5th UTIAS International Workshop on Aviation and Climate Change
Toronto 1 May 18th 2016

MARS: Manipulation of Reynolds Stress for Drag Reduction and Separation Control

An Europe FP7-China programme

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Outline

- General presentation of MARS, a Europe P7 programme and China joint venture
- Improved Physical Understandings
- Innovative Flow Control Devices
- Innovative Optimisation Strategies
- Limitations and Future Work

What are the new challenges ?

Vision 2020	FlightPath 2050
-50% CO_2	-75% CO_2
-80% NO_x	-90% NO_x
-50% noise	-65% noise

ACARE

Flow Control is one major issue…

MARS Objectives

- To control turbulent wall bounded shear flow effectively from a more fundamental level by investigating directly the behaviour of Reynolds stresses and their response to the manipulation of the dynamic components of the flow
- To conduct both experimental tests and computational simulations to extract reliable flow physics, including Reynolds stresses, for a number of active flow control devices
- To explore large scale unsteadiness (unsteady jets, wakes and vortices) produced from the capability of these devices to provide effective control of the dynamic components, and hence the Reynolds stresses, within the shear layers associated with large scale wakes and separations
- To identify key strategies that enable efficient control of dynamic fluid structures within shear layers and to design and optimise these devices for separation control (higher shear) and drag reduction (lower shear)
- To demonstrate the most promising device/devices at relevant scale, the ability to efficiently increase or decrease the Reynolds stresses
- To investigate the application of this capability within an aircraft context
- To foster further collaboration between European and Chinese researchers in the key technology area of flow control for the benefit of the civil aircraft industries on both sides.

The consortium

AVIC-ARI(CH, Tech Coordinator)

NUAA (CH), THU (CH), NWPU (CH), ZJU (CH), BUAA (CH), PKU (CH),
AVIC-ACTRI (CH), AVIC-FAI (CH)

University of Sheffield(UK, Tech Coordinator),
CIMNE (ES), CAE (CH), CNRS PPRIME (FR), DLR (GE), FOI (SE), Univ. Manchester (UK),

AIRBUS (EU), AGI (UK), NUMECA (BE), Dassault Aviation (FR), ALENIA (IT), INRIA (F),

Basic Idea

Start by considering the triple decomposition for the potential contributions to Reynolds Stress. Consider the equation for an instantaneous velocity, U

$$U = \overline{U} + \widetilde{u} + u'$$

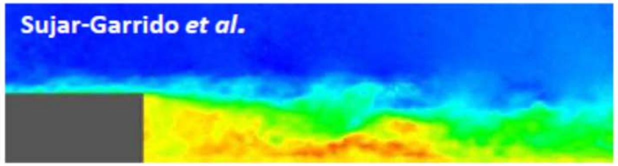
- The first term on the RHS is the time averaged mean velocity. If we attempt to control this via Flow Control then <u>most</u> devices offer little gain in efficiency on a global energy basis i.e. change in energy out equals energy in

- The periodic velocity component makes a significant contribution to Reynolds Stress for a number of specific flow cases. Typically those dominated by or producing narrow band velocity fluctuations that can affect skin friction, separation or dynamic loads.

- The final term on the RHS represents the broadband 'random' turbulent fluctuations whose control will remain the long term ambition for Flow Control.

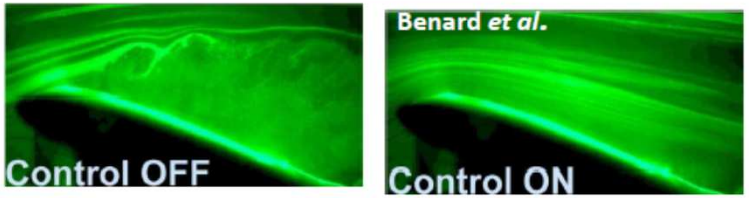
The two flow configurations of MARS Europe/China project

Backward Facing Step

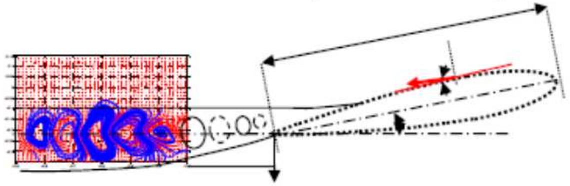


- Separated turbulent shear layer from a fixed sharp edge
- Periodic unsteady flows

Airfoil NACA0015



- Massive or partial flow separation
- Transient of the dynamic components



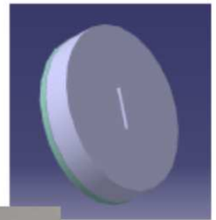
The main ingredients of flow control purposes are addressed: large scale instabilities, turbulent regime and in, a lesser extend, wall characteristics.

MARS: an almost complete set of actuators can be described as TWO categories

1. Actuators acting as **vortex generators:**

Wall jets

- Synthetic
  - Piezzo



  - Electro-magn

- Pulsed vanes

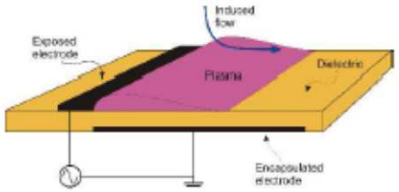
- Micro blowing/suction

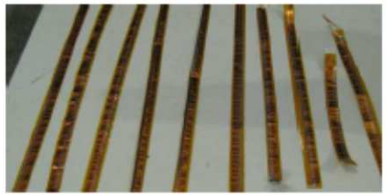
28/04/2016

MARS: an almost complete set of actuators

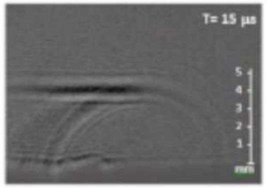
2. Acting near wall as **volume force**

- Plasmas
  - S-DBD

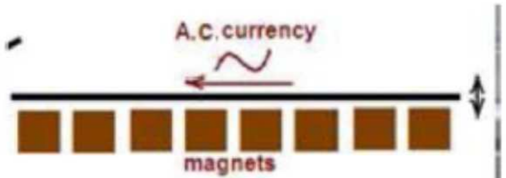


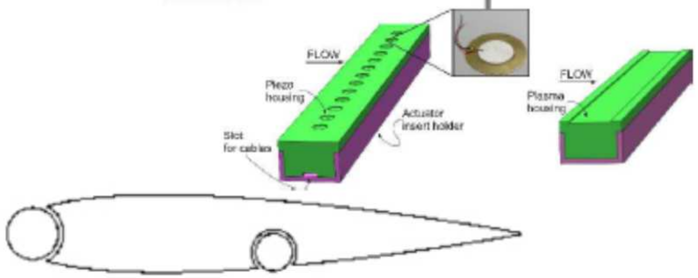


  - NS-DBD



- Wall effects
  - Lorentz force
  - Piezzo oscillating
  - Moving wall





Collaboration

experiment, simulation and optimisation

- Most control device cases were carried out with collaboration of experimental and computational partners to investigate the flow physics of the control devices
- Joint effects were crucial for the computational partners to build up their confidence for complicated flow simulations
- Simulations provided some turbulence flow structures for some further understanding of the flow control devices
- Some design optimisations based on computation were carried out but limited due the huge computation for resolved flow control fields

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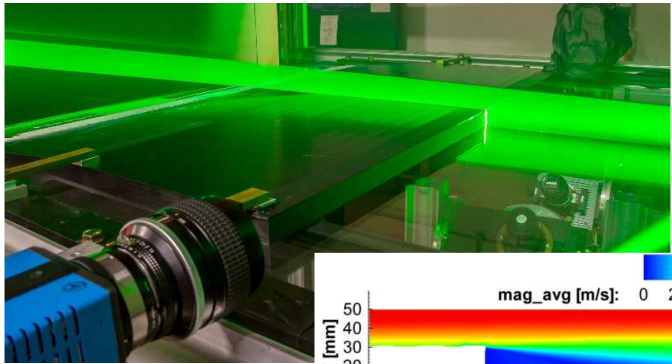
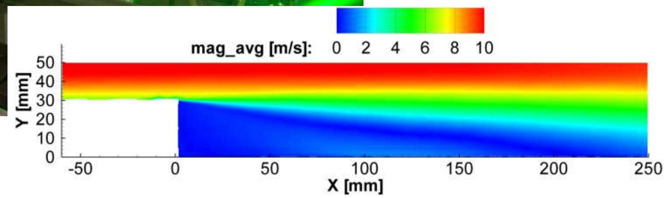
Time-resolved Tomographic PIV

