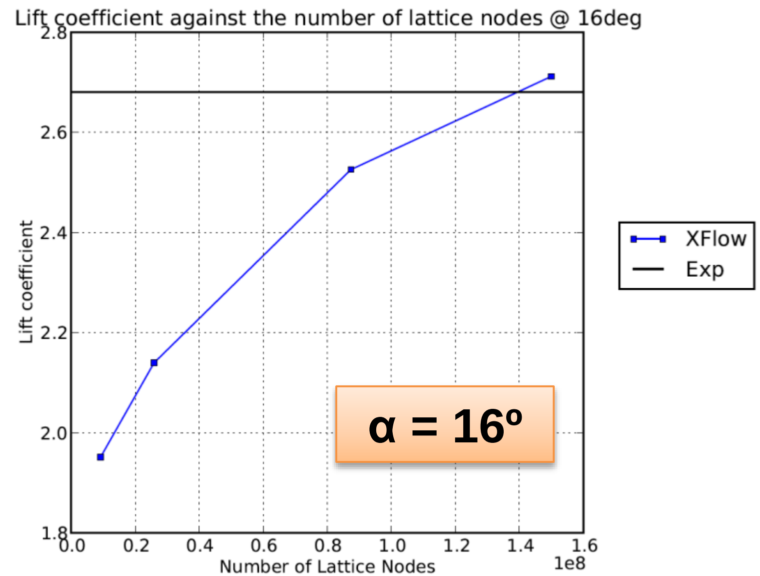
Extra-Fine	0.5 mm	2 mm	150,000,000	0.1 s	84 h	256





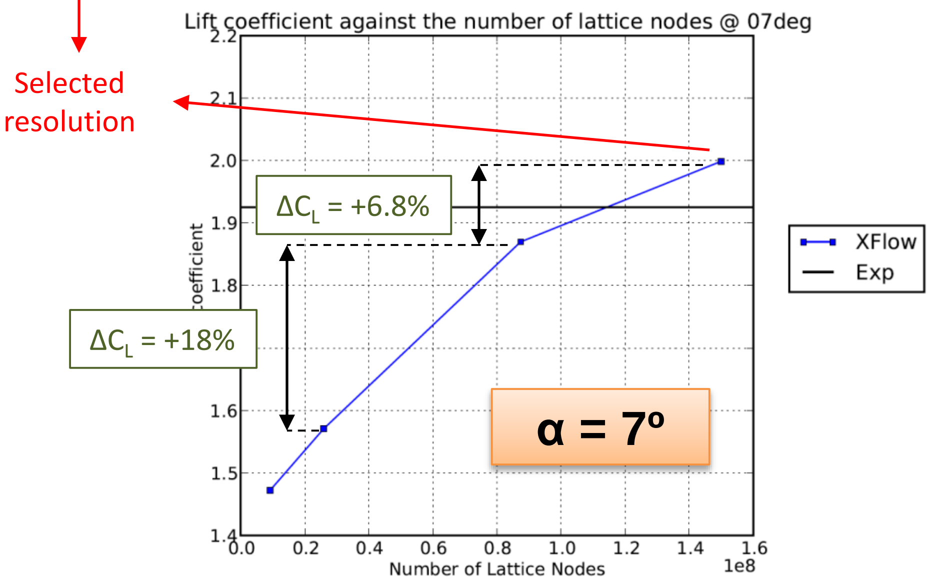
2nd HiLiftPW: Case 1

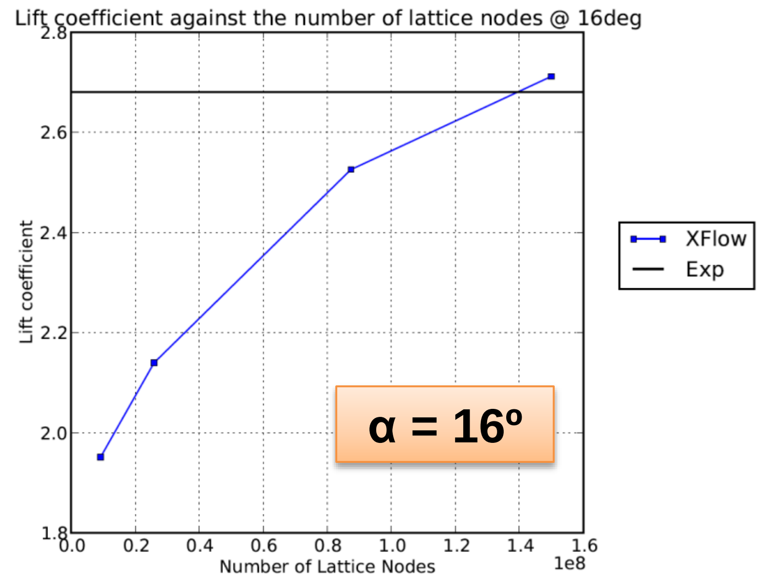
Global convergence

α = 16º

	Wing	Fuselage	# Elements	Sim. time	Comp. time	Cores
Coarse	4 mm	4 mm	43,600,000	0.1 s	1 h	160
Medium	2 mm	2 mm	52,500,000	0.1 s	5.2 h	160
Fine	1 mm	1 mm	87,400,000	0.1 s	33.8 h	160
Extra-Fine	0.5 mm	2 mm	150,000,000	0.1 s	84 h	256

CeSViMa
CENTRO DE SUPERCOMPUTACIÓN Y VISUALIZACIÓN DE MADRID





Outline

- XFlow CFD code
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  - Spatial discretization
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  - Case 1: Convergence analysis
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  - Case 3b: High Reynolds number condition
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- Conclusions

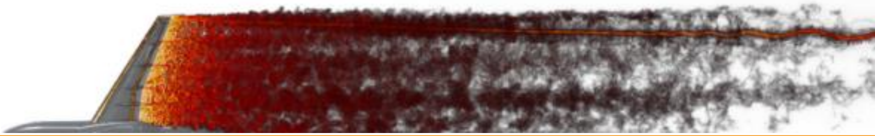
2nd HiLiftPW: Case 3a (low Re)

Computational information

Angle of attack	# Elements	Sim. time	Comp. time	Cores
0º	153,780,000	0.1 s	50 h	576
7º	156,120,000	0.1 s	49 h	576
16º	162,390,000	0.1 s	60 h	576
18.5º	164,090,000	0.1 s	68.5 h	576
19º	164,400,000	0.1 s	66.4 h	576
20º	165,040,000	0.1 s	64.8 h	576
21º	165,600,000	0.1 s	52 h	576
24º	167,300,000	0.15 s	66 h	576

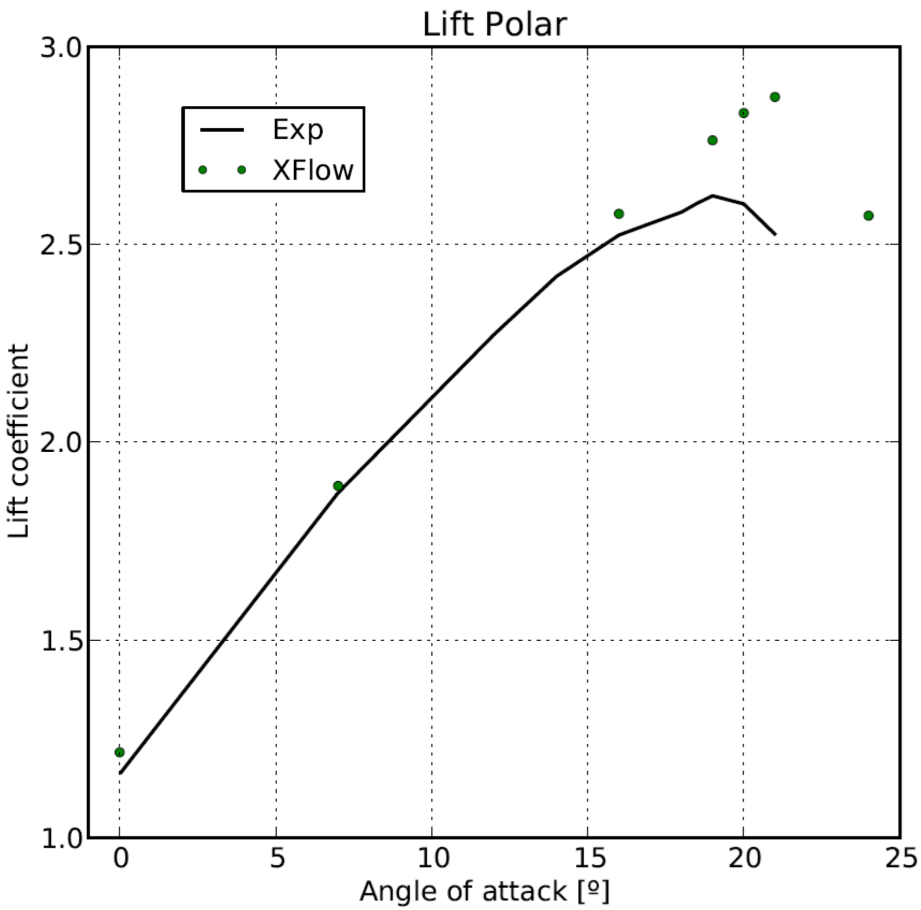
teideHPC

2nd HiLiftPW: Case 3a (low Re)

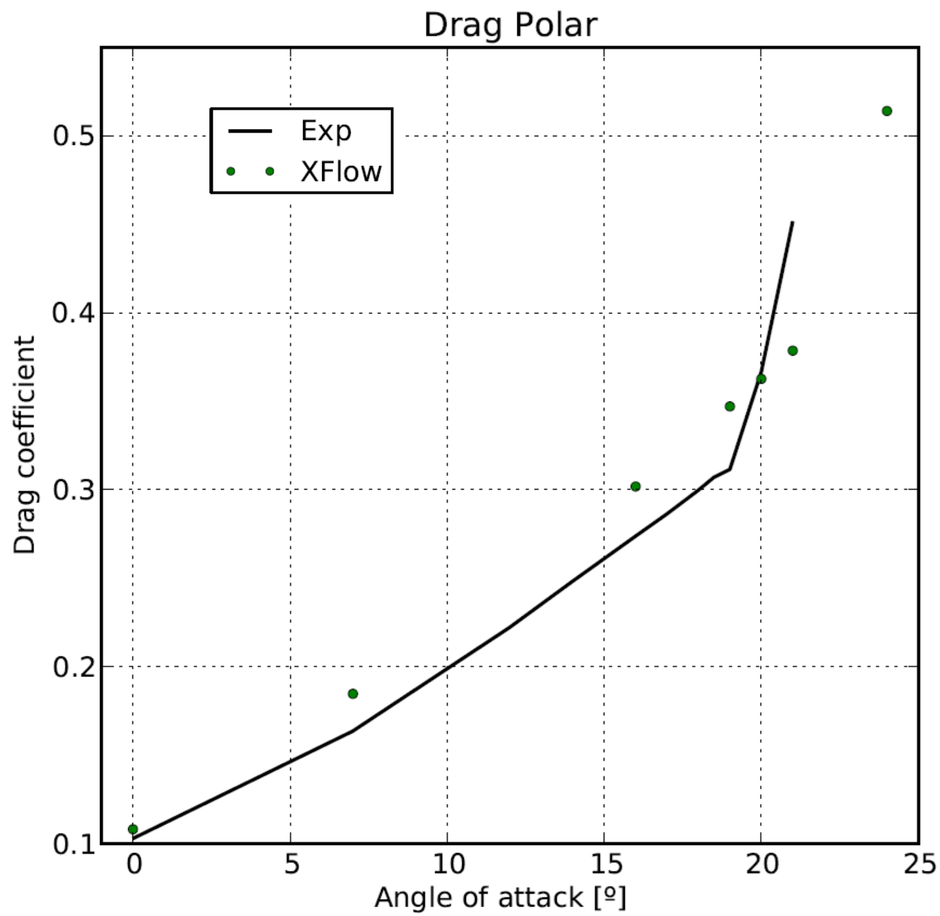


Lift and drag polars

LIFT



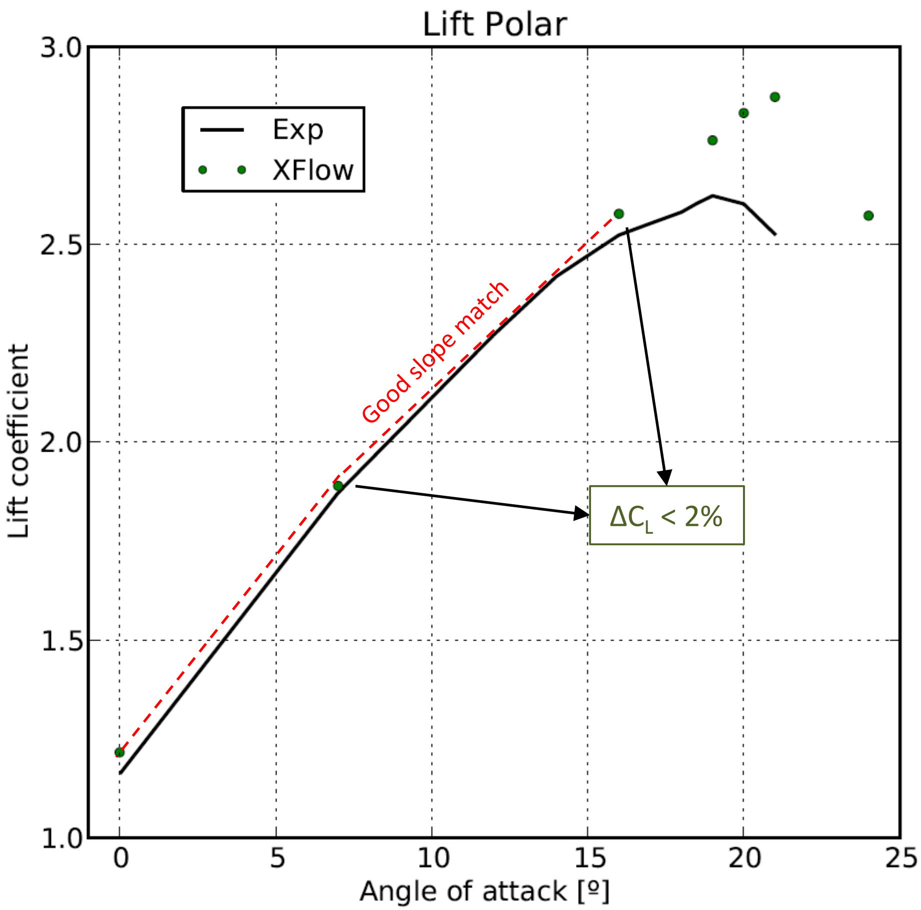
DRAG



2nd HiLiftPW: Case 3a (low Re)

