Bluff Body Flow Control through Piezoelectric Actuators

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MOTIVATIONS AND OBJECTIVE

In literature, only few active flow control techniques related to buff bodies are effective and efficient at ***high Reynolds Number***

The **aim** of the present research is to develop an active flow control technique with the following character tics:

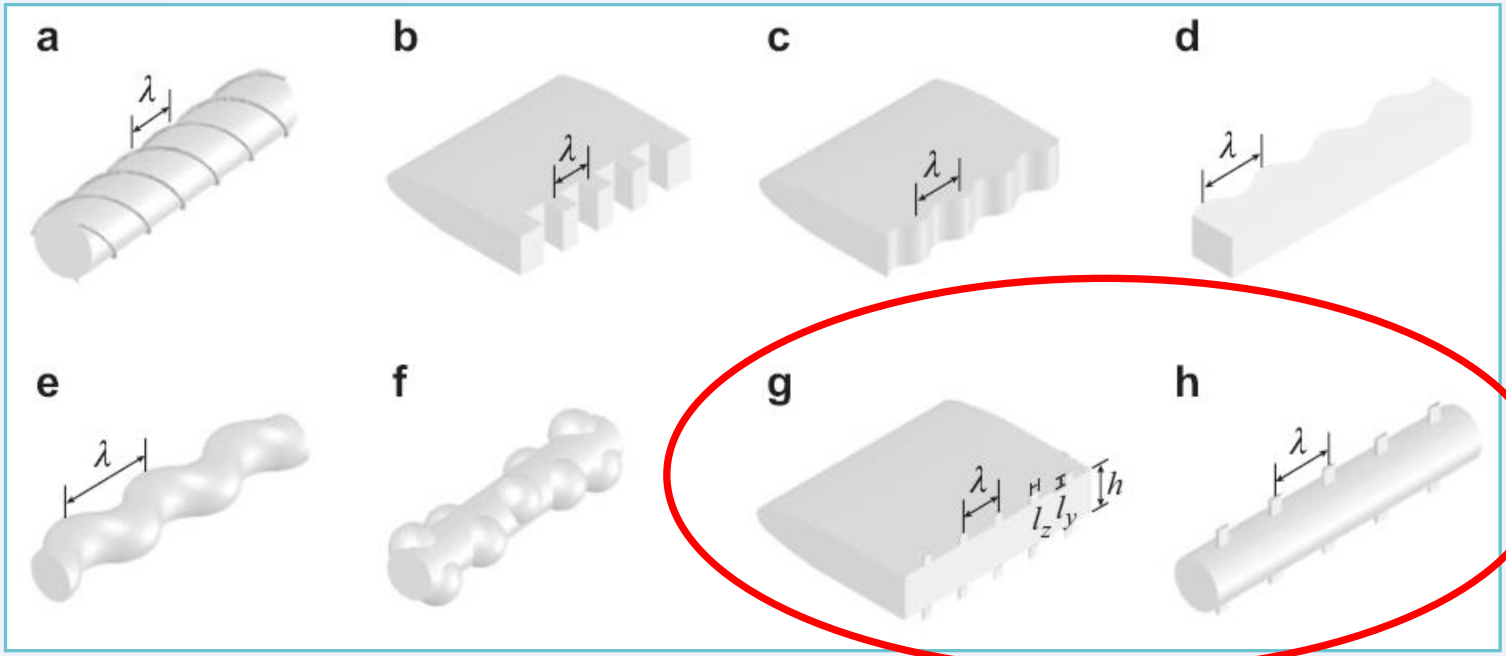
- ***Effective***, in both laminar and turbulent separation conditions
- ***Efficient***, thus having a low power absorption
- Ready for the implementation of ***closed-loop*** control strategies

STATE OF THE ART

PASSIVE FLOW CONTROL

Aim: vortex-shedding attenuation/suppression.

Drawback: Reynolds Number dependent effectiveness ➔ Hardly suitable for real applications



3D forcing by passive means: (*a*) helical strake, (*b*) segmented trailing edge, (*c*) wavy trailing edge, (*d*) wavy stagnation face, (*e*) sinusoidal axis, (*f*) hemispherical bump, and (*g*, *h*) small-size tab.

Choi et al., 2008

State of the art

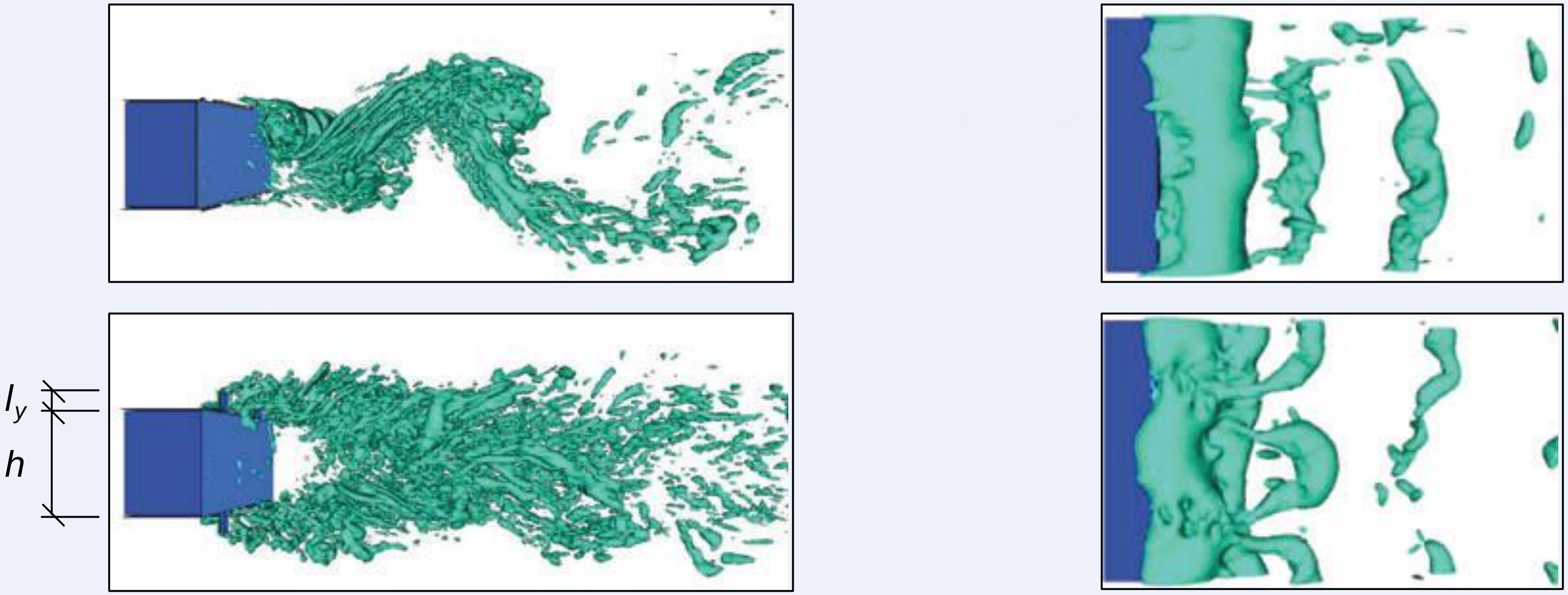
Passive flow control: micro-tabs

The ***micro-tabs*** (wake disrupters) seem to be the most promising passive control devices. They brake the coherence of spanwise vortices giving rise to:

➔ Reduction/suppression of the vortex-shedding

➔ Narrower wake

➔ Base pressure increment (up to 33%, Park et al.).



