Forcing large-scale flow asymmetries in the wake of a blunt body – wake equilibrium and drag reduction

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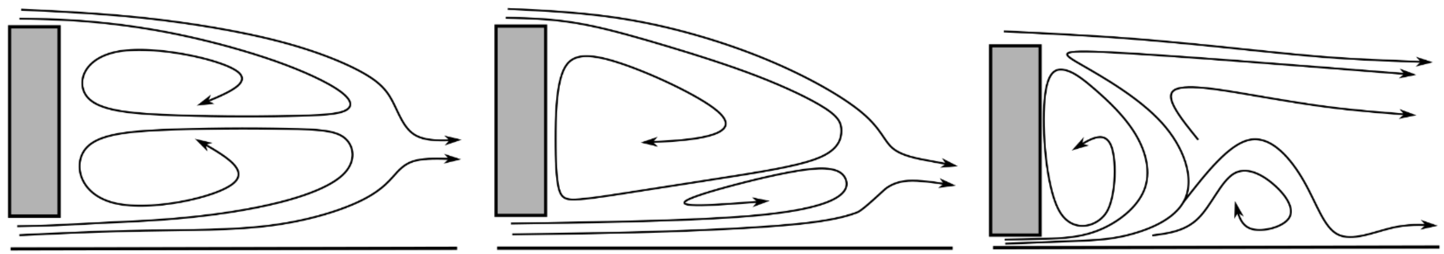
ANR project Activ_ROAD (ANR15CE220002)

Motivations

Introduction

Asymmetries in the wake of blunt bodies



- **Various asymmetries related to different geometric perturbations and changes**
- Bi-modality related to instantaneous asymmetry
- Static asymmetries when perturbing the underbody
- Wake equilibrium and topology changes for various modifications

Grandemange JFM 2014
Barros JFM 2017

Ground clearance
Aspect ratio
Pitch
Underbody flow changes

Grandemange PoF 2014
Gentile JFM 2017
Bonnavion 3AF 2017
Castelain IJWEA 2018

- Practical relevance in real flow conditions
- Influence on aerodynamic forces

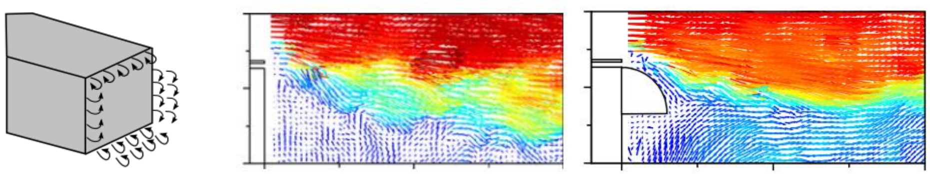
Motivations

Introduction

Drag reduction of blunt bodies : active flow control

- Pressure drag related to the low-pressure wake
- Various active and passive control strategies
- Efficient flow control strategies to reduce drag in the frame of ground transport vehicles
- Control adaptivity to and interaction with various asymmetries

- **Global high frequency unsteady forcing (+curved surfaces)**



Oxlade JFM 2015

Barros JFM 2016

- **Low frequency unsteady forcing for bi-modality control**

Brackston JFM 2016 Li EiF 2016

- **Low frequency unsteady forcing for yaw asymmetries mitigation**

Li PhD 2017

Aim of the present study

Introduction

- **Various wake asymmetries triggered by passive perturbations**
- Changing the vertical asymmetry and the dynamics of the wake

- **Global and localized high frequency forcing**
- Forcing localized along different edges
- Interaction with the fixed asymmetries

What is the effect of localized forcing on the wake depending on its asymmetry ?

What are the means to achieve maximal drag reduction ?

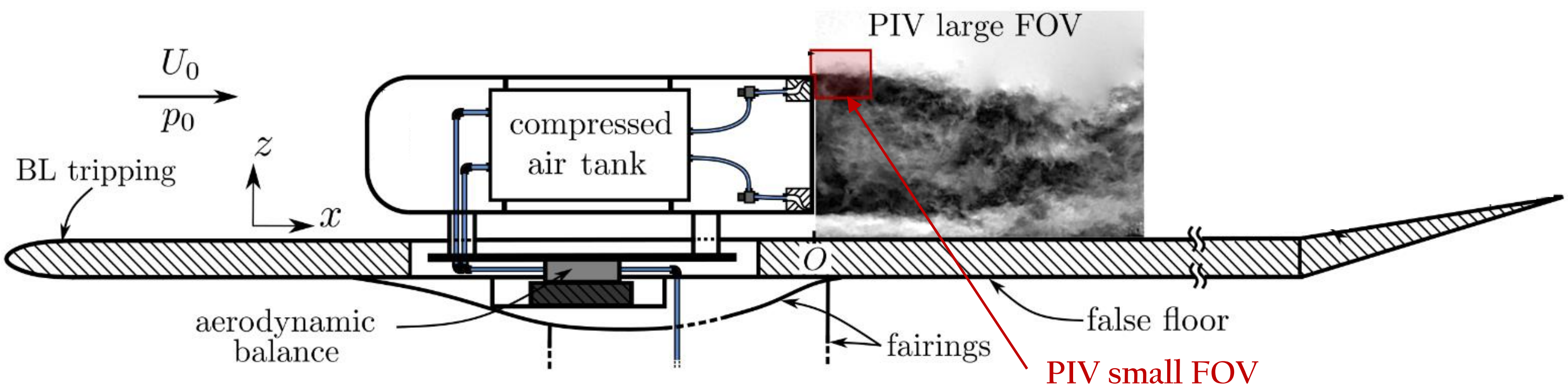
Drag reduction and flow control efficiency ?

Outline

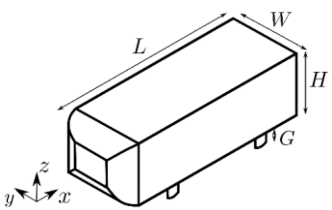
- Experiments and methods
- Unforced wakes
- Global effects of forcing
- Properties of the forced near wakes
- Conclusions and outlook