Four Weeks of Joint Measurement Campaign – Part 1: BFS

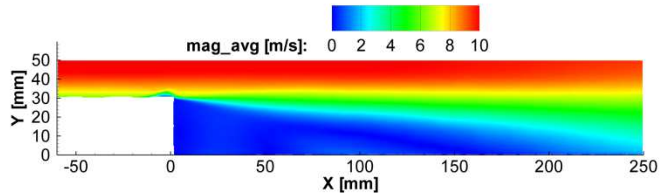


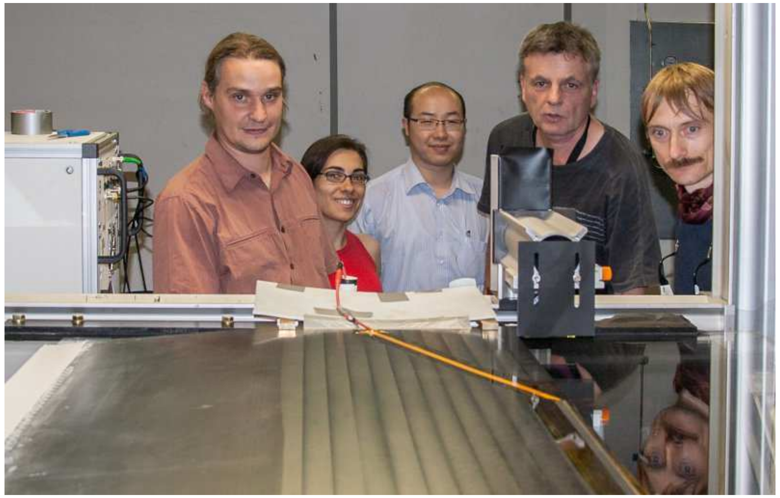
BFS with 2D PIV setup for TBL characterization

No actuator

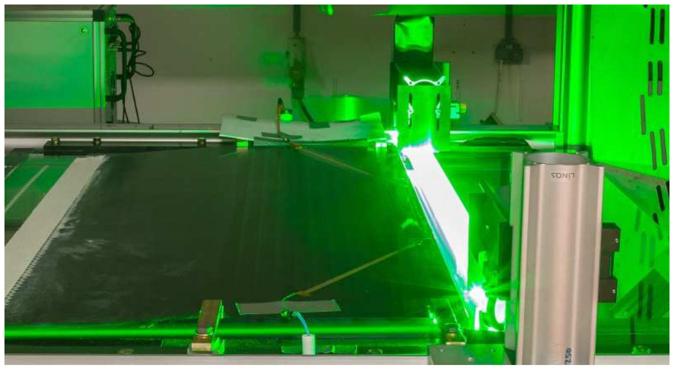


Plasma actuator at 83.3 Hz

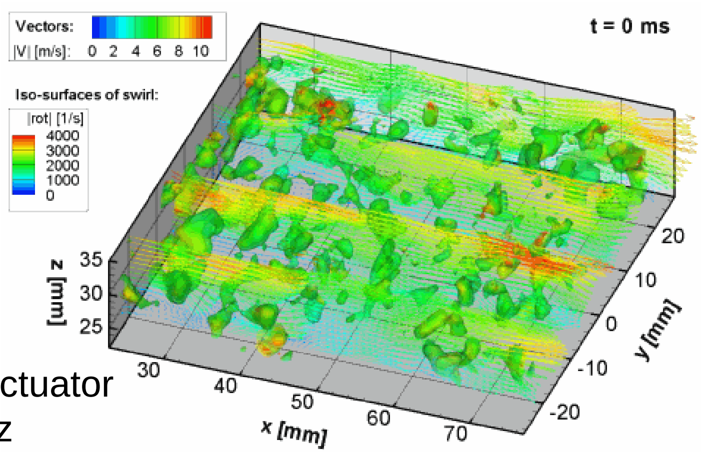




Plasma actuator test team (Poitiers, DLR)



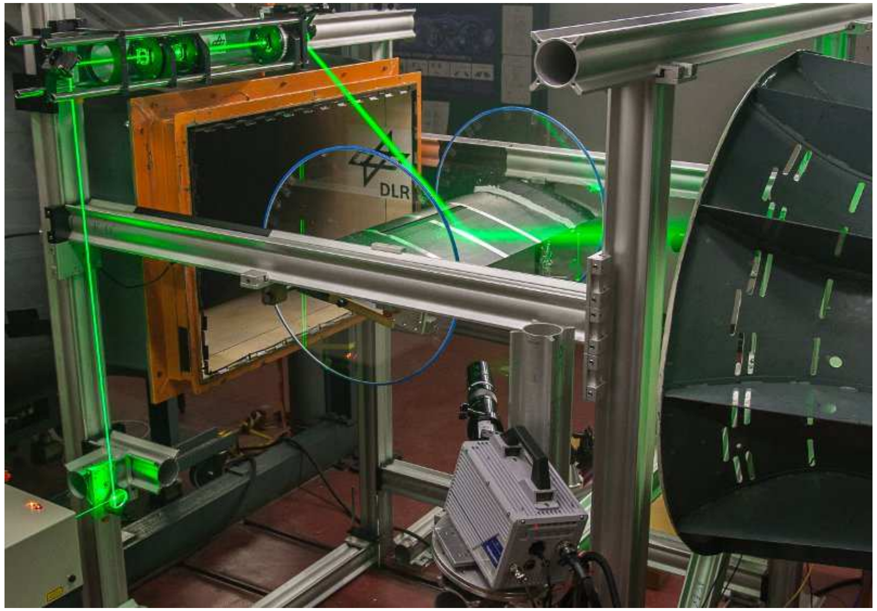
BFS with time-resolved tomographic PIV setup



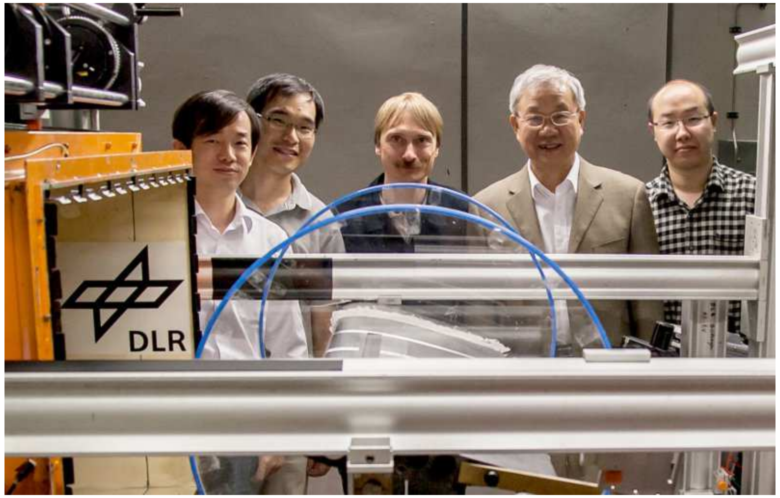
Plasma actuator at 83.3 Hz

Time-resolved Tomographic PIV

Four Weeks of Joint Measurement Campaign – Part 2: Wing



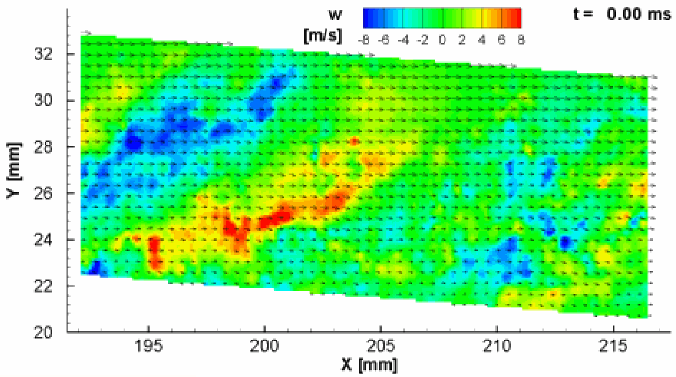
NACA 0015 with setup for time-resolved long-distance microscopic stereo PIV

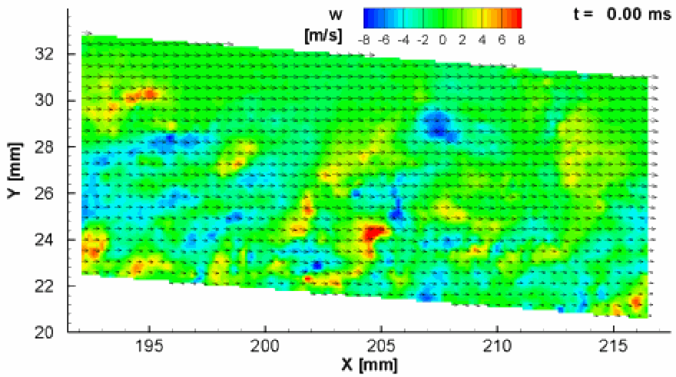


Synthetic jet test team (AVIC/ARI, NUAA, DLR)