Lift and drag polars: linear region

LIFT



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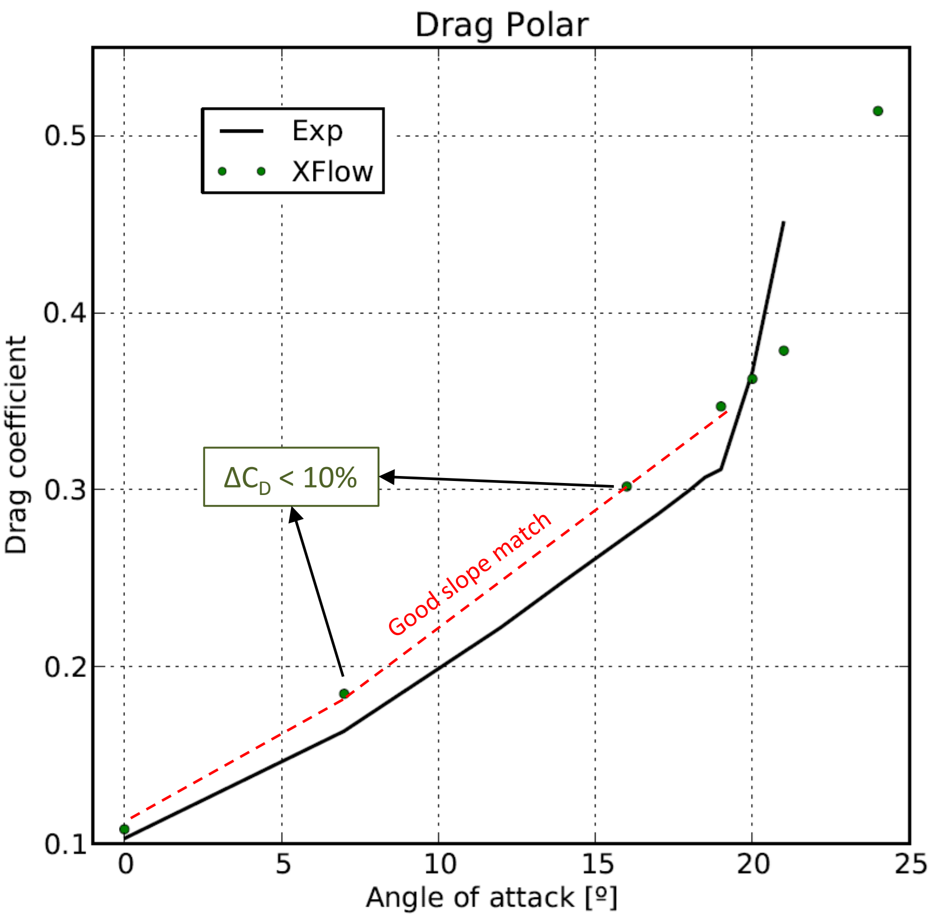
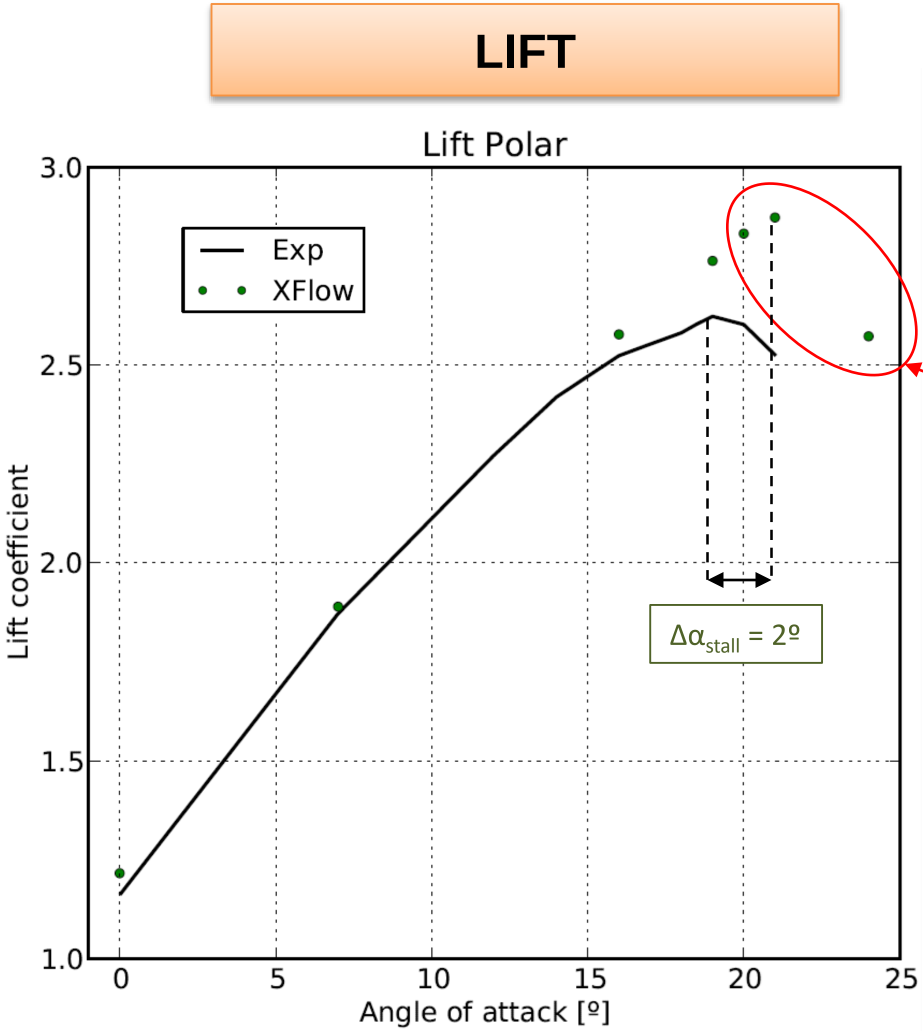
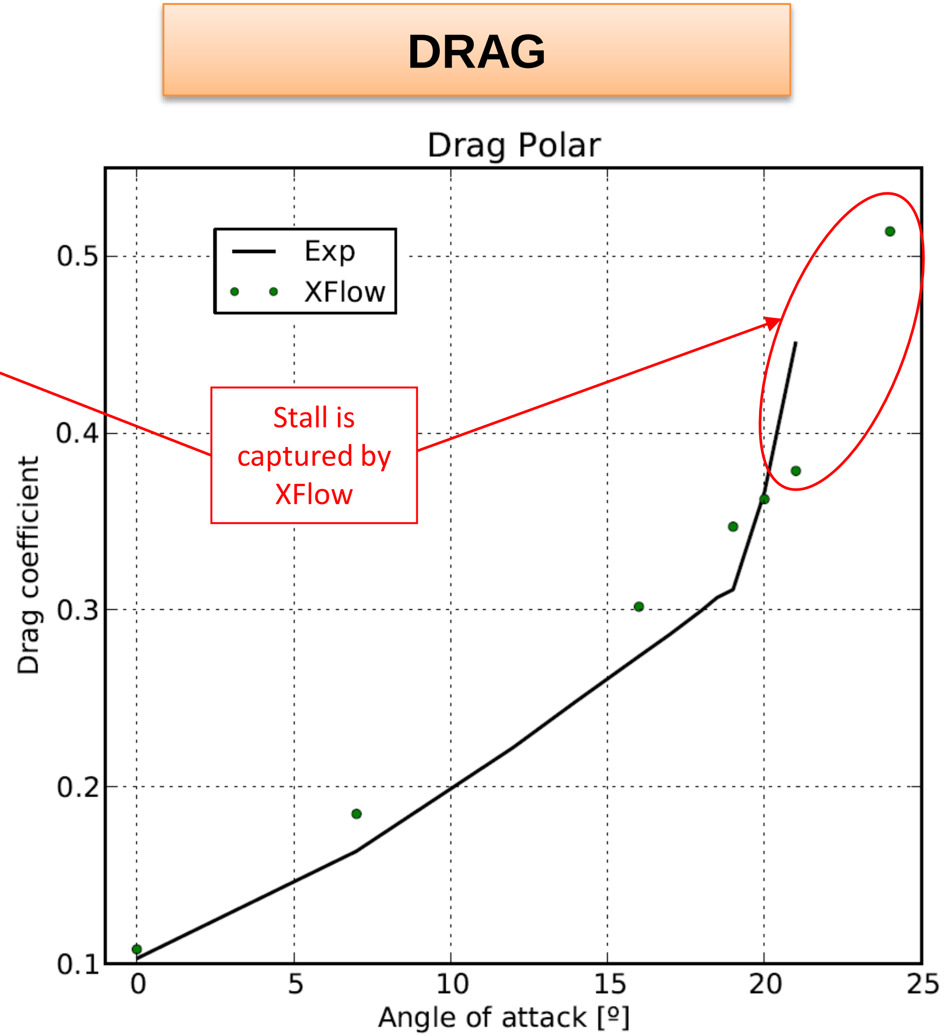
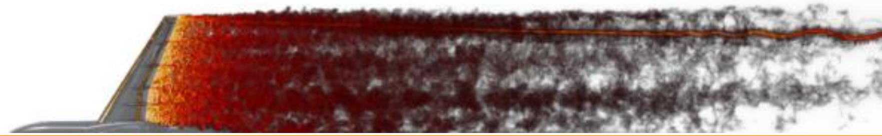


Lift and drag polars: stall region

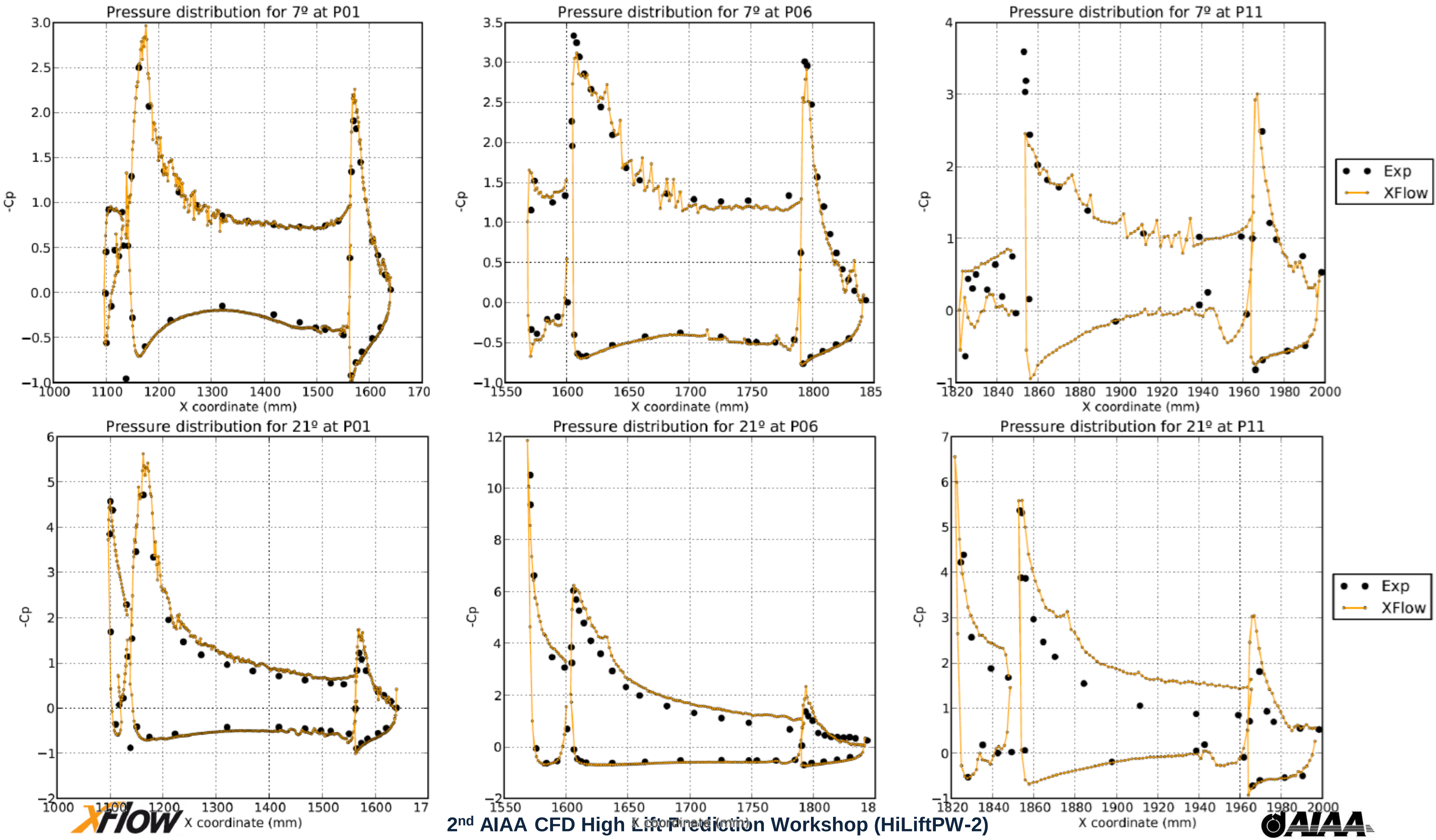




2nd HiLiftPW: Case 3a (low Re)

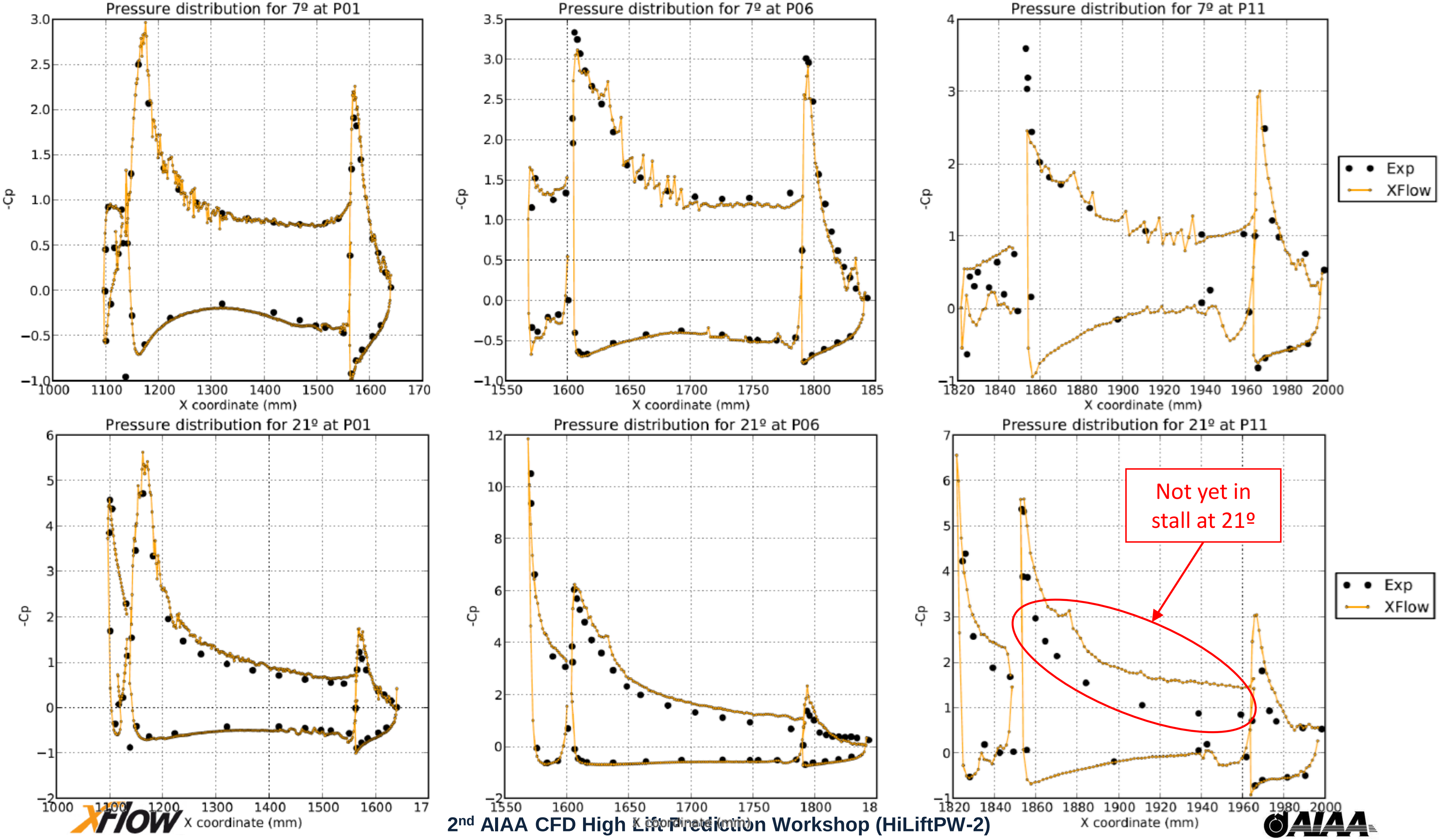


Pressure distribution



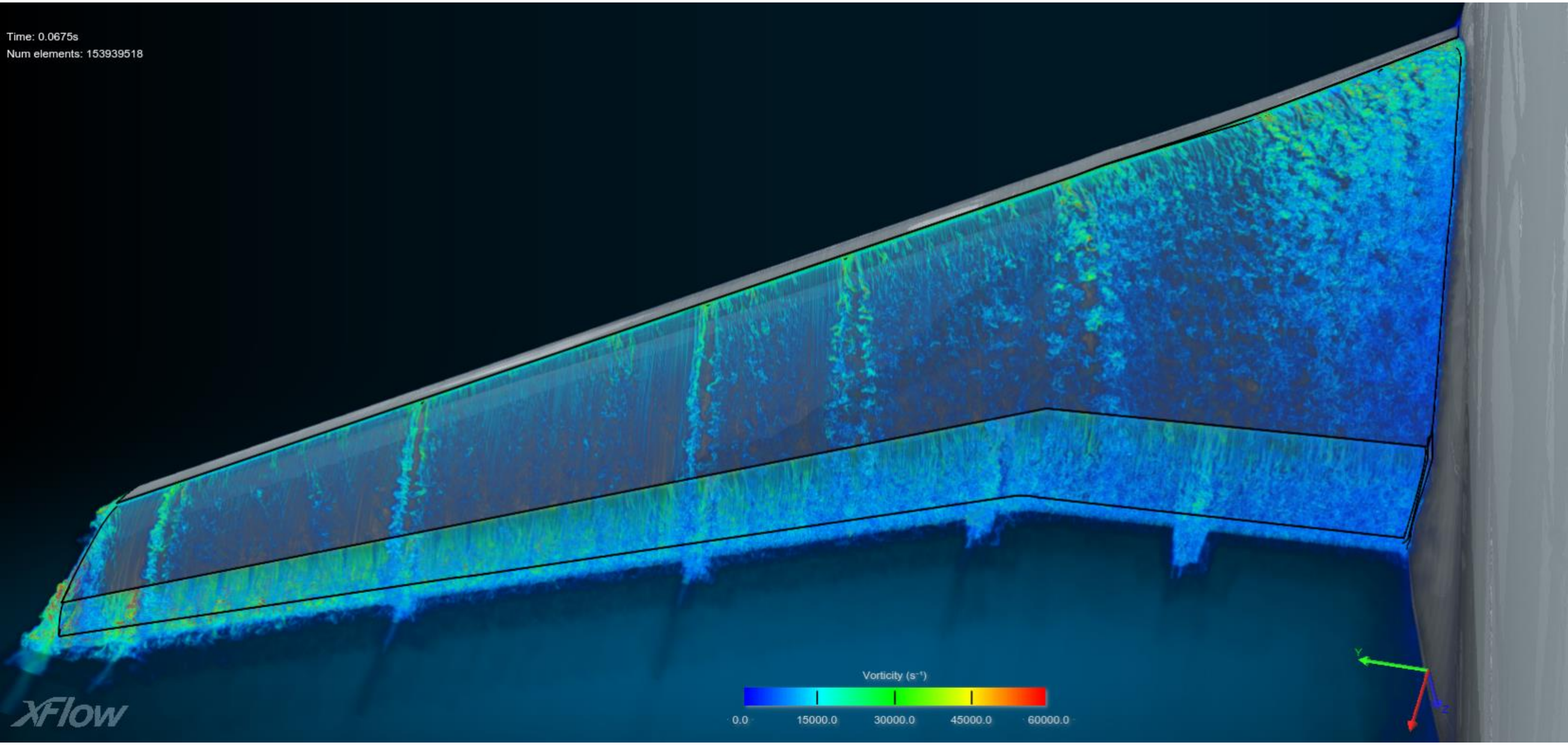
2nd HiLiftPW: Case 3a (low Re)