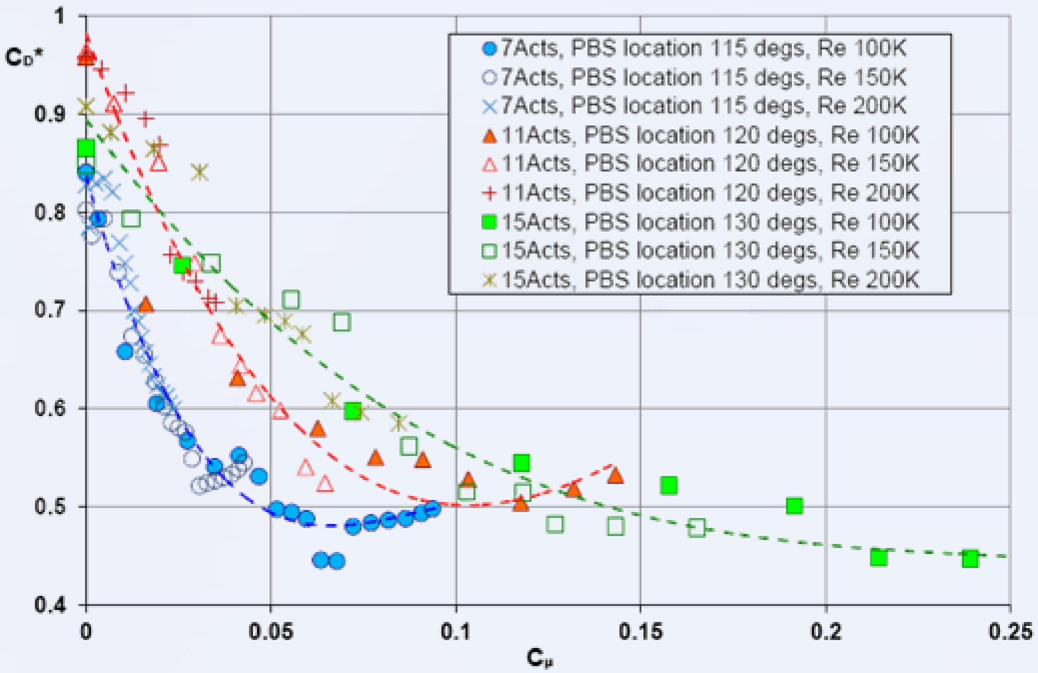
Instantaneous vortical structures in a wake (*$Re = u_\infty h/\nu$* = 4200, l_y/h = 0.2)

Park et al., *2006*

STATE OF THE ART

ACTIVE FLOW CONTROL: SUCTION AND OSCILLATORY BLOWING (SAOB)

Many active flow control techniques in literature related to bluff bodies are either effective only al low Reynolds number or they require high power actuators.



Drag coefficient versus momentum coefficient for different number of actuators , AFC locations and Reynolds numbers. Locations measured from the front, baseline stagnation point.

Shtendel and Seifert 2012

EXPERIMENTAL SETUP

CONTROL TECHNIQUE – ACTIVE ELEMENTS: ***Multilayer Piezoceramic Benders***

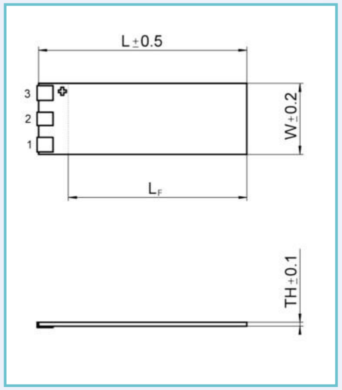
KEY FEATURES:

- ***Low power absorption***
- ***ENERGY RECOVERY feature***

Possible positive energy balance:

$\frac{1}{2}\rho U^{3*}\Delta Cd*D > P_{forcing}/B$

- ***Appropriate frequency response*** ➔ Possible future closed-loop control strategies

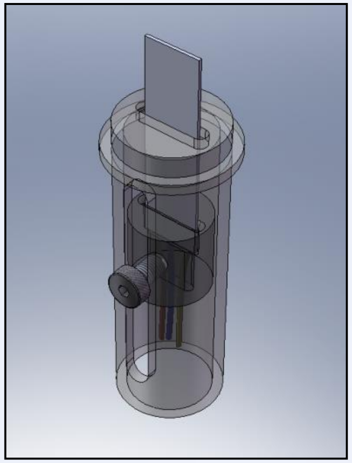


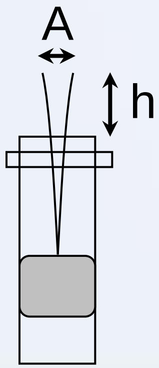
Order number	Operating voltage [V]	Displacement [µm] ±20%	Free length L_f [mm]	Dimensions L x W x TH [mm]	Blocking force [N] ±20%	Electrical capacitance [µF] ±20%	Resonant frequency [Hz] ±20%
PL140.10	0 - 60 (±30)	±1000	40	45 x 11 x 0.6	±0.5	2*4.0	160

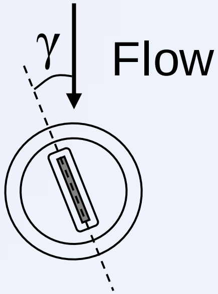
Experimental Setup

Control Technique - Smart Tabs

We were inspired by some of the most effective passive flow control devices, such as micro tabs and vortex generators, to create a versatile active actuator that we call ***Smart-tab***.





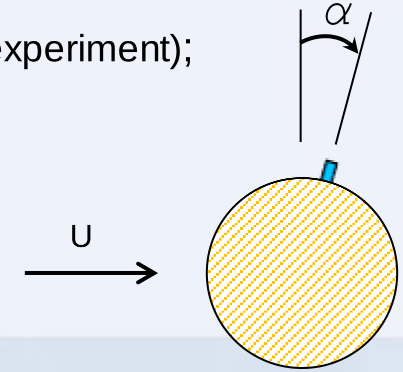


7 Control Parameters:

- Height (h_{max}=40mm);
- Angle of attack (0°<γ<90°➔***Vortex Gen***, γ=90°➔***Tab***);
- Oscillation amplitude (A_{max}=2.6mm);
- Oscillation frequency (f_{res}=160Hz);
- Waveform of the control signal;
- Pitch (p_{min} = 40mm);
- Phase (only 0° or 180° in this experiment);

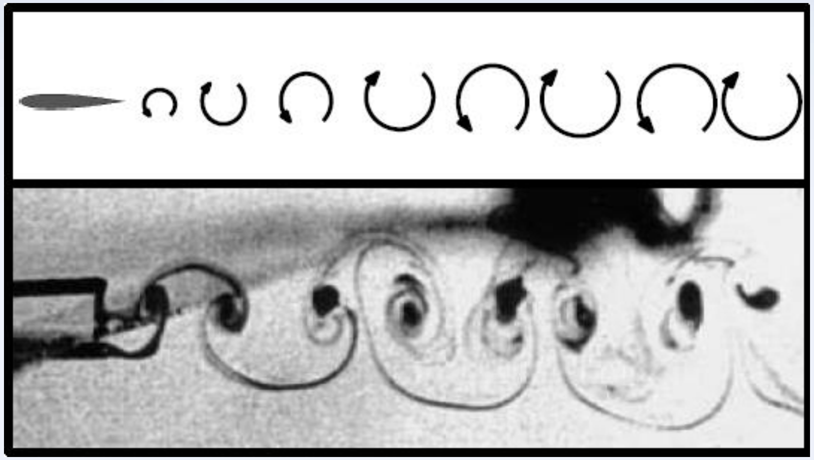
8th Parameter:

- Angular position (α)



Experimental Setup

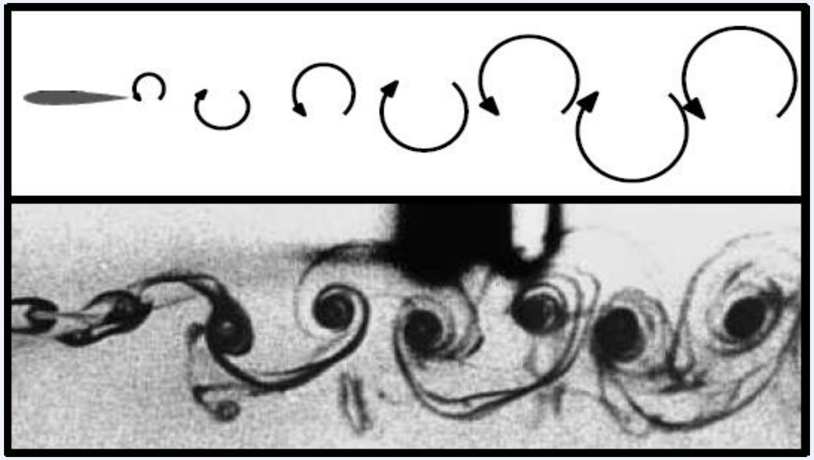
Control Technique - Preliminary Tests



$St=2Af/U \approx 0.18$

Alignment of CW/CCW Vortices

➔ Zero drag wake.