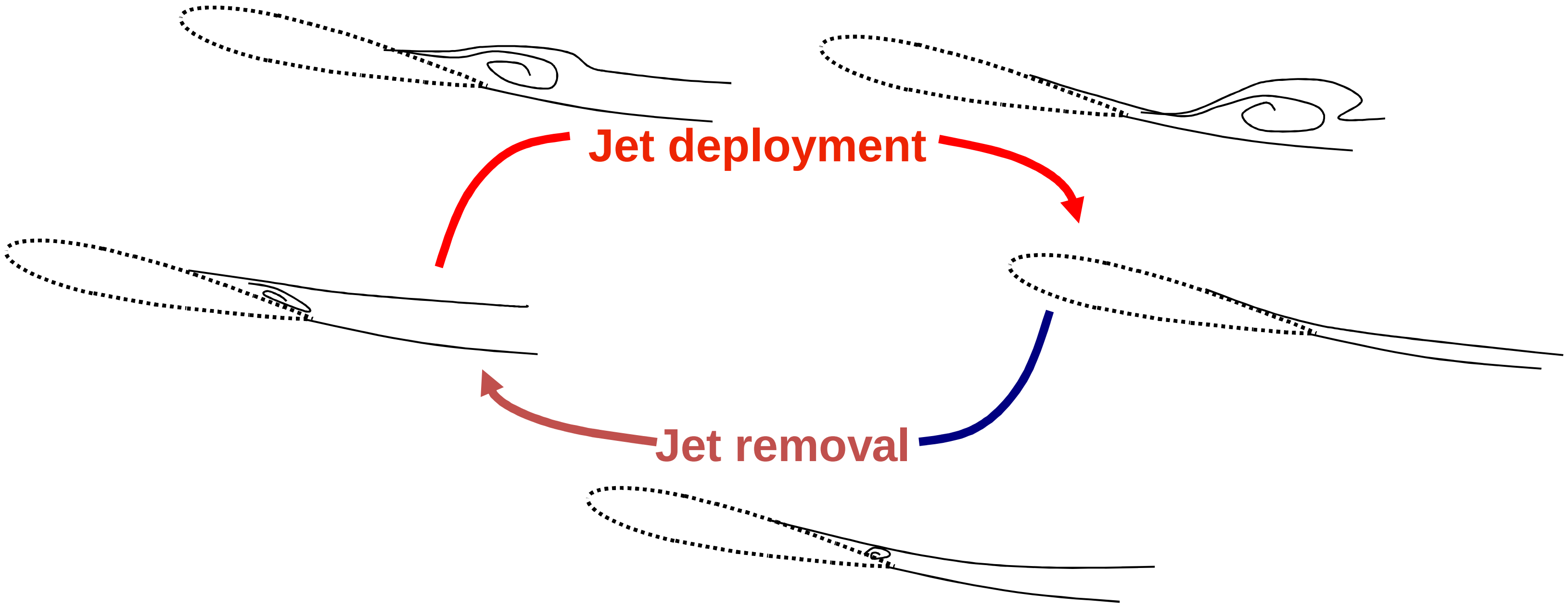
Stereo PIV sample results:

Time-resolved velocity vector fields with colour code of *w*-component without (left) and with (right) synthetic jet





Dynamics of flow attachment/separation over the airfoil surface of a NACA 0015 in response to impulsive deployment/removal of fluidic vortex generators (FVG).



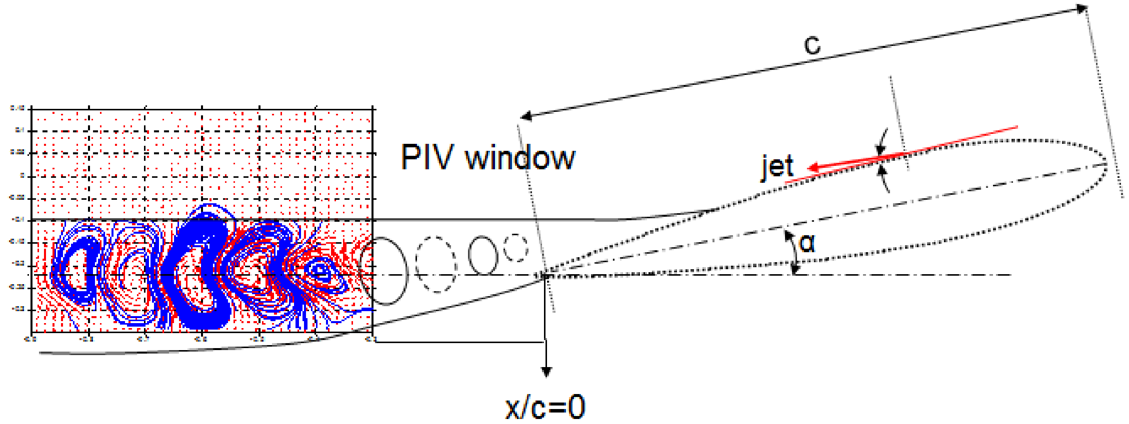
Transient wake of NACA0015 airfoil forced by pulsed jets (WL Siaw, JP Bonnet)

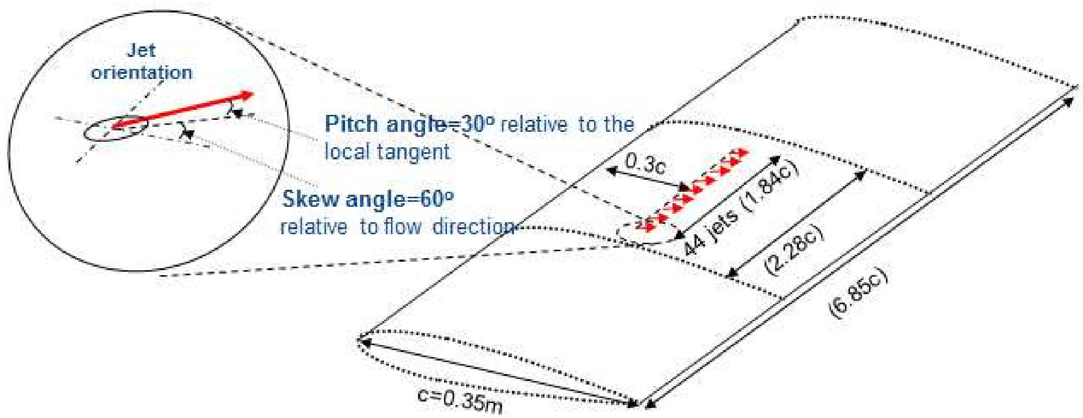
Experimental setup

- Chord 350 mm
- Span 2.4 m (AR = 7)
- Freestream velocity of 40 m/s
- Re = 1 M
- Fixed incidence 11˚
- 44 FVG Positioned at x/c=0.3
- Pitch angle=30˚ and skew angle=60˚
- 1 mm orifice diameter
- Jets spaced 15 mm apart

Metrology

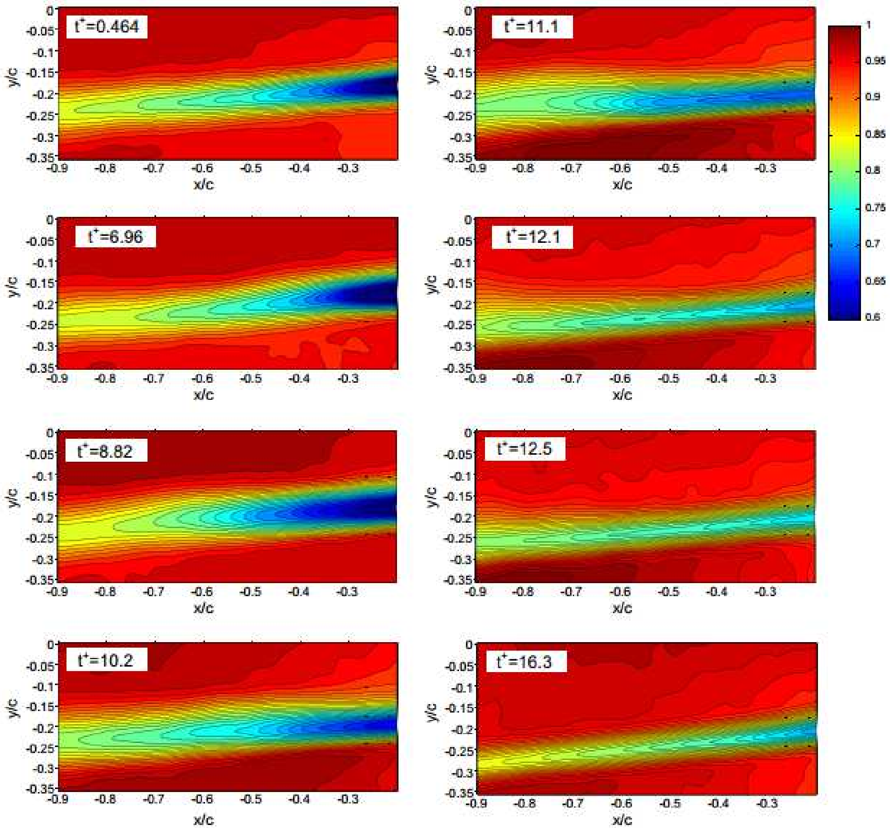
- PIV (phase-average procedure)



