Model-free based pitch control of a wind turbine blade section: aerodynamic simulation

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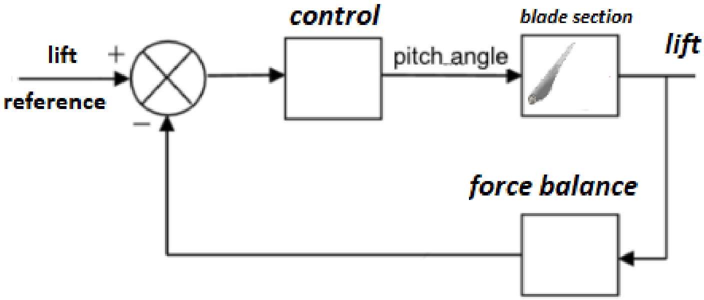
Principle of the lift control

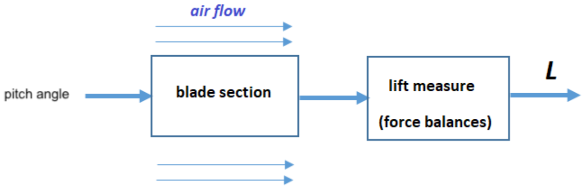
- The control of the lift is performed thanks to a control loop that drives the *pitch angle* according to the measured lift, to track the lift reference



Principle of the lift control

Methodology

The lift L can be modified using the *pitch angle*

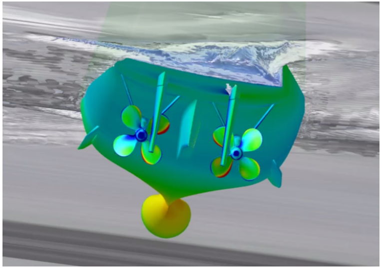


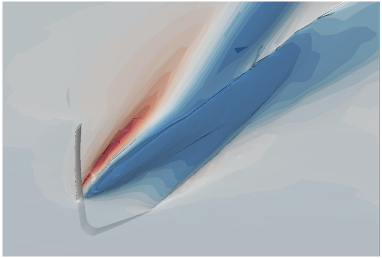
Goal : What is the control to apply to track the lift L (*associated to the output variable* y) closed to a reference L^* (*associated to the output variable reference* y^*)?

ISIS-CFD flow solver

- Developed at ECN/CNRS,
- Part of FINE/Marine from Cadence.

- Two-fluid Navier-Stokes,
- Face-based Finite-Volume discretisation,
- Several RANS and hybrid RANS/LES turbulence models,
- Body motion,
- Adaptive grid refinement.





Model-Free Control methods

- **(Fliess, Join - 2008)** [1] The *model-free control* algorithm can be considered as an extended PI (Proportionnal Integral) controller that uses a very simple local approximation of any complex system
- **(Michel - 2011)** [2] A derivative-free version has been proposed as a "self-tuned integrator" (recent applications in neural-network learning, HIV epidemiology control)

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[1] *Int. J of Control, 2013* & *Int. J of Robust and Nonlinear Control, 2021* presentation available at `https://mps2016.labri.fr/archives/join.pdf`

[2] preprint arXiv (2011) : `https://arxiv.org/abs/1202.4707`

Derivative-free & model-free control

A system $u \mapsto y$ can be controlled to track a reference y^*

Para-model control

$$u_k = \Psi_k . \int_0^t K_i (y_k^* - y_k)\, d\tau$$

with

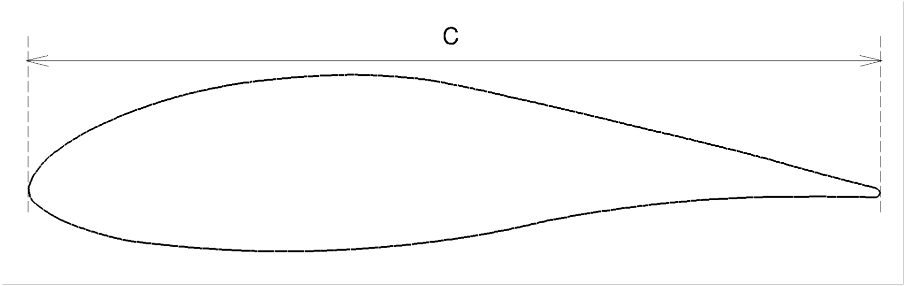
$$\Psi_k = \Psi_{k-1} + K_p (k_\alpha e^{-k_\beta . k} - y_k)$$

where: u_k is the output of the control; y^* is the output reference trajectory; y is the measured output; k is the discrete iteration index; K_p, K_I, k_α and k_β are real positive tuning gains