Model and wind-tunnel setup

Experimental setup



Parameters

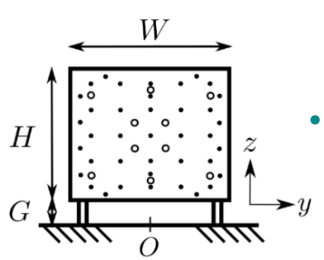


U_0 = 25 m/s
H = 0.3 m
Re_H = 5.10⁵
Blocage : 2.5 %

Aerodynamic balance

- 6-component balance
- 1% precision on drag

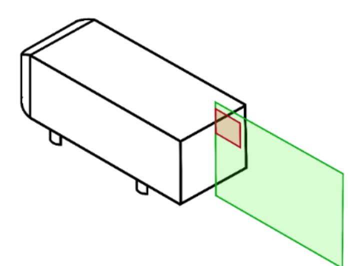
Base pressure measurements



- 2% precision on C_p

PIV

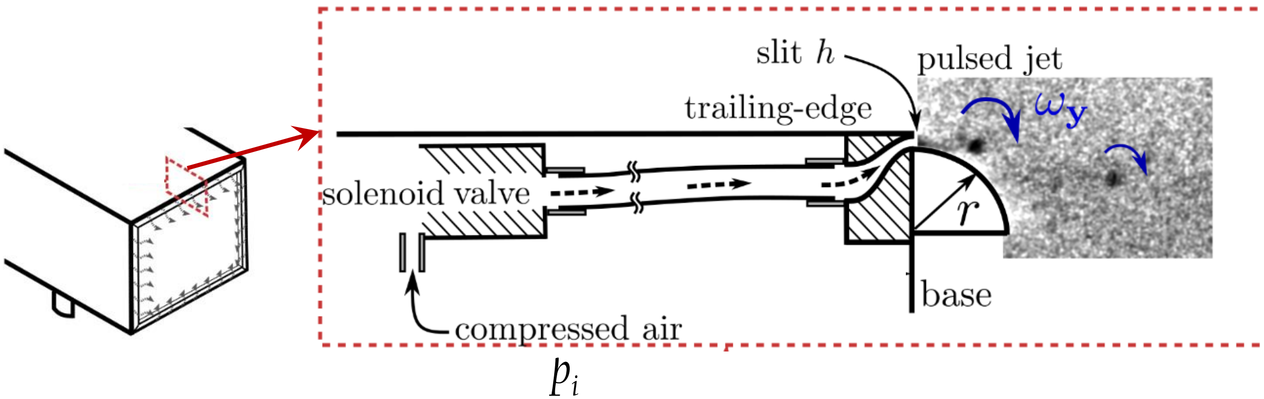
- 2D2C – 4 Hz



Actuation system

Experimental setup

Pulsed jets actuators at trailing-edge



Pulsed jets parameters

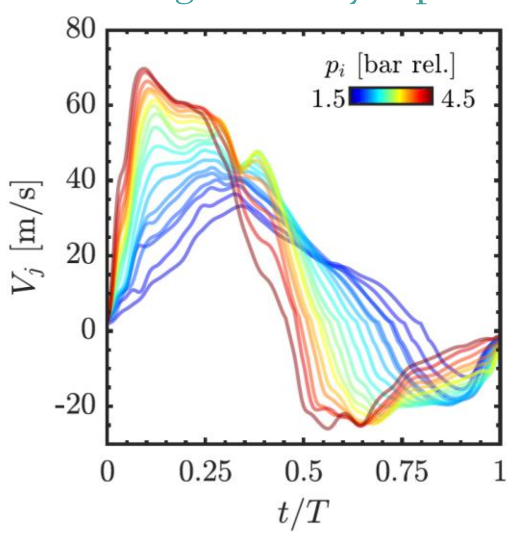
Slit thickness $h = 1$ mm

Curved surface radius $r = 9h$

Pulsing frequency $f = 1050$ Hz, $St_\theta = 0.096$

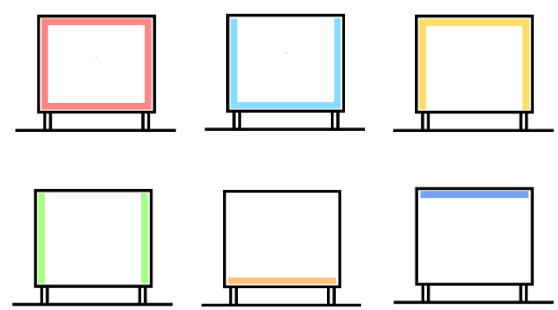
Pulsing amplitude $C_\mu = \frac{s_j V_{j_{max}}^2}{S U_0^2}$

Phase-averaged velocity of pulsed jets



Hot-wire measurements at the center of the slit

Localized forcing



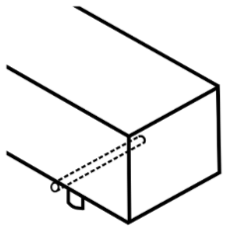
Outline

- Experiments and methods
- Unforced wakes
- Global effects of forcing
- Properties of the forced near wakes
- Conclusions and outlook

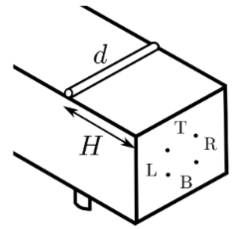
Unforced wakes asymmetries

Unforced wakes

Bottom perturbed | Natural | Top perturbed

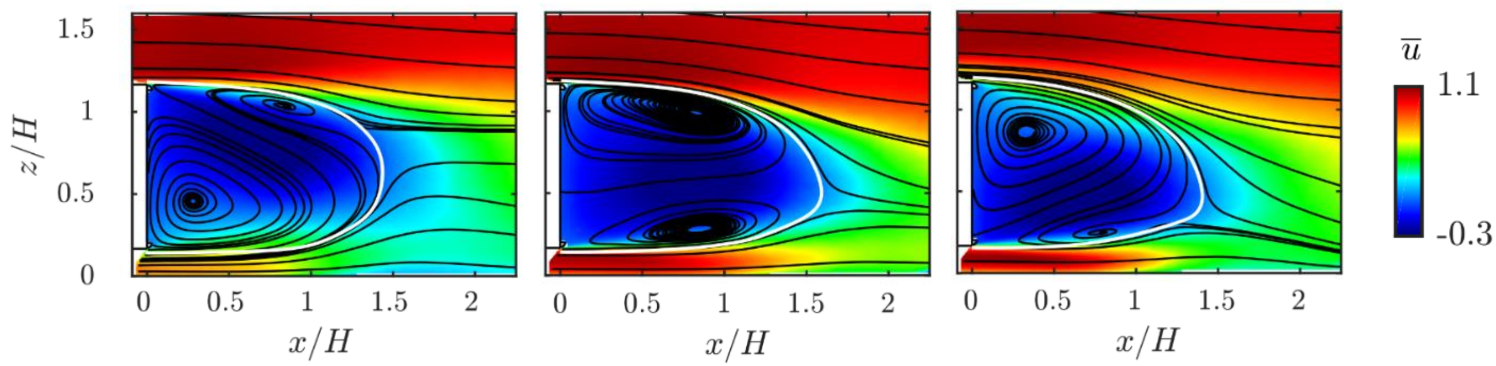


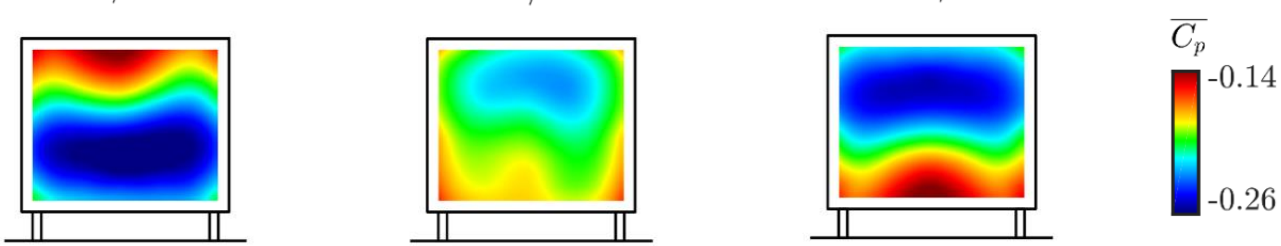
No perturbation



$d = 0.06\,H$

Mean flow

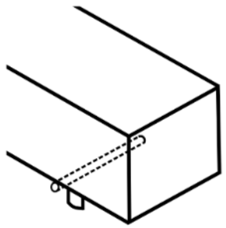




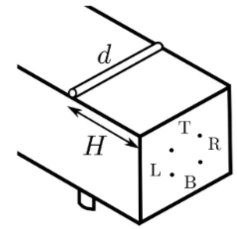
Unforced wakes asymmetries

Unforced wakes

Bottom perturbed	Natural	Top perturbed



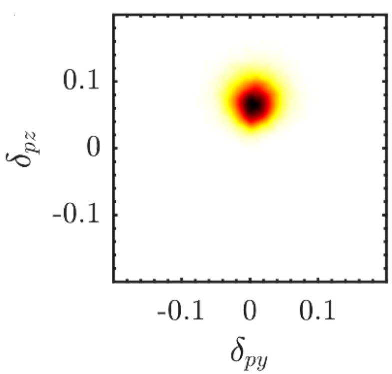
No perturbation

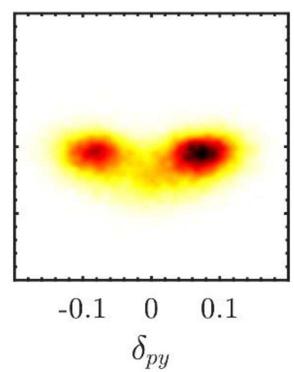


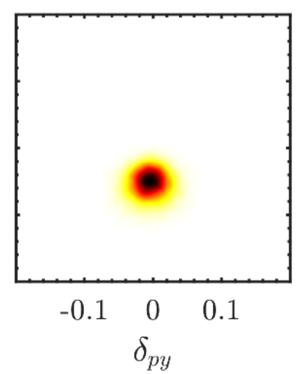
$$\delta_{pz} = C_p(T) - C_p(B)$$

$$\delta_{py} = C_p(L) - C_p(R)$$

Base pressure gradient dynamics







Global aerodynamic characteristics

Perturbation	$\overline{C_{pb}}$	$\overline{\delta_{pz}}$
—	−0.196	−0.009
Top	−0.209	−0.052
Bottom	−0.215	0.068