Pressure distribution



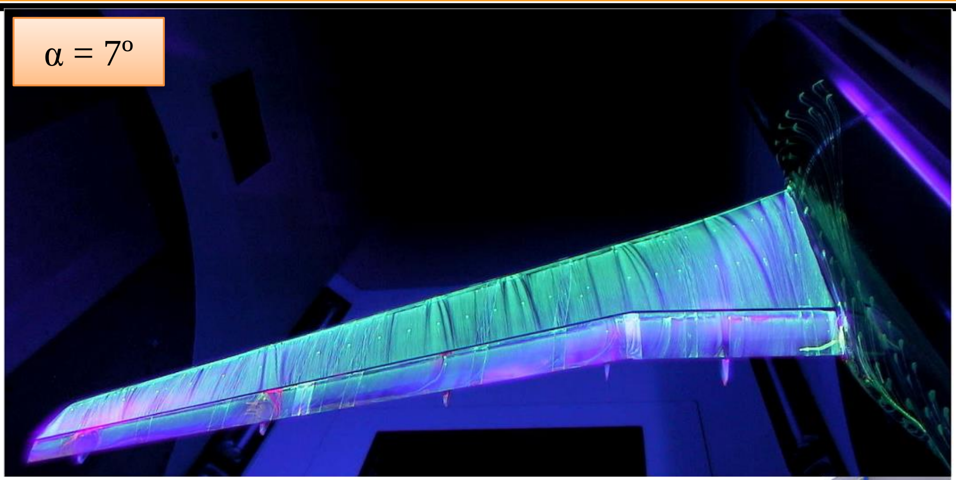
Flow structure

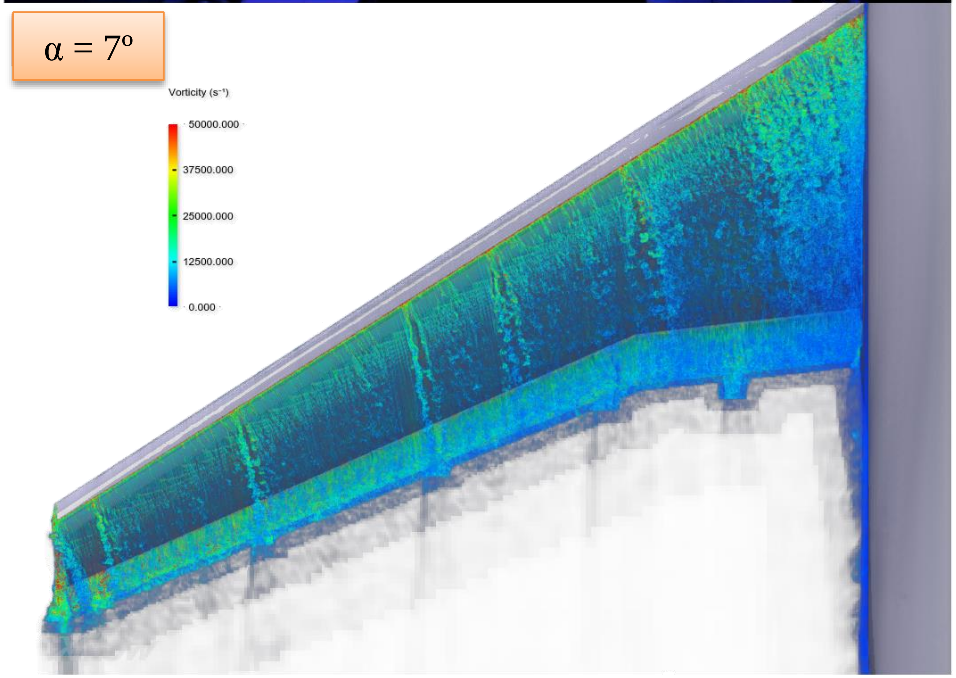
Vorticity at 7º



2nd HiLiftPW: Case 3a (low Re)

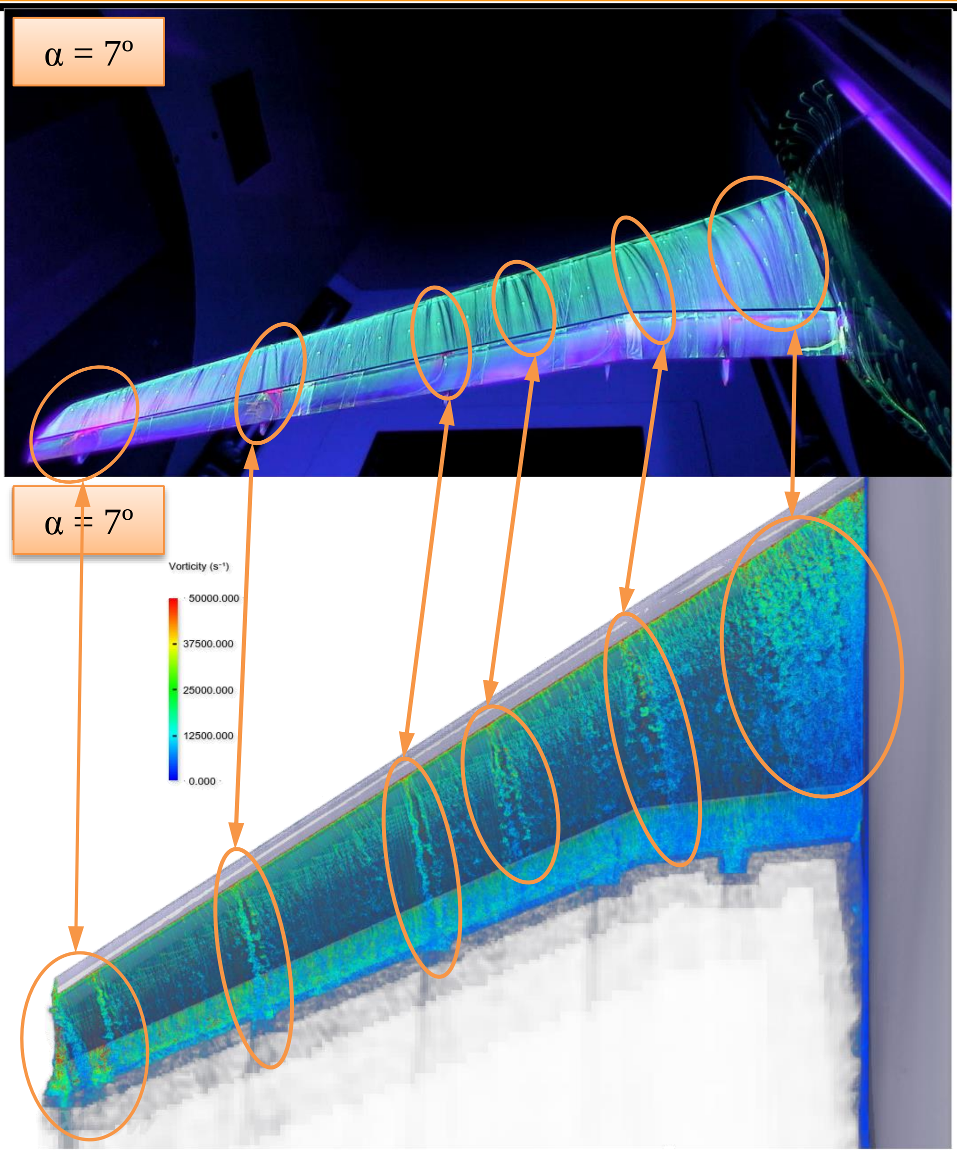
Flow structure





2nd HiLiftPW: Case 3a (low Re)

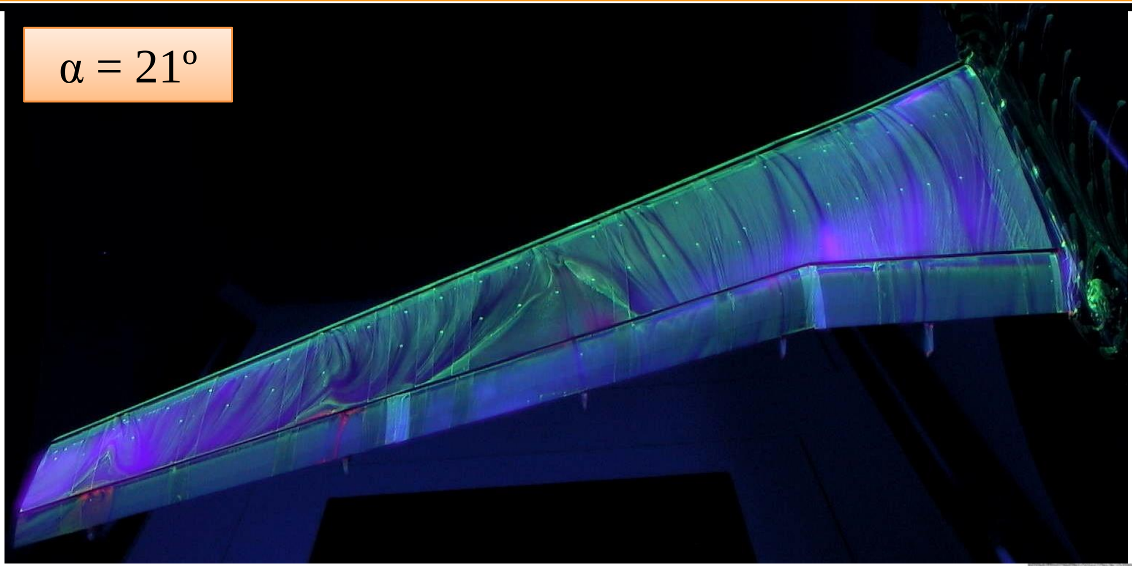
Flow structure



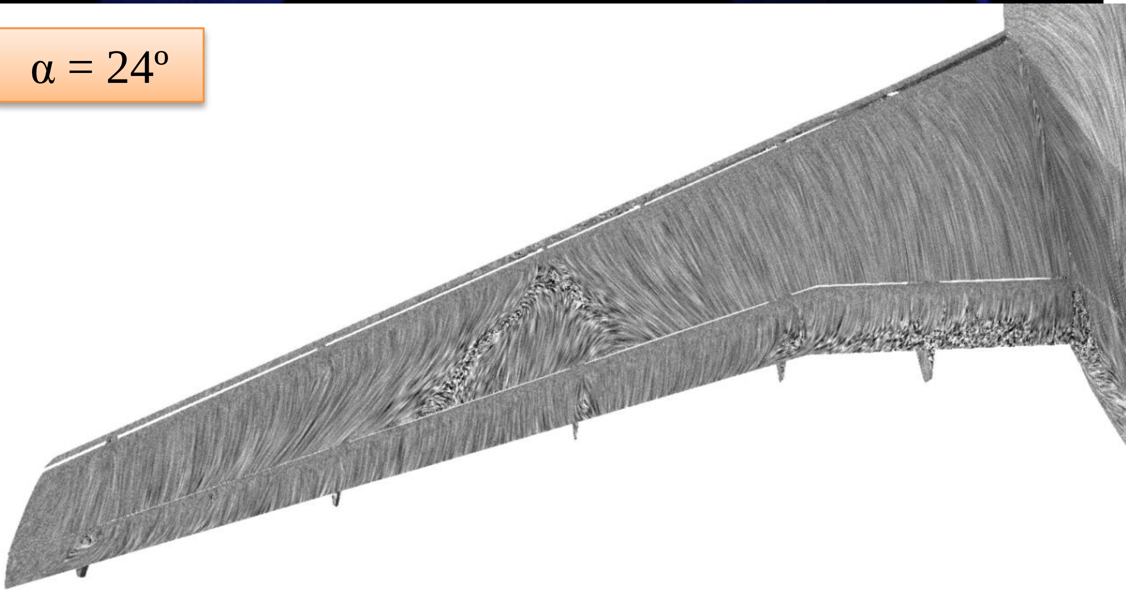
2^{nd} HiLiftPW: Case 3a (low Re)

Flow structure

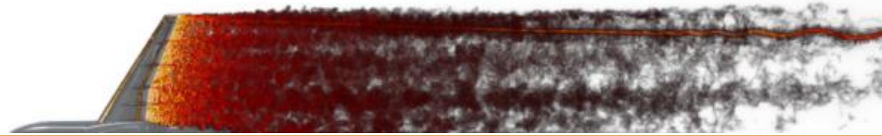
$\alpha = 21^o$



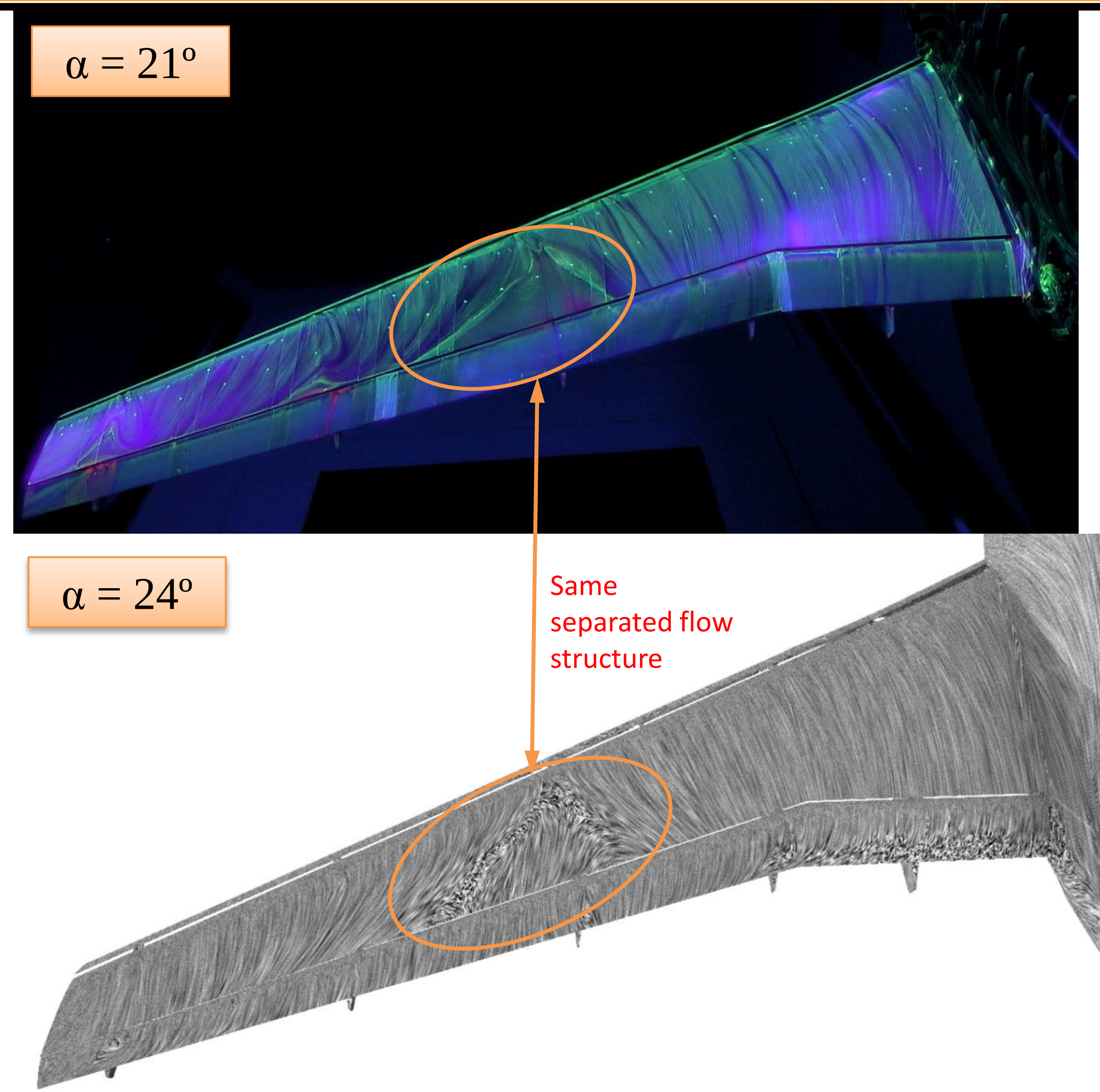
$\alpha = 24^o$



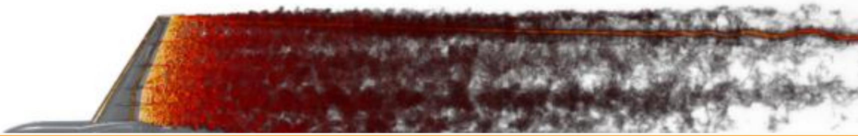
2nd HiLiftPW: Case 3a (low Re)



