Bluff Bodies as a Potential Open Challenge Problem for Active Flow Control

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AIAA Flow Control Meeting. AIAA Flow Control Applications and Impacts Discussion Group

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Outline of the talk

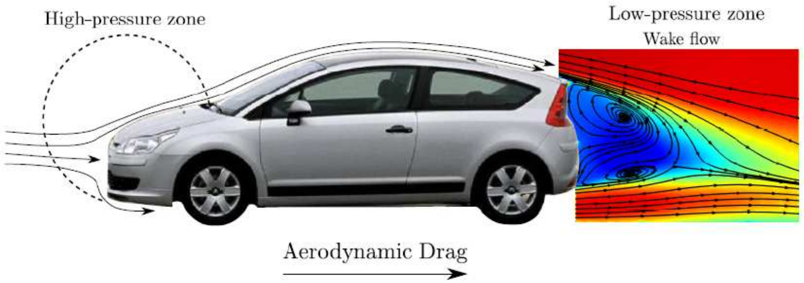
- Context and proposition
- Case A: Square back wake
- Case B: Slanted and smoothed aft geometry
- Synthesis

Context : 3D bluff bodies

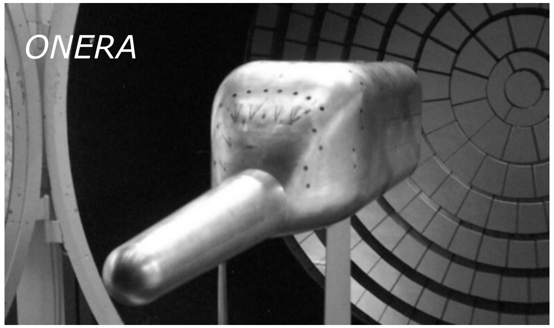
- **Locally or massively separated flows**
  - Pressure induced, inertial
  - Shedding of vorticity in the flow.

- **Goals of the open challenge**
  - To develop techniques for bluff body wake manipulation (actuation methods, **A**ctive **F**low **C**ontrol approaches)
  - To understand the origins of wake and drag changes

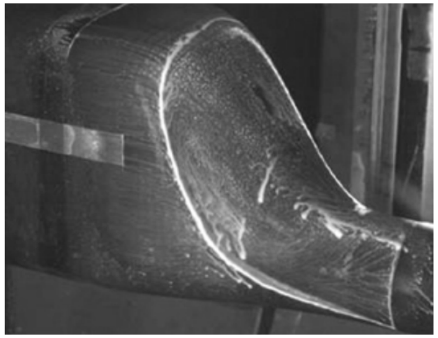
Context : 3D bluff bodies



- **Road vehicles**
  - Design driven by functionality, comfort, customer feedback including subjective aspects (brand, look, feelings while driving, …)
  - ***Drag reduction*** *and* ***driving stability*** *are key problems.*



Le Pape, Lienhart et AL JAHS 2015

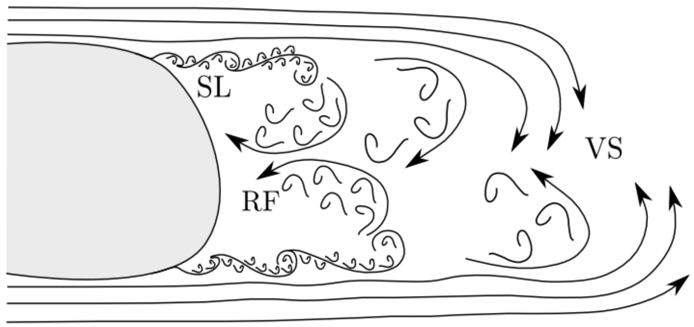


Woo, Glezer et al AIAA 2016

- **Aeronautics**
  - To cope with functionality and aerodynamics
  - Helicopter or airplane transport : Large, flat loading ramps, poor aerodynamics of the aft body
  - ***Fuselage drag reduction*** *and* ***unsteady load alleviation*** *are key challenges.*

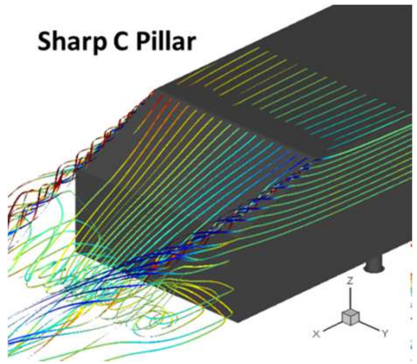
Wide range of length and time scales at significant Re (≈10^6)

- **Large scale mode: global wake mode**
  - **Vortex shedding (VS)**
    - Absolute instability, Self sustained oscillations
  - **Reflexional Symetry Breaking (RSB)**
    - Random switching with a long time dynamics
    - Observed in the laminar regime for a wide range of *Re* *(Grandemange, Cadot, JFM 2013, PRE 2012)*



Barros PhD 2015

- **Specific flow structures**
  - **Turbulent shear layers surrounding the near wake**
    - Convective instability, Noise amplifier behavior – *Ho & Huerre ARFM 1984*
  - **3D conical vortices of trailing type** – *Edstrand JFM 2016, Jerman – 2016*



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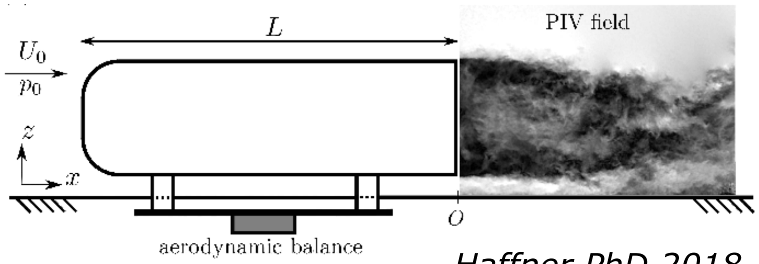
Proposition of two open challenges problems for AFC

- **A: Square back wake**
  - **Goal:** Obtain a robust AFC strategy for a canonical near wake
  - ***<u>Whatever model alignment</u>*** *(perfectly aligned, slight yaw & pitch,…)*

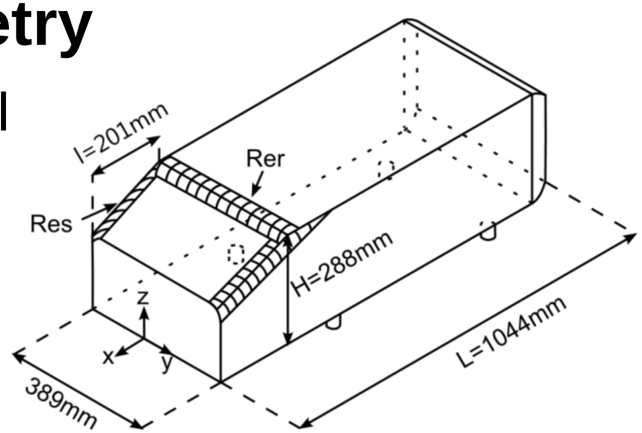
$\Rightarrow$ Drive the wake toward an unsteady symmetric state
$\Rightarrow$ Prevent the slow asymmetric dynamics



Haffner PhD 2018

- **B: Slanted and smoothed aft geometry**
  - **Goal:** Deal with introduction of longitudinal vorticity in the near wake.

$\Rightarrow$ Find relevant strategies upstream, at or downstream separation !



Rossitto PhD 2016

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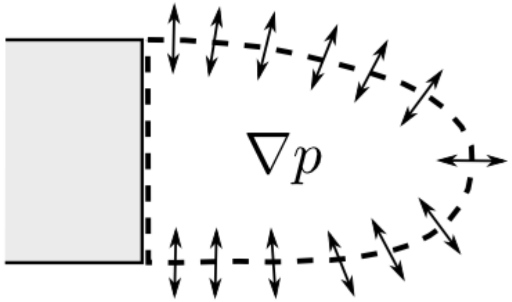
A focus on the Drag force : Pressure drag

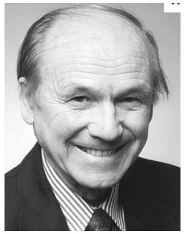
- **First order role of flow properties at separation**
  - Shape of the body,
    Mass and Momentum exchange
    across the shear layers

    ↕

  - Cp magnitude and mean streamline
    curvature at separation



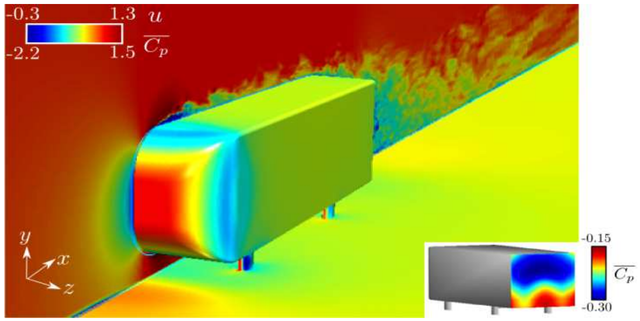
Barros JFM 2016



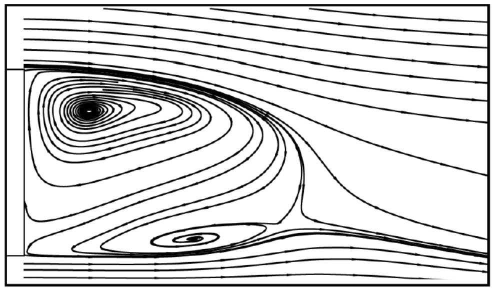
$$\frac{L_r}{H^\star}$$

Wake bluffness
Aspect ratio
Rohko 1955

- **Clear footprint of the recirculating (slow) dynamics**
  - Large scale rotating flow in the near wake