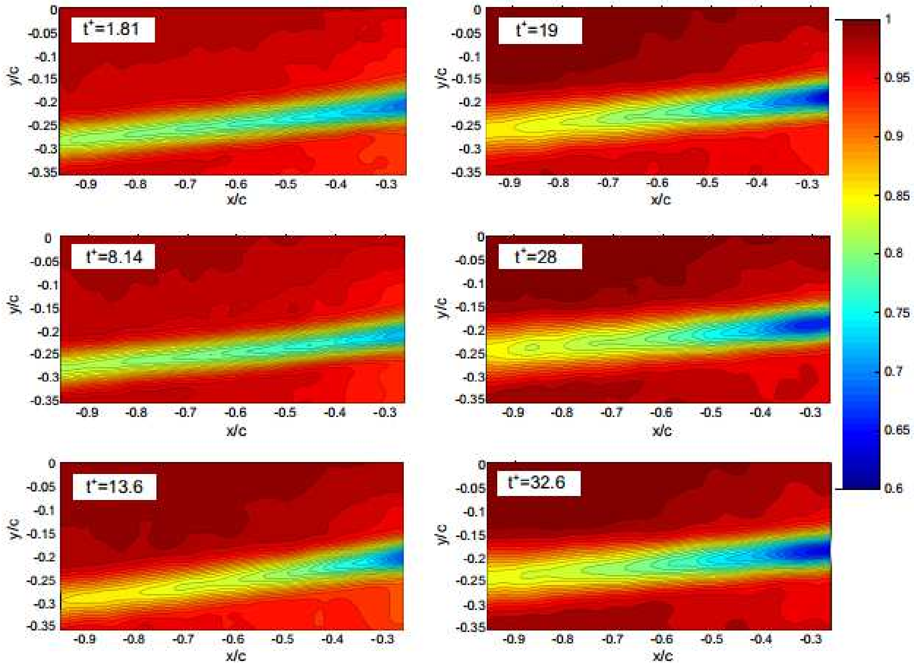


SEVENTH FRAMEWORK PROGRAMME

Transient flow velocity for jet deployment and removal



Evolution of the ensemble-averaged mean streamwise velocity of the airfoil wake during the attachment process

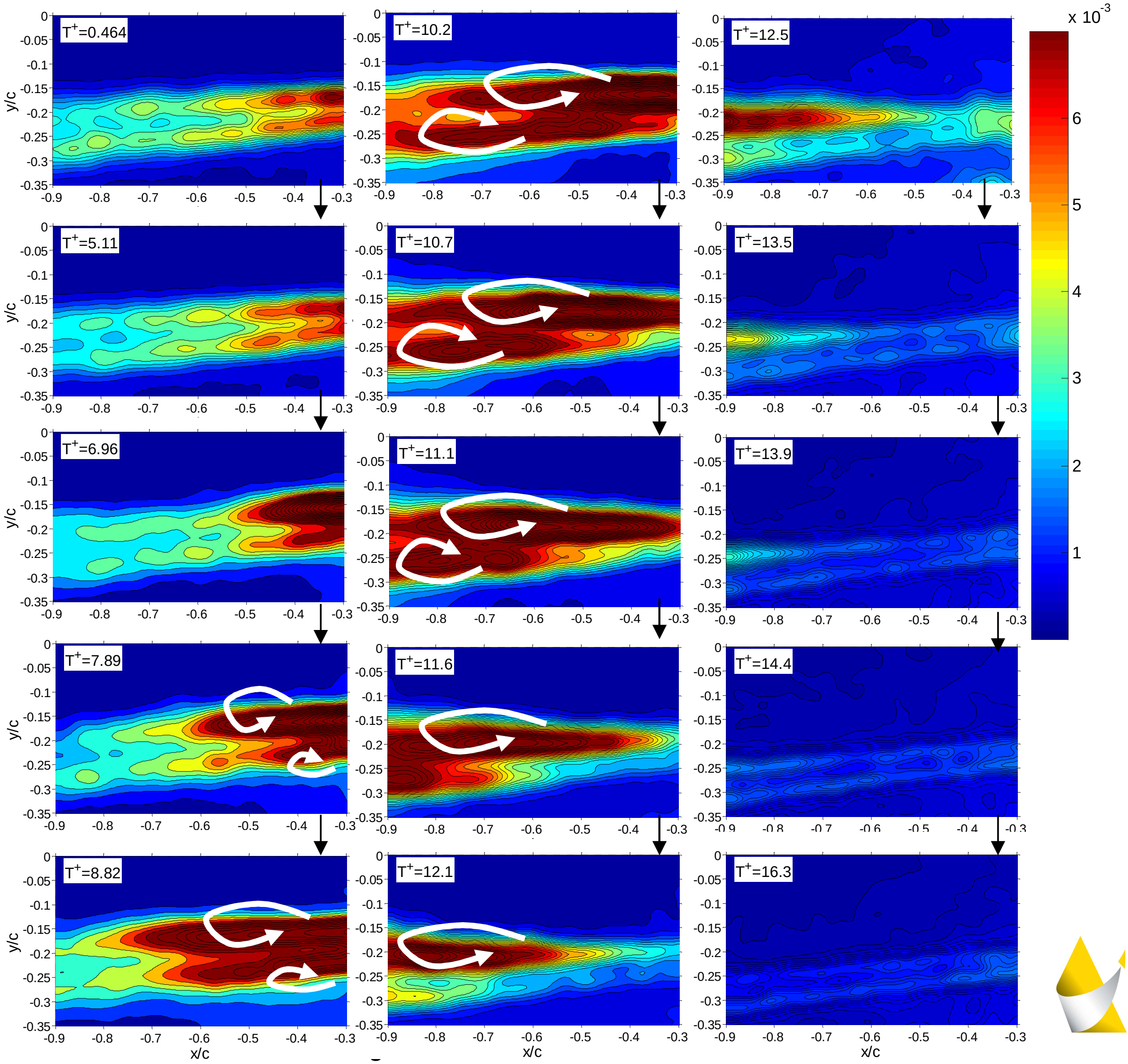


Evolution of the ensemble-averaged mean streamwise velocity of the airfoil wake during the separation process

SEVENTH FRAMEWORK PROGRAMME

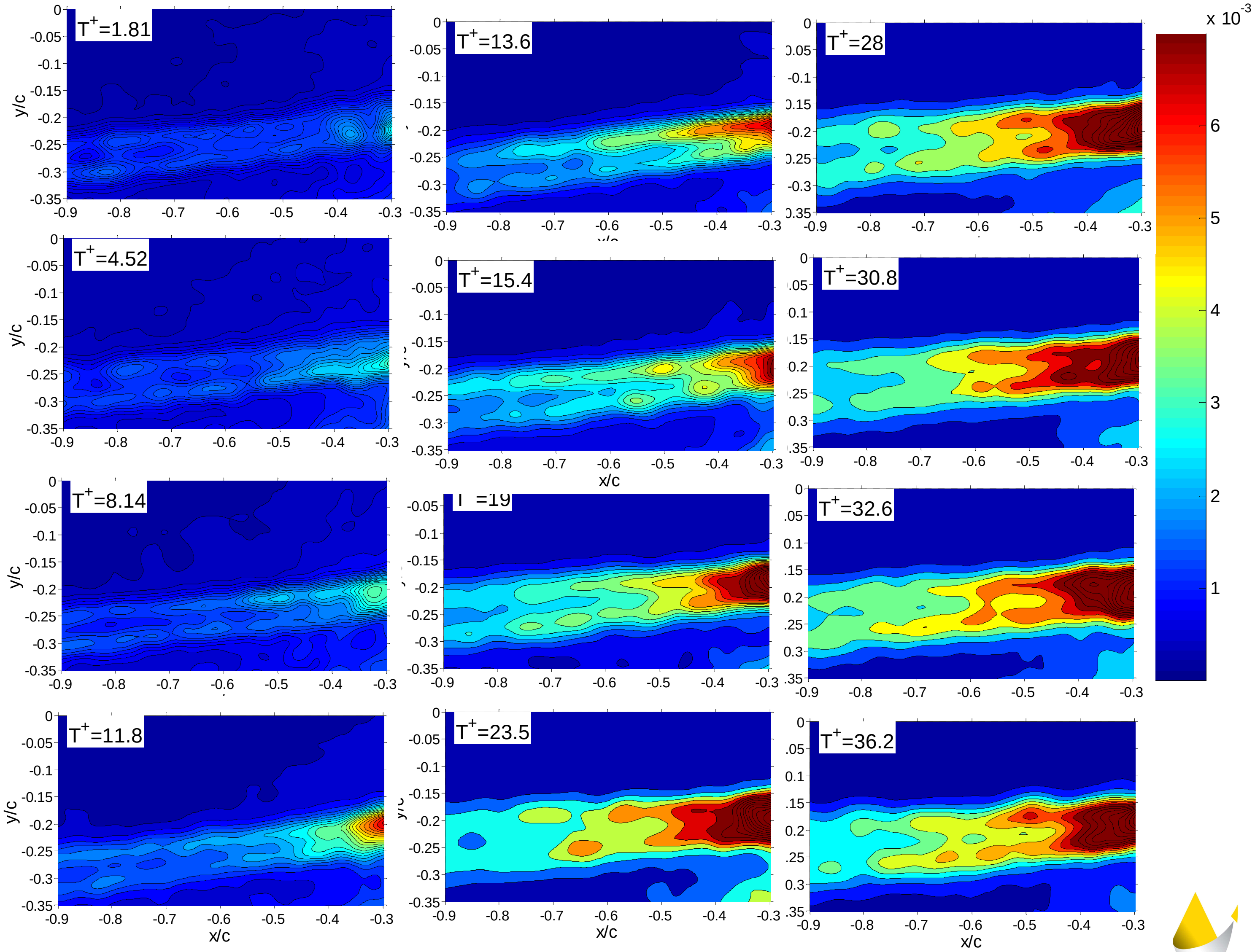
Transient Process in the Wake During FVG Deployment