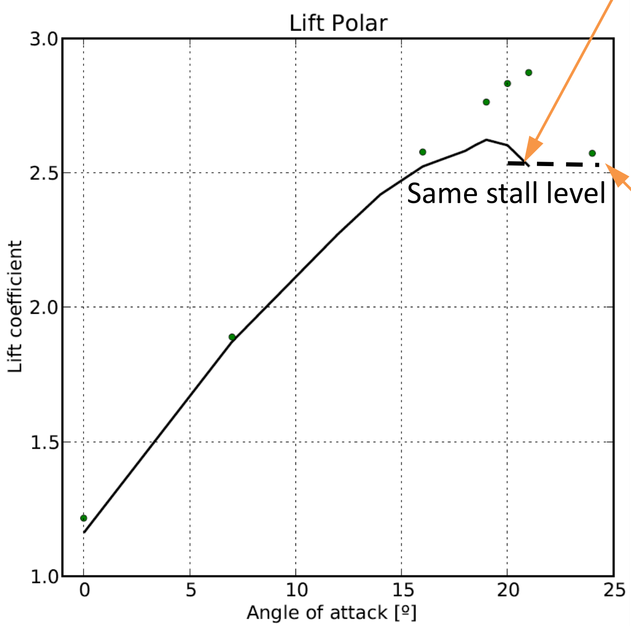
Flow structure

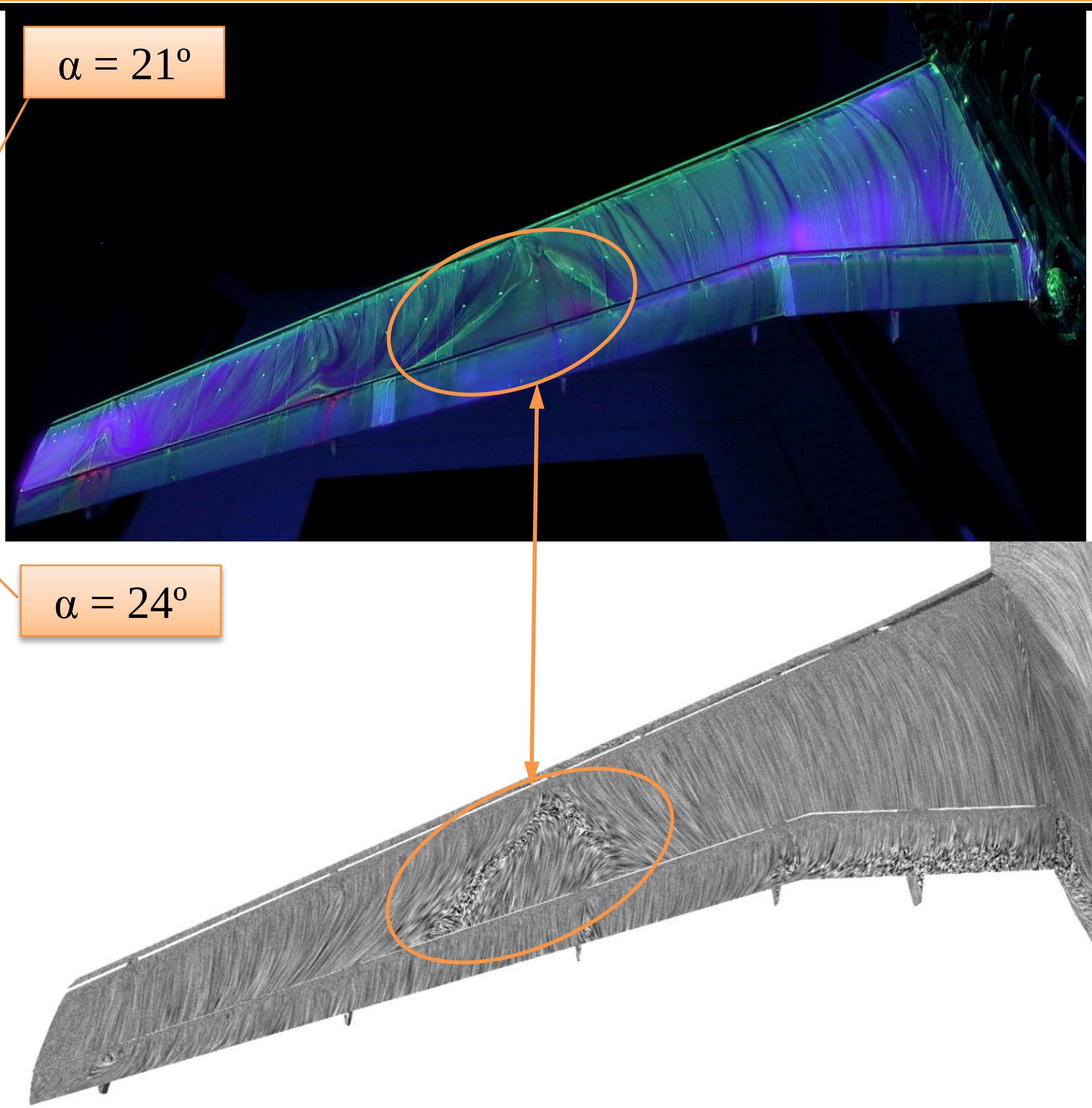


2nd HiLiftPW: Case 3a (low Re)

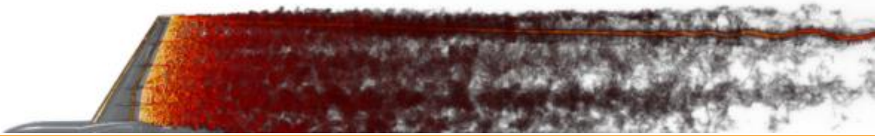


Flow structure





Outline



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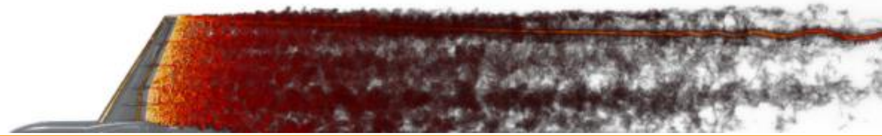


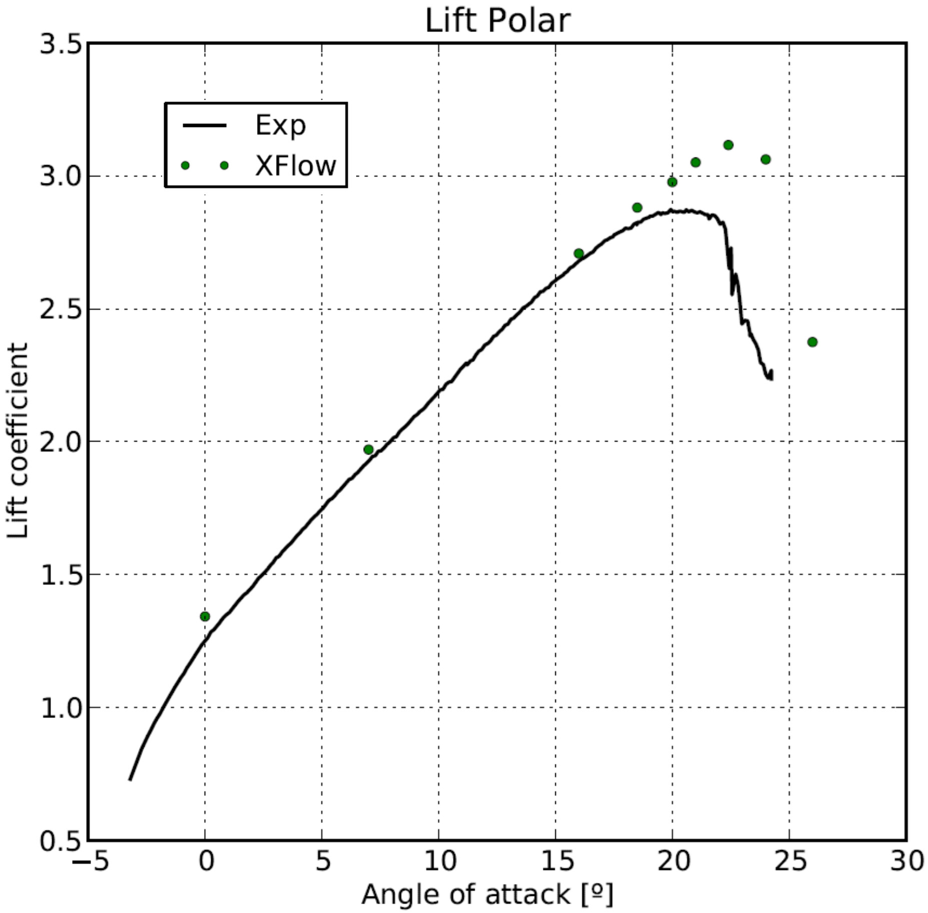
Computational information

Angle of attack	# Elements	Sim. time	Comp. time	Cores
0º	153,780,000	0.1 s	44.2 h	576
7º	156,120,000	0.1 s	41.4 h	576
16º	162,390,000	0.1 s	43.9 h	576
18.5º	164,090,000	0.1 s	33.9 h	1152
20º	165,040,000	0.1 s	40.6 h	576
21º	165,600,000	0.1 s	49.2 h	576
22.4º	166,400,000	0.1 s	47.6 h	576
24º	167,300,000	0.1 s	54.1 h	576
26º	168,200,000	0.15 s	34.6 h	2304

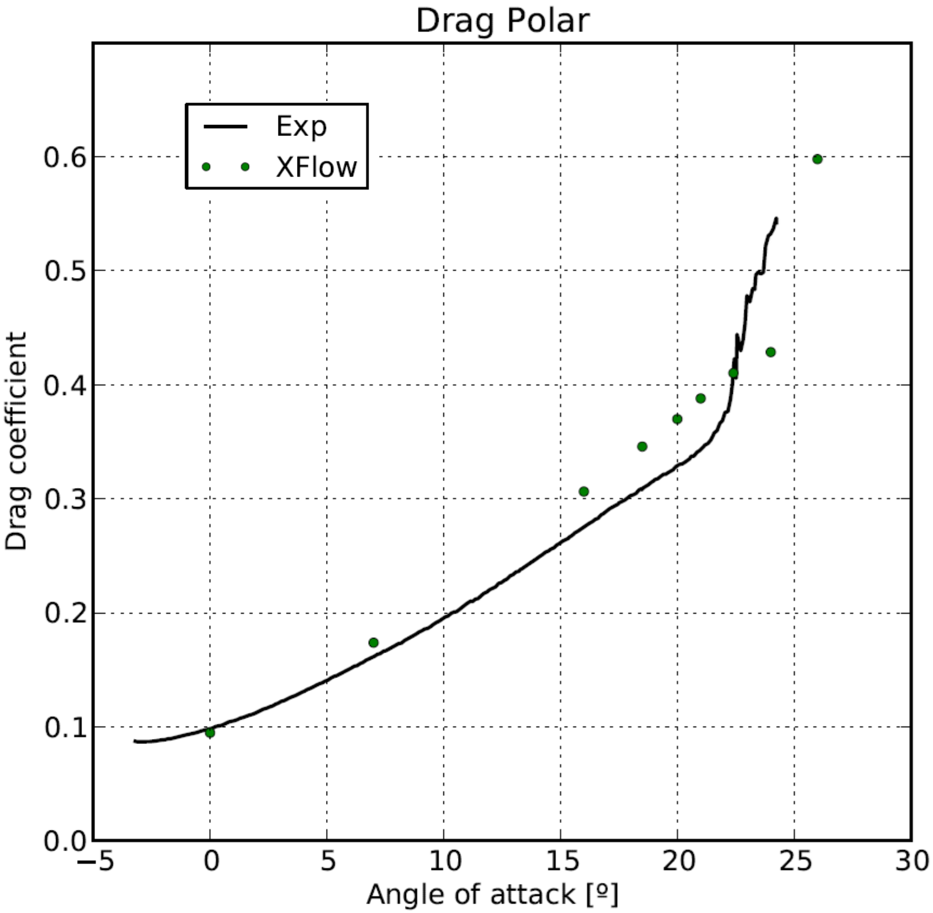
2nd HiLiftPW: Case 3b (high Re)

Lift and drag polars

LIFT



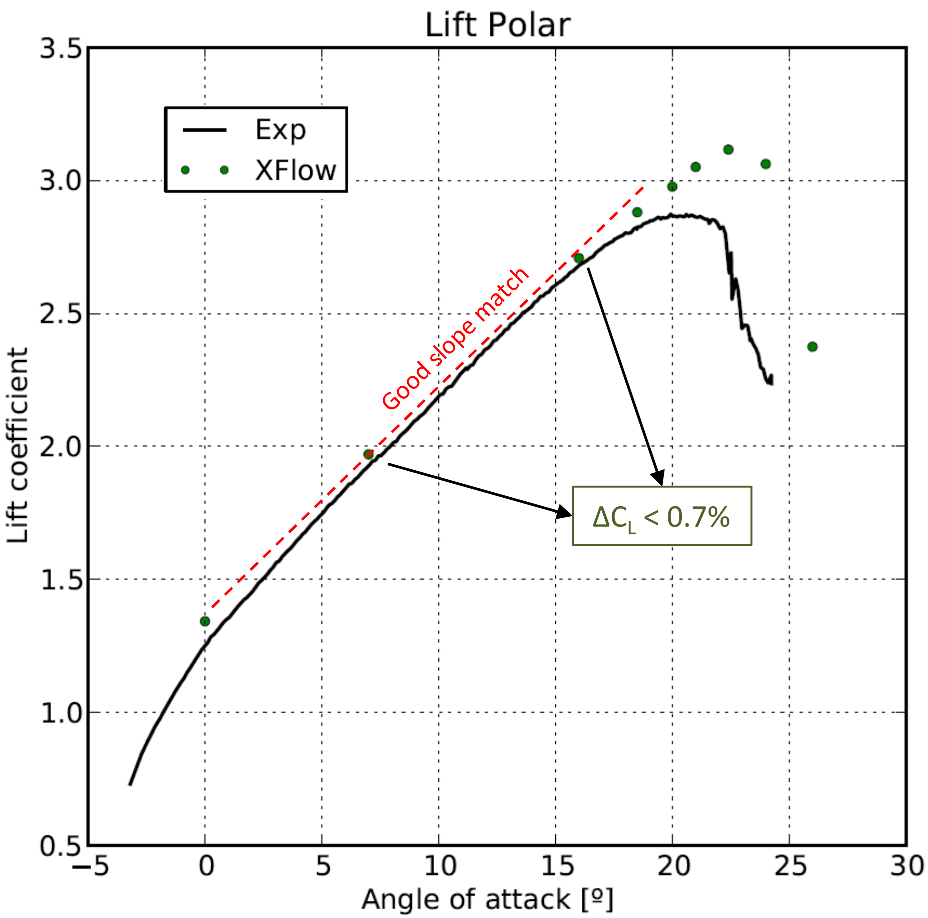
DRAG



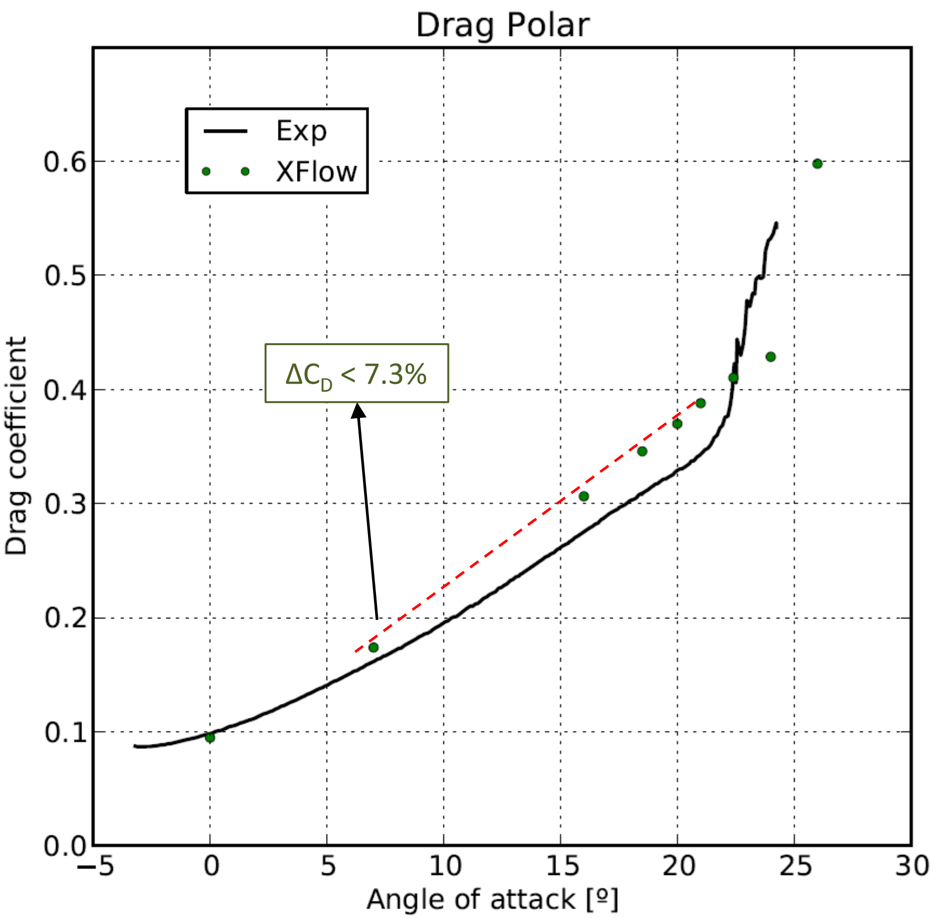
2^{nd} HiLiftPW: Case 3b (high Re)