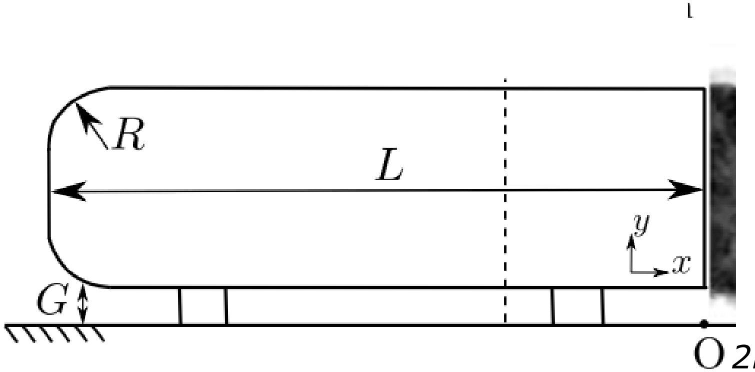
Large Eddy Simulation Östh JFM 2014

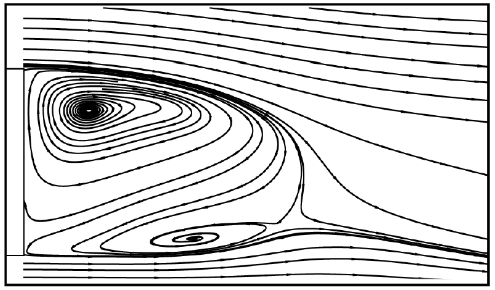


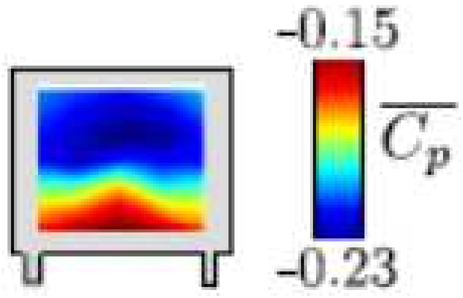
2D PIV in the wake. Barros PhD 2015

Square back wake : states of the near wake

- **Ahmed body** *(Barros et al. JFM 2017)*







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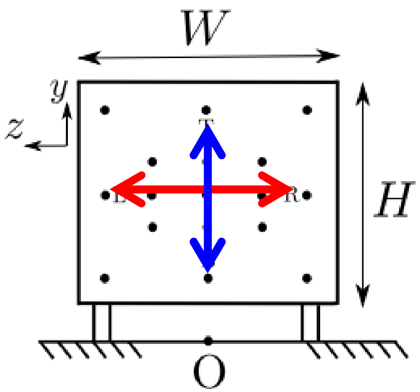
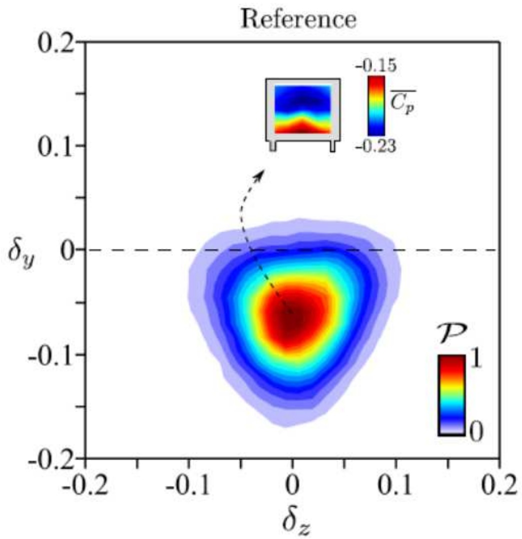


$\delta_z = C_{pL} - C_{pR}$

$\delta_y = C_{pT} - C_{pB}$



Normalized PDF P(δy; δz)

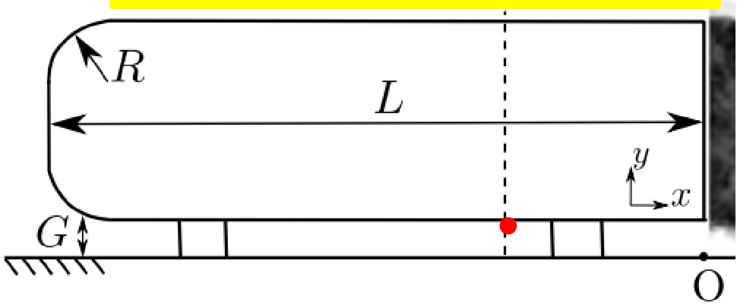
δ_z : Lateral « pressure gradient »

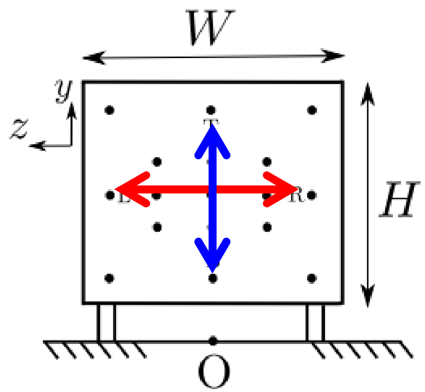
δ_y : Vertical « pressure gradient »

Square back wake : states of the near wake

- **Ahmed body** *(Barros et al. JFM 2017)*

Position of « *d* » Perturbation :
x/H=-1





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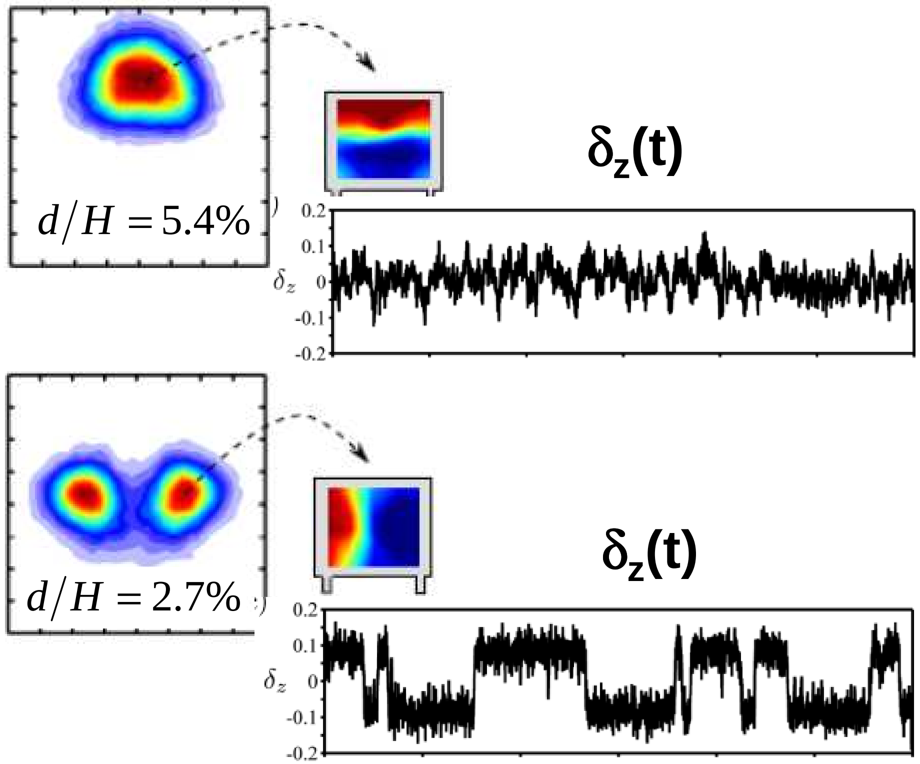
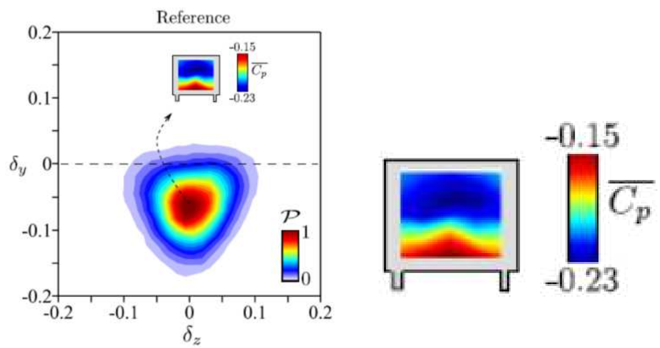




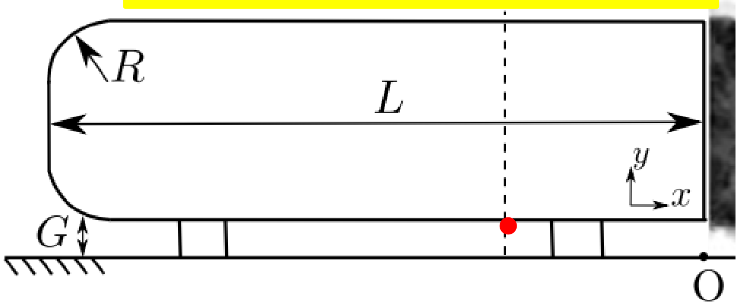
δ_z **: Lateral « pressure gradient »**

δ_y **: Vertical « pressure gradient »**

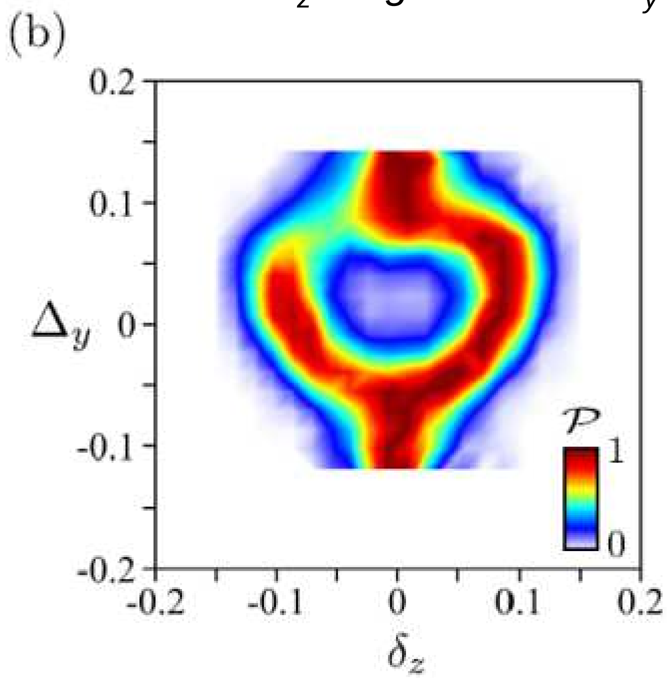
Square back wake : states of the near wake