Ψ is a series that "adjusts" online the gain of the integrator → adaptive control

Test-case

Airfoil shape = 2MW wind turbine blade section at 82% of its length

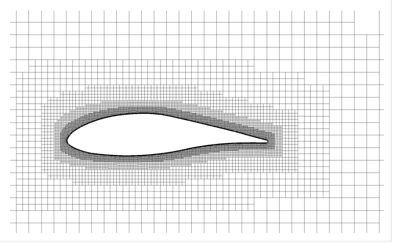


- Chord: C = 1.25 m,
- Upstream velocity: U_∞ = 28.4 m/s, 42.5 m/s, 56.7 m/s,
- Reynolds number: Re = 2.35×10^6, 3.52×10^6, 4.70×10^6,
- Angle of attack: -10° ≤ α ≤ 20°

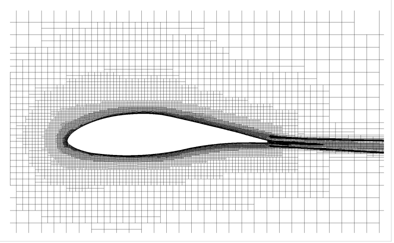
Numerical setup

- Turbulence model: k-ω SST
- Time steps:
  - Re $= 2.35\times10^6$: Δt $= 4.4\times10^{-4}$ sec
  - Re $= 3.52\times10^6$: Δt $= 2.9\times10^{-4}$ sec
  - Re $= 4.70\times10^6$: Δt $= 2.2\times10^{-4}$ sec
- Automatic grid refinement:
  - Refinement criterion: Flux component Hessian
- Size of the computational domain:
  - $-20\times C \leq X \leq 20\times C$
  - $-20\times C \leq Y \leq 20\times C$
- Mesh generated using Hexpress^{TM} ($y^+ < 1$): Unstructured mesh

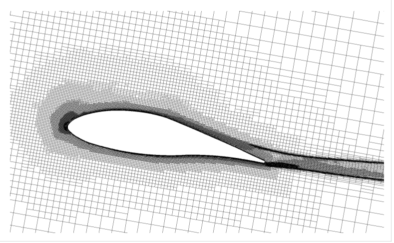
Views of the mesh



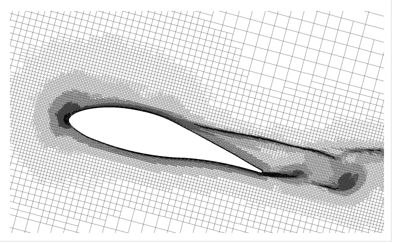
AoA= 0° (original mesh)



AoA = 0° (final mesh)



AoA = 10°



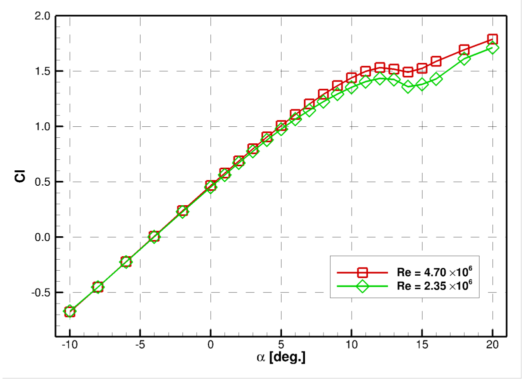
AoA = 15°

Static angles

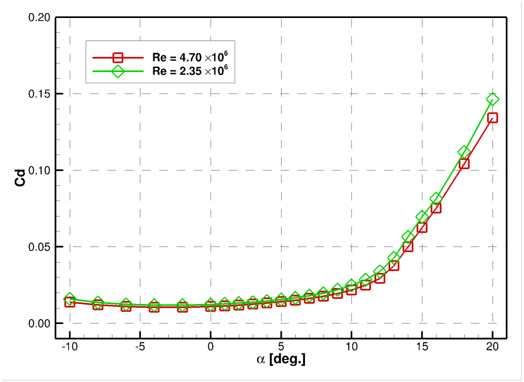
- Further Reynolds number investigated for AoA $\in$ [-5°; 20°]
- $\Longrightarrow$ Know the evolution of aerodynamic forces