- Evolution of the contour of $\langle u'u' \rangle / U_\infty^2$ consisting of 40 time delays
- Note the convection of a region of high turbulent fluctuation

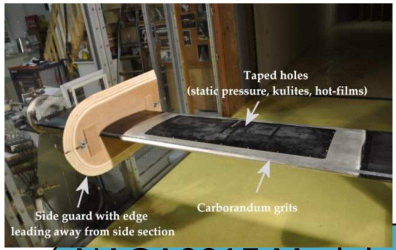


Transient Process in the Wake During FVG Removal

- Evolution of the contour of $\langle u'u' \rangle / U_\infty^2$ consisting of 40 time delays

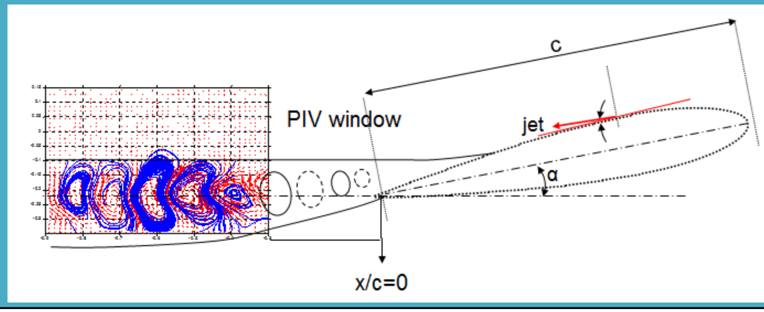


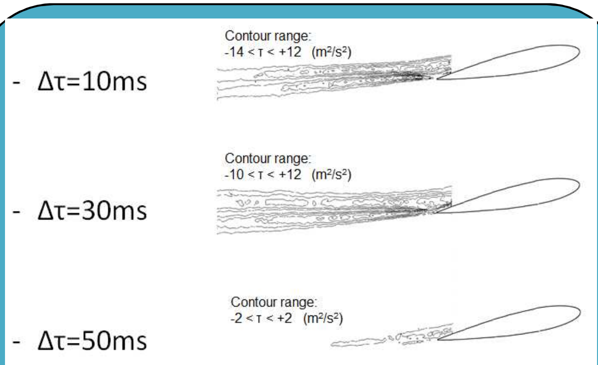
NACA0015 – Pulsed Jets



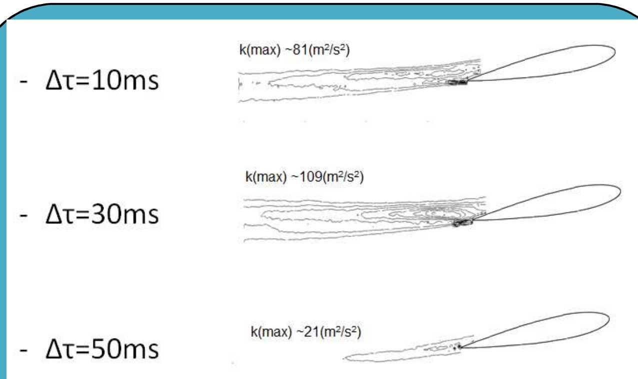
NACA0015 Model characteristics:

- Chord 350 mm
- Span 2.4 m (AR = 7)
- External velocity 40 m/s (Re = 1 M)
- Fixed incidence 11˚
- PIV measurements by phase-average (40 instants)

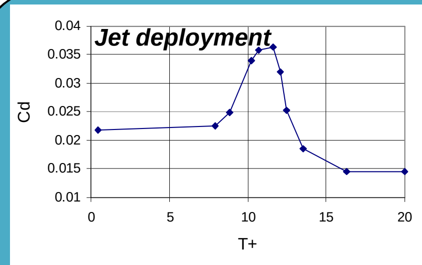


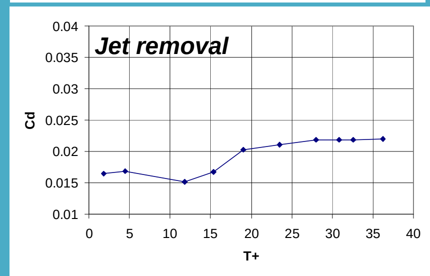


Transient SS during jet deployment



Transient TKE during jet deployment





Estimated temporal drag

NACA0015 wake flow control by pulsed jets with focus on transient regimes

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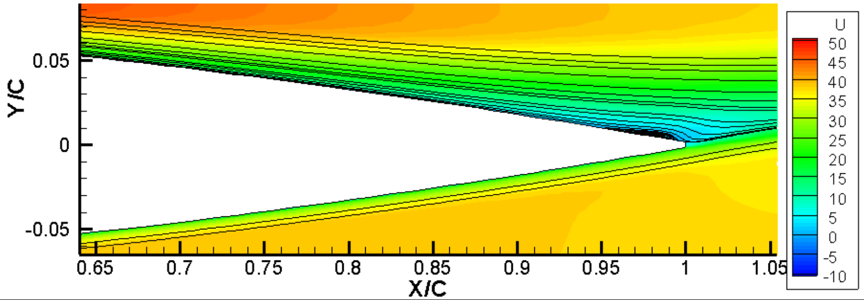
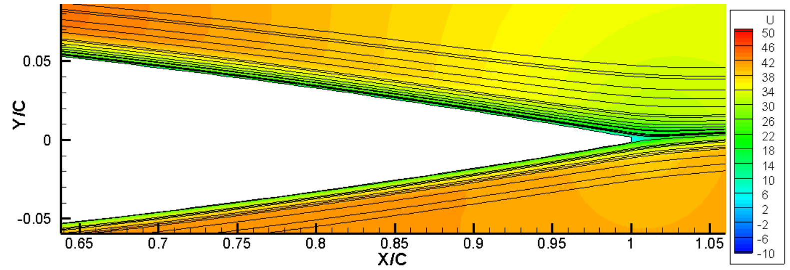
Improved Understanding: Validation of simulation

Comparison of RANS, DES, IDDES (Improved Delayed Detached Eddy *simulation)*

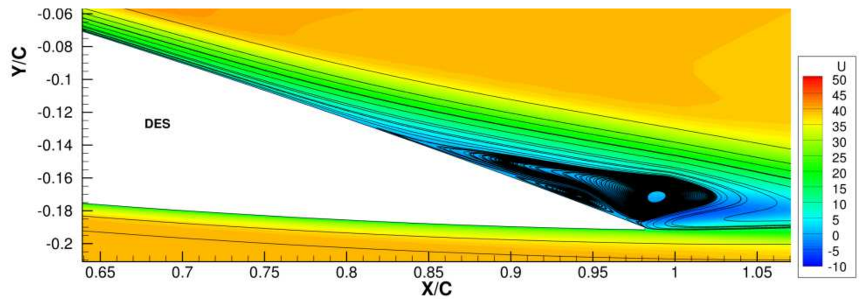
2D RANS



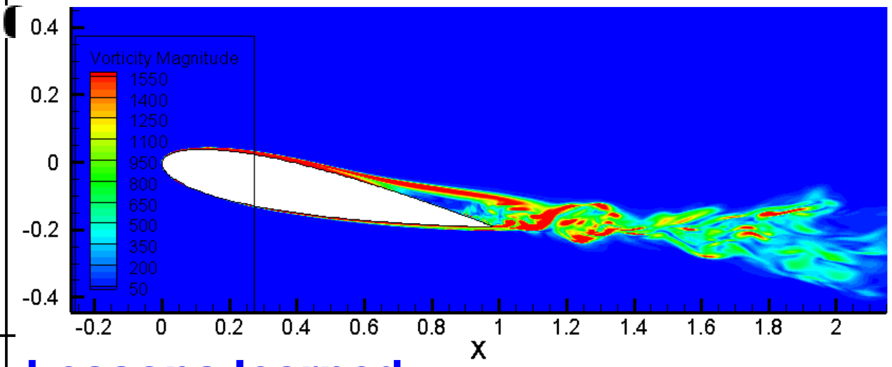
3D URANS



3D DES (3.7M)