- **Near wake states are asymmetric**

Position of « *d* » Perturbation : x/H=-1



PDF of δ_z for given mean Δ_y



- **Similar observations for :**

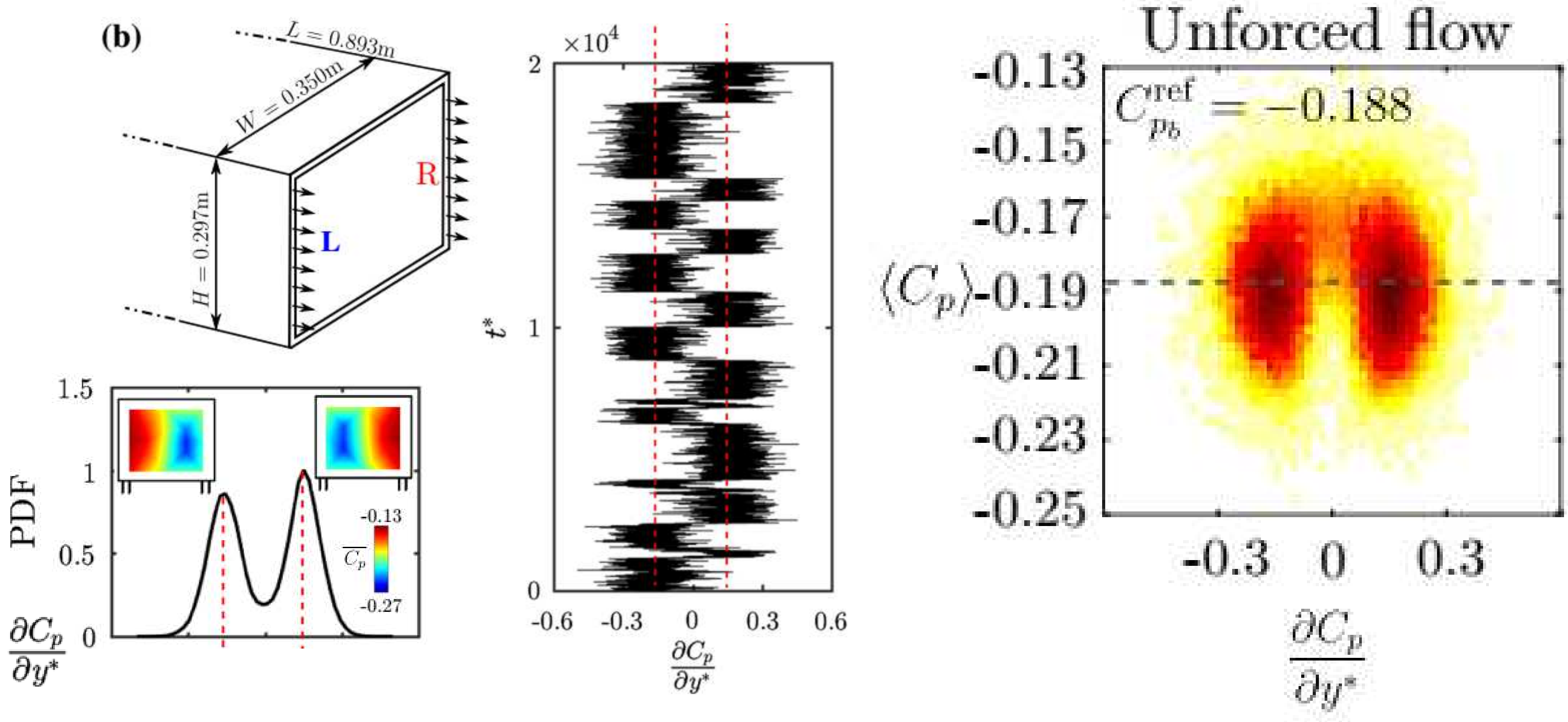
→ **Variable Pitch** *(Bonnavion et Al.)*

→ **Variable Yaw** *(Li et Al.)*

Description of symmetry breaking by a stochastic models
Rigas et al. 2014, Brackston et al. 2016, Barros et al. 2017

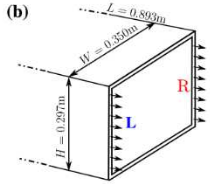
Square back wake : example of lateral asymmetry

- **Choice of a carefully aligned bistable situation** *(Grandemange et al. JFM 2013, Li et al. EIF 2016)*

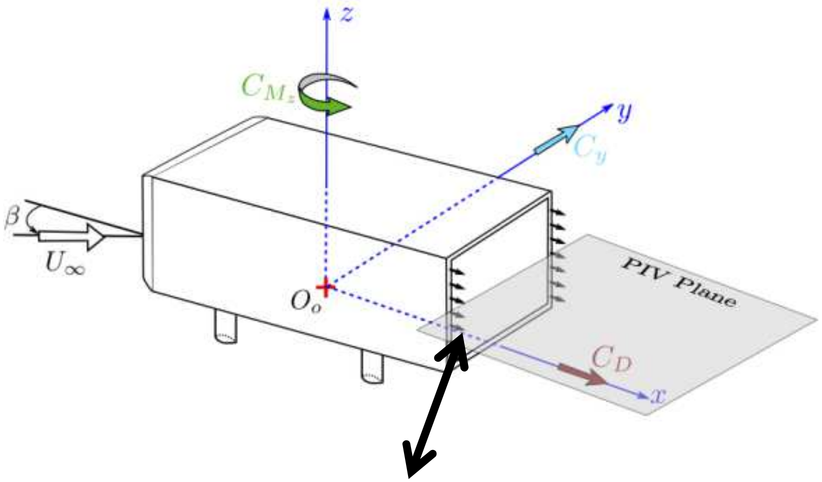


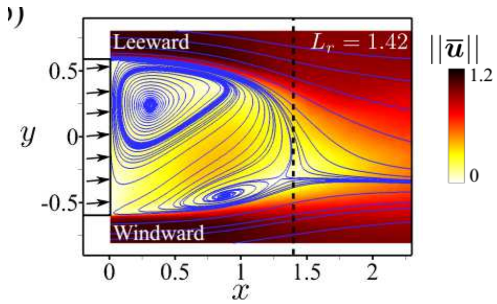
  - **Transitional flow state are slow (≈ 40 Convective times H/U$_\infty$), corresponds to Higher <C$_p$> and lower Drag.**
  - ⇒ **Potential for drag reduction** *(Li et Al. EiF 2016, Brackston JFM 2016)*

Square back wake : extension to moderate yaw

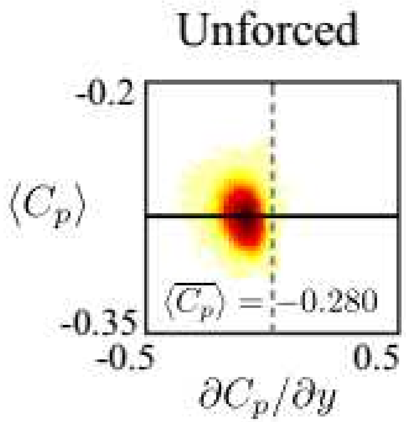


- **Generally, the AFC should be applied to all types of asymmetry. Example of Moderate Yaw.** *(Li et al. 2018 Submitted)*

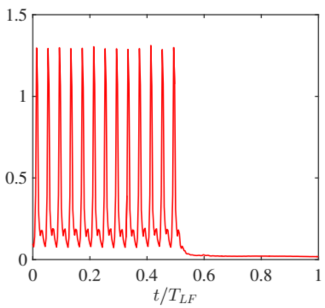




Natural flow :
asymmetry

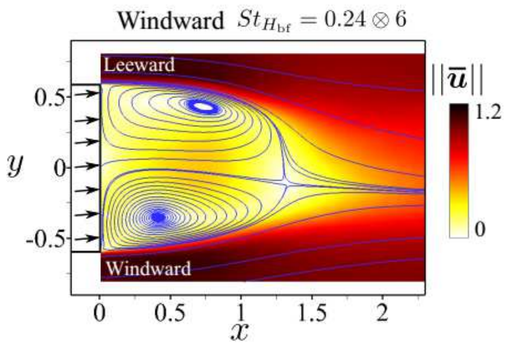


ΔC_D = -7%

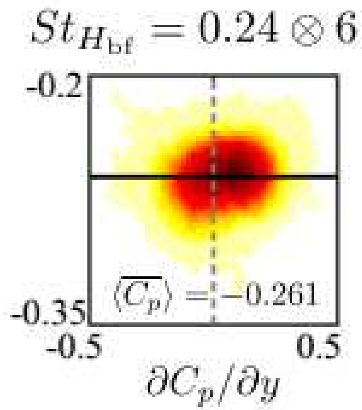


Windward side :
Modulation of pulsed jets

$St_H = 0.24 \otimes 6$

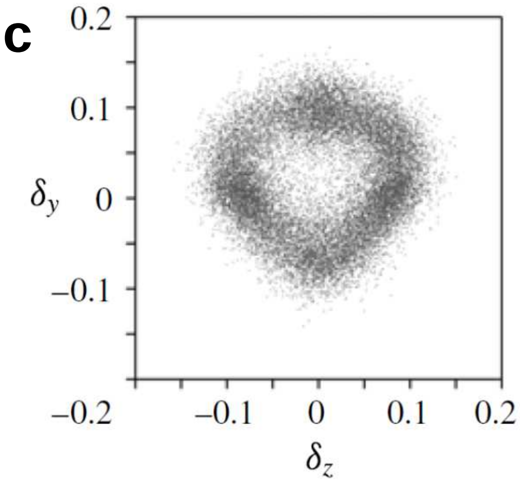


Actuated flow :
mean symmetry



Wake asymmetry : control target ?