Aerodynamic forces

Static angle of attack for Re = 2.35E06 and Re = 4.70E06

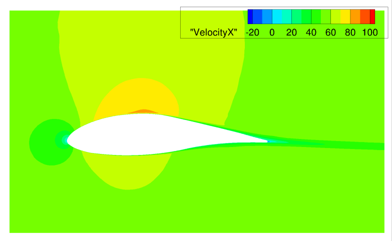


Cl

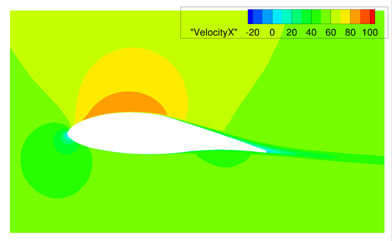


Cd

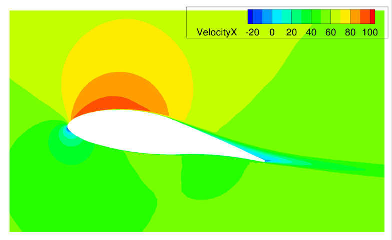
Velocity



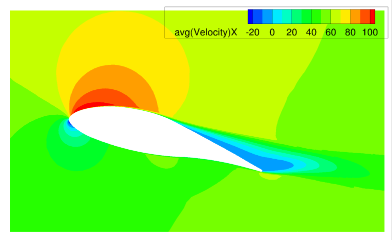
AoA= 0°



AoA = 5°

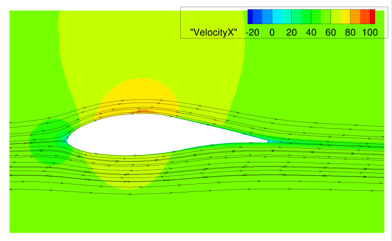


AoA = 10°

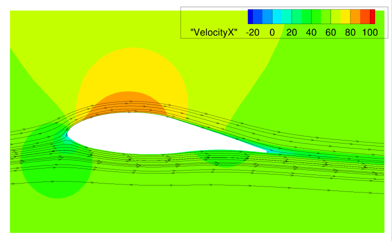


AoA = 15°

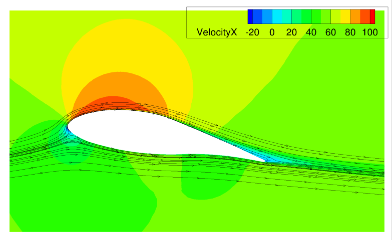
Velocity and streamlines



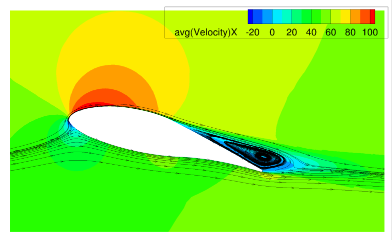
AoA= 0°



AoA = 5°



AoA = 10°



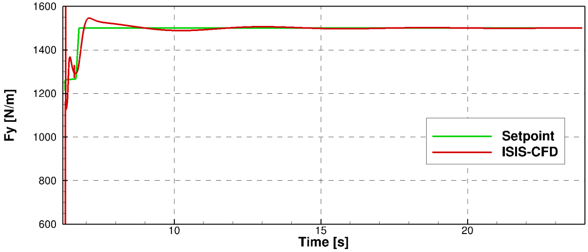
AoA = 15°

Pitch control

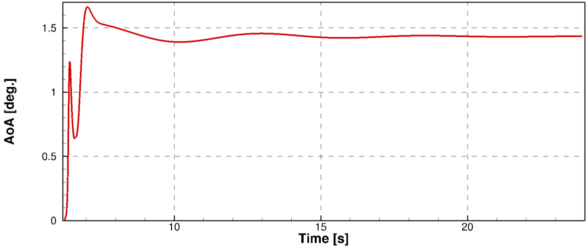
- Objective: Control by the lift force or the lift coefficient
- For some cases, the inlet speed will vary over time
- For all cases, the simulation will start from the simulation result obtained for an AoA of 0°