Lift and drag polars: linear region

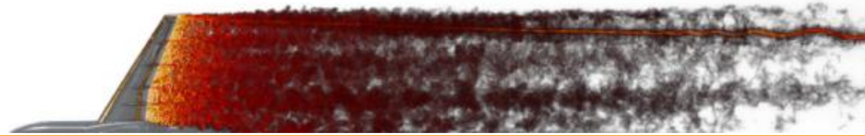
LIFT



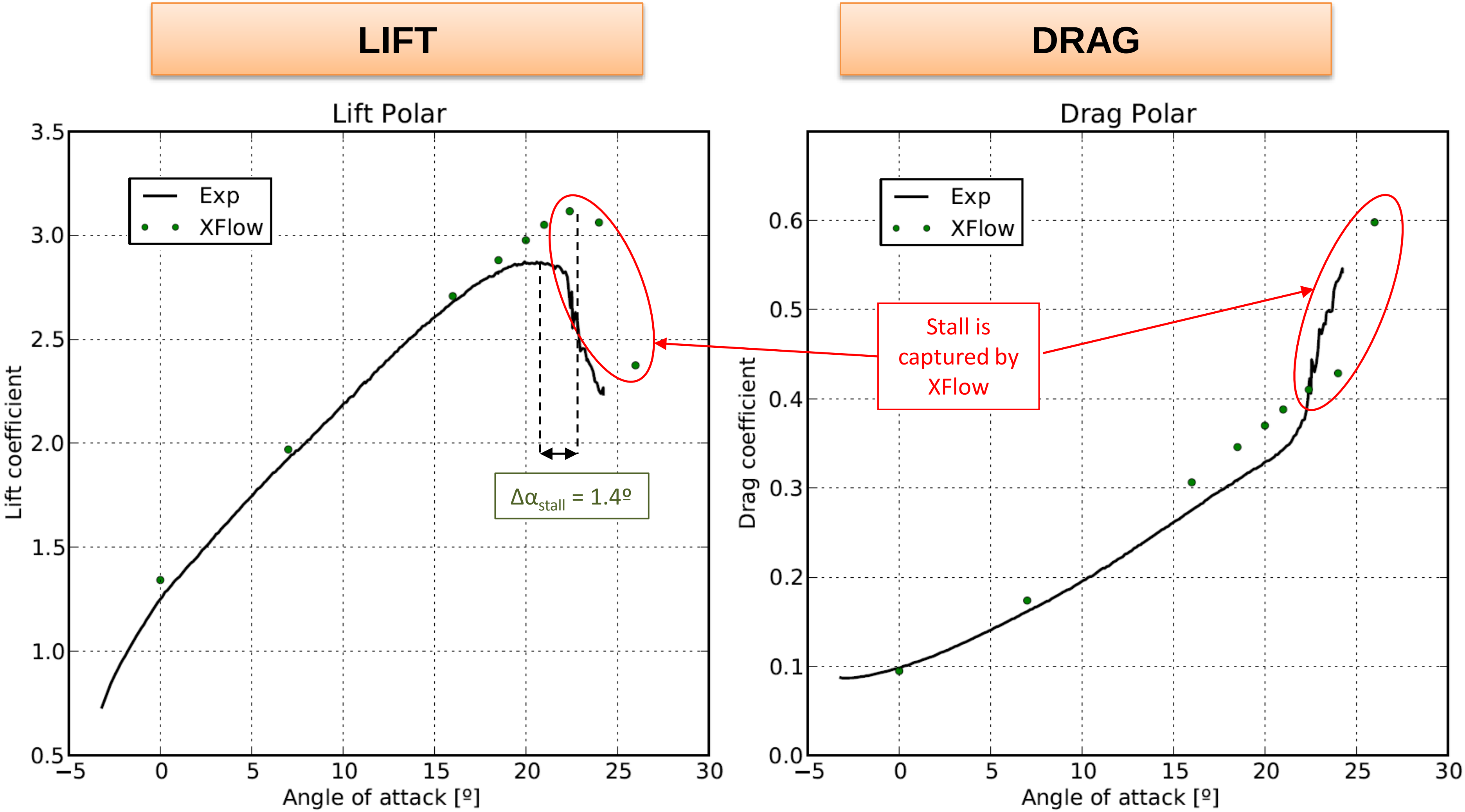
DRAG



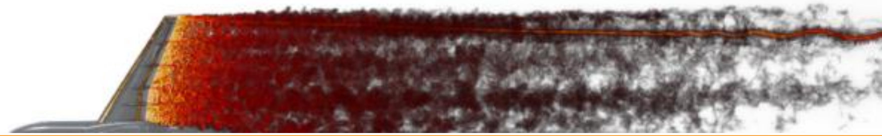
2nd HiLiftPW: Case 3b (high Re)



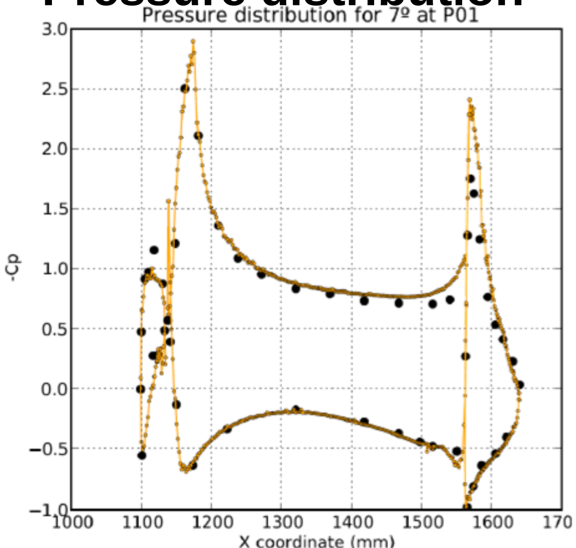
Lift and drag polars: stall region

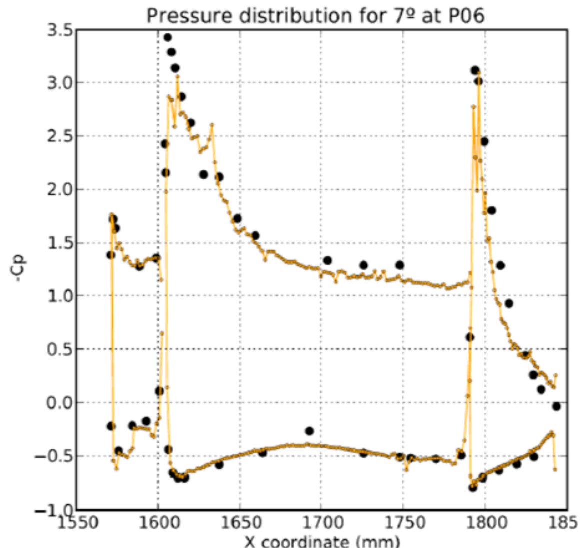


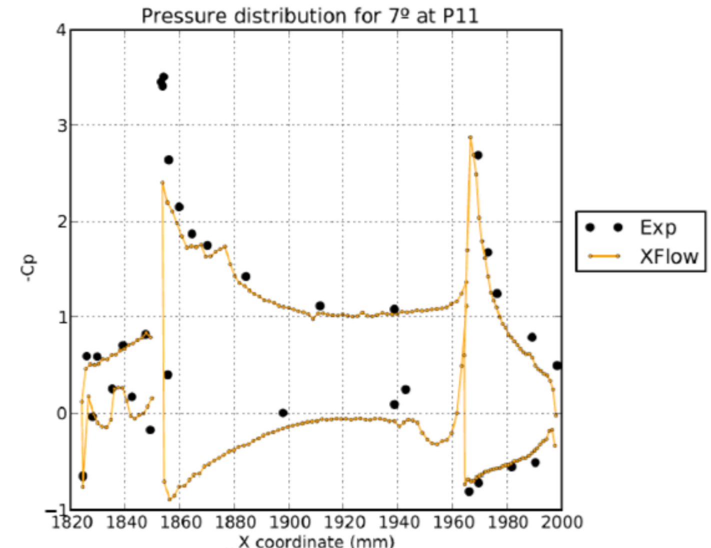
2^{nd} HiLiftPW: Case 3b (high Re)

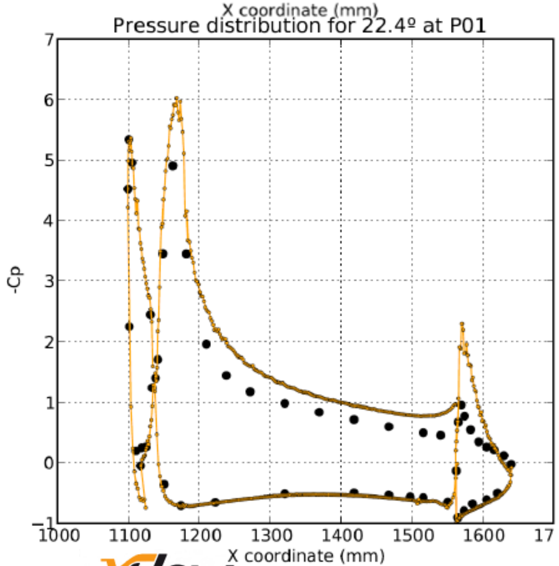


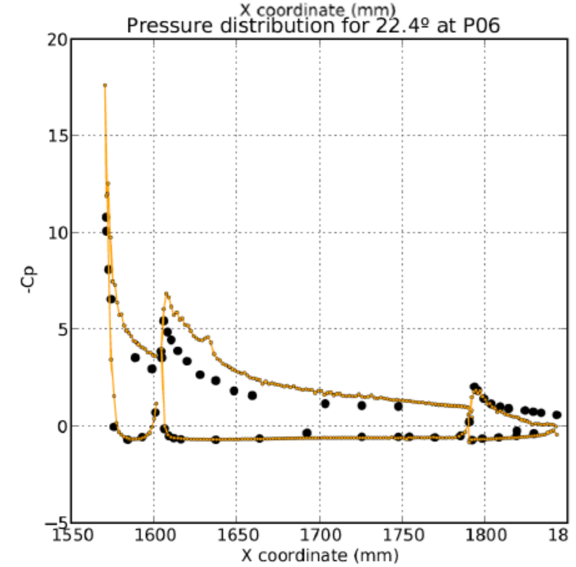
Pressure distribution

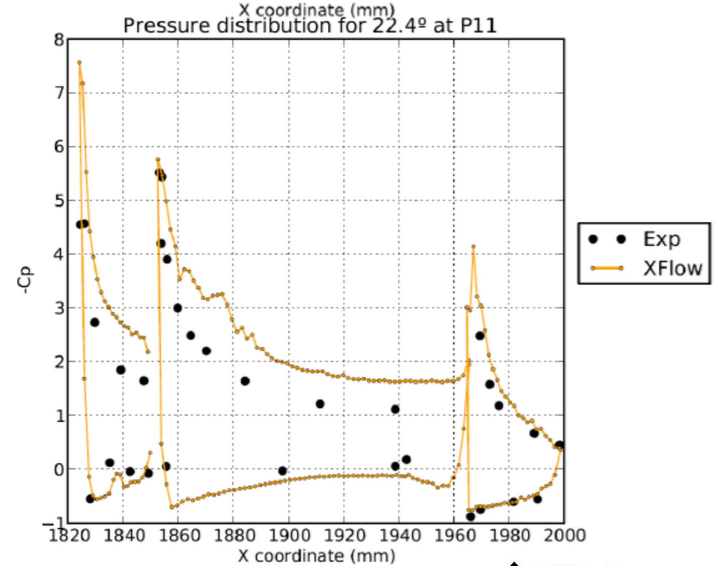




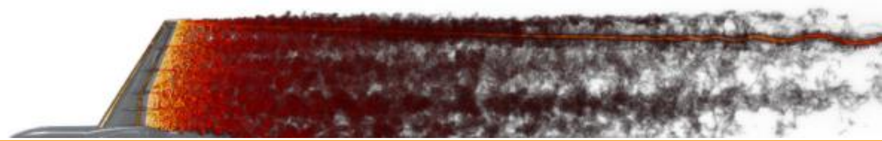




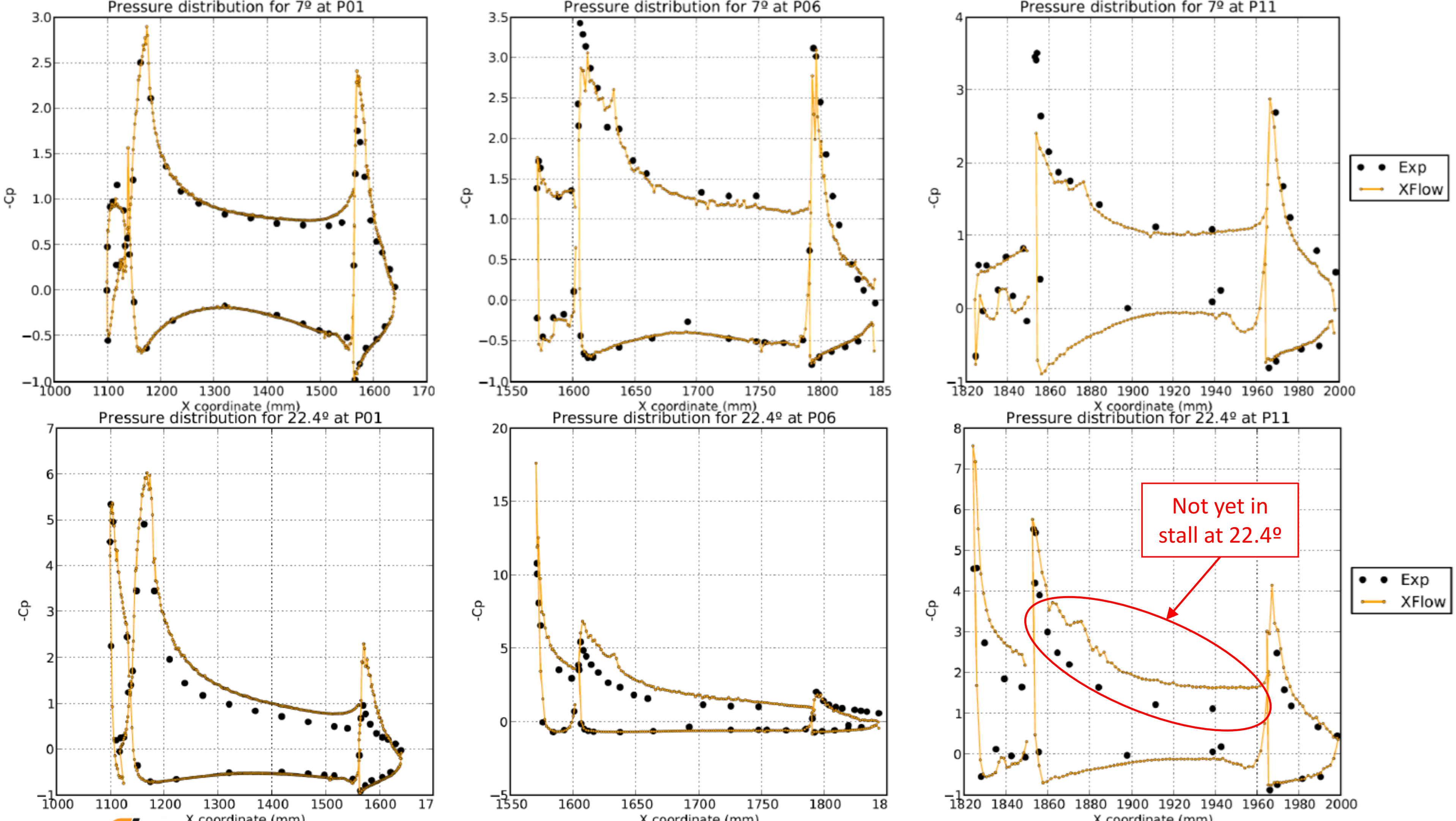




2nd HiLiftPW: Case 3b (high Re)