- **Quasi-steady states of near wake are asymmetric**
- **Asymmetric states are responsible for higher pressure drag**



- **Practical control target :**

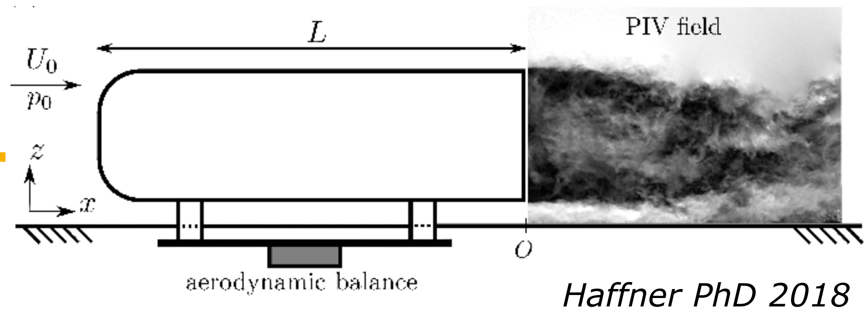
  $\Rightarrow$ Drive the wake toward an unsteady symmetric wake.

  $\Rightarrow$ Prevent the slow organization dynamics of the asymmetric state

  $\Rightarrow$ **Do not organize and enhance the shedding mode !!**

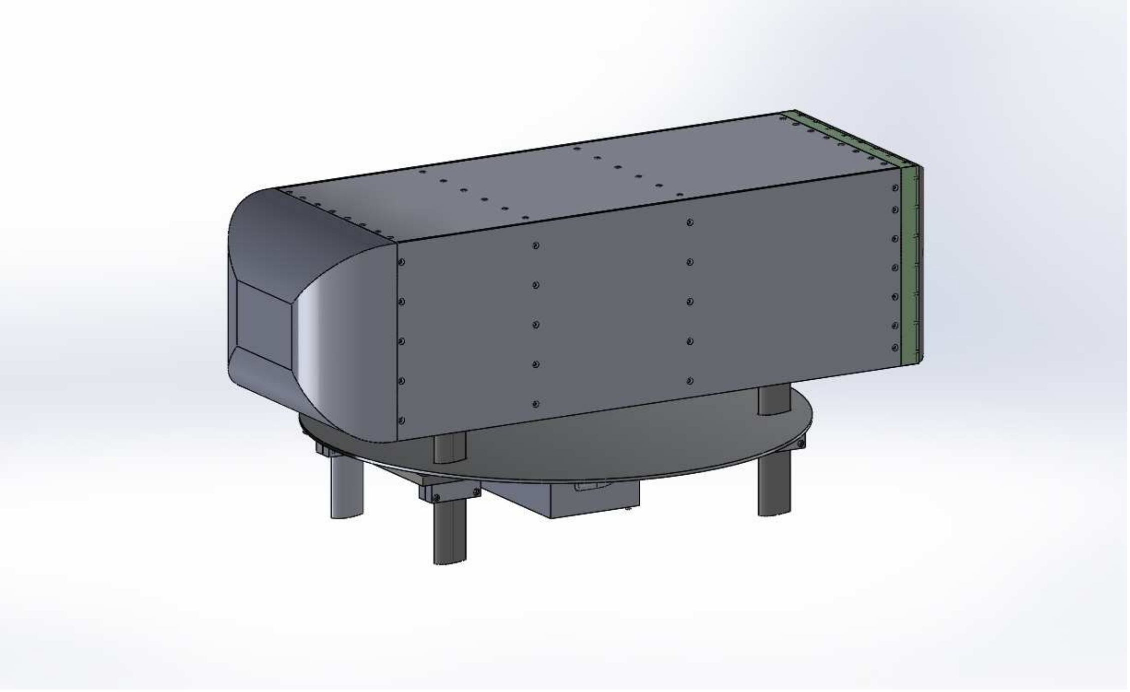
- **Valid goal for a wide range of situations : Free-stream incidence, perfect alignement, moderate yaw & pitch, surface roughness, …**

Square back wake



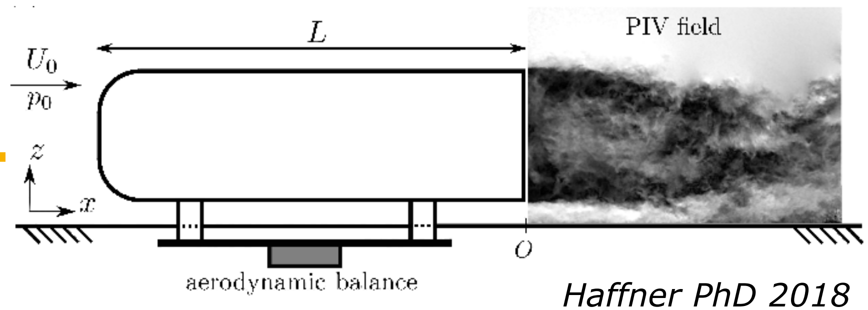
Haffner PhD 2018

- **Proposed geometry**
  - Rectangular Square back (Width/Height ratio : 1,2)
  - Similar to Ahmed geometry
  - Careful design of the <u>front/nose surface to avoid flow separation</u>.



- Geometry designed by a joint effort with industrial partners
- **PSA** and **Volvo Trucks** in **ANR Project *Activ-Road***
- Agreement to share geometry.

Square back wake



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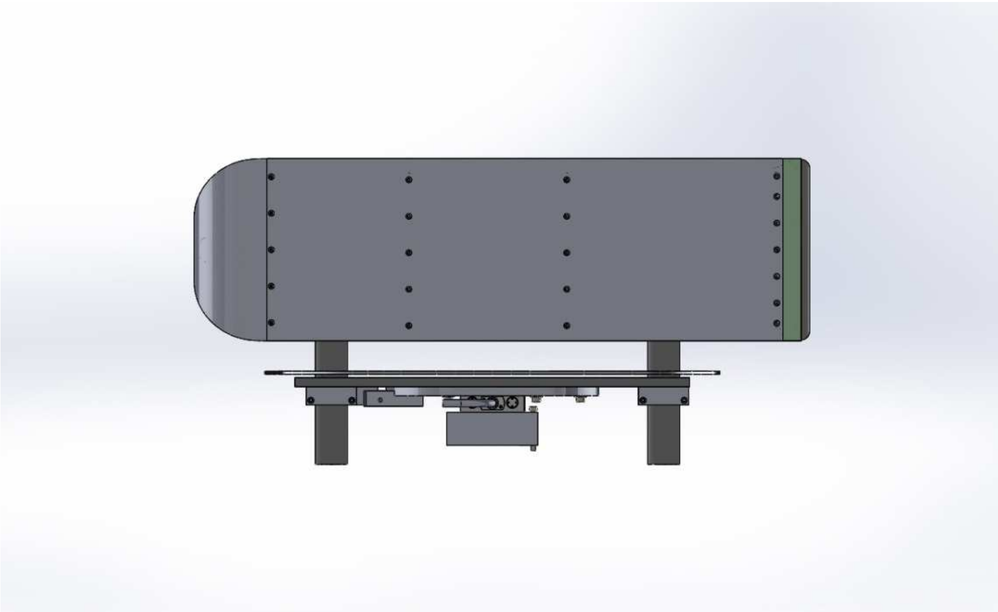

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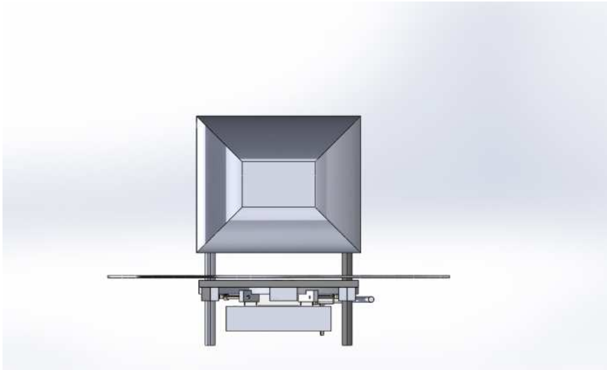
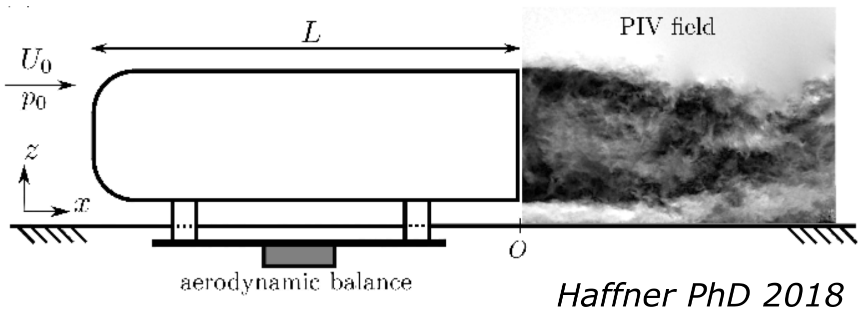