Pitch control by imposing lift force

$Fy = 1500\ N/m,\ Re = 4.70 \times 10^6\ (U_\infty = 51.715\ m/s)$



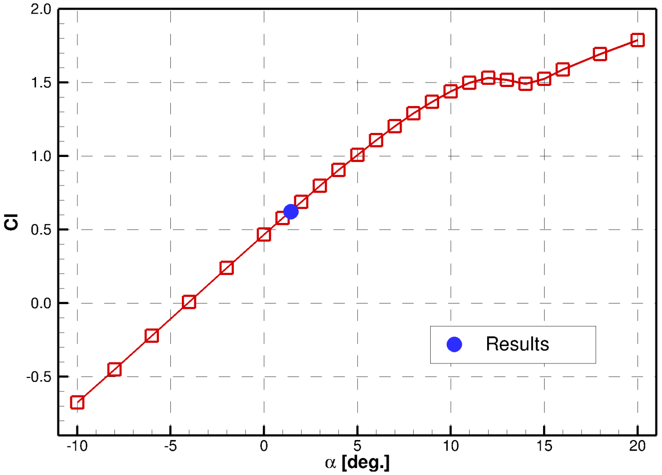
$Fy = 1500\ N/m,\ Cl = 0.75$



$AoA = 1.43°$

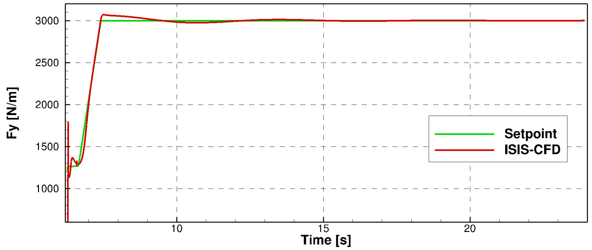
Pitch control by imposing lift force

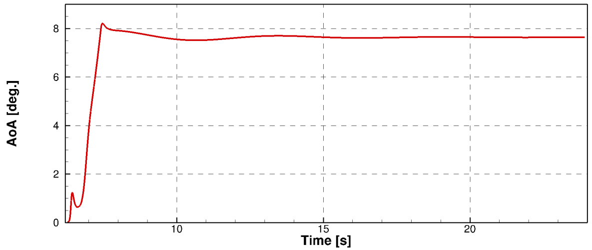
Fy = 1500 N/m, Re = 4.70×10^6



Pitch control by imposing lift force

Fy = 3000 N/m, Re = 4.70×10^6 (U_∞ = 51.715 m/s)