$St>0.18$

Inverse Von Karman Vortex Street

➔ Thrust generation (jet-like wake).

Wake Structures Behind Plunging Airfoils: A Comparison of Numerical and Experimental Results.

K.D.Jones et al. 1996

Experimental Setup

Control technique - preliminary tests

EXPERIMENTAL SETUP

MODEL REALIZATION

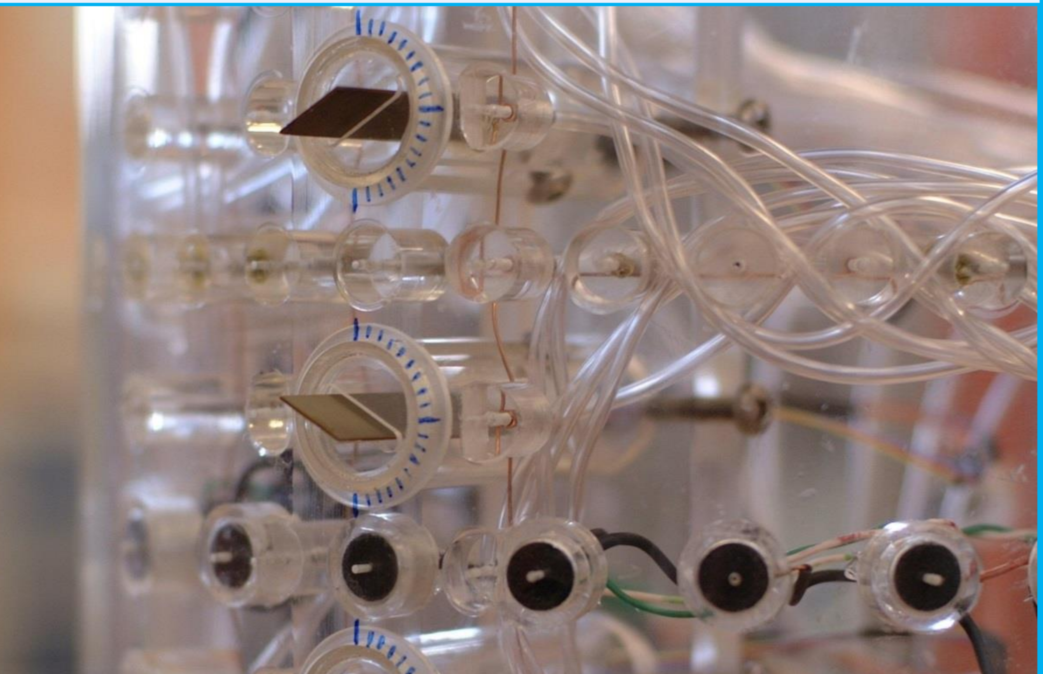
Geometry:

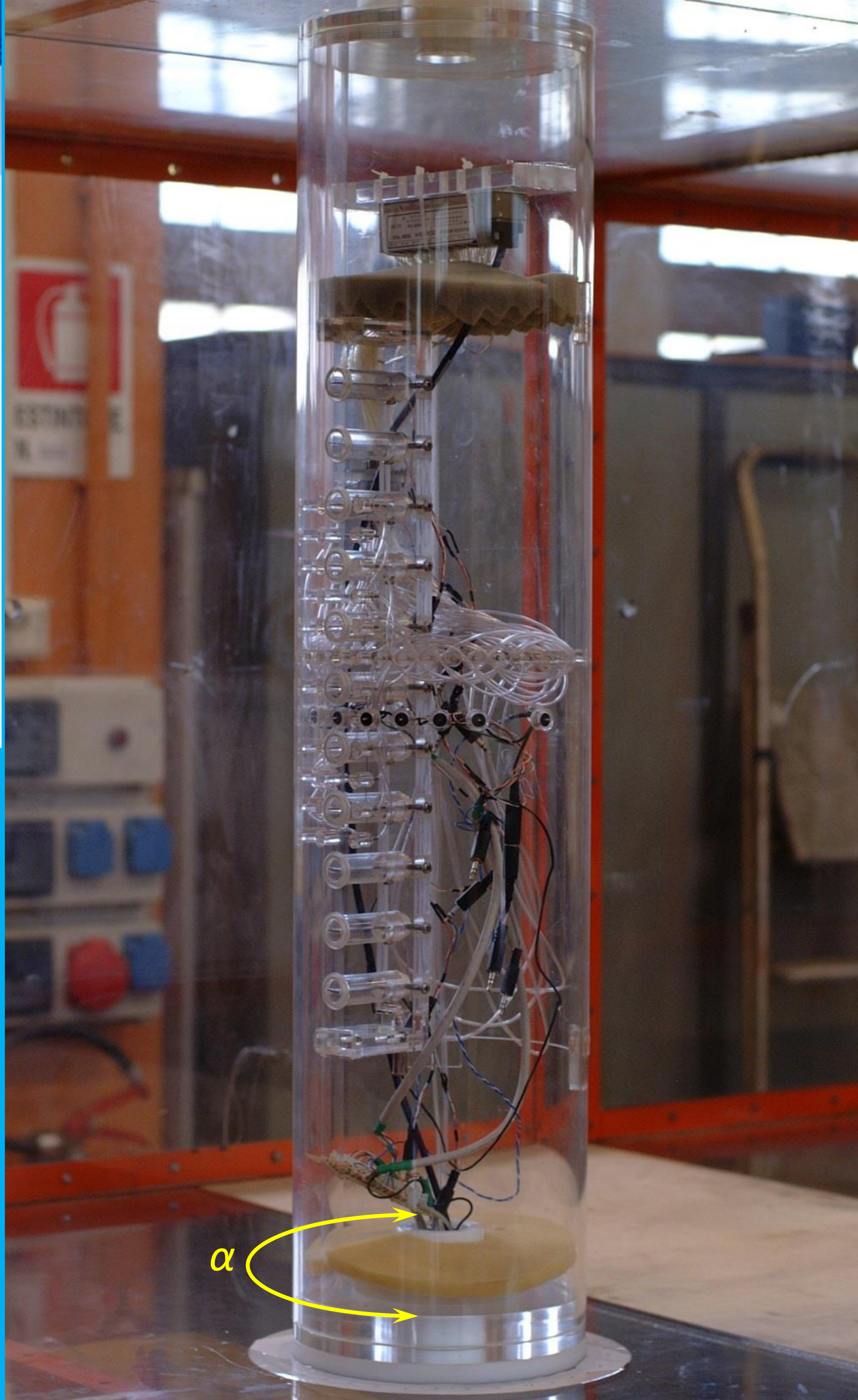
- Material: Plexiglass
- D = 200mm
- B = 885mm
- s = 5mm
- Adjustable actuators angular position on cylinder (α)

Instrumentation:

- Scanivalve ZOC33 pressure trasducer: 28 taps in the middle section + 3 rows x 10 taps in the spanwise direction

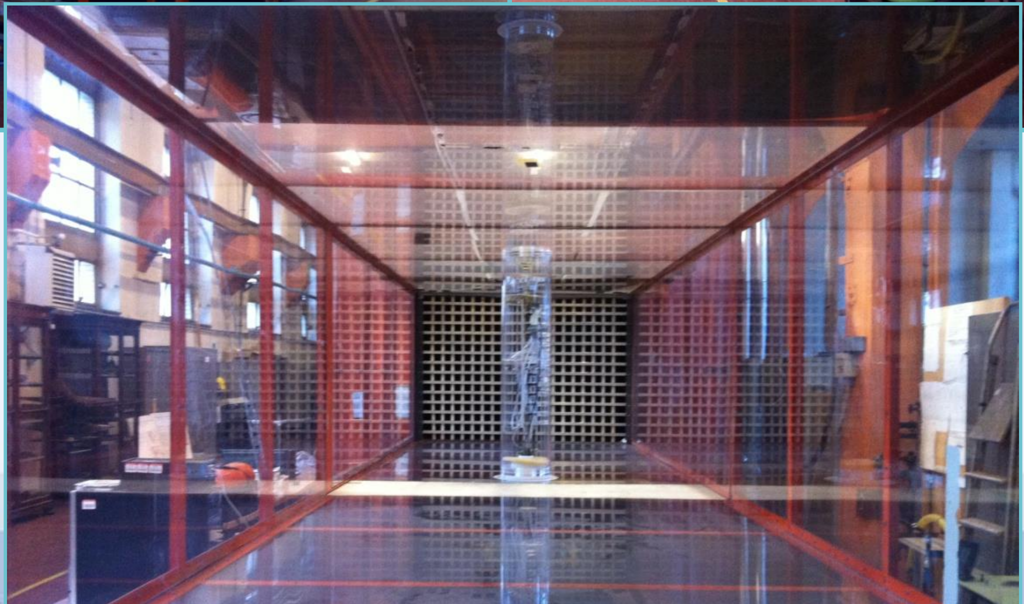
-15 fluctuating pressure trasducers (electret microphones)