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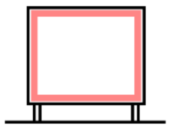
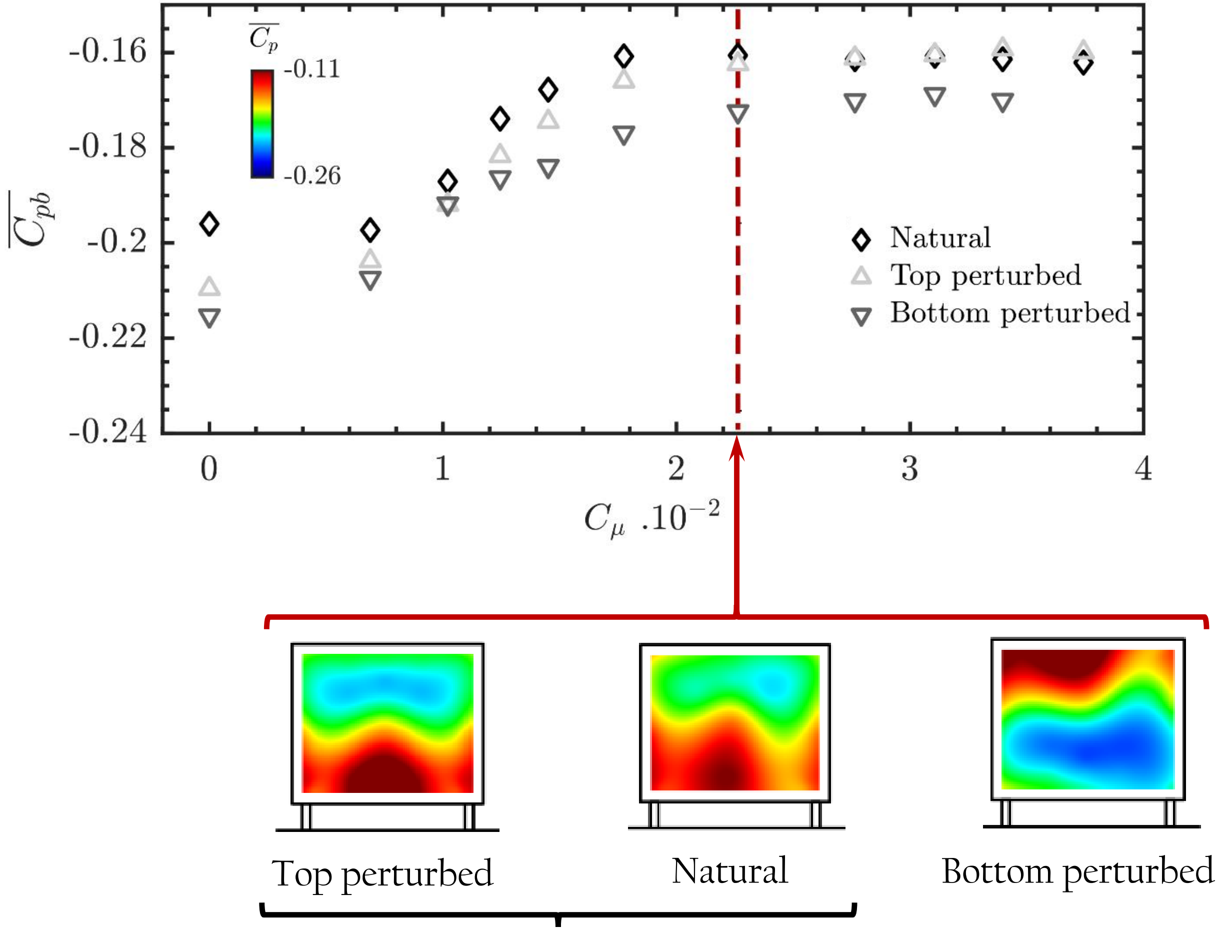
Maximum base pressure recovery and equilibrium

Global effects of forcing

Forcing



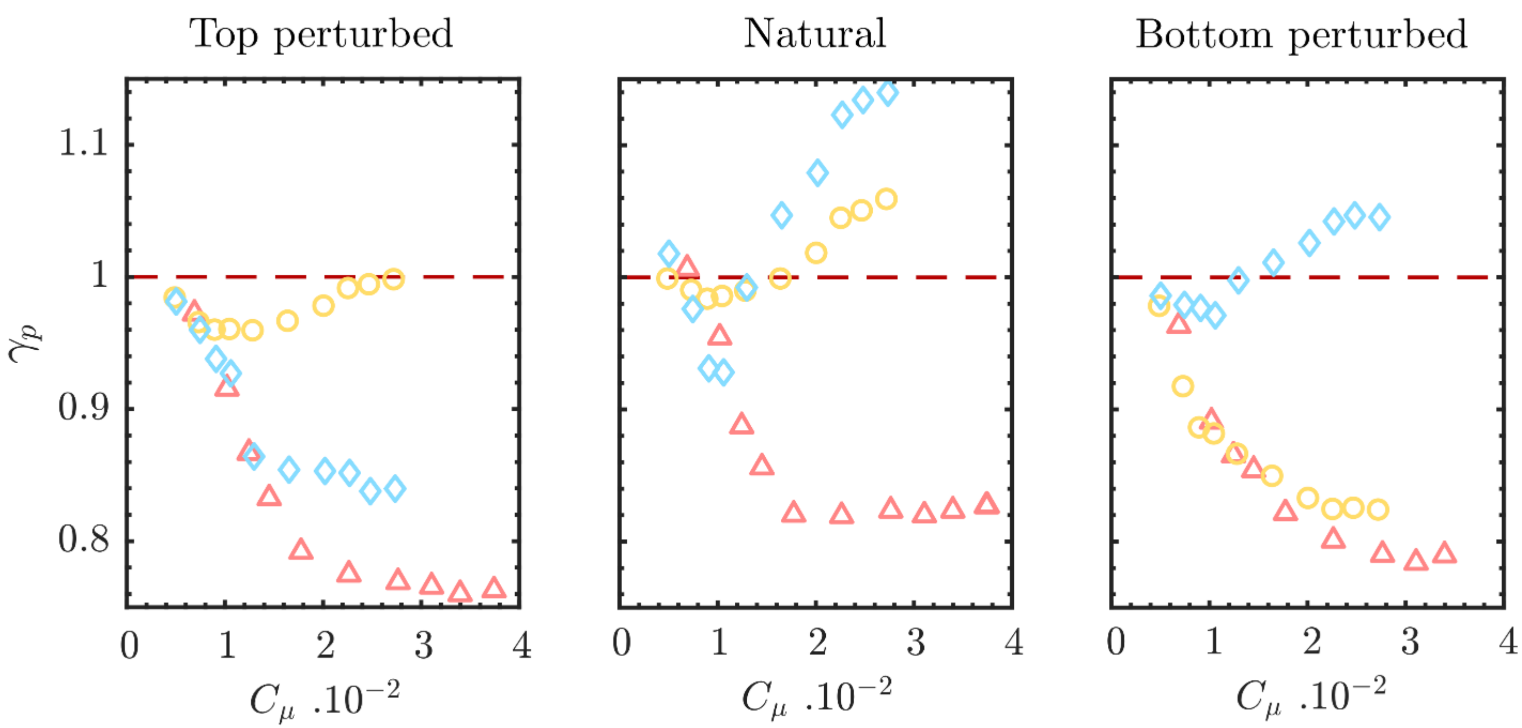


- Similar base drag but with different near-wake equilibrium

Further base drag reduction by vertically symmetrizing the wake ? Or symmetrizing would at the same time lessen the global effect of base pressure recovery ?