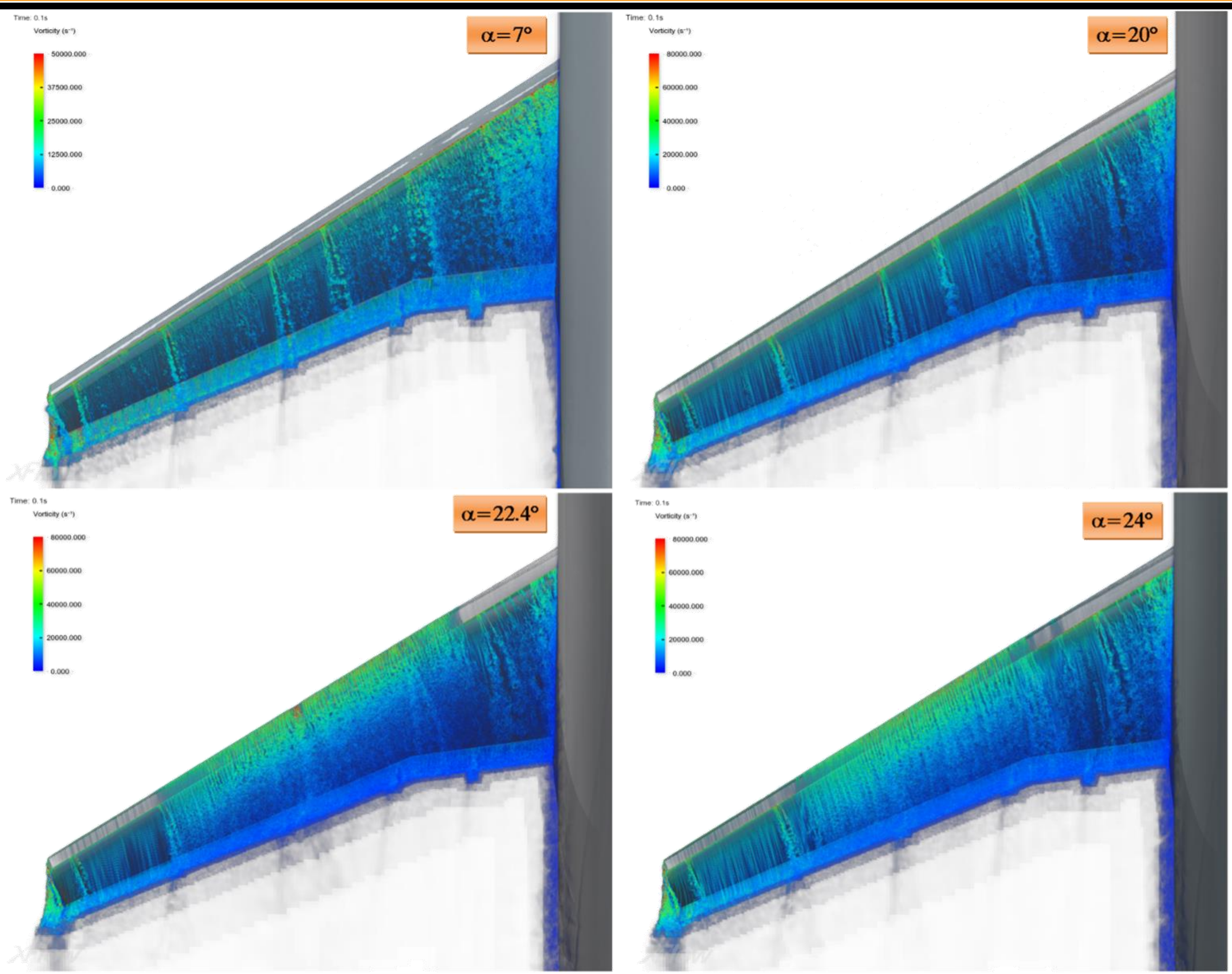


Pressure distribution

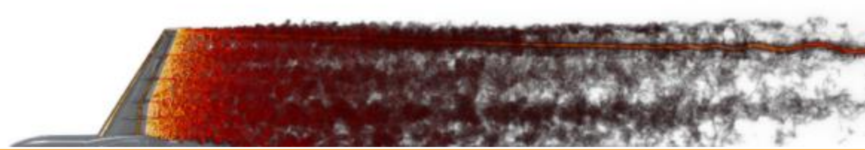


2nd HiLiftPW: Case 3b (high Re)

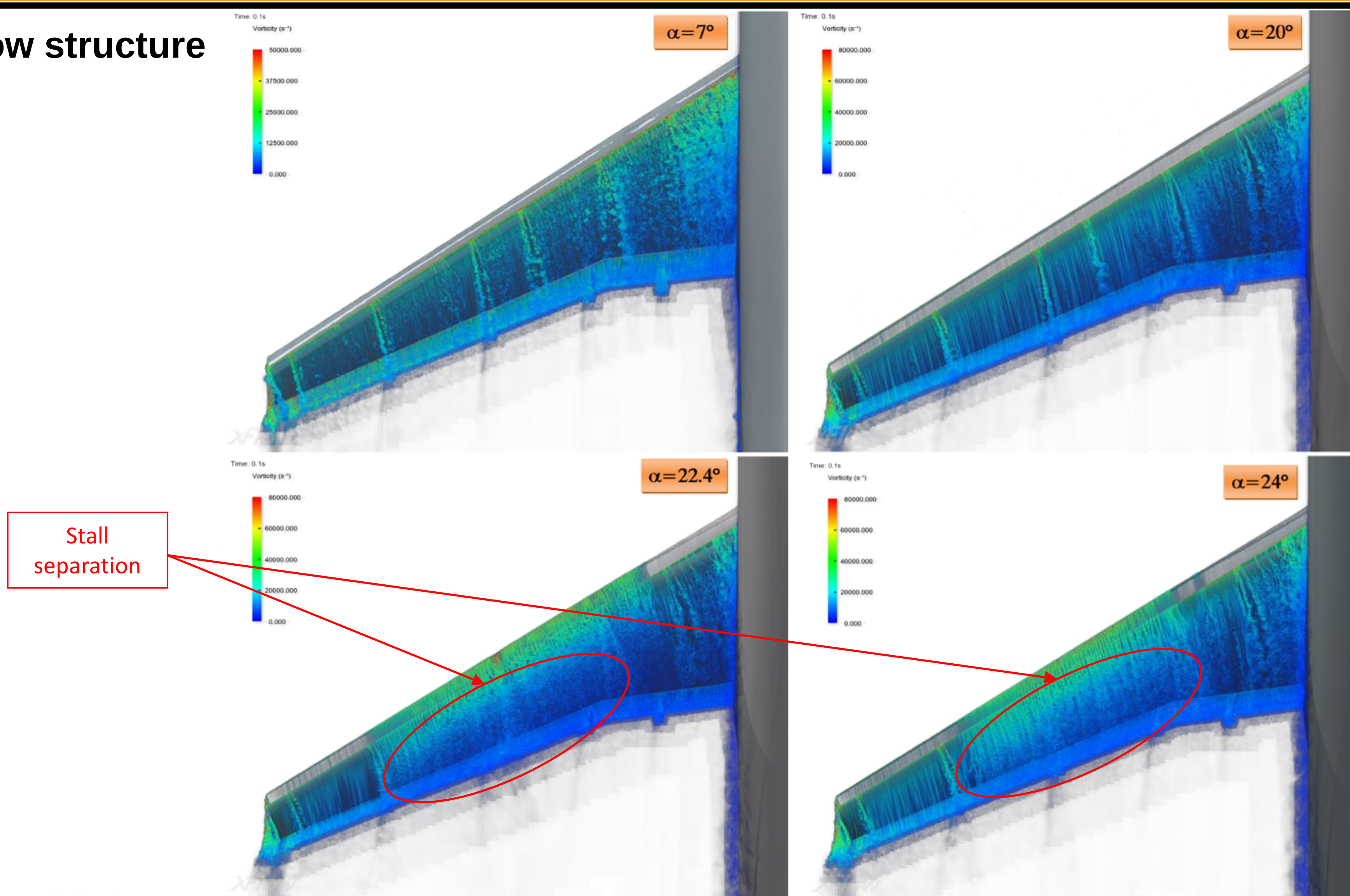
Flow structure



2nd HiLiftPW: Case 3b (high Re)

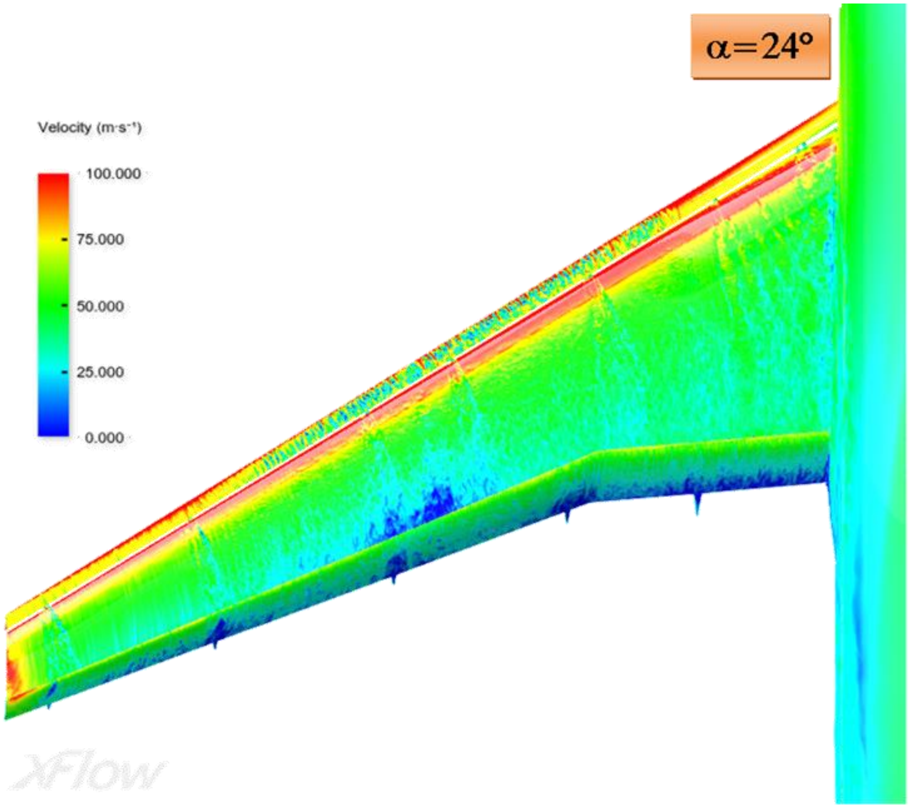


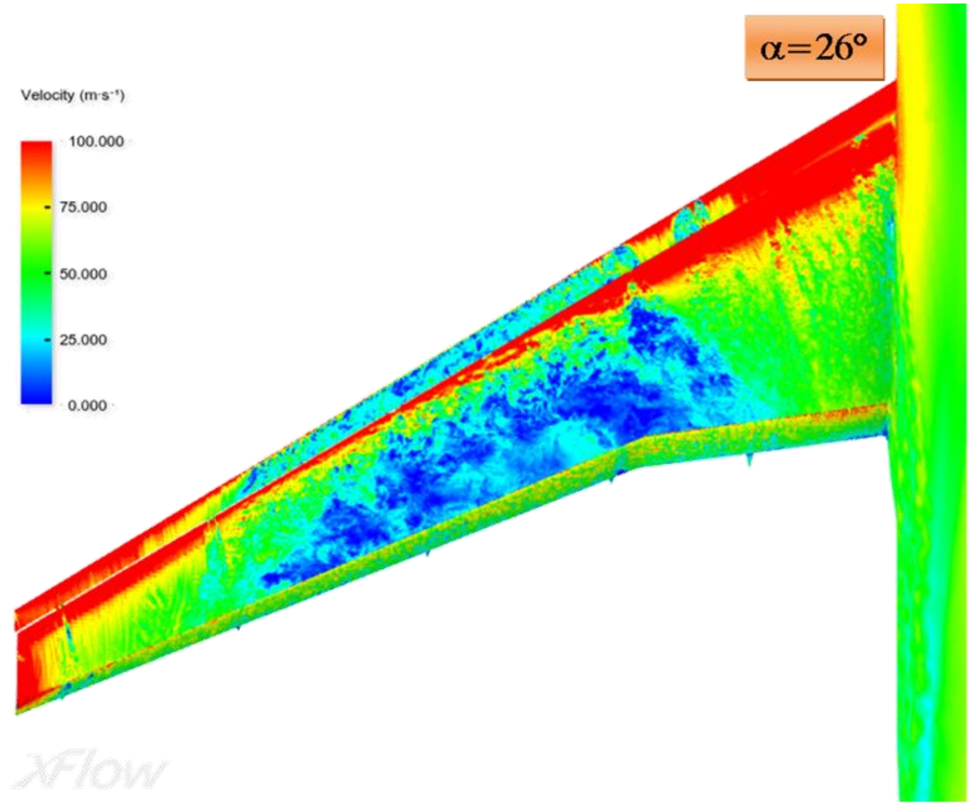
Flow structure



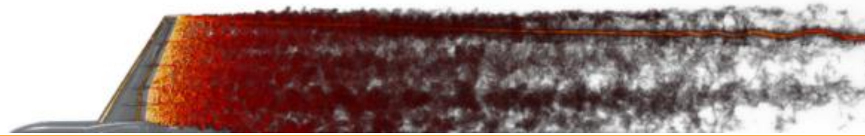
2nd HiLiftPW: Case 3b (high Re)