Experimental Setup

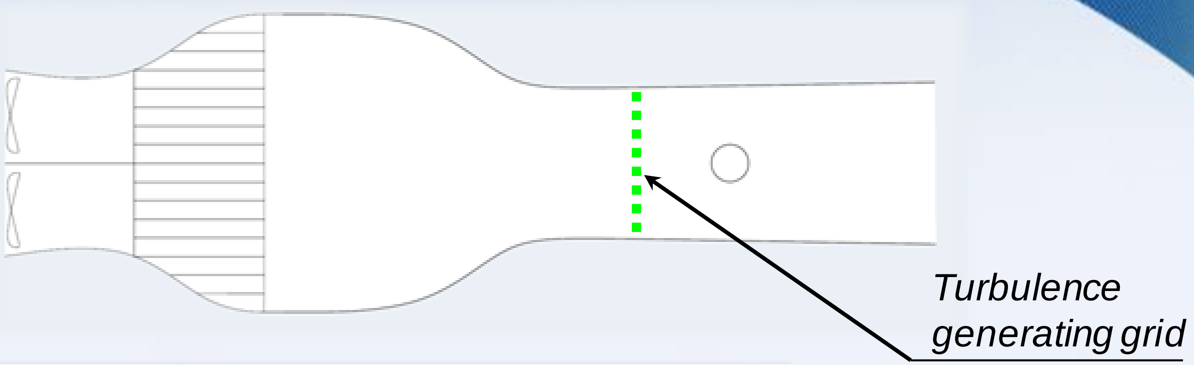
Wind Tunnel and Test Conditions

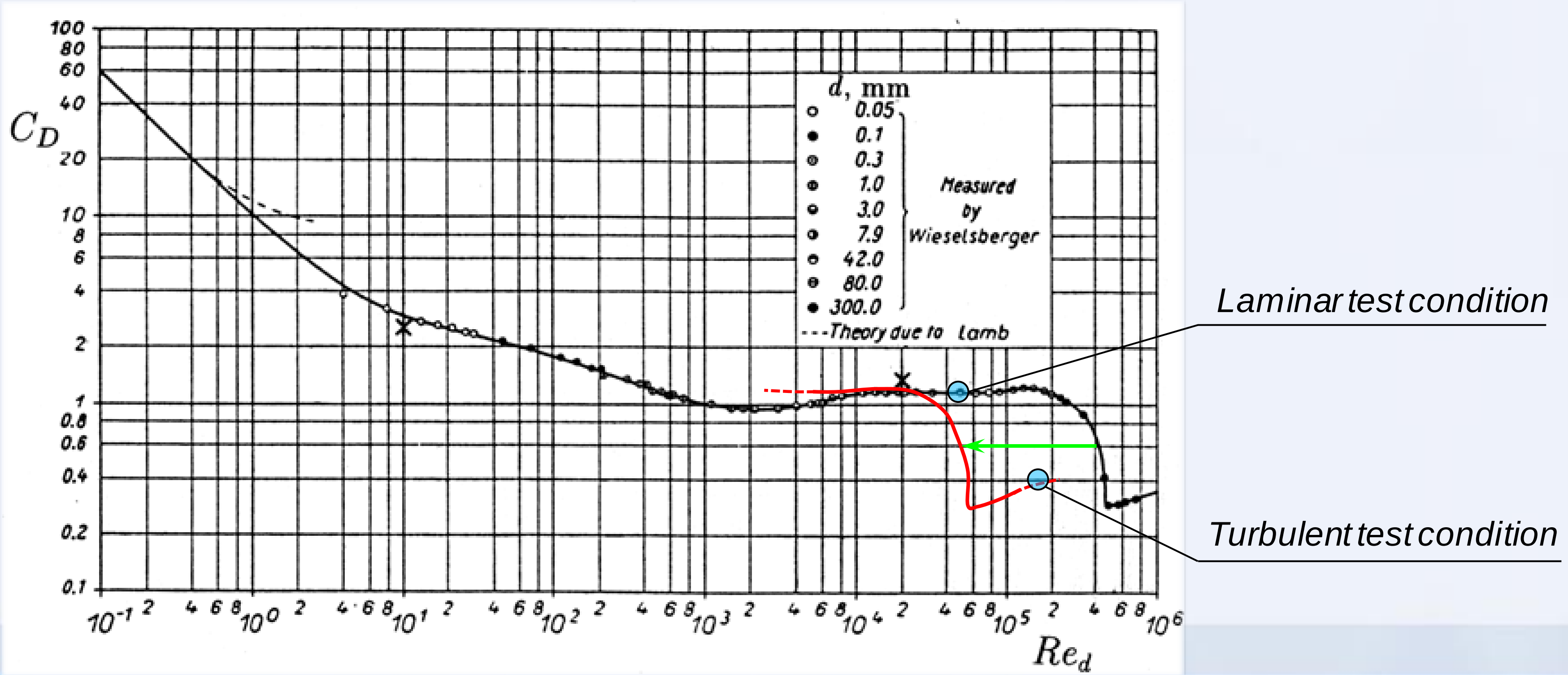


Experimental Setup

Wind tunnel and test conditions

- Blowing open-return type
- $U_{max} \approx 16$ m/s ➔ $Re \approx 2.1 \cdot 10^5$



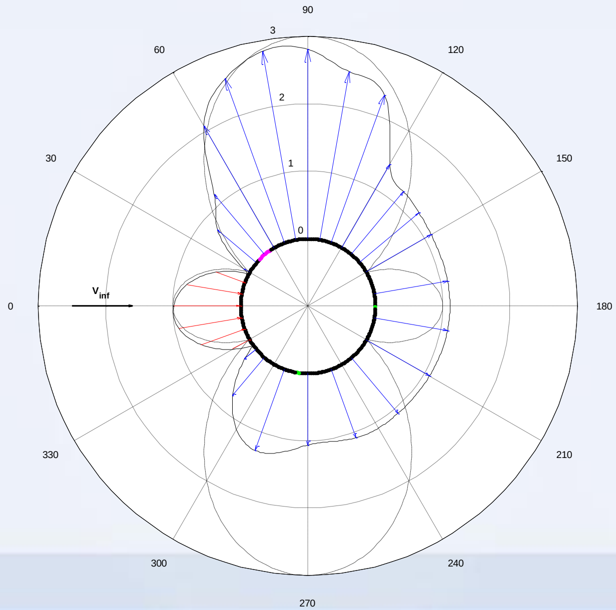


Experimental Setup

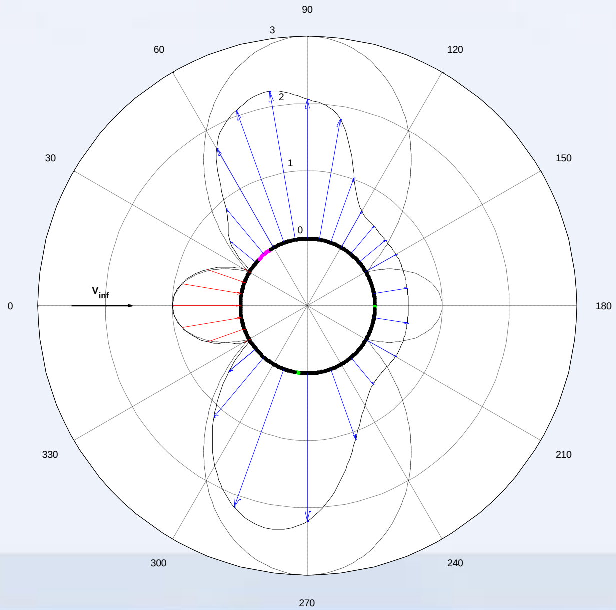
Wind Tunnel and Test Conditions

Forcing the transition also leads to ***flow symmetrization*** around the cylinder which otherwise is not granted.