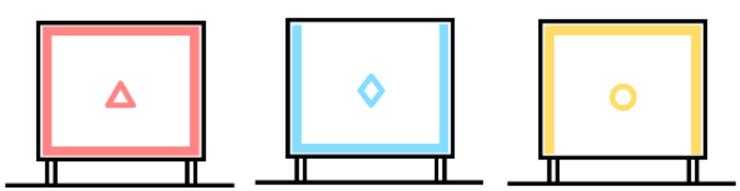
Effects of control in presence of asymmetries

Global effects of forcing



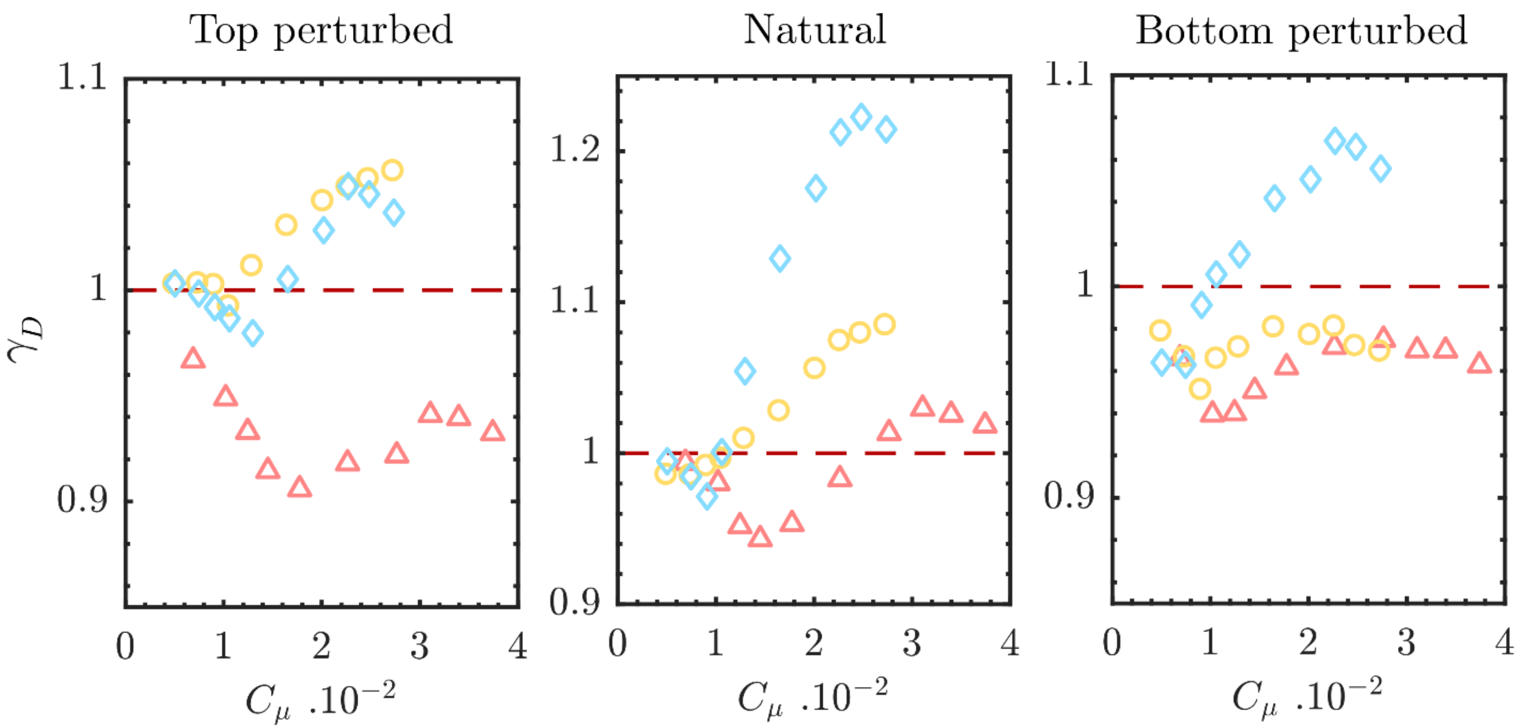
$$\gamma_\mathbf{p} = \frac{\mathbf{C_p}}{\mathbf{C_{p0}}}$$

Forcing



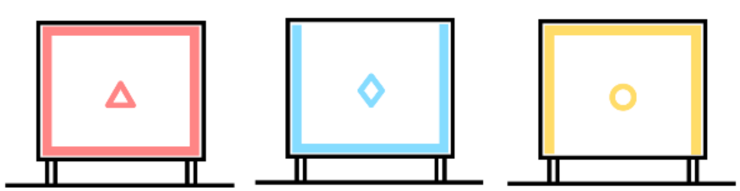
Effects of control in presence of asymmetries

Global effects of forcing



$$\gamma_{\mathbf{D}} = \frac{\mathbf{C_D}}{\mathbf{C_{D0}}}$$

Forcing



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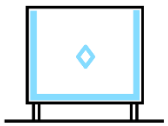
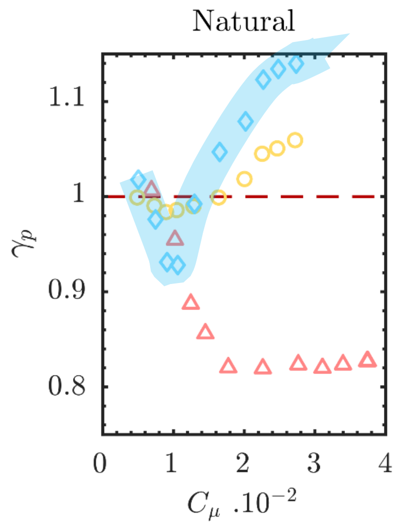
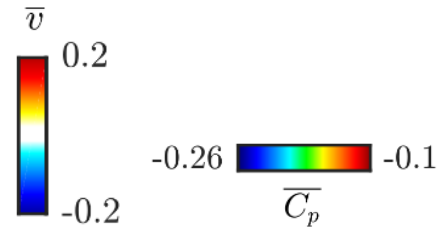
Vertical symmetry and aerodynamic drag