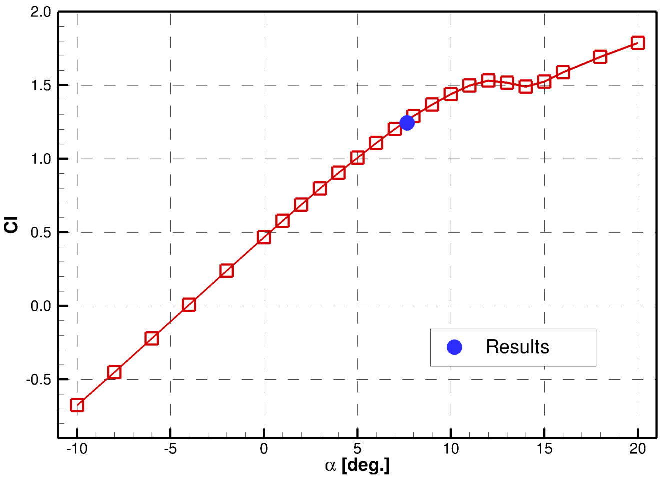


Fy = 3000 N/m, Cl = 1.24

AoA = 7.64°

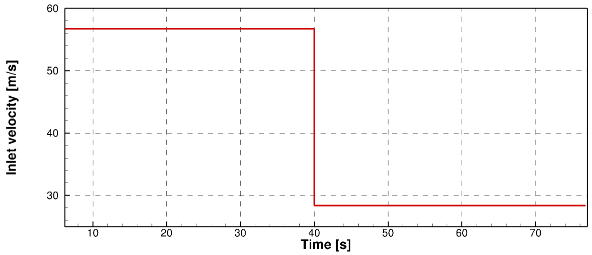
Pitch control by imposing lift force

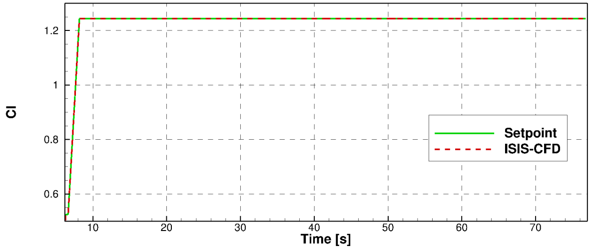
Fy = 3000 N/m, Re = 4.70×10^6



Pitch control by imposing lift coefficient

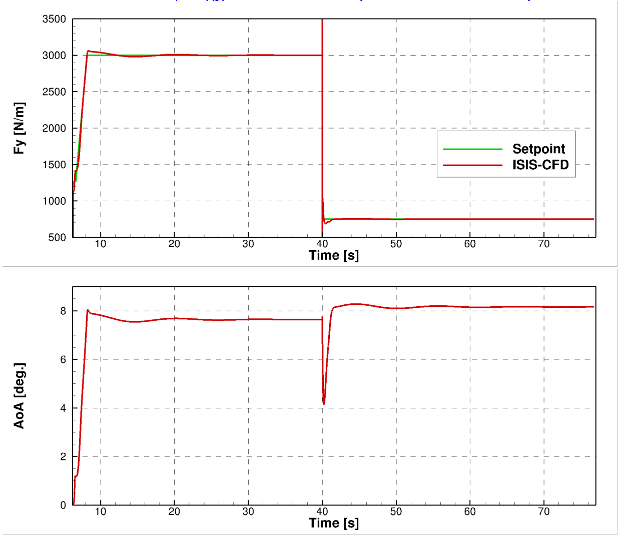
$Cl = 1.24$, $U_\infty = 51.715$ m/s to 28.3575 m/s





Pitch control by imposing lift coefficient

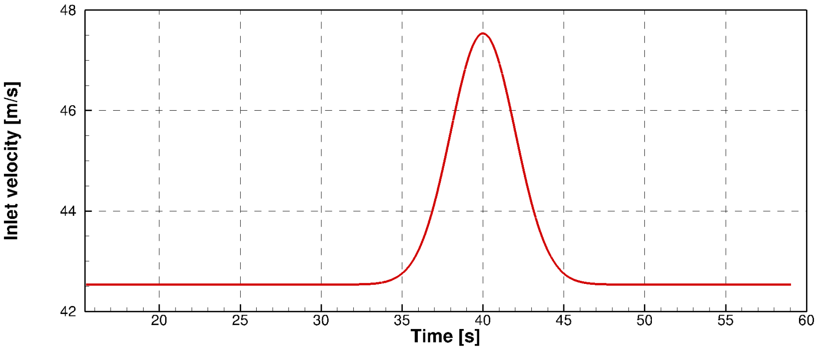
$Cl = 1.24$, $U_\infty = 51.715$ m/s to 28.3575 m/s



Pitch control by imposing lift force

Fy = 1347 n/m, U_∞ = 42.54 m/s (Re = 3.52×10^6

Inlet velocity with a gust

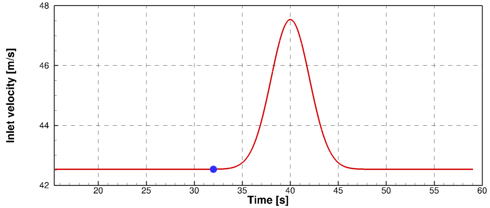


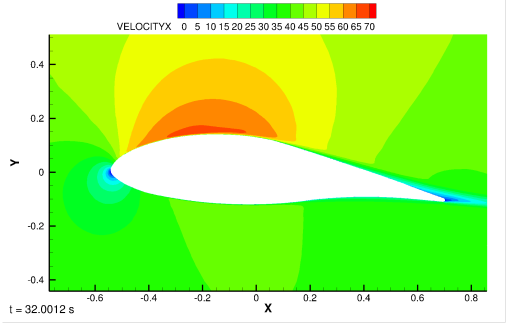
Pitch control by imposing lift force

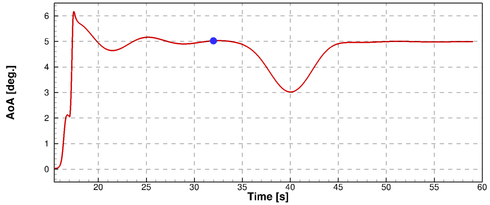
Fy = 1347 n/m, U_∞ = 42.54 m/s (Re = 3.52×10^6