Square back wake

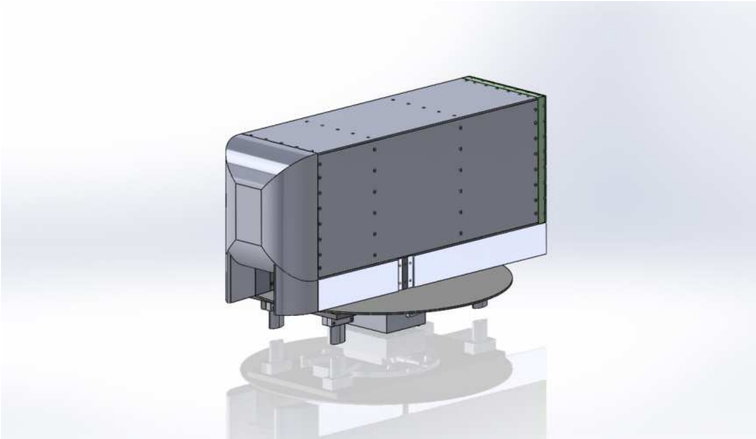


Haffner PhD 2018

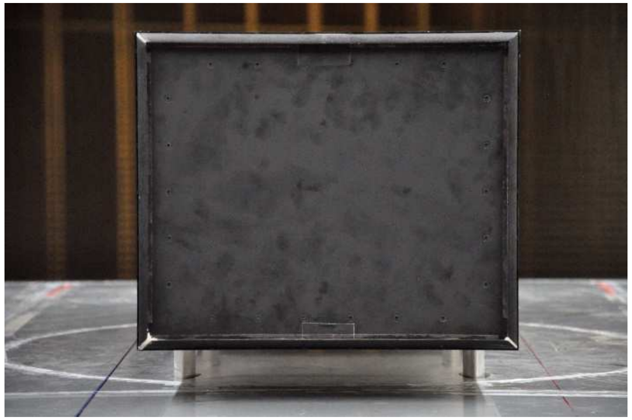
- **Proposed geometry**

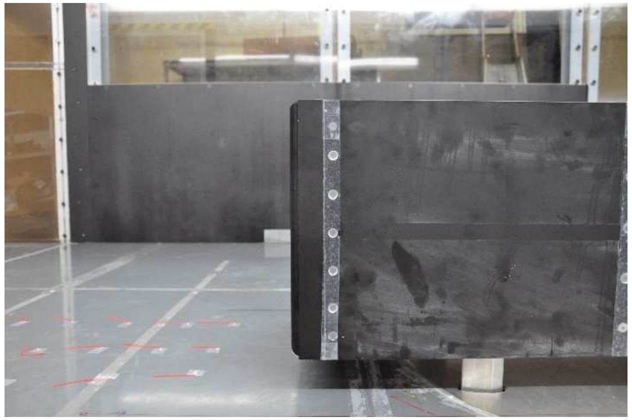
  - Variable Ground clearance :
    - « High values » G/H ≈ 16% : High underbody flow and near wake detached from ground
    - « Low values » G/H ≈ 1% : Weak underbody flow and 3D backward facing step
    - « Critical » intermediate values are found for G/H ≈ 5% corresponding to high drag
    - *See Grandemange et al (PoF 2013) ;*

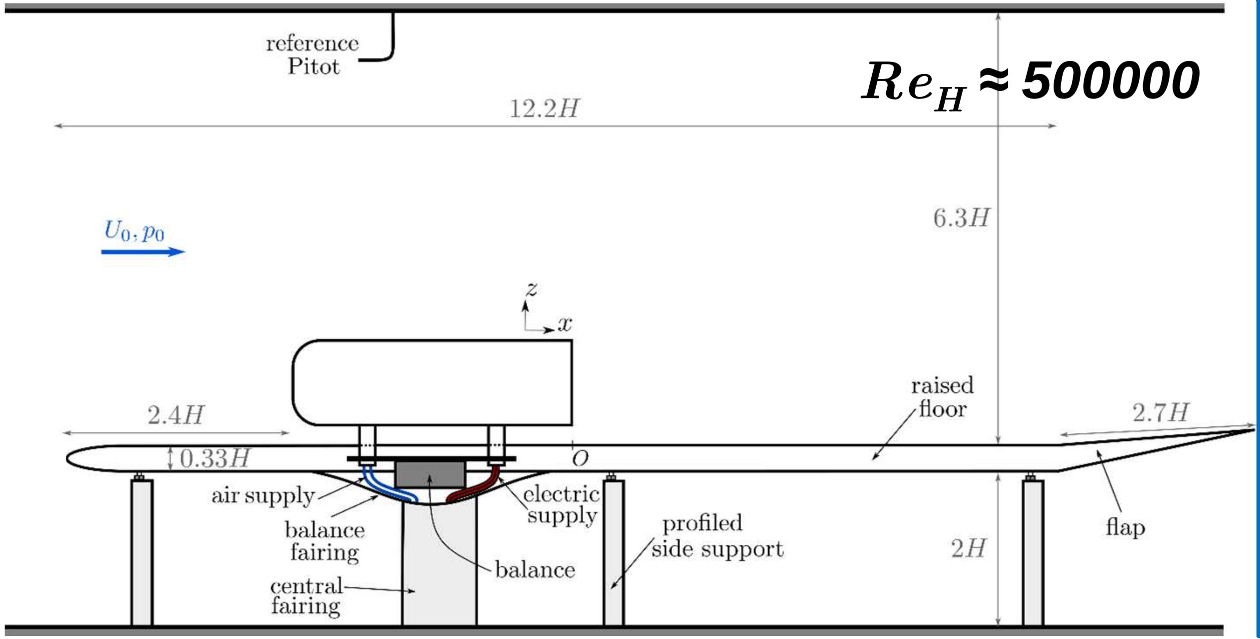
      Castelain et al. (JWEIA 2018) for truck configurations.



Square back wake : experimental set-up

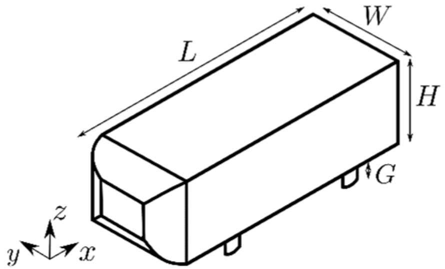






$Re_H \approx 500000$

Main geometric features



$L = 1\ m$

$W = 0.36\ m$

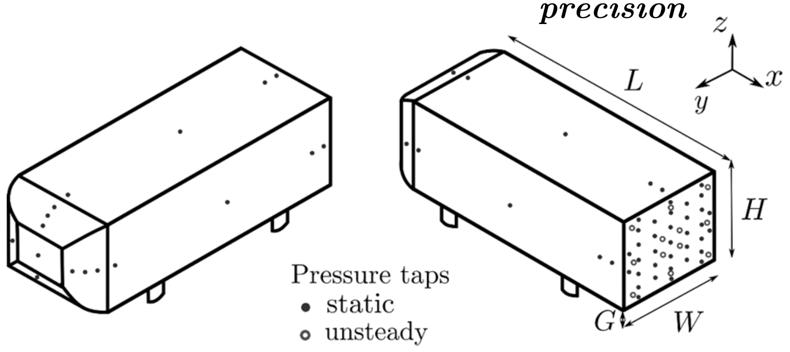
$H = 0.3\ m$

$G = 0.05\ m$

Square back wake : measurement devices

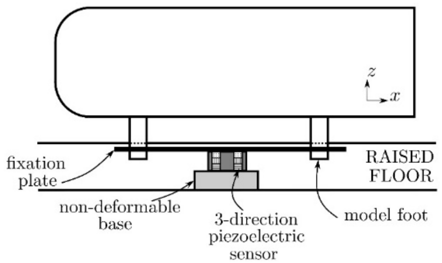
Pressure measurements

- *Diff. pressure sensors*
  - *12 base taps + 4 Coanda taps*
  - *2 kHz bandwidth*
  - *3% Cp precision*
- *Pressure scanner*
  - *64 taps (33 on the base)*
  - *@ 200 Hz*
  - *2% Cp precision*



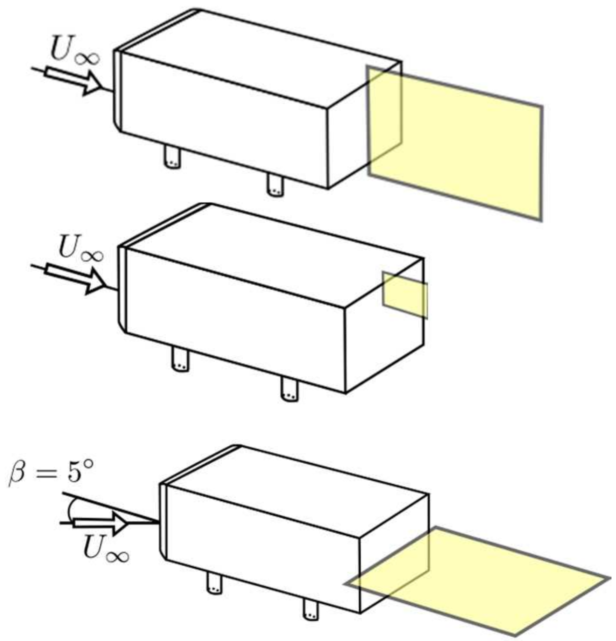
Aerodynamic balance

- *6-component balance*
- *10 Hz-low-pass-filtering*
- *1% precision on drag and lift*



PIV set-up

- *2D2C*
- *Large FOV*
  - *2.5H x 1.6H*
- *Small FOV*
  - *Random or phase-locked fields*
  - *HSPIV (10 kHz)*
  - *0.35H x 0.25H*



Square back wake : measurement devices

- **AFC from unsteady pressure data.**
- **TomoPIV or Scaning SPIV**
  - May be interesting for analysis
- **Hot Wire measurements**
  - Boundary Layer on the floor (1 H upstream the body).
  - Boundary layer at separation on top and lateral wall
  - Underbody flow.
- **Measurement of the skin friction before separation may be interesting**
  - See *Morris & Foss JFM 2003*
  - Transition from Bounday layer to Shear layer is important for near wake properties.

PIV set-up

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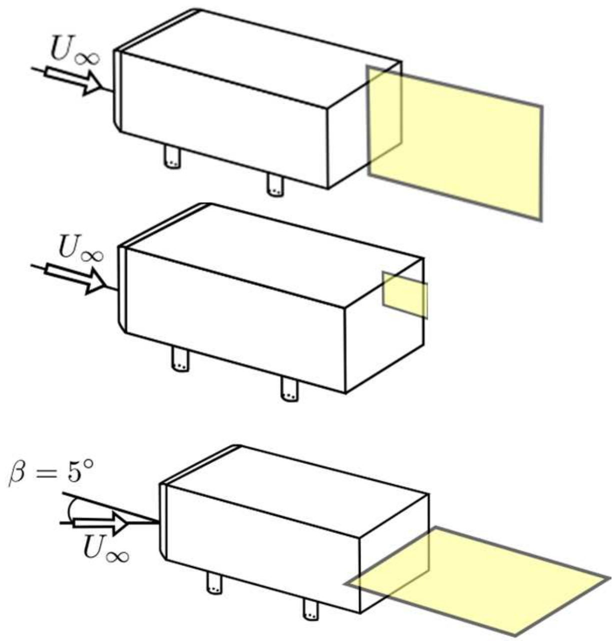
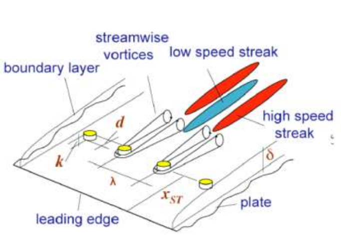
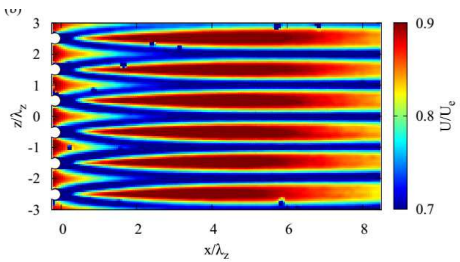