Properties of the forced near wake

Forcing

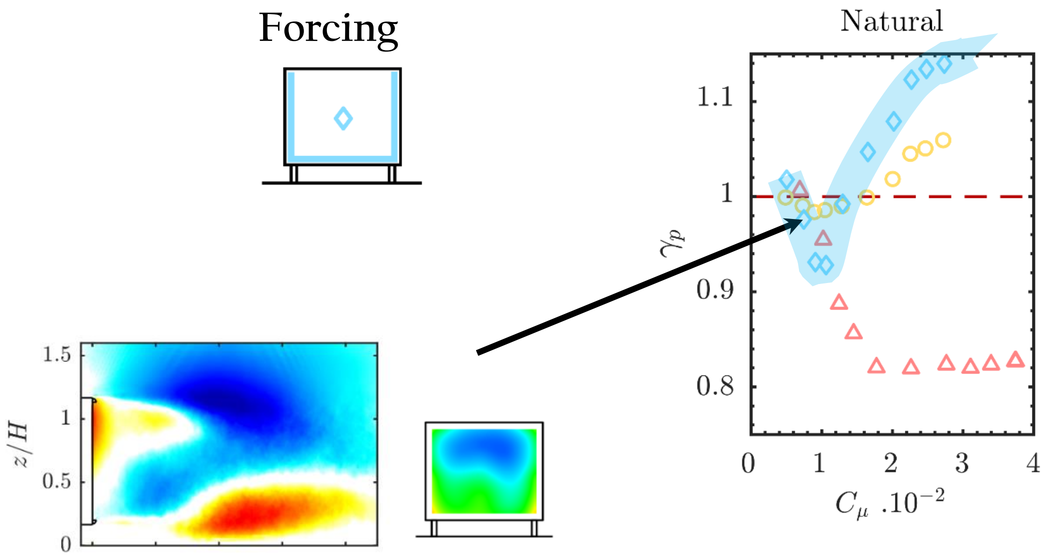


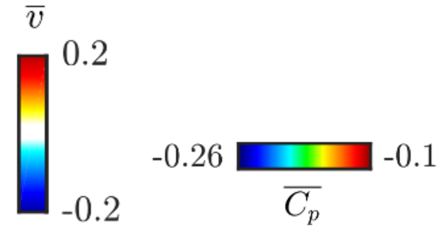




Vertical symmetry and aerodynamic drag

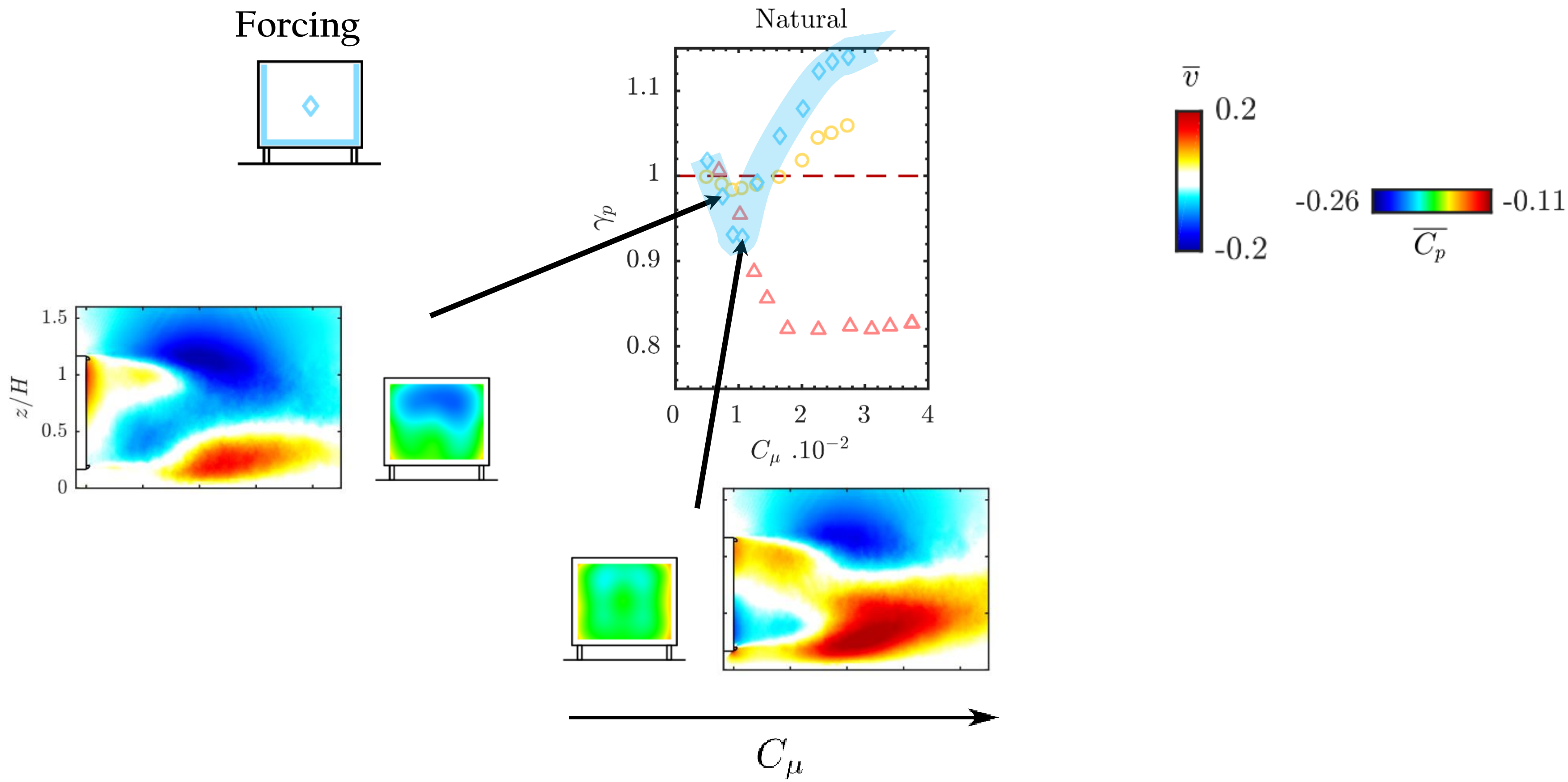
Properties of the forced near wake





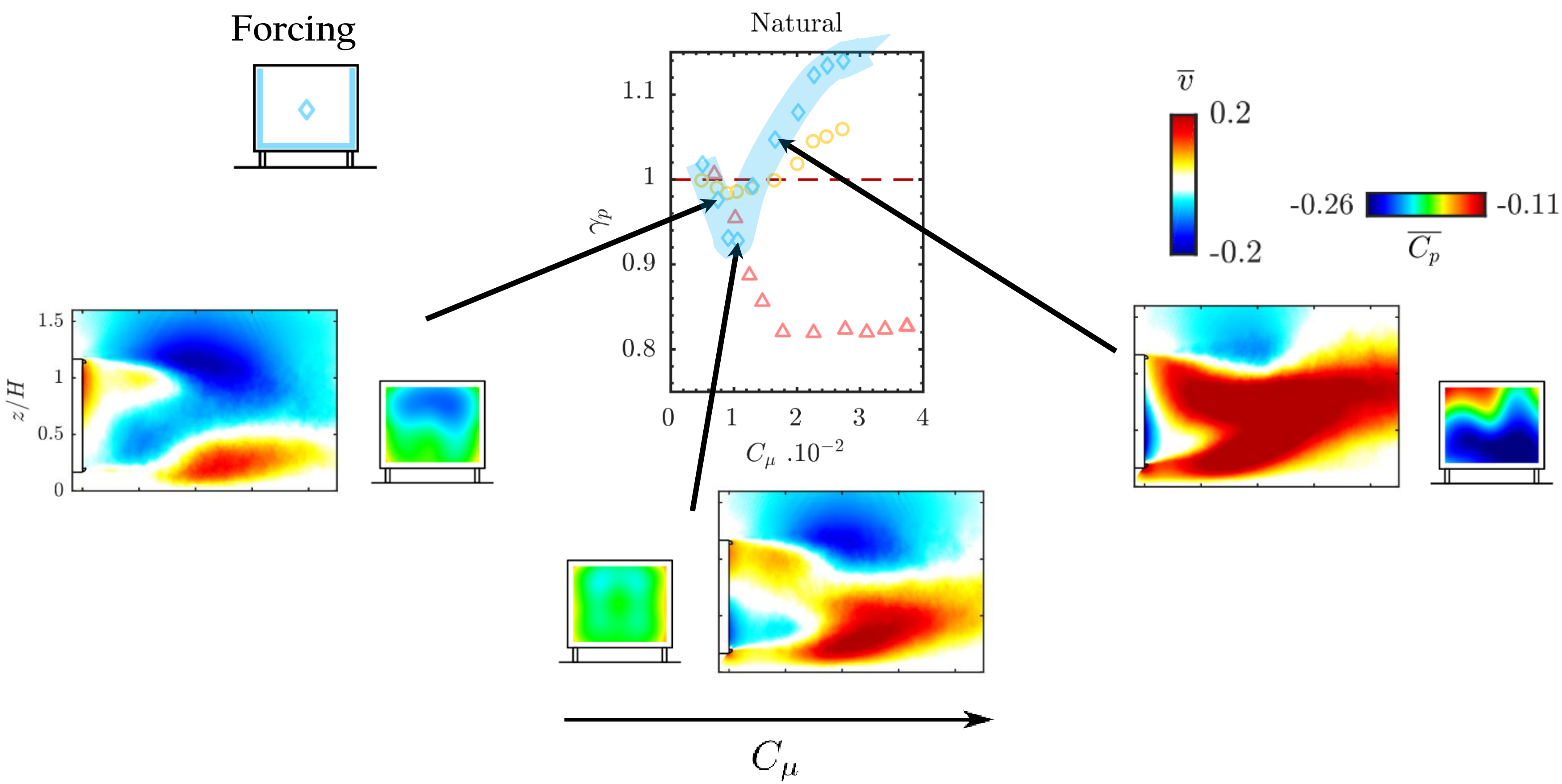
Vertical symmetry and aerodynamic drag

Properties of the forced near wake



Vertical symmetry and aerodynamic drag

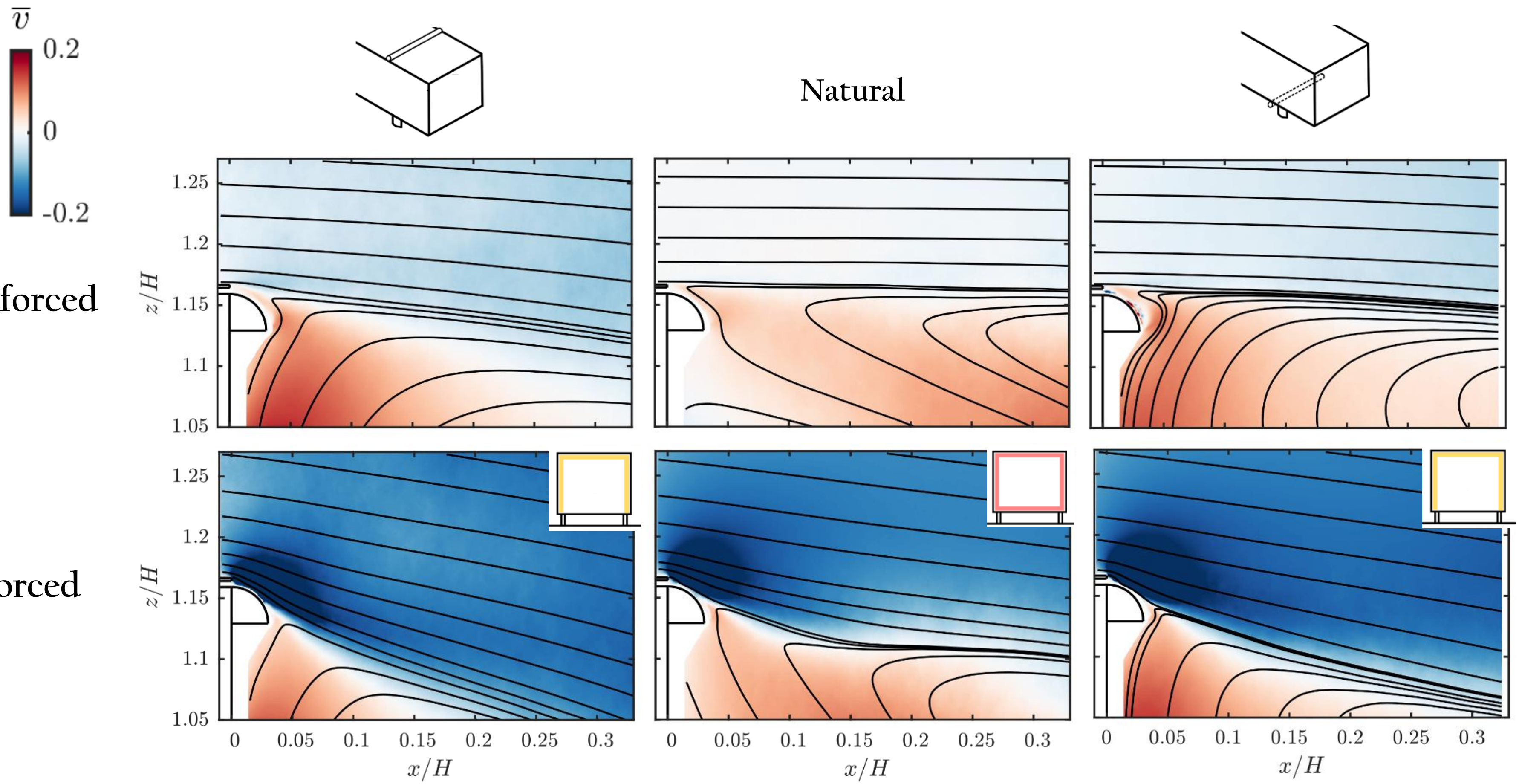
Properties of the forced near wake