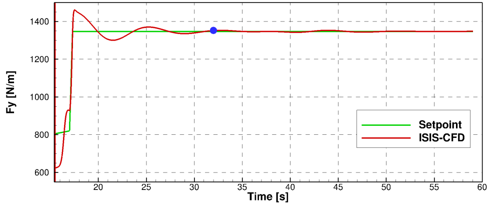
t = 32.00 sec: U_∞ = 42.54 m/s

$\Longrightarrow$ AoA = 5.02°







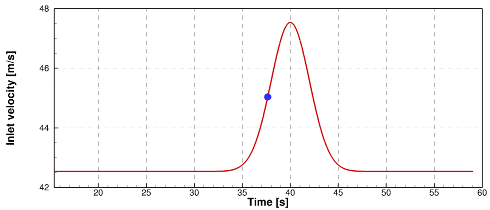


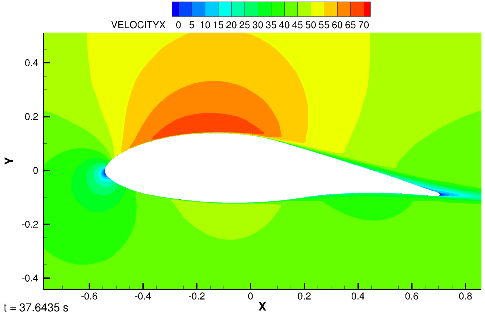
Pitch control by imposing lift force

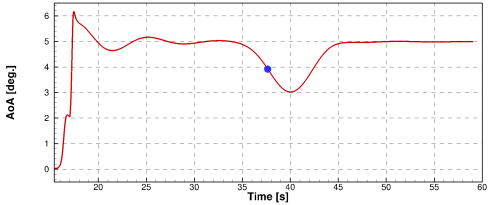
Fy = 1347 n/m, U_∞ = 42.54 m/s (Re = 3.52×10^6

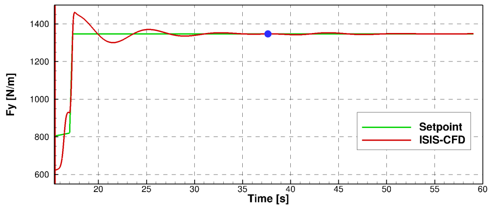
t = 37.64 sec: U_∞ = 45.03 m/s

$\Longrightarrow$ AoA = 3.92°







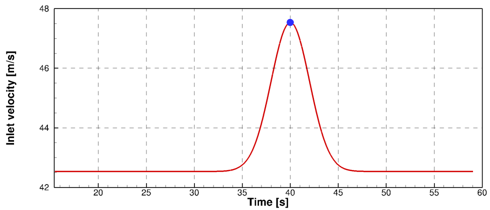


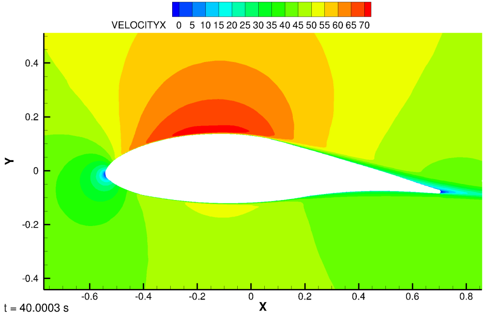
Pitch control by imposing lift force

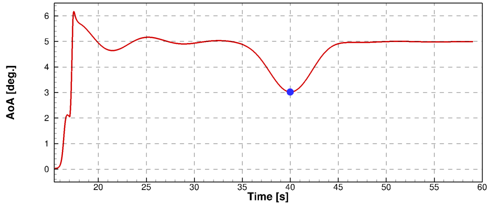
Fy = 1347 n/m, U_∞ = 42.54 m/s (Re = 3.52×10^6