Polar pressure coefficient distributions:



Without Grid



With Grid

Measurements Techniques

Current:

- ***Pressure distributions***: cross-section + 3 spanwise rows
- ***Pressure fluctuations***: cross-section using pin-hole mounted electret microphones
- ***Boundary layer velocity profiles*** using a 0.3 mm OD total pressure probe
- ***Actuators power absorption*** using a commercial watt-meter

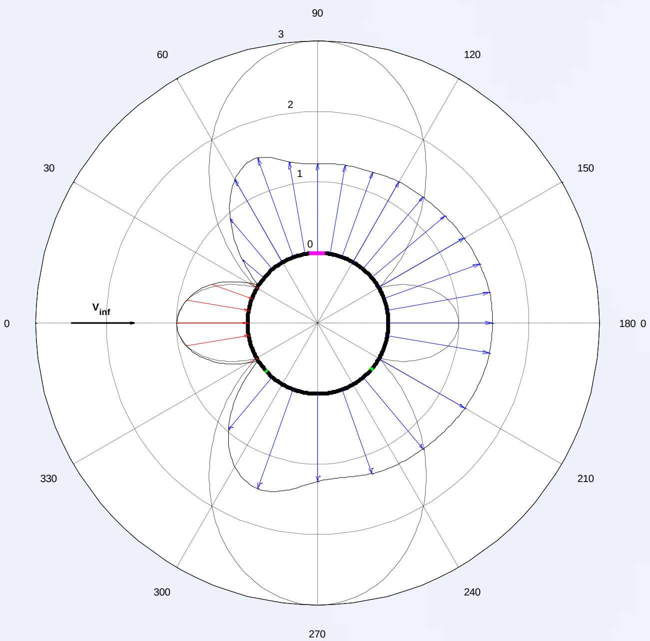
Future:

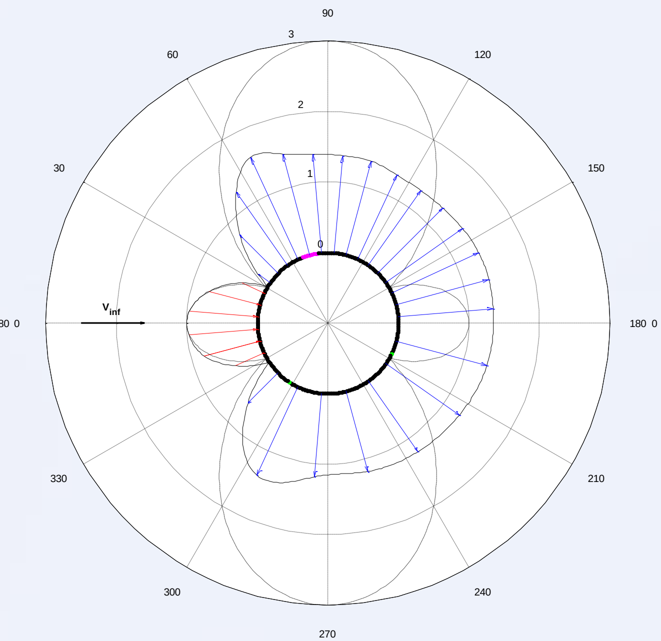
- ***Smoke flow visualizations***
- ***Wake analysis***
- ***PIV***
- **Hot wire anemometry**

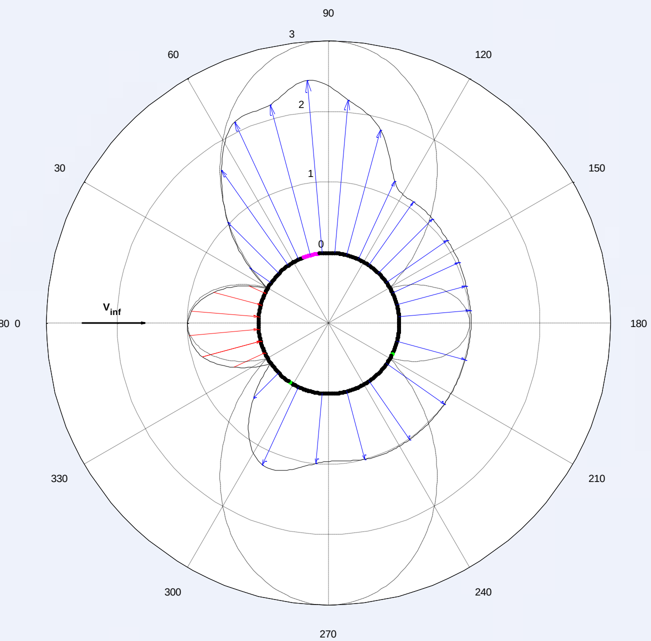
Results

Laminar separation control (Re = 52000)

Natural Flow	*Smart tabs (Passive)*	*Smart tabs (Active)*
	$\alpha = -15°$, $h = 5mm$, $\gamma = 0°$, $f = 0Hz$	$\alpha = -15°$, $h = 5mm$, $\gamma = 0°$, $f = 80Hz$







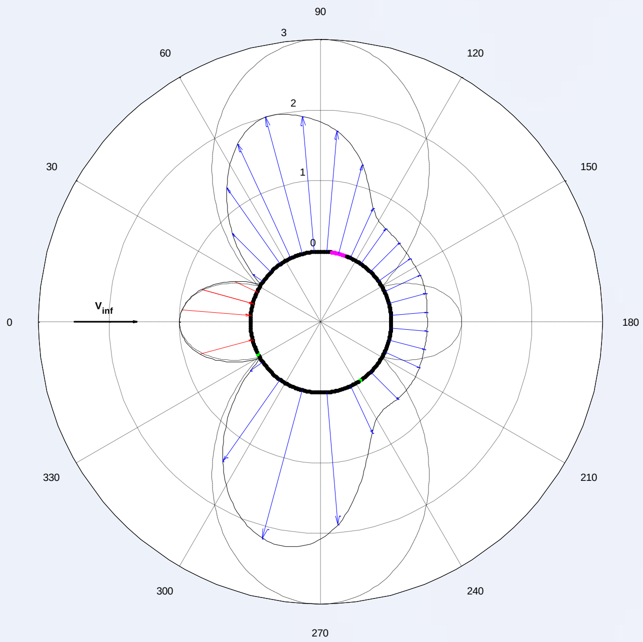
$C_d = 1.341$ → $C_d = 1.263$, $\Delta C_d = -5.8\%$ → $C_d = 0.943$, $\Delta C_d = -29.7\%$

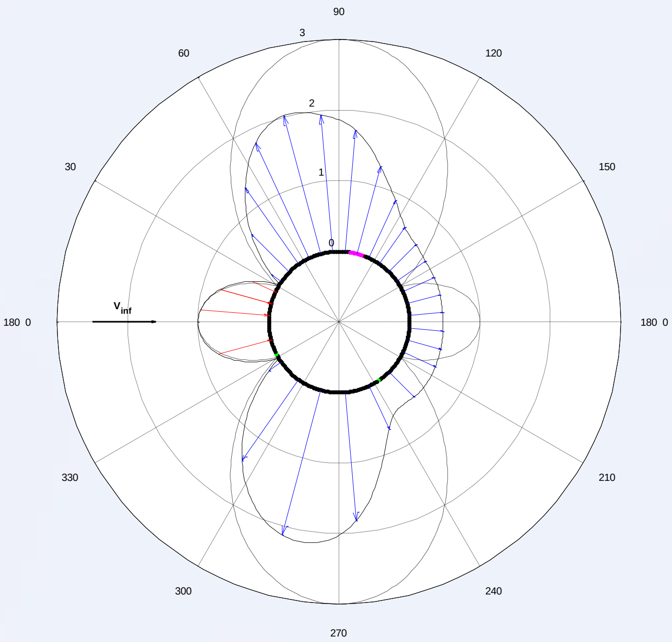
$(C_l = 0)$ $(C_l = 0.141)$ $(C_l = 0.607)$