Static vertical symmetry is a local optimum for both drag reduction and forcing efficiency

Local modifications to forcing effect

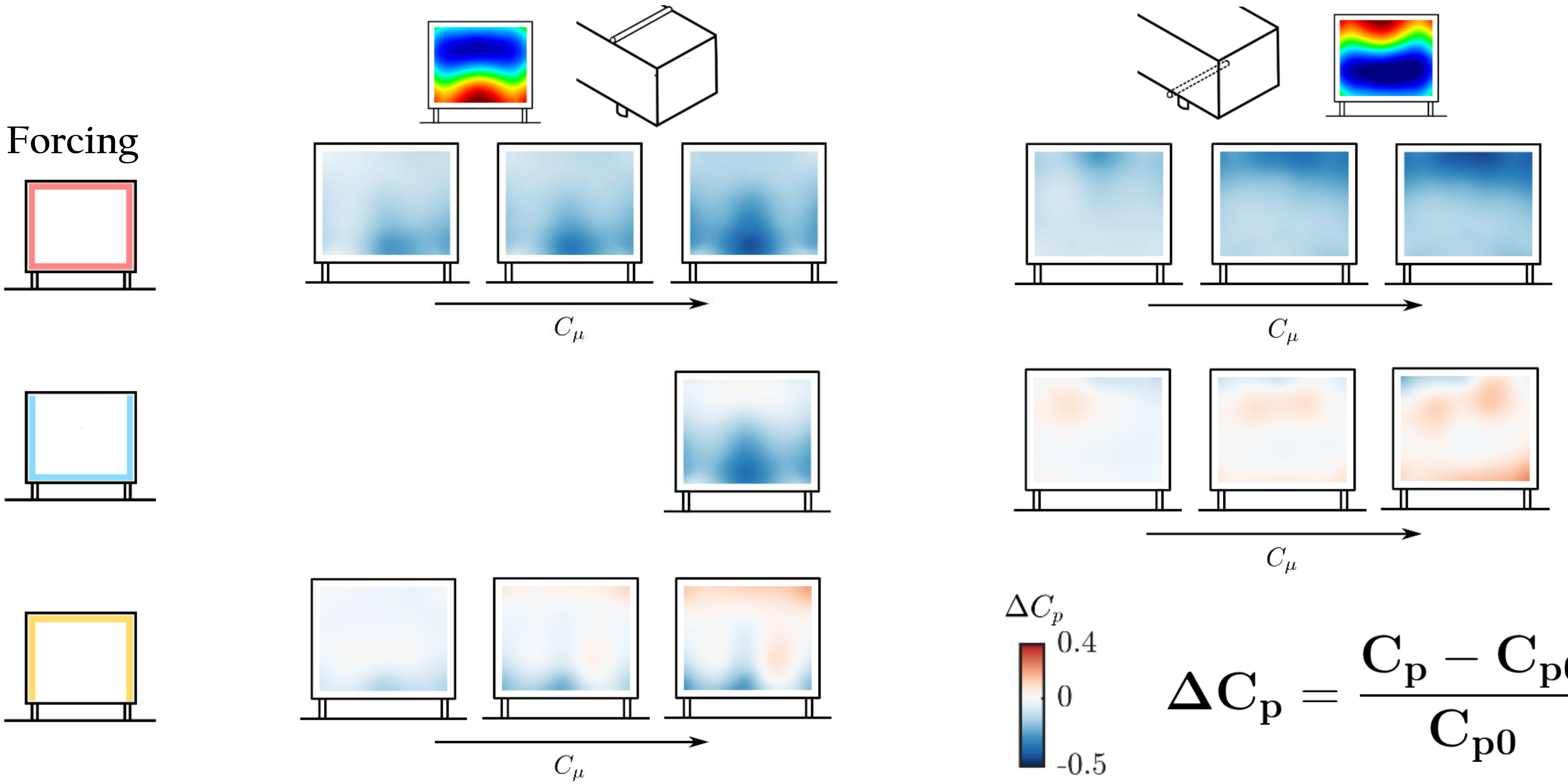
Properties of the forced near wake



- Strong influence of recirculating flow on the effect of high frequency forcing
- Change of curvature and deflection of outer flow and its effect on base pressure linked to the recirculating flow state
- Relation between opposite edge forcing or not and effect of separating streamline curvature on base pressure recovery