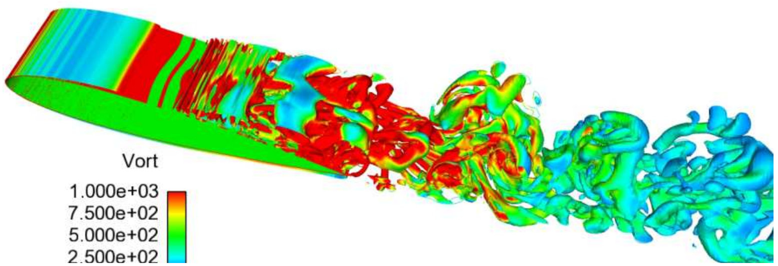
3D IDDES (3.7M)

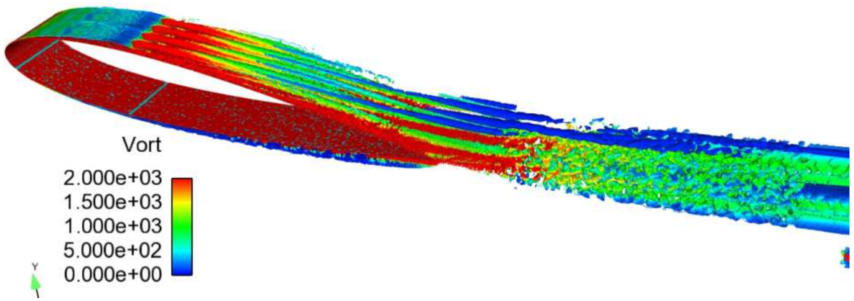


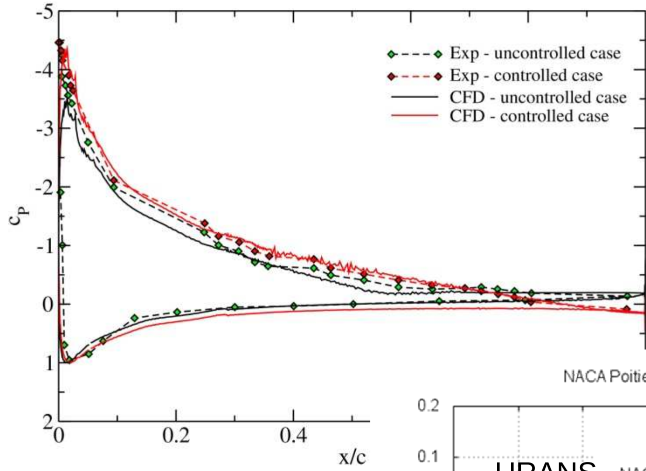
Lessons learned

- RANS and URANS(3D) failed to predict separation
- With the same mesh, IDDES performances better than DES in capturing separation region.
- IDDES with sufficient mesh gives good separation as compared with exp

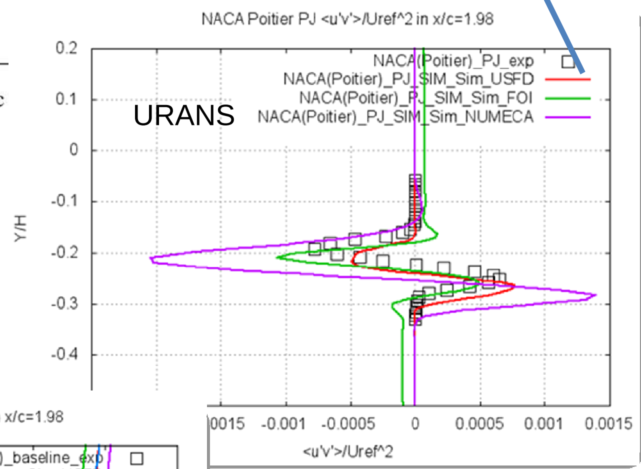
Improved Understanding:
coherent structures and Reynolds stresses