Flow structure

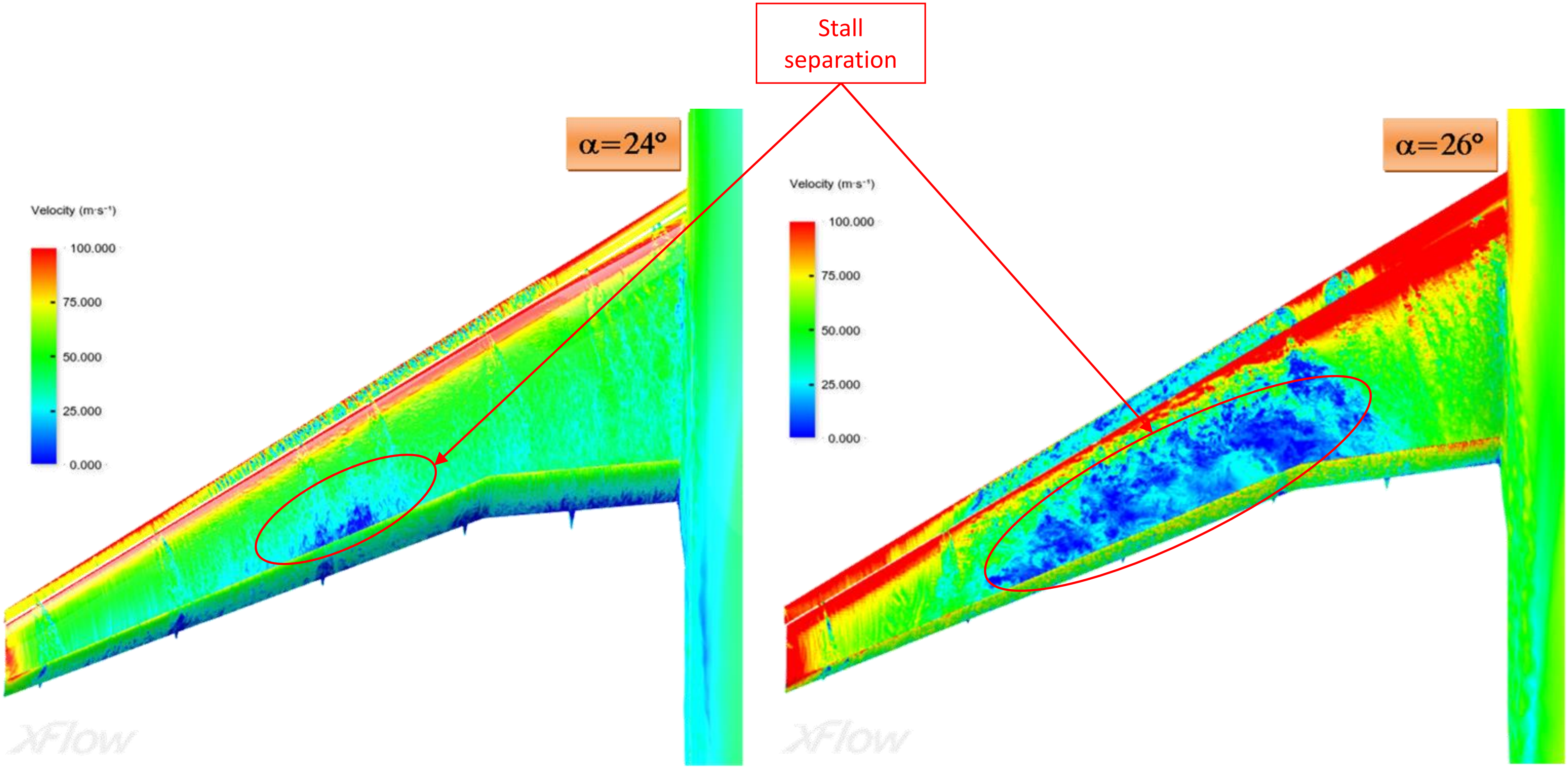




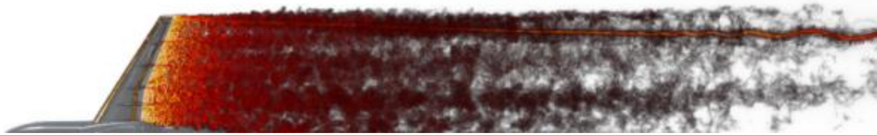
2nd HiLiftPW: Case 3b (high Re)



Flow structure



Outline



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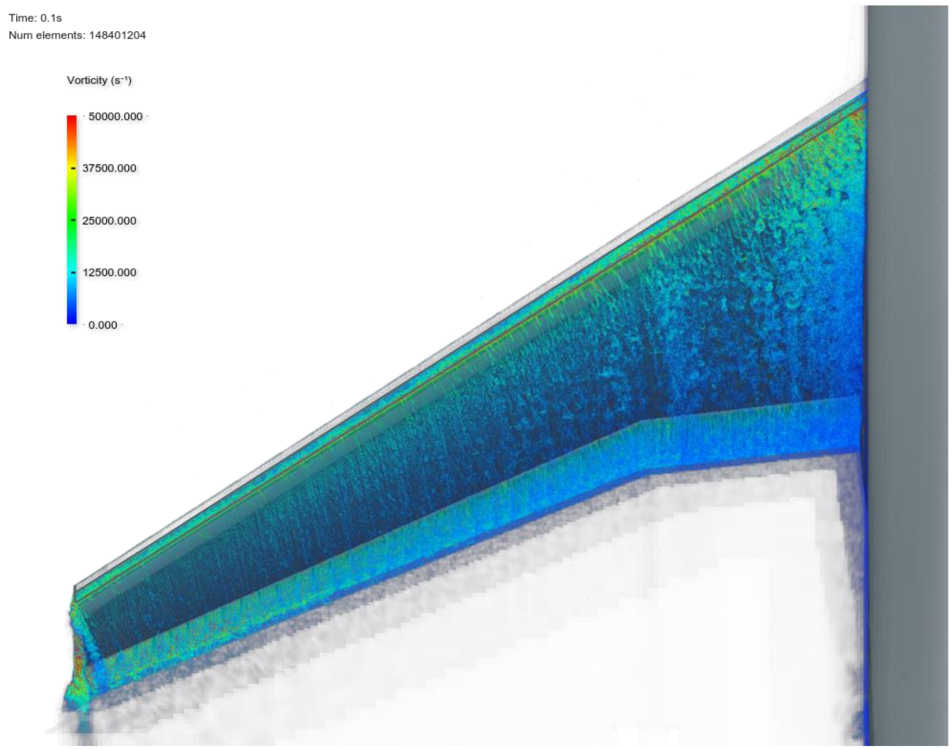
2nd HiLiftPW: Config. comparison