Localization of base pressure changes

Properties of the forced near wake

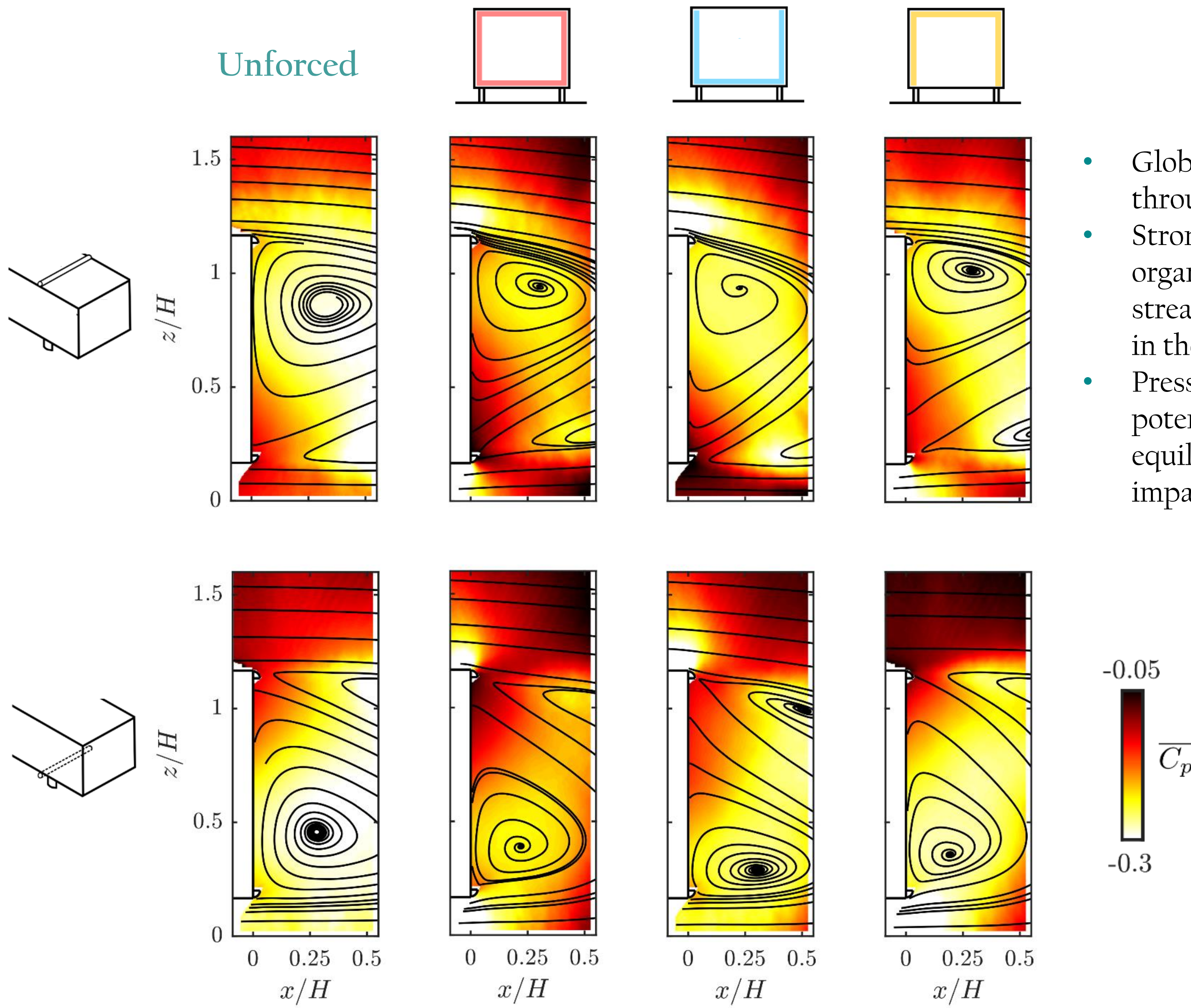


$$\Delta \mathbf{C_p} = \frac{\mathbf{C_p} - \mathbf{C_{p0}}}{\mathbf{C_{p0}}}$$

- Spatial distribution of pressure recovery strongly dependent on forcing localization

Pressure changes in the near wake

Properties of the forced near wake



- Global pressure recovery through the wake
- Strong influence of spatial organisation of forcing on streamwise pressure gradient in the wake
- Pressure changes in the potential region linked to equilibrium modifications impacting the base pressure

Pressure field from direct integration of momentum equations

Outline

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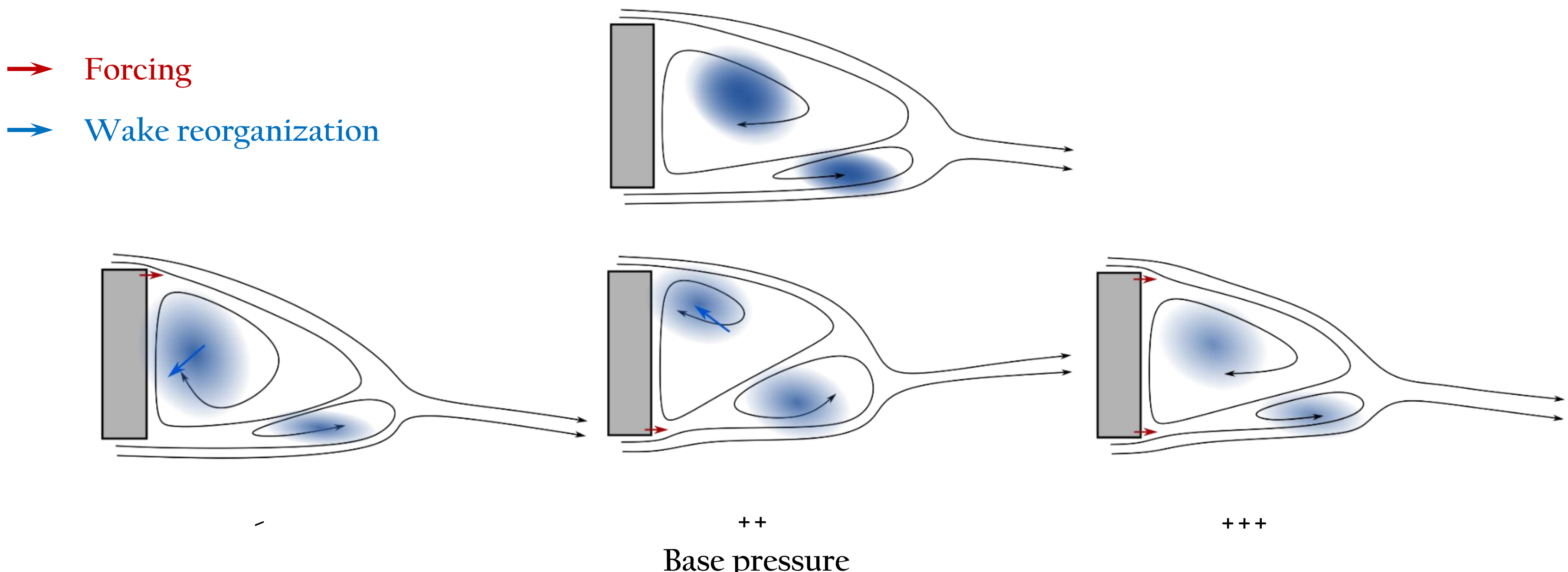
Main conclusions