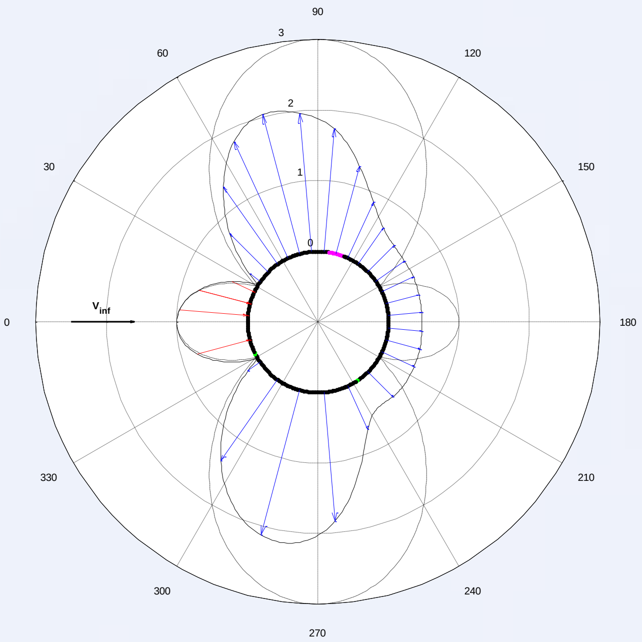
RESULTS

TURBULENT SEPARATION CONTROL (RE = 115000)

Natural Flow	*Smart tabs (Passive)*	*Smart tabs (Active)*
	α =-15°, h=10mm, γ =±30°, f = 0Hz	*α =15°, h=10mm, γ =±30°, f =100Hz*





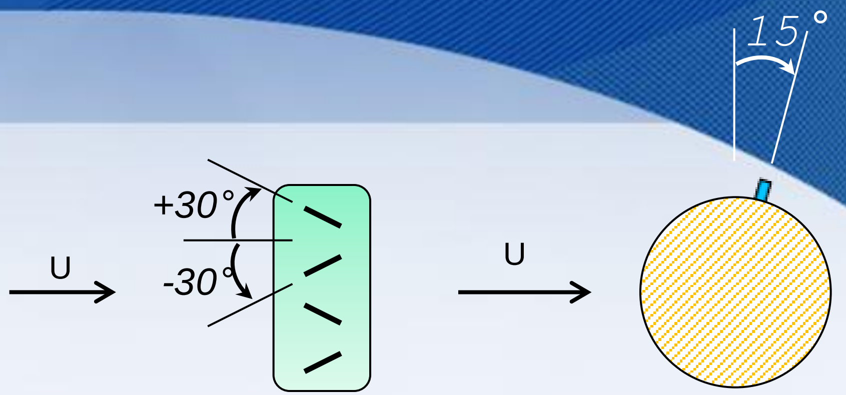


C_d = 0.445 → *C_d = 0.417*
ΔC_d = -6.3% → *C_d = 0.408*
ΔC_d = -8.3%

RESULTS

DRAG REDUCTION COLORMAP:

Boundary layer thickness δ ≈ 5mm (α = 15°)



KEY FEATURES:

- ***Height effect (Static effect):***

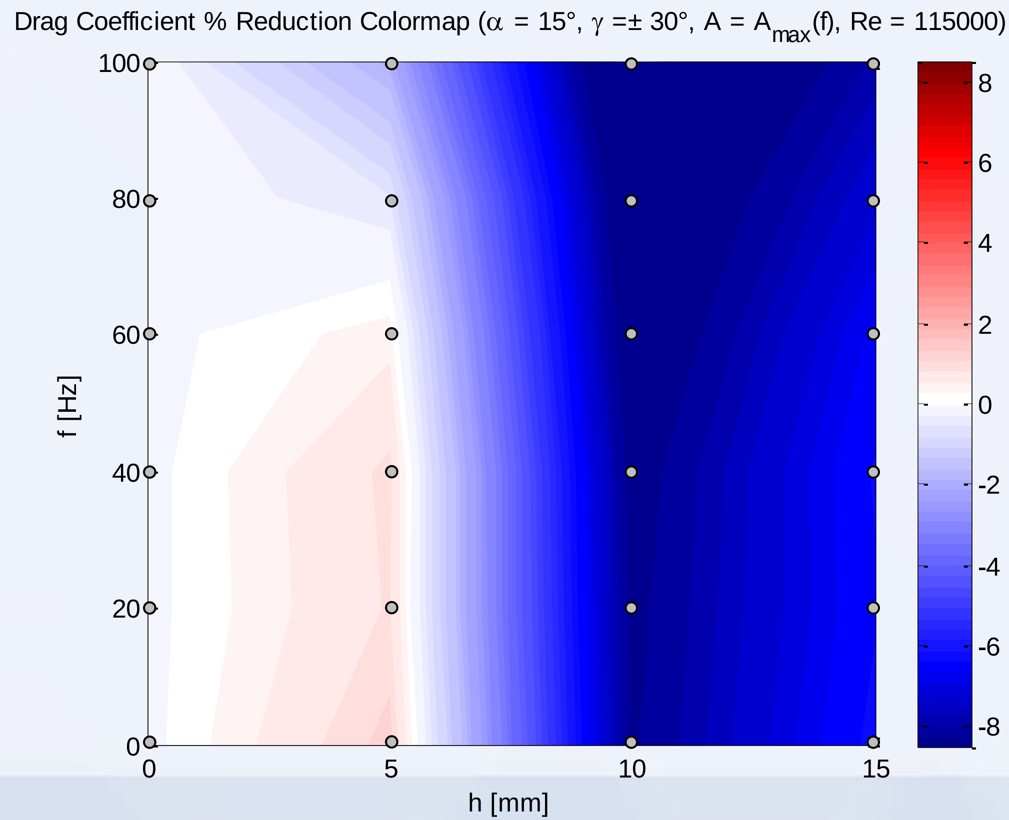
  For h≤5mm (h/δ≤1) there are no significant effects.

  Maximum drag reduction attained for h=10mm (h/δ≈2);

- ***Frequency effect**:*

  The drag alleviating effect always grows with the forcing frequency.

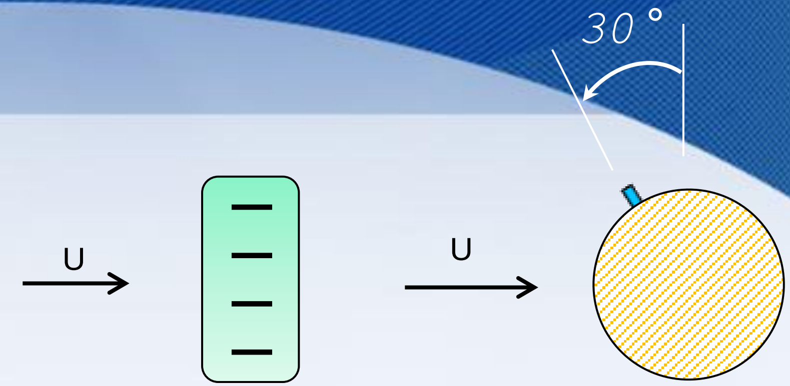
  For h/δ<2 the forcing contribution to drag reduction is more significant.



RESULTS

DRAG REDUCTION COLORMAP:

Boundary layer thickness δ ≈ 1.5mm (α = -30°)



KEY FEATURES:

- ***Height effect:***

  High values of the actuators height lead to drag augmentation for all the tested cases.