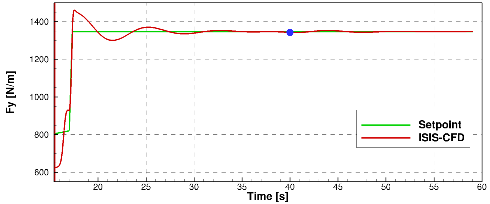
t = 40.00 sec: U_∞ = 47.54 m/s

$\Longrightarrow$ AoA = 3.02°







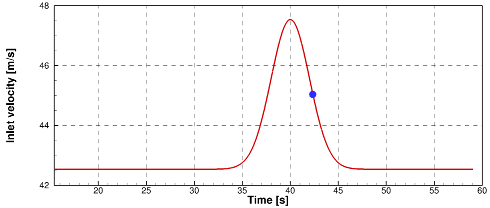


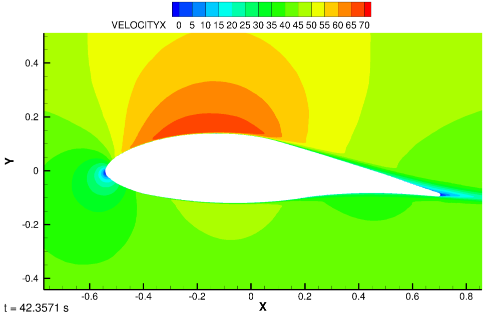
Pitch control by imposing lift force

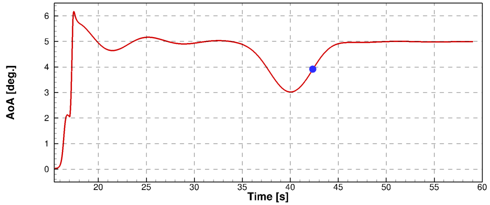
$Fy = 1347$ n/m, $U_\infty = 42.54$ m/s ($Re = 3.52\times 10^6$

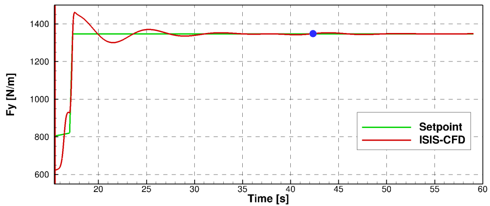
$t = 42.36$ sec: $U_\infty = 45.03$ m/s

$\Longrightarrow$ AoA $= 3.92°$







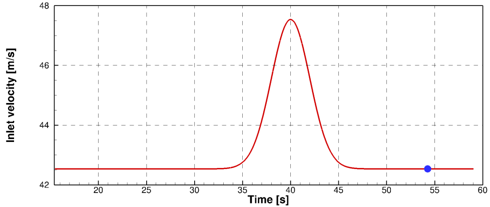


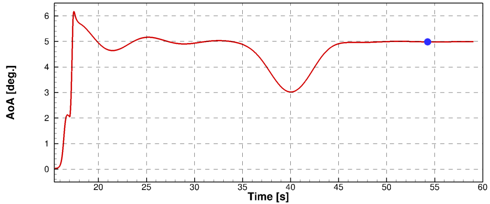
Pitch control by imposing lift force

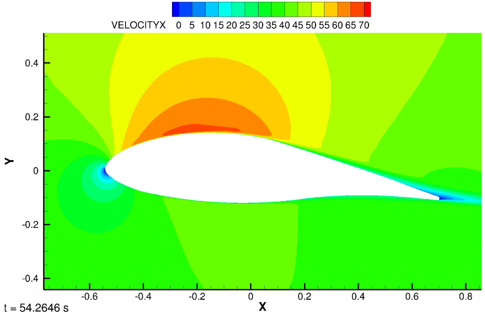
Fy $= 1347$ n/m, $U_\infty = 42.54$ m/s ($Re = 3.52\times10^6$)

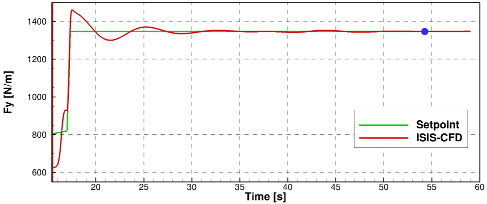
t $= 54.26$ sec: $U_\infty = 42.54$ m/s

$\Longrightarrow$ AoA $= 4.98°$









Conclusion

- A model-free control based algorithm for the manipulation of the lift force using pitch angle has been used numerically
- Different scenarios of tests[3] have been carried out to illustrate the robustness of the control
- Good tracking performances have been obtained despite the strong perturbations at the beginning of the simulation
- Further studies will be carried out to compare with the experimental data
- 3D simulations are also planned

[3] Video available at `https://uncloud.univ-nantes.fr/index.php/s/jKqz4jkWyswSiCb`

Thank you for your attention!