Conclusions and outlook

- <u>Effect of global and localized high-frequency forcing on 3D wakes presenting different asymmetric states</u>

- Global forcing : robust drag reduction independently of the unforced asymmetric states considered

- Strong interplay between induced asymmetries and control balance/localization around the trailing edge



Outlooks

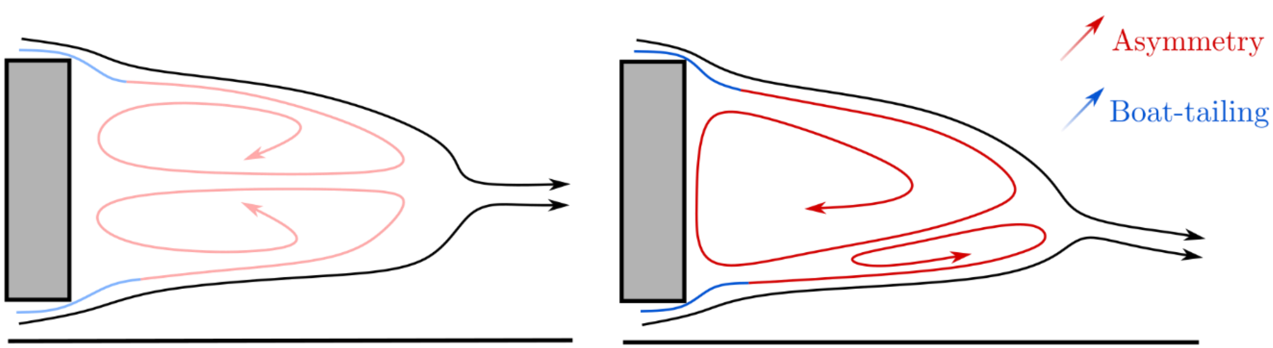
Conclusions and outlook

- Extension of forcing interaction with other types of wake asymmetries : variable underbody velocity or change of ground clearance

Szmigiel PhD 2017 Castelain IJWEA 2018

Need for asymmetric forcing adaptable to the asymmetry configuration to further improve drag reduction and tackle the question of energetic efficiency

- Closed-loop control for adaptive purposes
- Spatially adapt the forcing to the given flow asymmetry for optimized drag reduction and energetic efficiency of forcing
- Further drag reduction by targeting an additional flow symmetrization : base pressure barycenter tracking
- Is there a trade-off between boat-tailing effect/wake recompression and resymmetrization of the wake in the achievable drag reduction ?



Thank you for your attention.

Any questions ?

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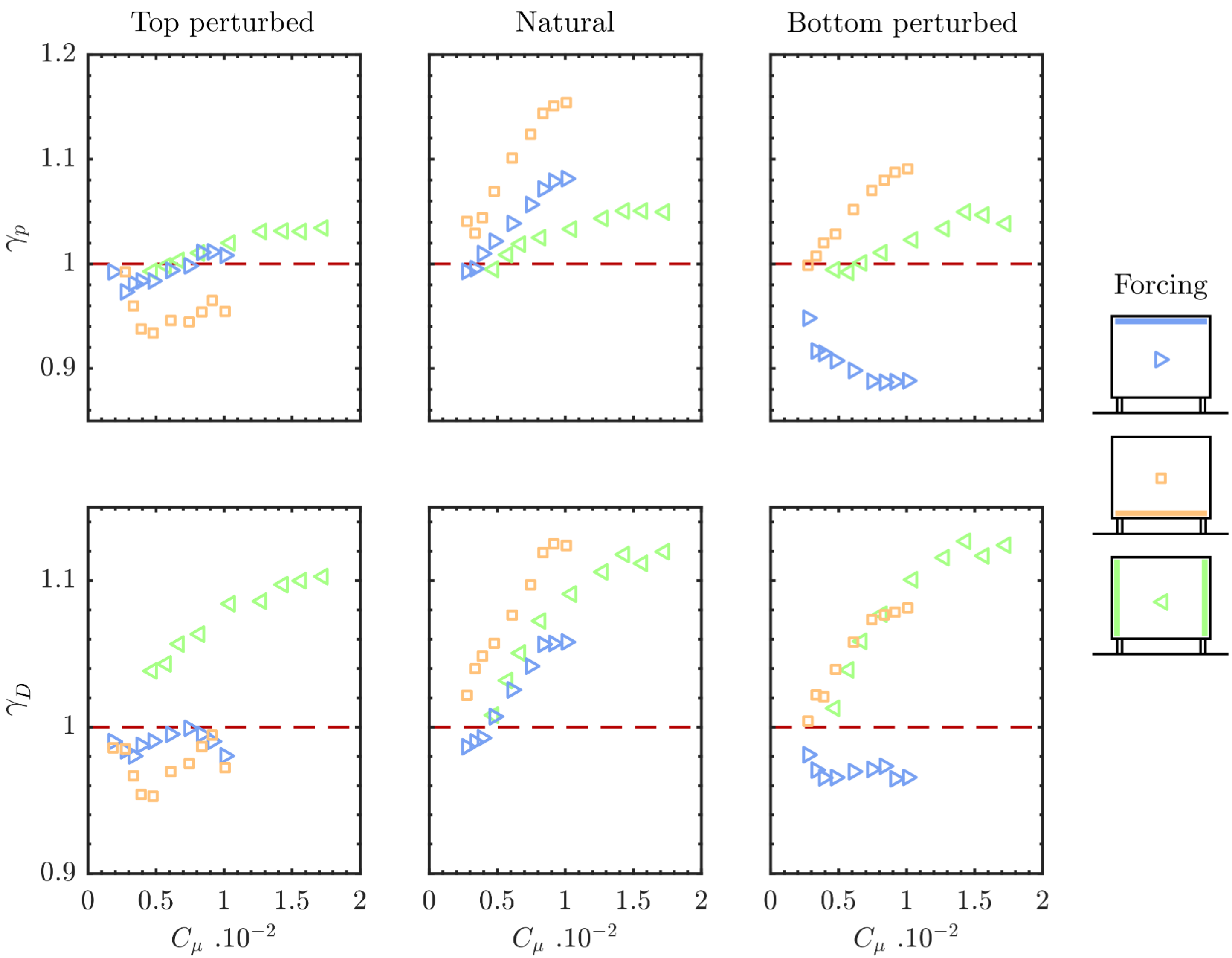
Effects of control in presence of asymmetries

Appendix

$$\gamma_\mathbf{p} = \frac{\mathbf{C_p}}{\mathbf{C_{p0}}}$$

$$\gamma_\mathbf{D} = \frac{\mathbf{C_D}}{\mathbf{C_{D0}}}$$



Pressure integration

Appendix

$$-2\frac{\partial \overline{C_p}}{\partial x} = \overline{U}\frac{\partial \overline{U}}{\partial x} + \overline{V}\frac{\partial \overline{U}}{\partial y} + \frac{\partial \overline{u'u'}}{\partial x} + \frac{\partial \overline{u'v'}}{\partial y}$$

$$-2\frac{\partial \overline{C_p}}{\partial y} = \overline{U}\frac{\partial \overline{V}}{\partial x} + \overline{V}\frac{\partial \overline{V}}{\partial y} + \frac{\partial \overline{u'v'}}{\partial x} + \frac{\partial \overline{v'v'}}{\partial y}$$

Direct integration along randomly generated paths

Oxlade PhD 2013