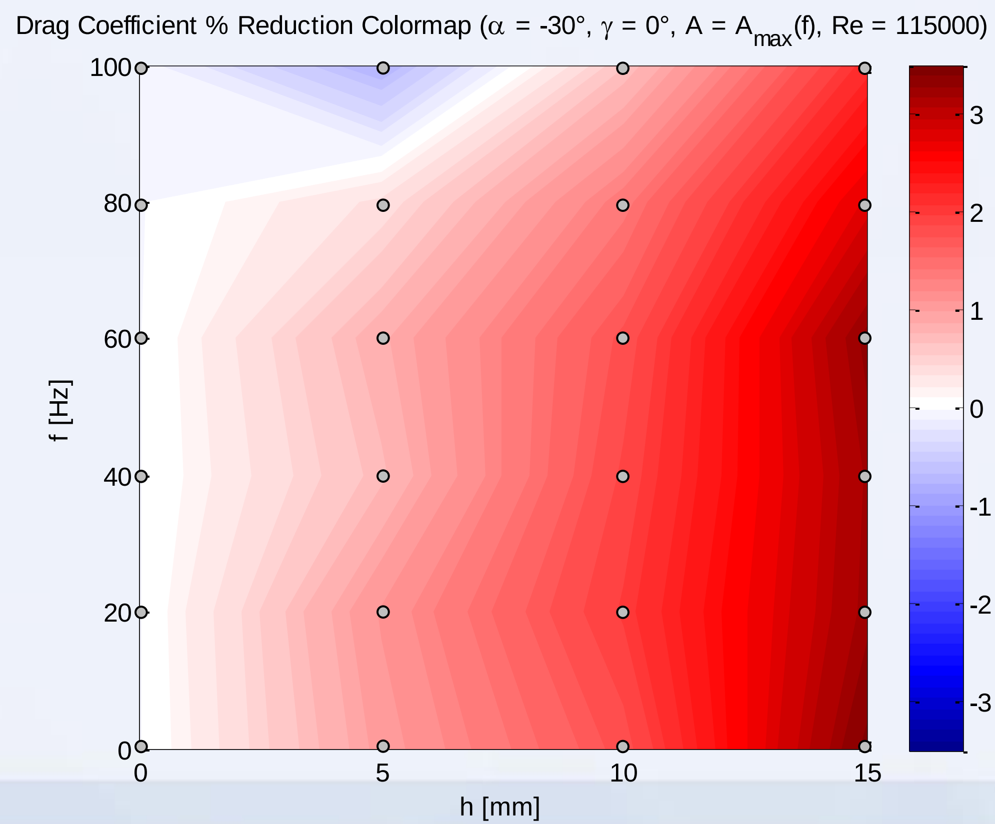
  The protrusion h is probably too high compared to δ.

  ➔ ***h/δ*** *appears to be a* ***key parameter****.*

- ***Frequency effect****:*

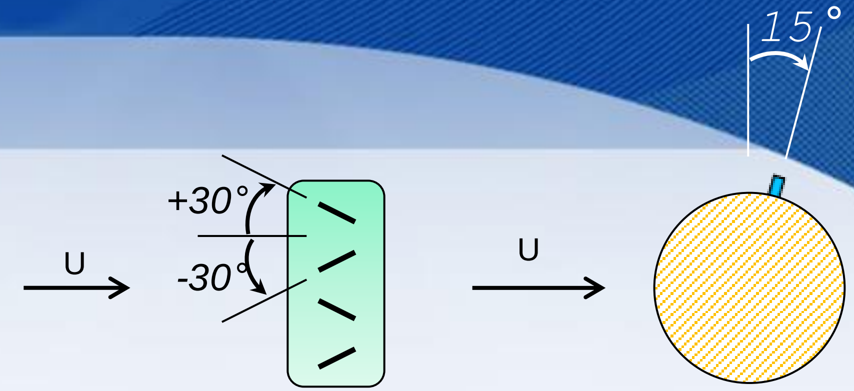
  The forcing frequency leads to ***drag alleviation independently from the static effect****.*

  ➔ *Different drag reduction mechanism may be involved.*



RESULTS

DRAG REDUCTION MAP



<u>*KEY FEATURES:*</u>

- ***Amplitude effect:***

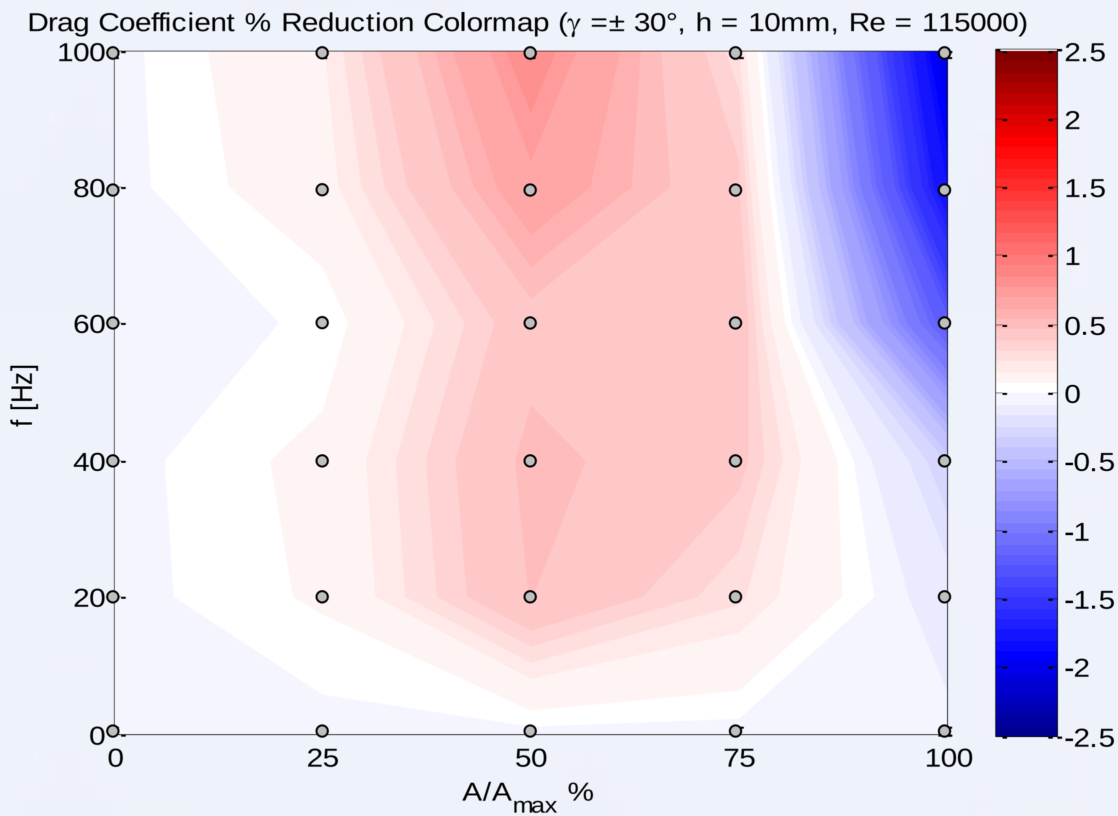
  All the field for A/A_{max} < 75% seems unaffected by the forcing.

  *➔ Actuators with **higher displacement** should be taken into account for future research.*

- ***Frequency effect**:*

  The drag alleviation grows with the forcing frequency although becoming significant for f >40 Hz.

  For A/A_{max} = 50% a small increase in drag with the frequency is observed (ΔC_d < 0.6%).



RESULTS

ACTUATORS POWER ABSORPTION MAP

KEY FEATURES:

- ***Very Low power absorption:***

  Less than 5W for 11 actuators in any condition

- ***Amplitude effect:***

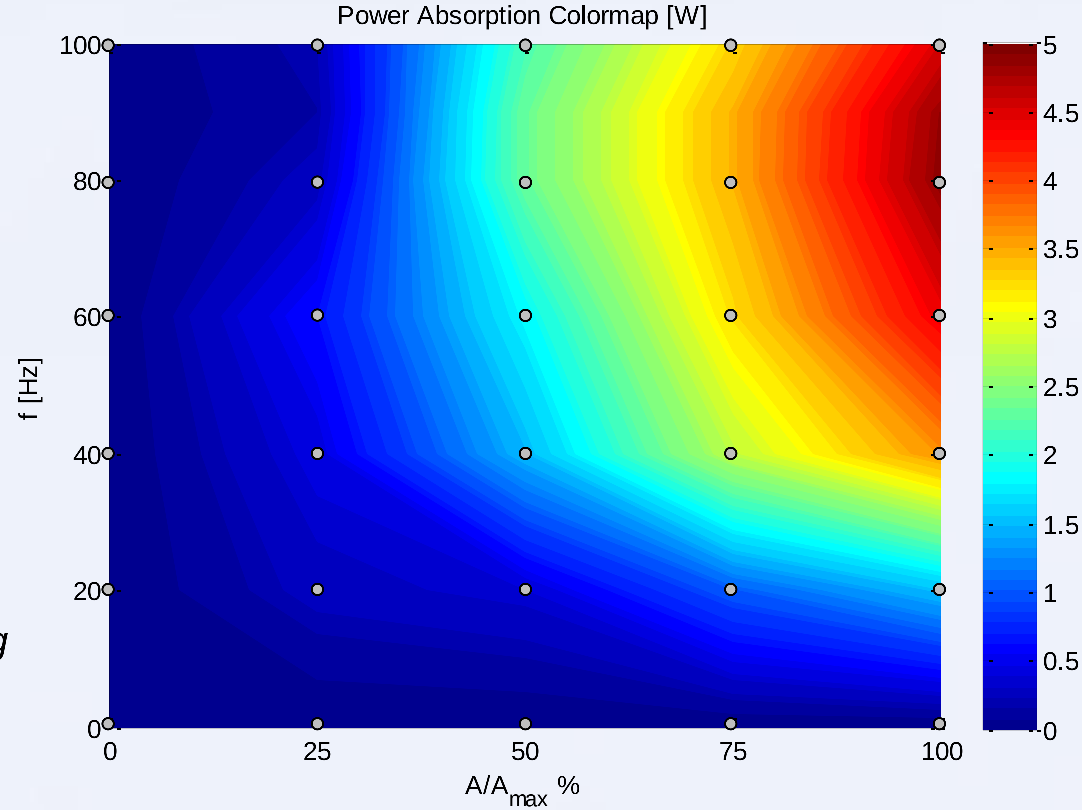
  Power consumption grows monotonically with the amplitude.