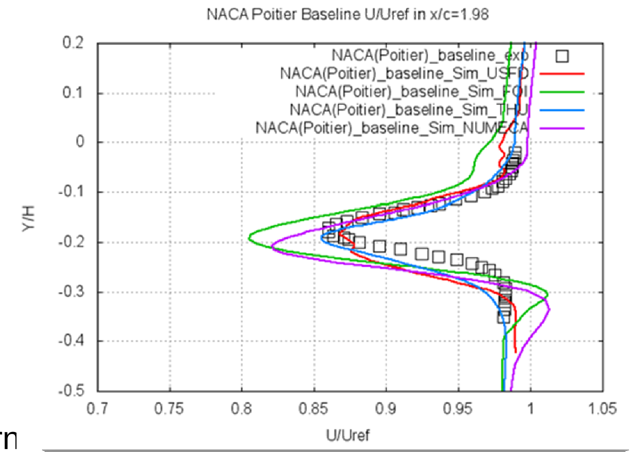




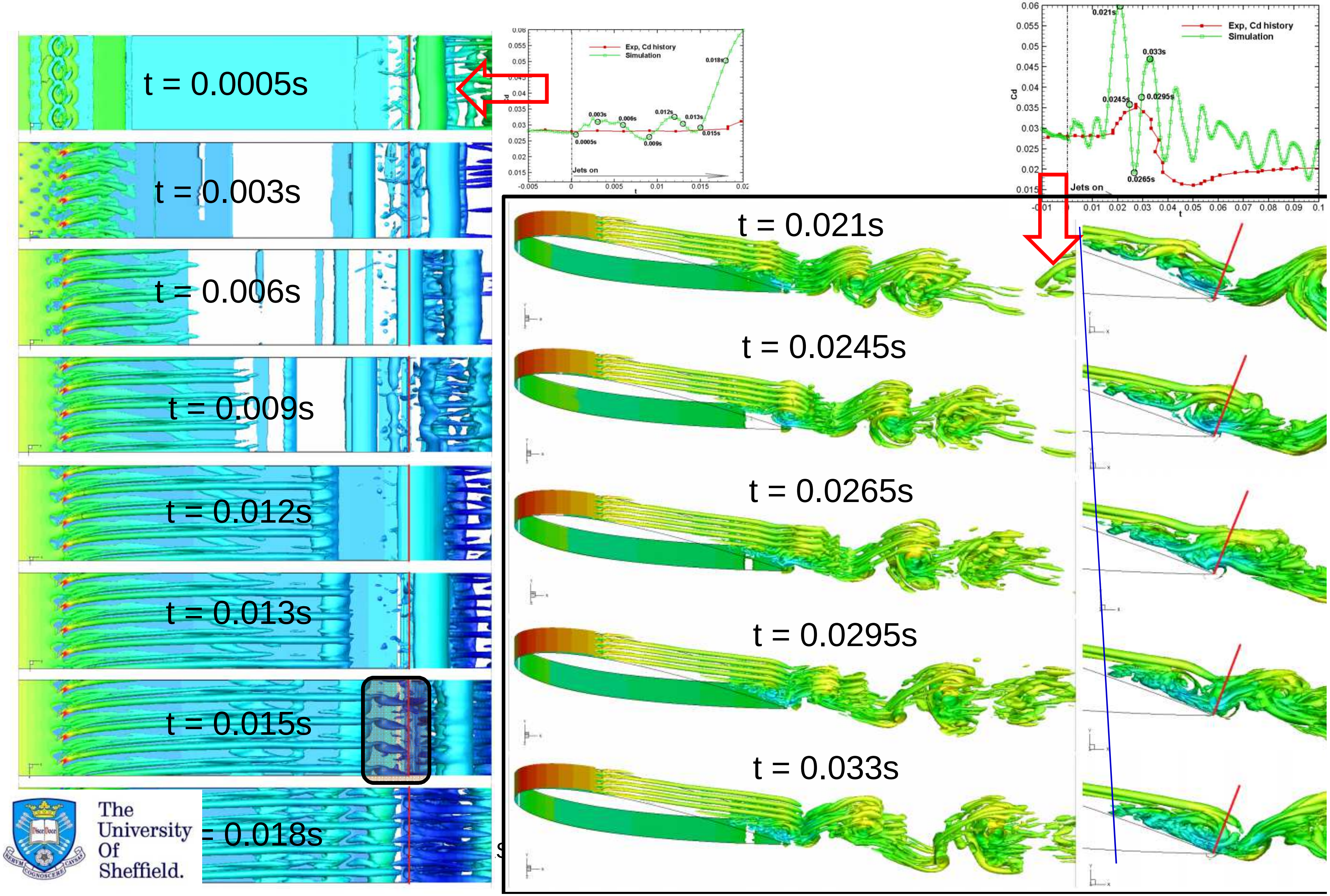


USFD
IDDES





Flow development after jets deployment



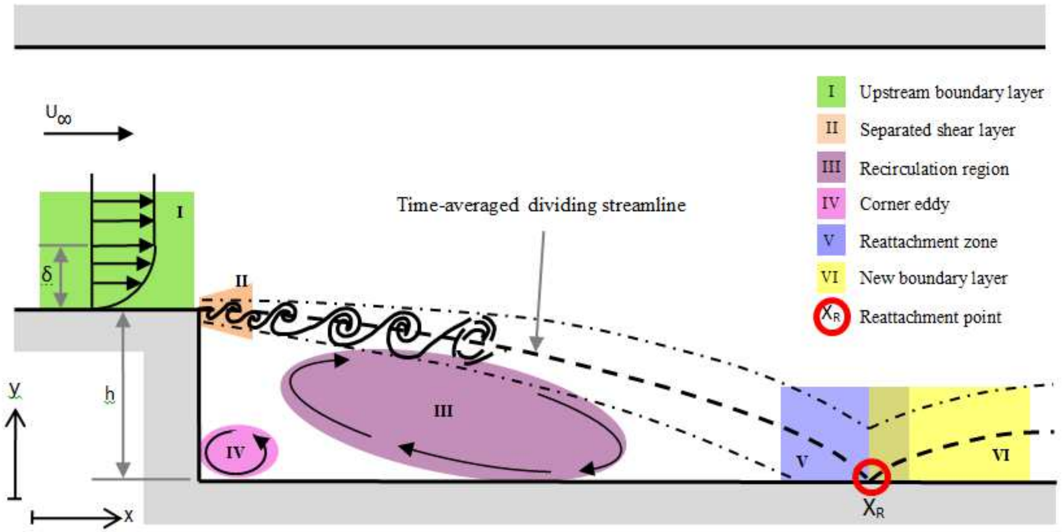
The University Of Sheffield.

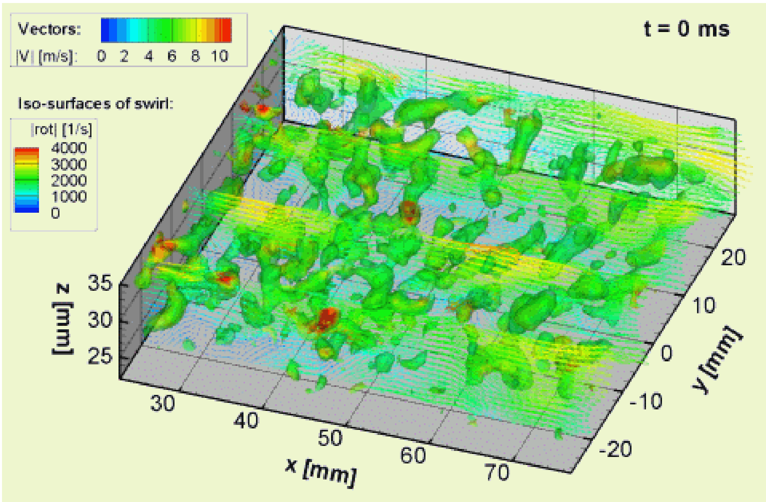
Backward Facing Step flow

A simple geometry but a complex flow

- Several instability wavelengthes
- Many periodic organizations
- Two recirculating zones
- Vortical and flapping motions
- 3D organization of flow structures

An ideal test case for flow control

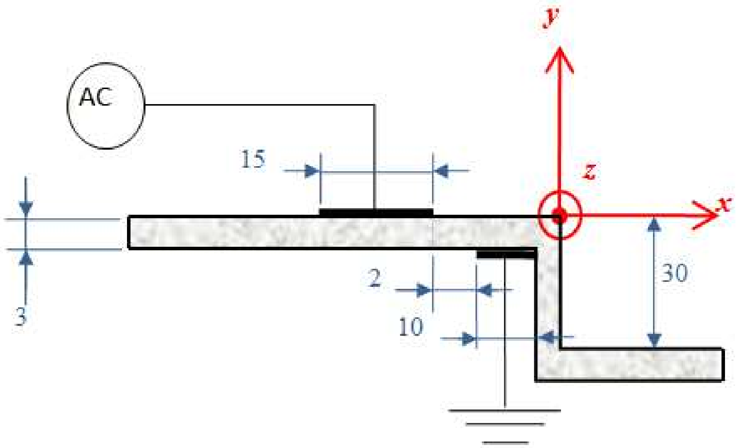




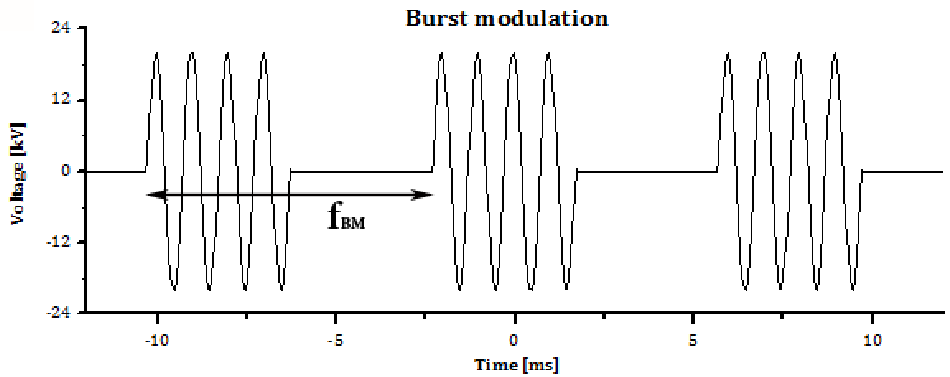
R. Geisler (DLR) and N. Benard (PPRIME)

DBD Actuators

Non-thermal plasma actuator driven by ac frequency



Electrode arrangement on the BFS model

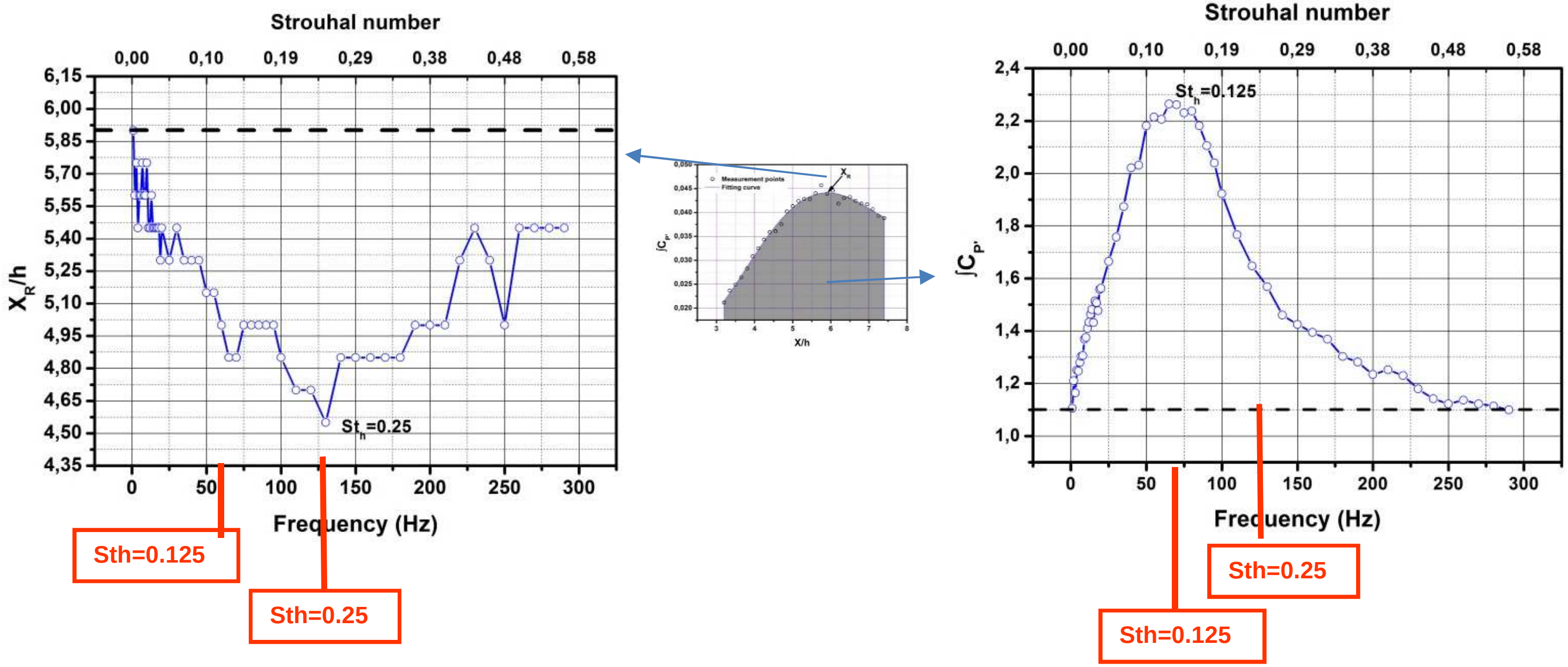


Electrical signal applied to the actuator

- Electrode arrangement for electric wind production in positive x direction
- 3-mm thick dielectric (PMMA)
- Voltage amplitude of 20 kV
- Driven ac frequency of 1-2 kHz
- Variable pulsed frequency f_{BM}
- Variable duty-cycle