Square back wake : actuation

- **Actuation at separation**
  - Flaps *(Brackston et Al. JFM 2016, IJHFF 2018)*
  - Coanda *(Pfeifer & King Exp in Fluids 2018)*
  - Unsteady pulsed jets *(Oxlade JFM 2015, Barros JFM 2016)*
  - HF pulsed jets + Coanda *(Barros JFM 2016)*
  - For Backward facing step : Synthetic jet actuation *(Berk et al PRF 2017)*

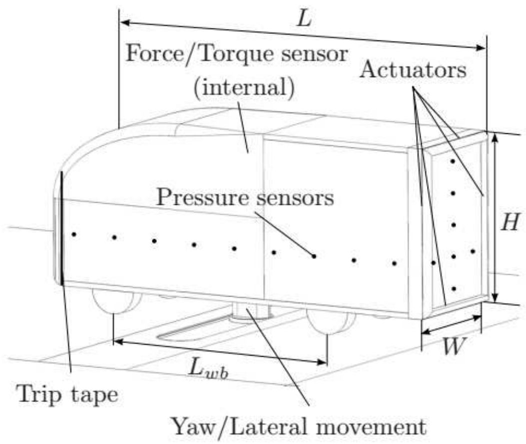
- **Introducing perturbations** along the wall upstream of the separation
  - Streaks *(Pujals EIF 2010, JOT 2010)*



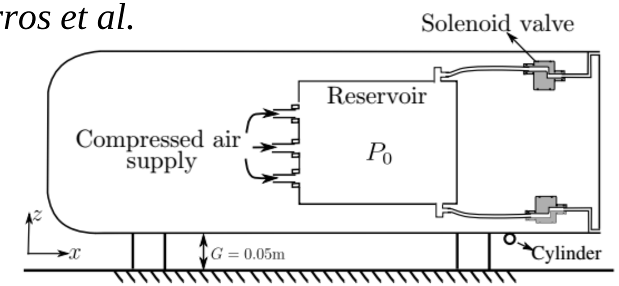


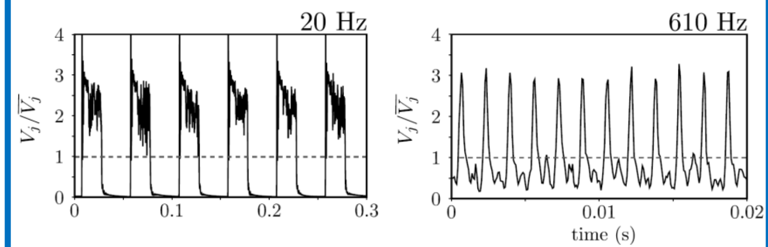
Del Guercio PhD 2014

Pfeifer & King EIF 2018

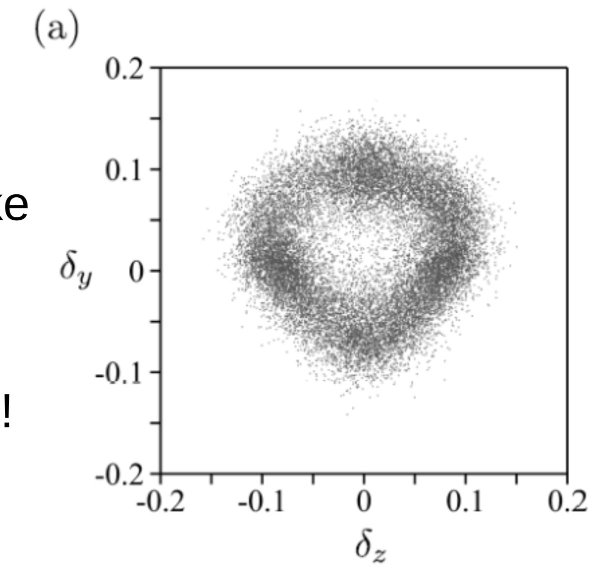


Barros et al.





Wake asymmetry : control target ?



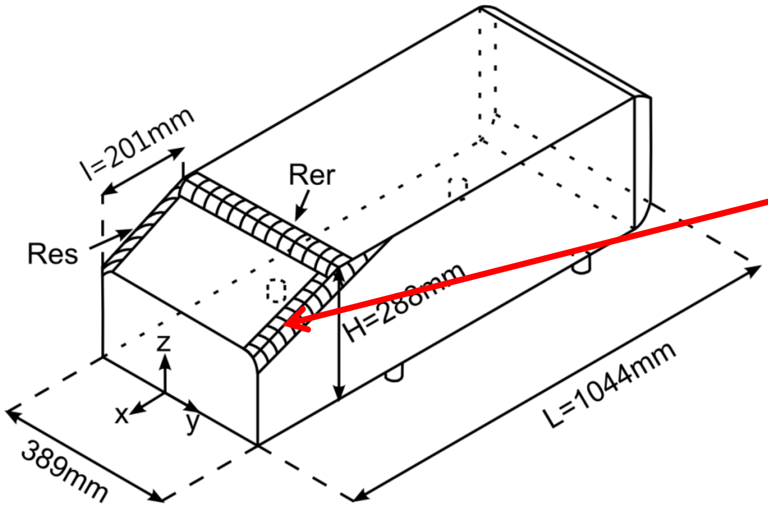
- **Practical control target :**
  - ⇒ Drive the wake toward an unsteady symmetric wake
  - ⇒ Prevent the slow organization dynamic of the asymmetric state
  - ⇒ Do not organize and enhance the shedding mode !!

- **A challenge for closed loop control methodologies :**
  - **Model identifications, design of linear controllers (Brackston et Al. JFM 2016)**
  - **Opposition control (Li et Al Exp. In Fluids 2016)**
  - **Machine Learning Control using LGP (Li et Al. Exp. In Fluids 2017)**
  - **Dynamical system approach (Varon et Al. PRF 2017)**

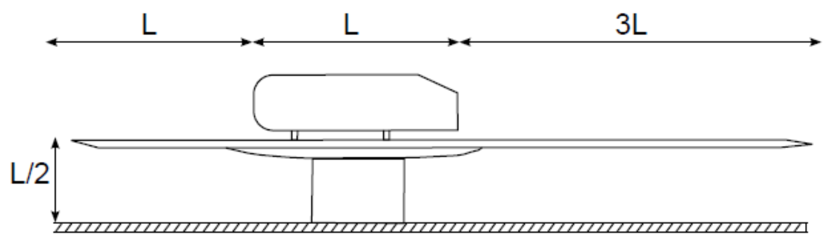
Outline of the talk

- Context and proposition
- Case A: Square back wake
- **Case B: Slanted and smoothed aft geometry**
  - **Goal:** Deal with introduction of longitudinal vorticity in the near wake.
- Synthesis

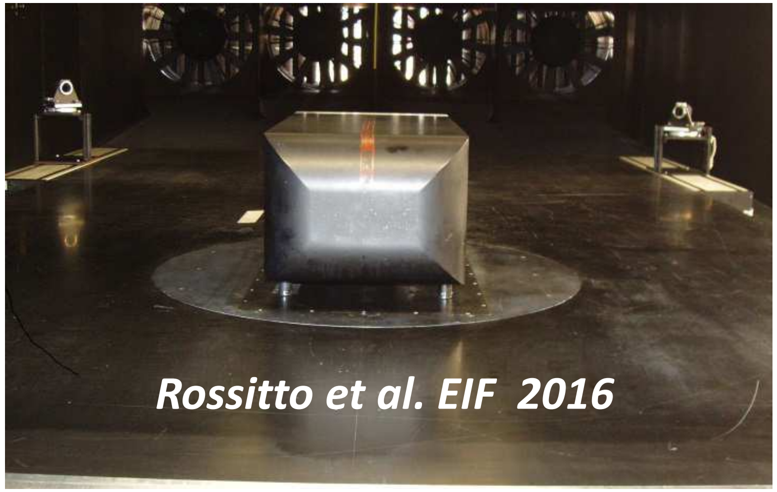
Example : Modified Ahmed geometry



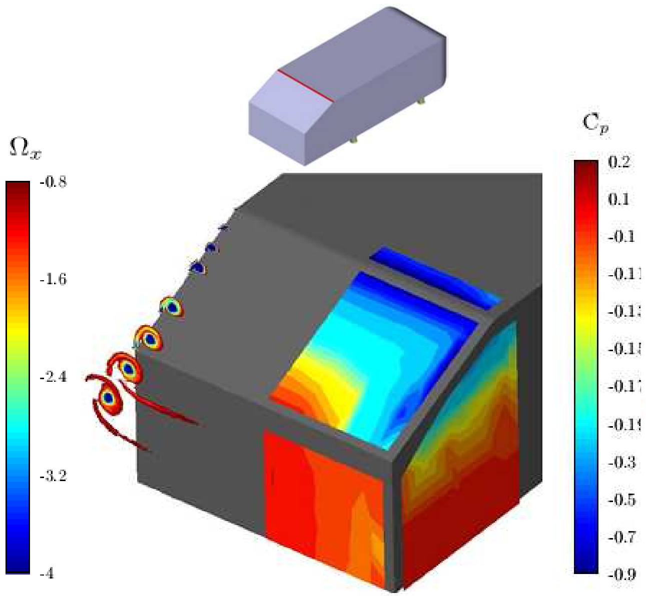
Variable C Pillar Radius :
*** Sharp**
*** 20mm = 10% of l**