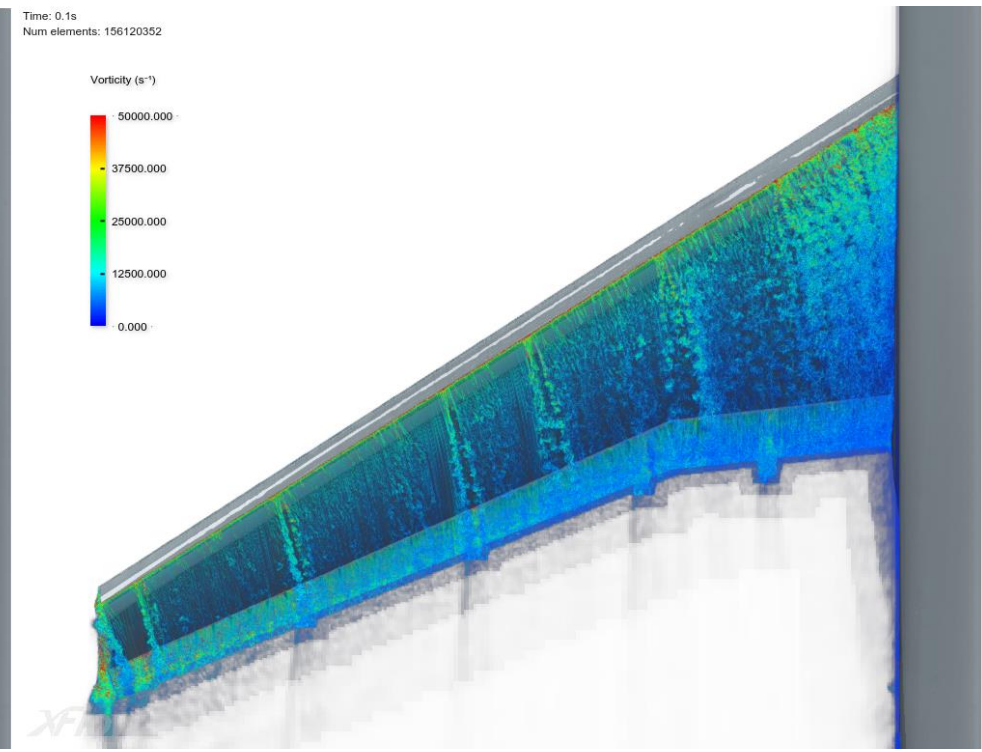
Flow structure influence

$\alpha = 7^o$

Config. 2



Config. 5

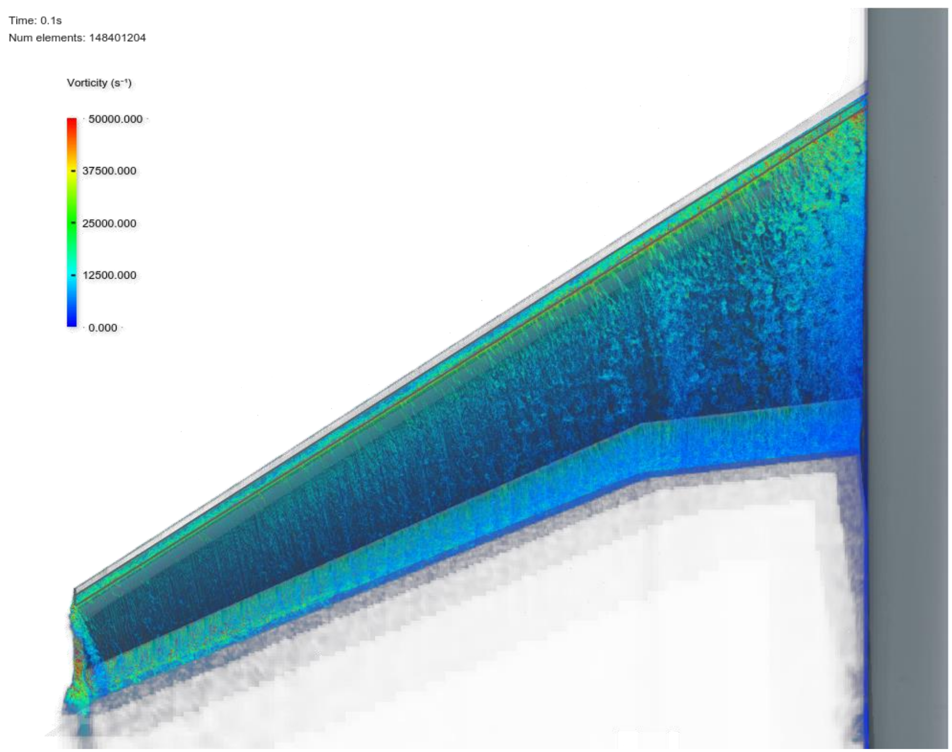


2nd HiLiftPW: Config. comparison

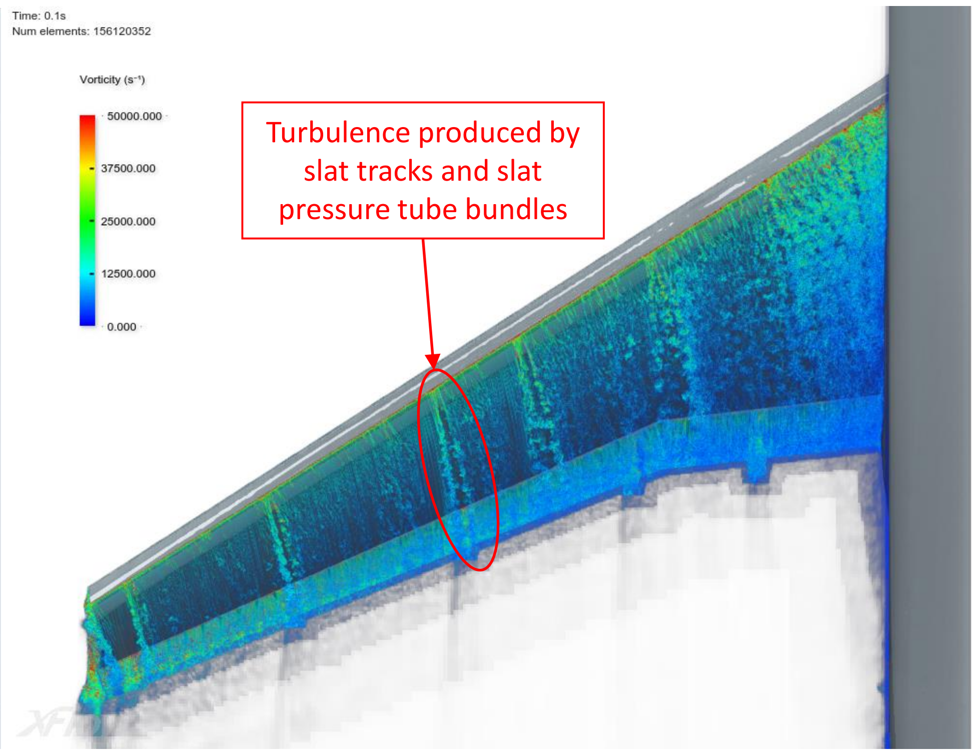
Flow structure influence

$\alpha = 7^{o}$

Config. 2

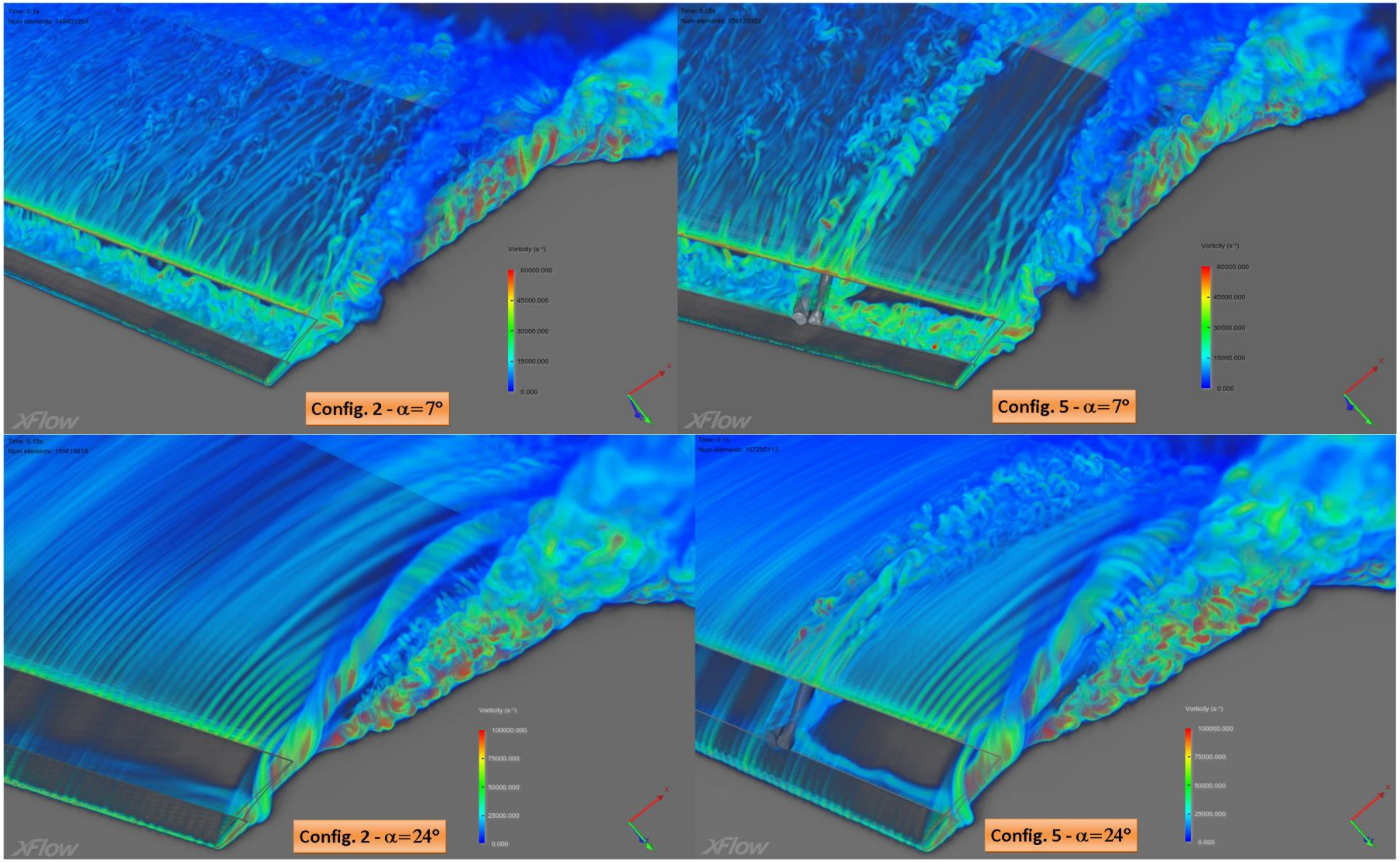


Config. 5



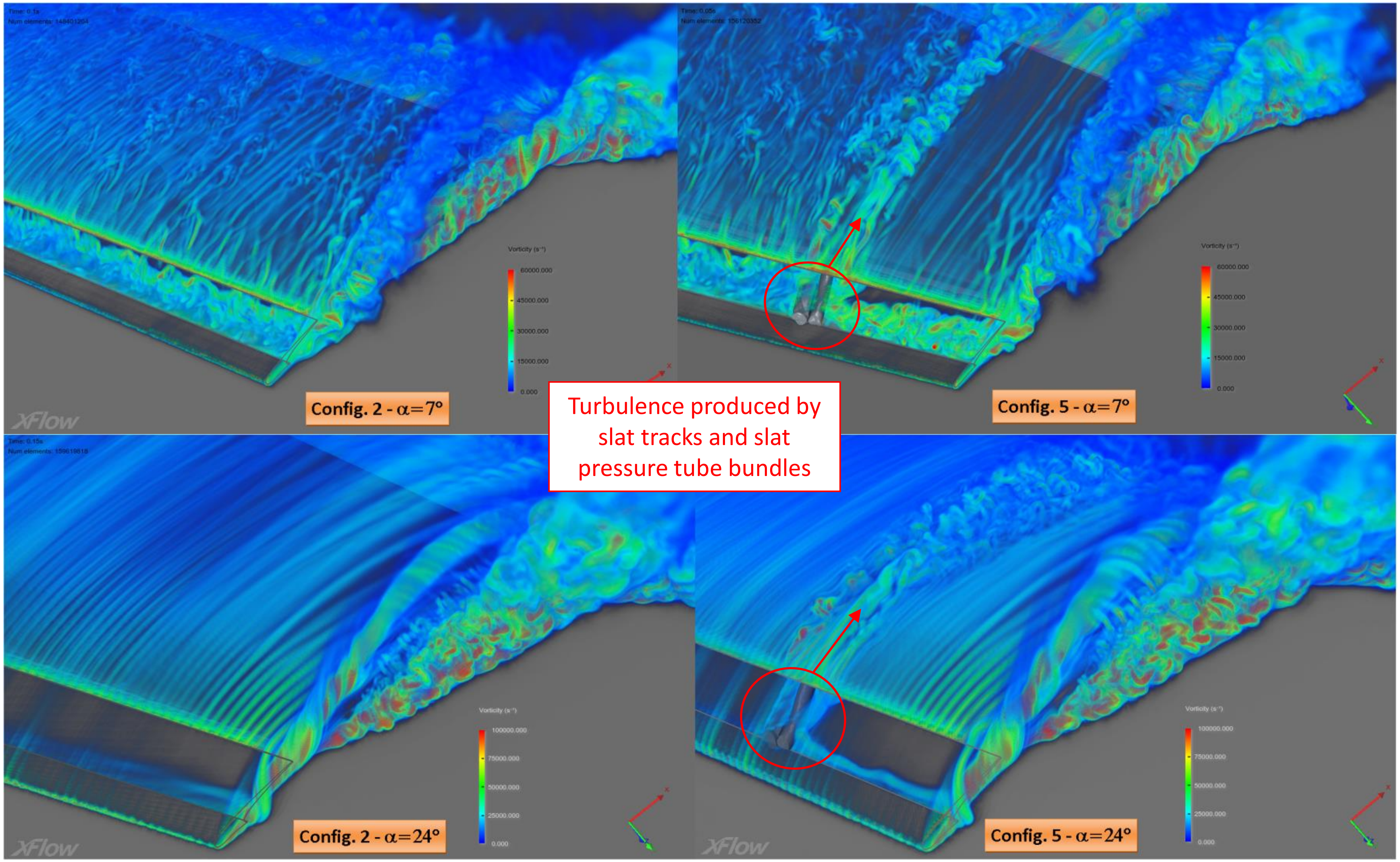
2nd HiLiftPW: Config. comparison

Flow structure influence



2nd HiLiftPW: Config. comparison

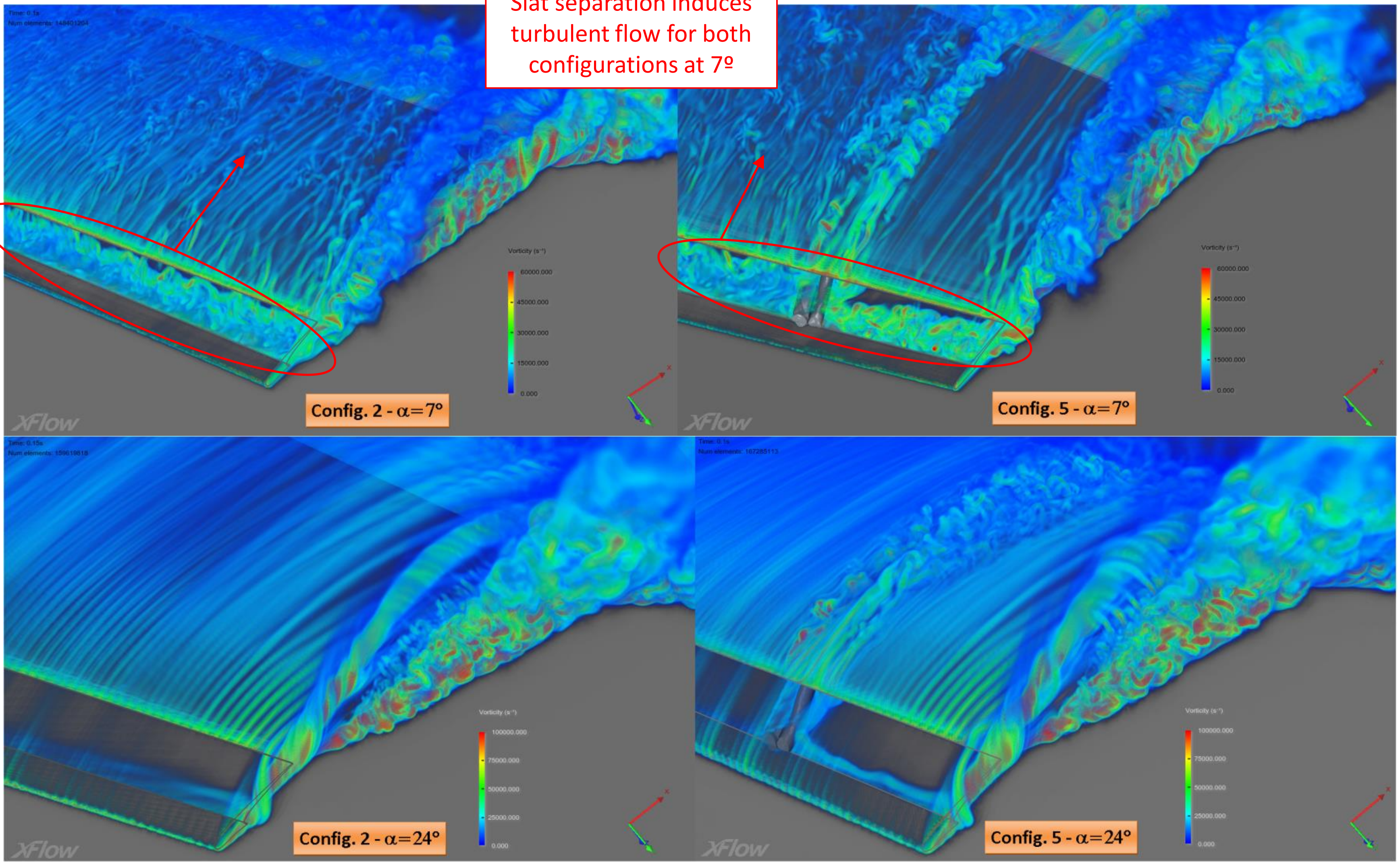
Flow structure influence



2nd HiLiftPW: Config. comparison

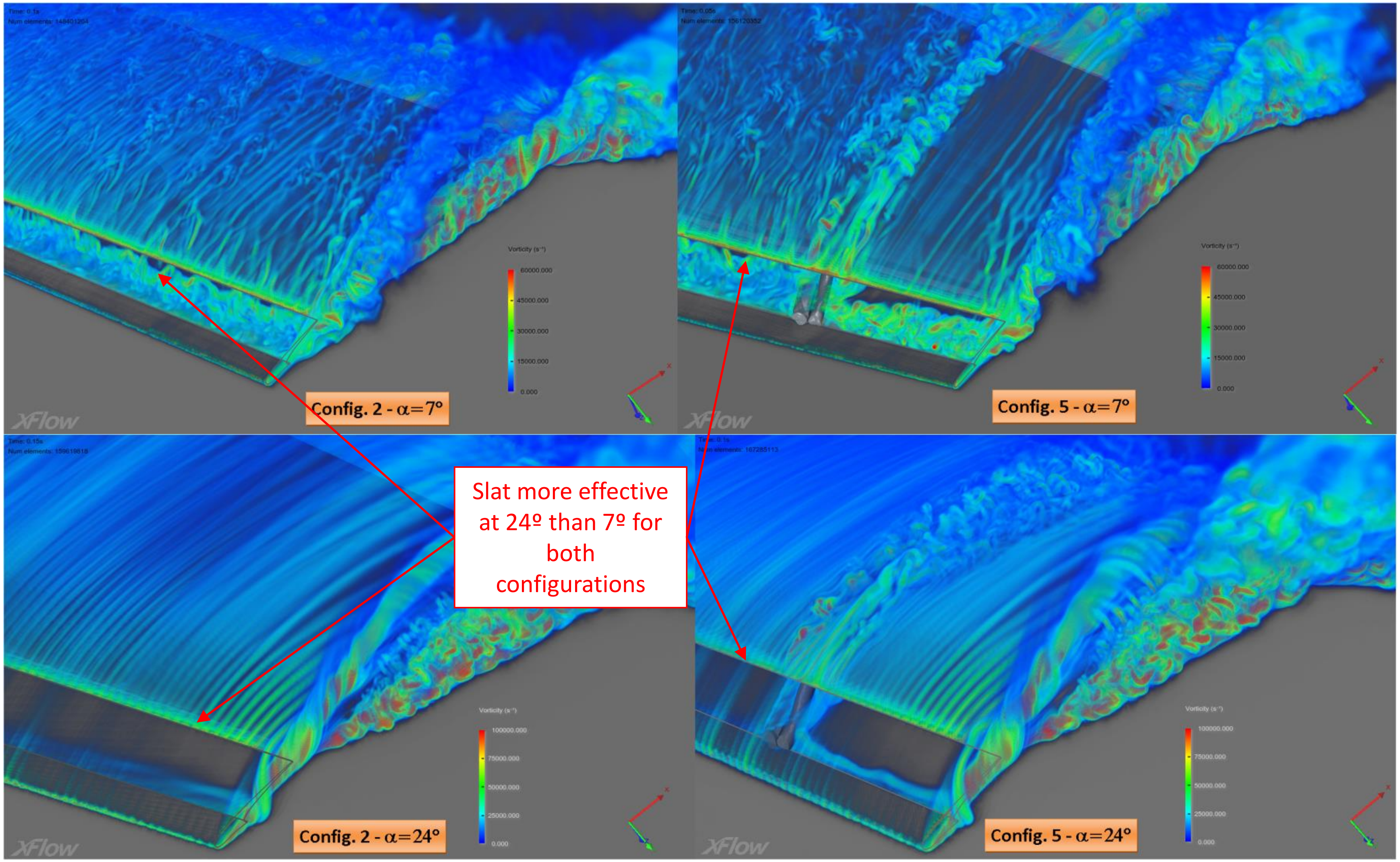
Flow structure influence

Slat separation induces turbulent flow for both configurations at 7º

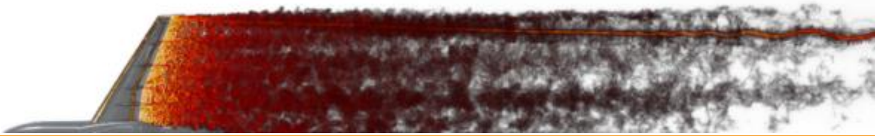


2nd HiLiftPW: Config. comparison

Flow structure influence



Outline



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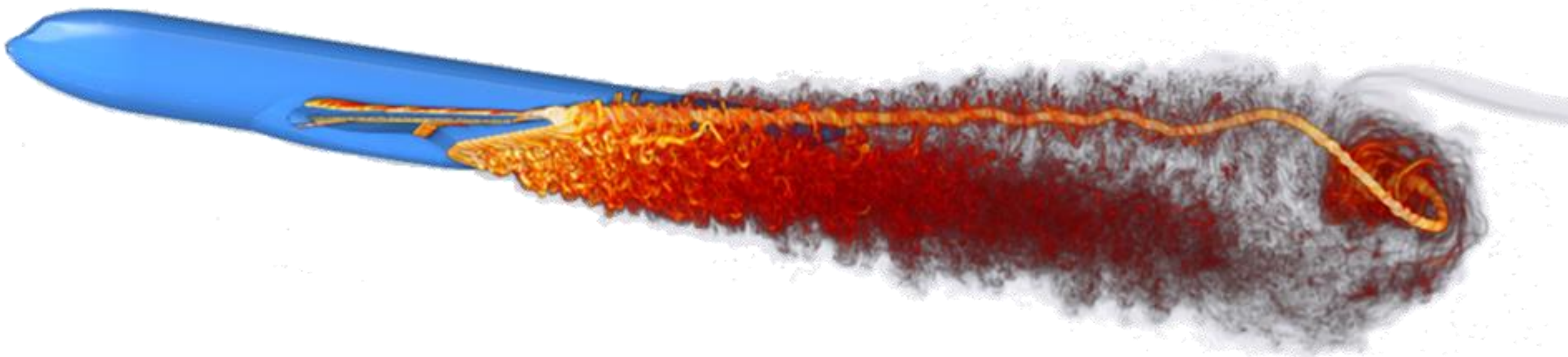
Conclusions

- The **CFD setup** and preparation is **short and easy** despite the complex geometry and analyses shown in the presentation
- Results for the **HiLiftPW-2** are in **good agreement** with experimental data
- XFlow is able to **capture the stall entry** with good accuracy
- The **WMLES** approach provides a **unique insight** on the **flow structure**
- The influence of **small geometrical details** on the flow structure is captured with **no additional effort**
- **XFlow is shown to be well suited for high lift aircraft design**
- Future work to optimize resolution could improve the stall entry prediction



Acknowledgements

<u>**David M. Holman**</u>
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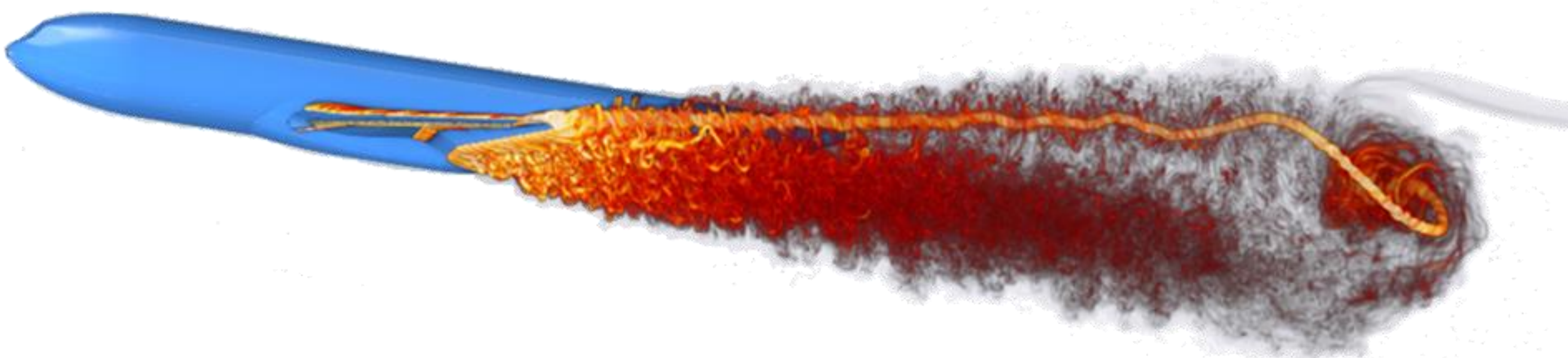
Miguel Chávez Modena
Eusebio Valero Sánchez



Acknowledgements

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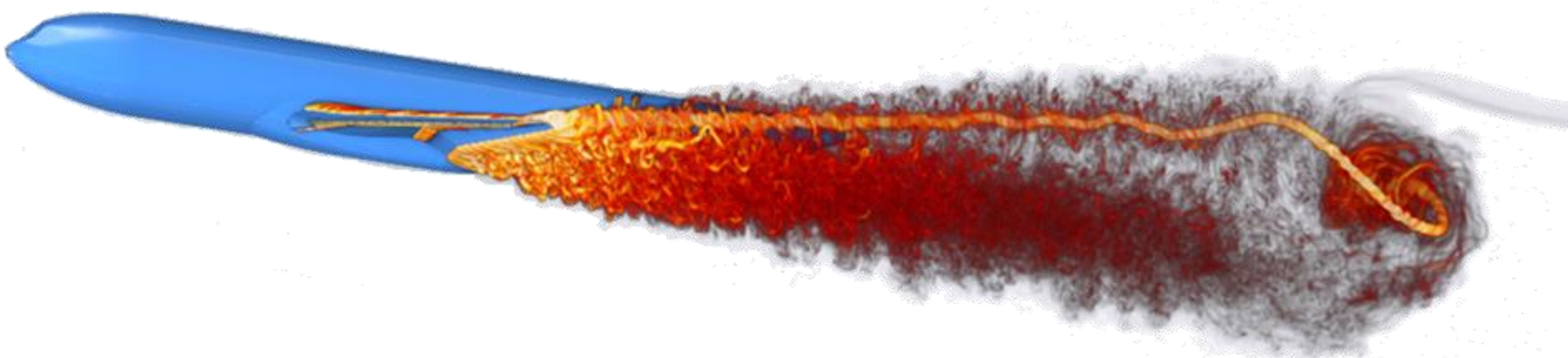
Jonatán Felipe García
Santiago Cruz Díaz



Thank you for your attention!

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