- ***Frequency effect:***

  The power consumption grows with the frequency up to 80-85 Hz

  after which it decreases as approaching the resonance frequency (160 Hz)

  ➔ *High efficiency in* ***resonance conditions***



Results

Power balance

$P_{Drag} = ½ρU^{3*}C_d{*}D \approx 40W$ (Re = $1.15{*}10^5$)

$P_{forcing}/B \approx 10.23W$

To achieve a **positive energy balance:**

$\Delta C_d > P_{forcing}/(½ρU^{3*}D{*}B) = 0.122$ (Re = $1.15{*}10^5$)

Obtained so far: $\Delta C_{d\_max} = 0.045$

<u>Considerations:</u>

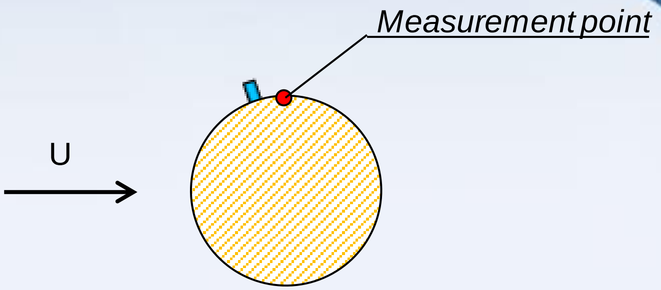
- Effects of the smart-tabs probably dependent on f*A/U
- The power related to drag alleviation grows with U^3

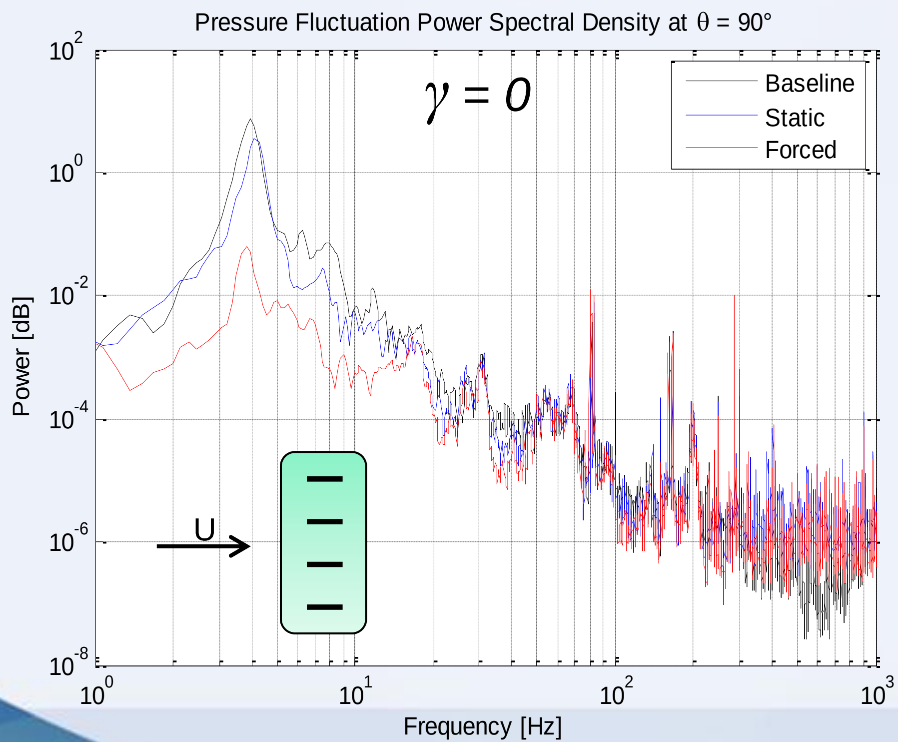
➔ For high U is easier to obtain a positive energy balance

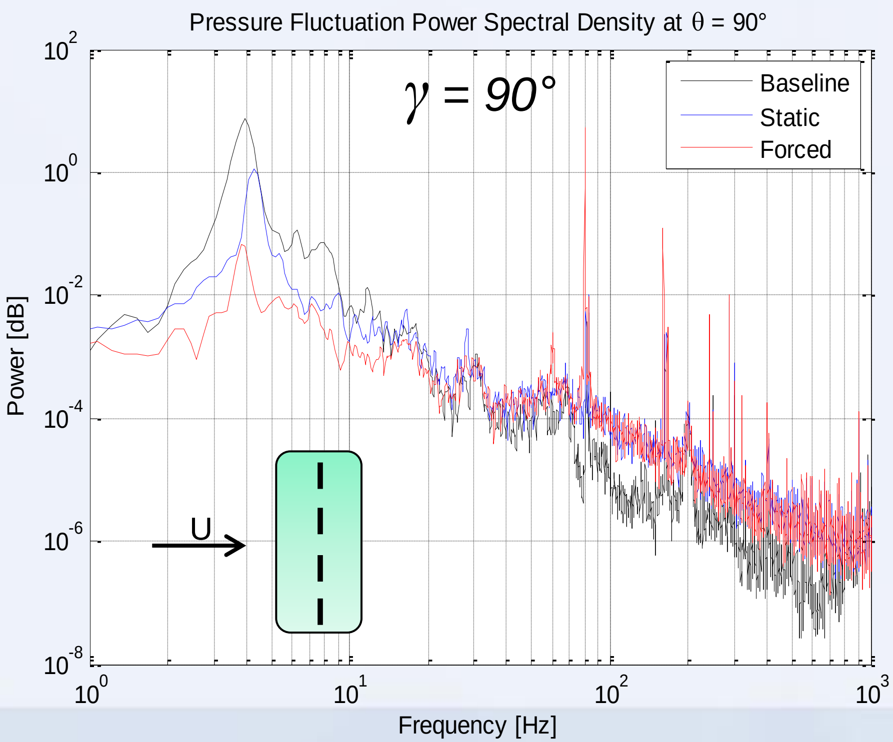
RESULTS

PRESSURE FLUCTUATION POWER SPECTRAL DENSITY (LAMINAR SEPARATION)

The ***vortex-shedding*** is reduced by the static action of the smart-tabs (when γ = *90°)* and is ***almost completely suppressed*** when the forcing is active.







PSD for Re = 52000, α = -15°, h=5mm, f = 80Hz

CONCLUSIONS

• In good agreement with the literature, the smart-tab used as wake disrupters or vortex generators (static conditions) are ***effective in both laminar and in turbulent separation*** conditions, although in the latter the effects are less marked.

• The effect of ***active forcing always leads to better results*** with respect to the static conditions, even with turbulent separation and even in the cases where the static protrusion of the tabs leads to an increment of drag.

•The ***protrusion of the tabs attenuates the vortex-shedding*** while the ***active forcing leads to an almost complete suppression***.

•The employment of piezoelectric benders as a flow control device has confirmed the expectations in terms of ***effectiveness*** and ***low power consumption***.

• For future research it is advisable to chose an actuator with ***higher displacement*** and able to work in ***resonance conditions*** in order to enhance effectiveness and efficiency of this flow control device.

THANK YOU FOR YOUR ATTENTION!