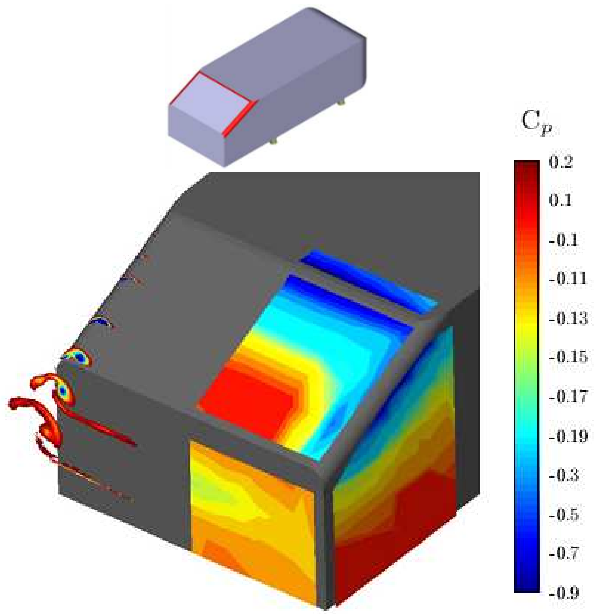
U=40m/s, L=1	Re=2E+06
2C and 3C PIV statistics based on 800 samples for each X,Y planes	
120 pressure probes distributed on the rear end of the body	
6 components external balance	



Modified Ahmed geometry

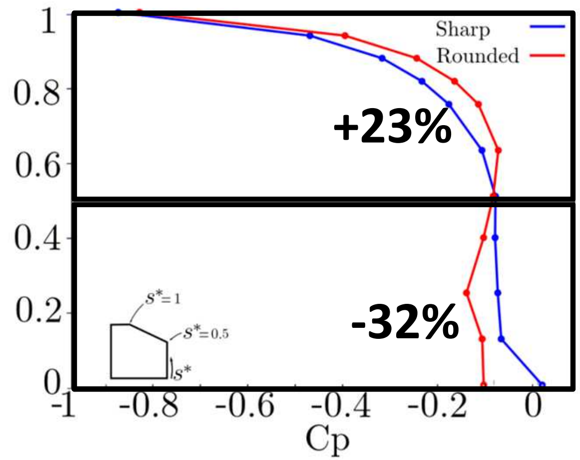


Sharp C Pillar



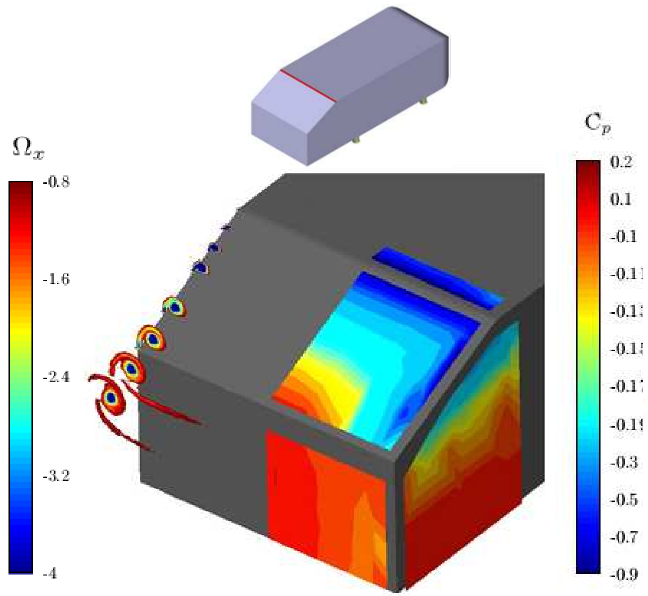
Rounded C Pillar

$$C_p = \frac{p - p_0}{1/2\,\rho U_0^{\,2}}$$

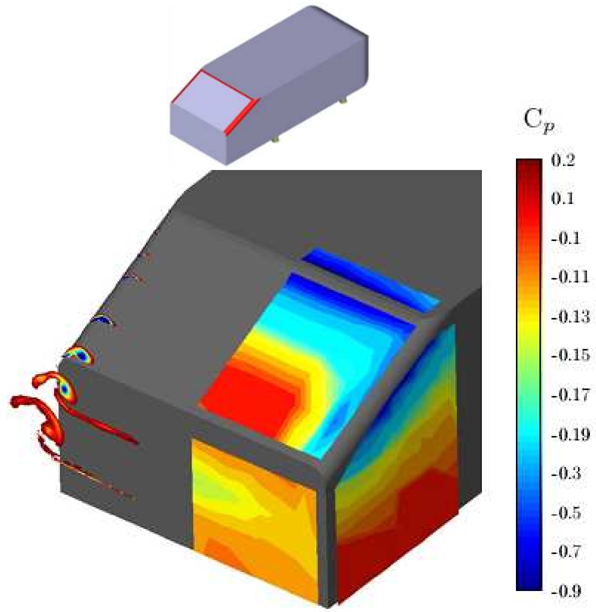


	Delta Cd	Delta Cl
Sharp C Pillar	-	-
Rounded C Pillar	0%	-26%

Modified Ahmed geometry

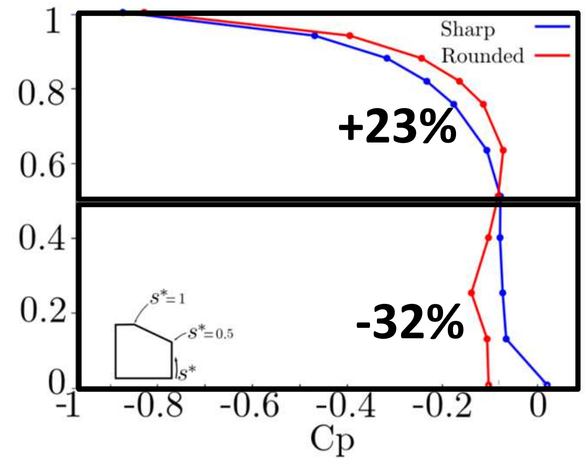


Sharp C Pillar



Rounded C Pillar

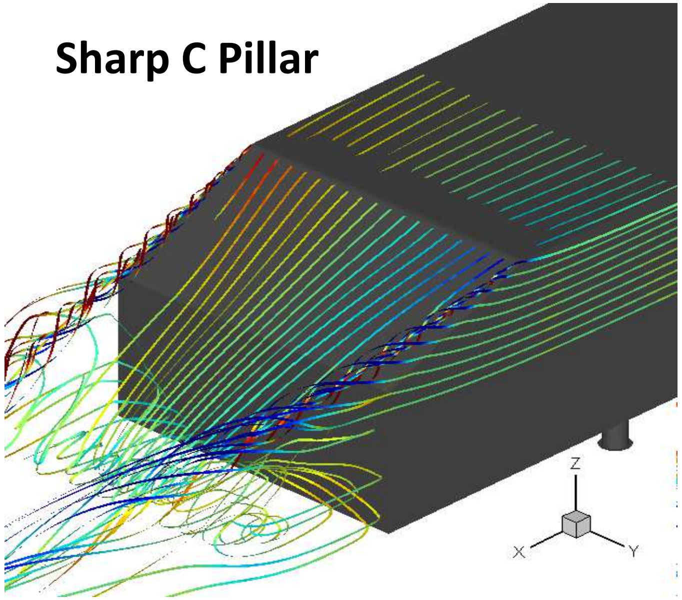
$$C_p = \frac{p - p_0}{1/2\,\rho U_0^{\ 2}}$$

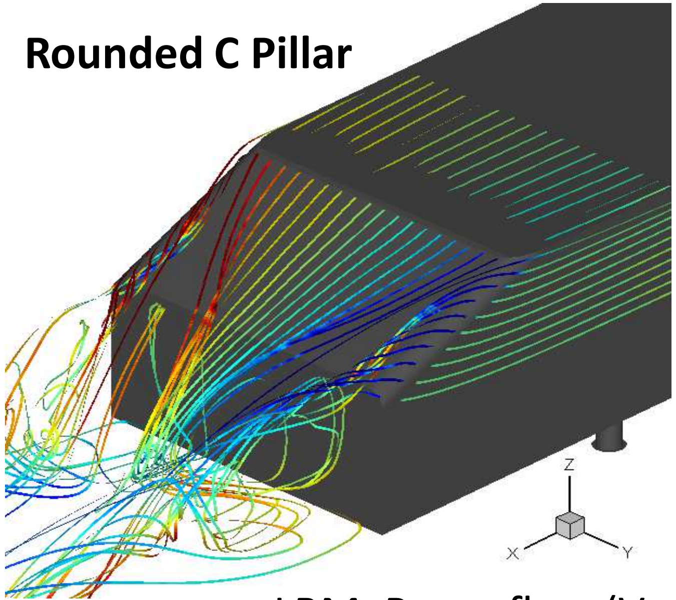


- **On the slanted surface : Modification of the 3D interaction between C-Pillar vortices and flow over the slant**
  - Origin of longitudinal vortices displaced downstream
  - Streamwise vorticity less concentrated and weaker
  - Lower downwash speed induced by the trailing vortices across the backlight

➡ **More uniform and higher Cp** *Fuller & Passmore JWEIA 2014*

Ahmed model: numerical streamlines



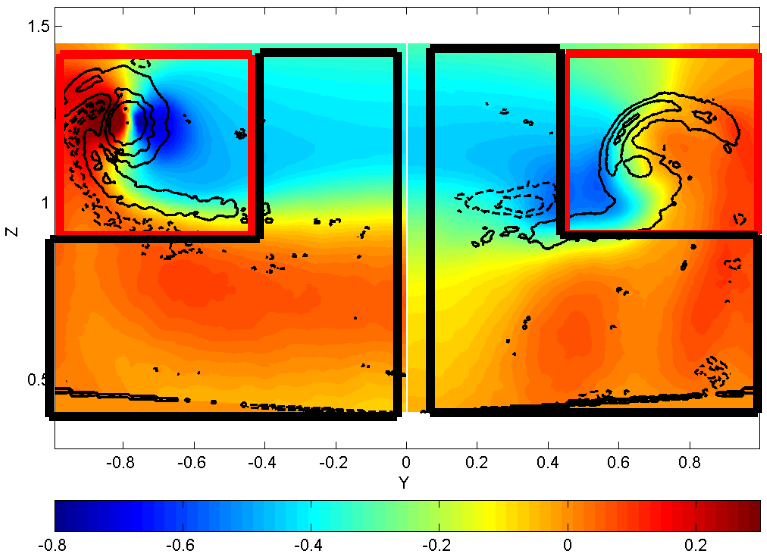


LBM, Powerflow (Version 5.0)

Profound change of the Near wake organisation

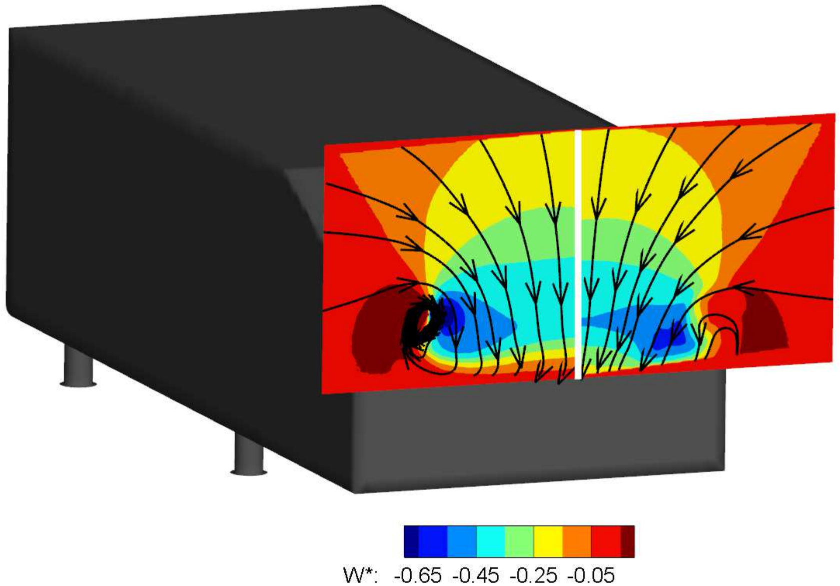
- The sharp edges “shield” the wake separation region at the base and enable a “2D” separation
- The separation at the base is notably 3D for the rounded model
- ***Longitudinal vorticity shed in the near wake flow***

Effect of rounding side edges on the streamwise vorticity



$$\Gamma^* = \int_{S^*} \Omega_x^* dS$$

Circulation (Γ*)	Sharp side	Rounded side
Vortex region	0,42	0,30
"Wake"	0	0,27

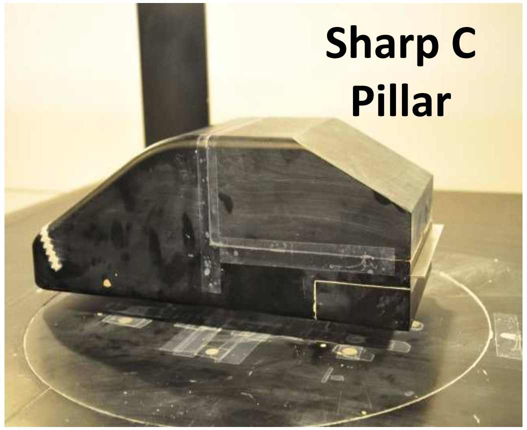


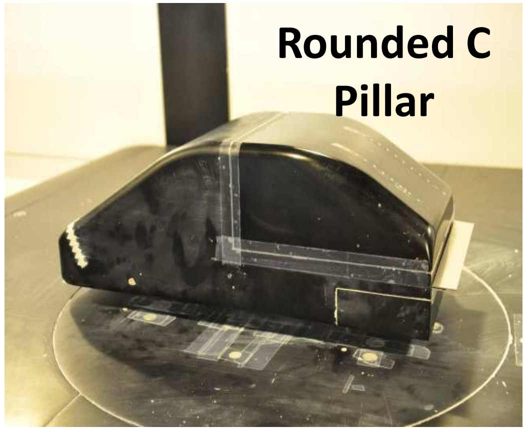
Cross-flow plane, X*=L/2

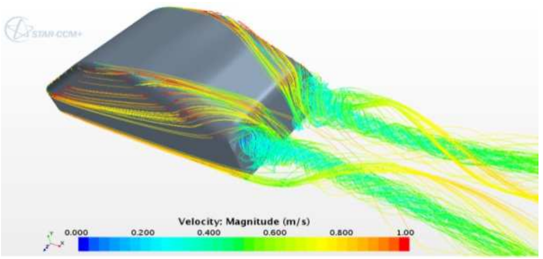
Recirculation of mean streamwise vorticity next to the vertical base is responsible for low-pressure regions.

Rossitto et al EIF 2016

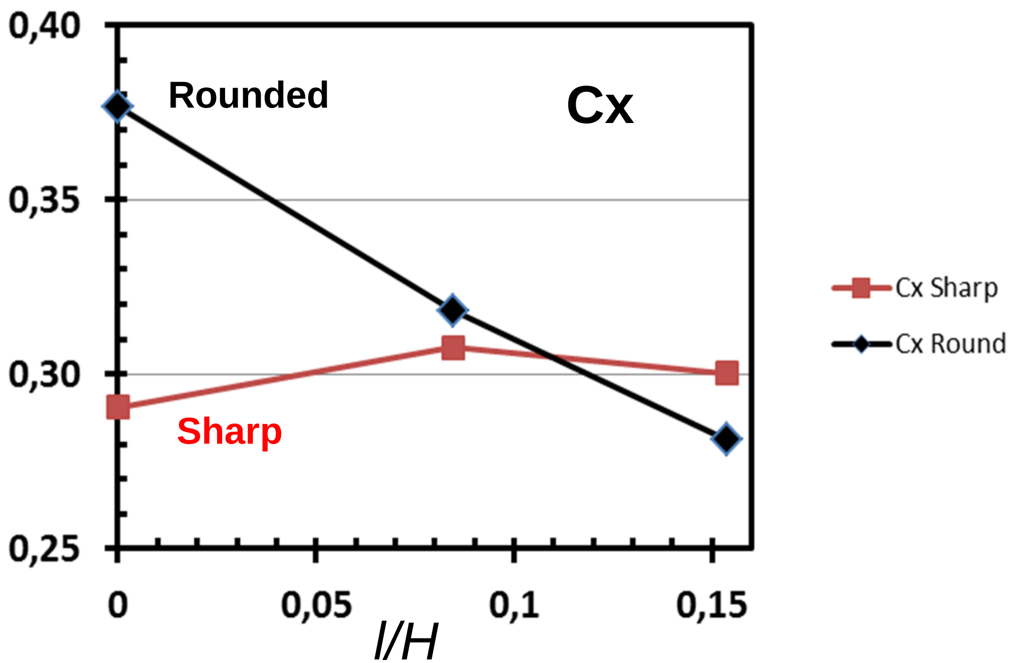
A simple test with the students (using passive devices)!



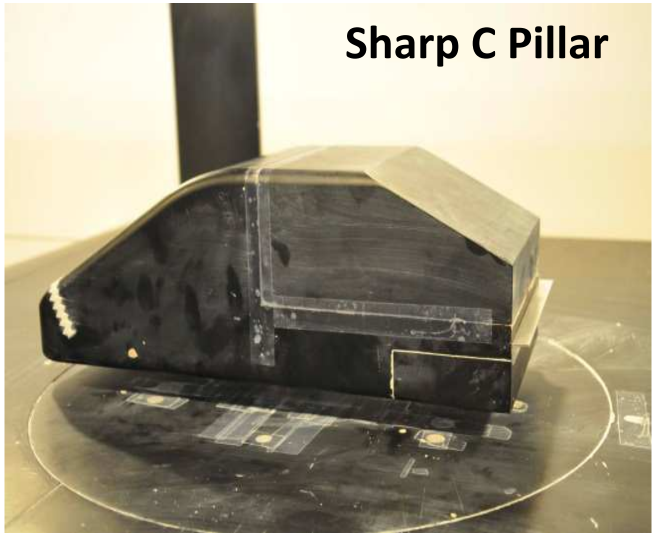


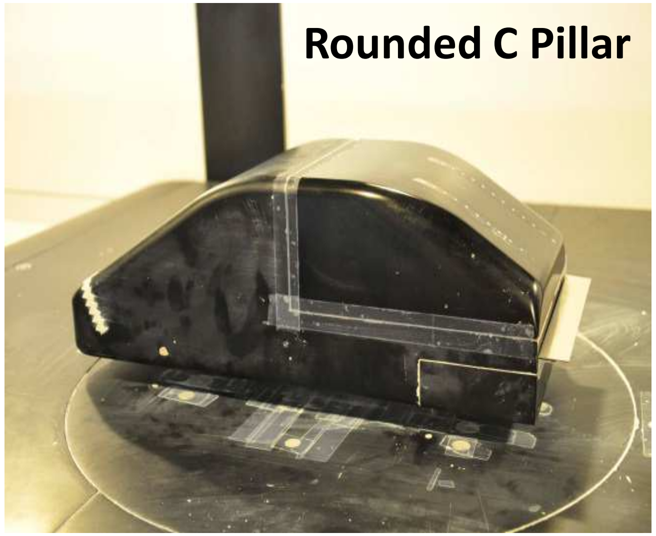


- **Re ≈ 300000**
- **Horizontal separating plate (*l= 11 or 20 mm*) added in near wake region**
  - No effect if sharp C pillars
  - Significant reduction for rounded aft body.



Body with slanted and smoothed aft geometry





- **Goal:** keep advantage (higher Cp) of rounding along the slanted part.
- Deal with the introduction of longitudinal vorticity in the near wake.
- Find relevant strategies upstream, at or downstream separation !
- **AFC:** Pulsed jets, compliant walls or flaps … may be selected

Outline of the talk

- Context
- Case A: Square back wake
- Case B: Body with slanted and smoothed aft geometry
- **Synthesis**

Synthesis

- **Case A : Square back wake**
  - Proposition of an open geometry (joint-work with industrial partners) Geometry is fully open.
  - An exiting applied and fundamental challenge :
    - Drive the wake toward an unsteady symmetric state
    - Prevent the slow organization dynamic of the asymmetric state
  - Control authority by Pressure control (Flaps) or Turbulence control (Shear layer entrainment and mixing properties)

- **Case B : Body with slanted and smoothed aft geometry**
  - Address interactions of flow structures and near wake properties.
  - Open geometry should be defined to drive interest from helicopters, airplanes or road vehicles.

INSTITUT

Thank you for your attention