Parametric study - A influence of AC-DBD frequency

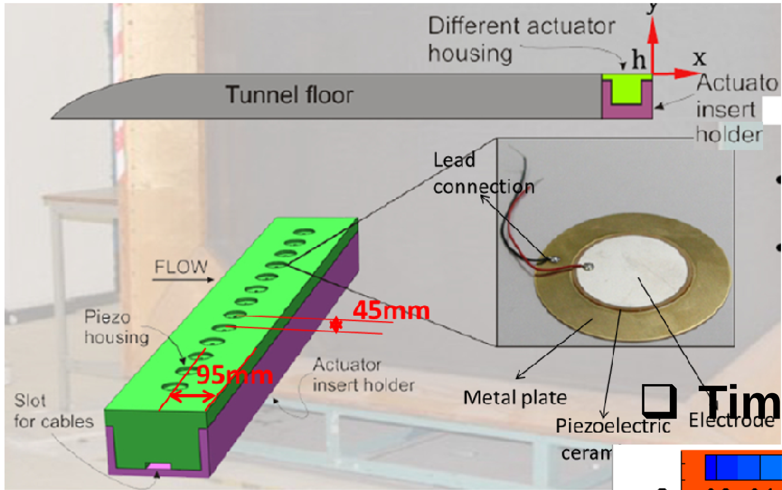
Two parameters: recirculation length and Wall pressure fluctuations

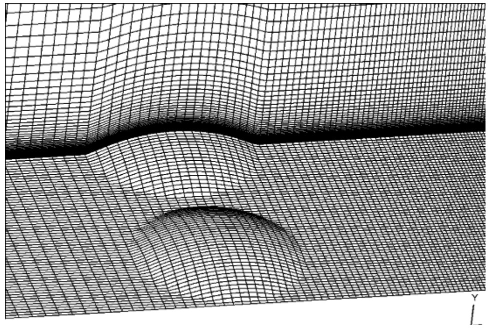


Position of the reattachment location and integral of wall pressure fluctuations according to the imparted periodic fluctuation frequency

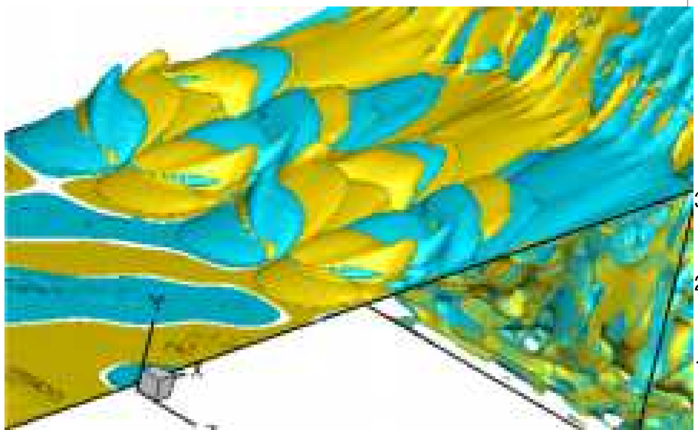
- Large Xr reduction (-20%) when flow forced at f_{BM}=125 Hz (St_h=0.25, St_{Xr}=1.4)
- Also reduction in Xr for 62.5 Hz or St_h=0.125 (St_{Xr}=0.7)
- Large increase in the spatially integrated wall pressure fluctuations at St_h=0.125 (St_{Xr}=0.7)

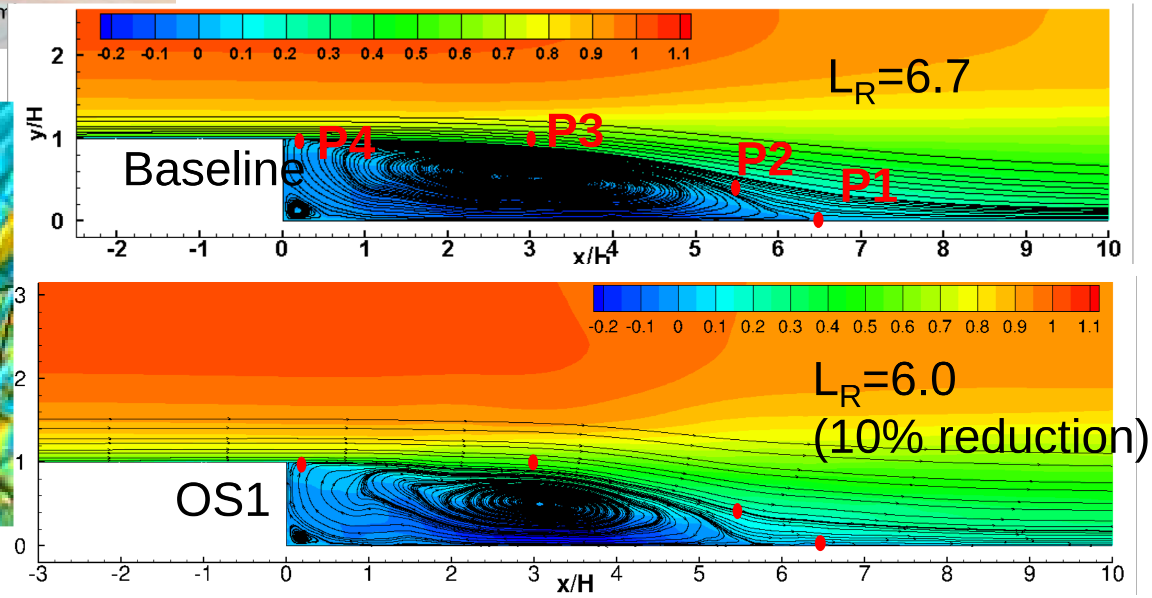
BFS – Piezo Oscillating Surface





- Time and space averaged streamlines

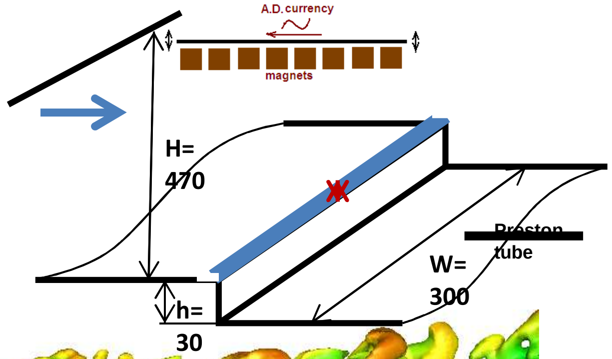




Spanwise Vortex Generator – a Novel Flow Control Device

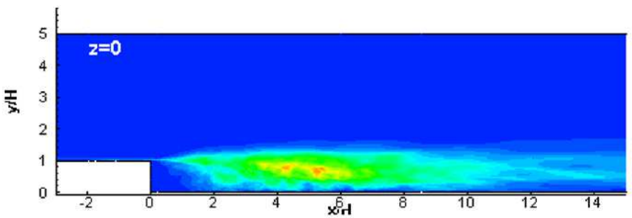
3D simulation setup

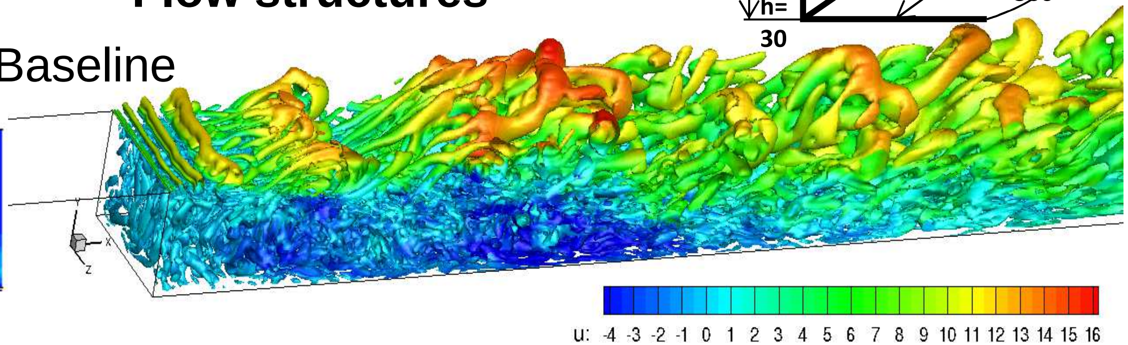
- The width of the SVG is 5mm
- The neutral position 3mm above the step wall.
- Amplitude is 2mm.



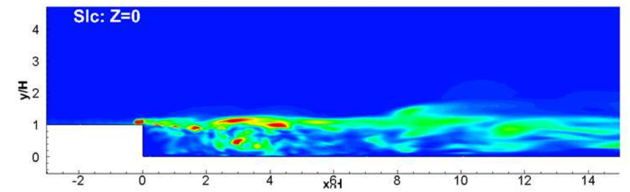
Flow structures

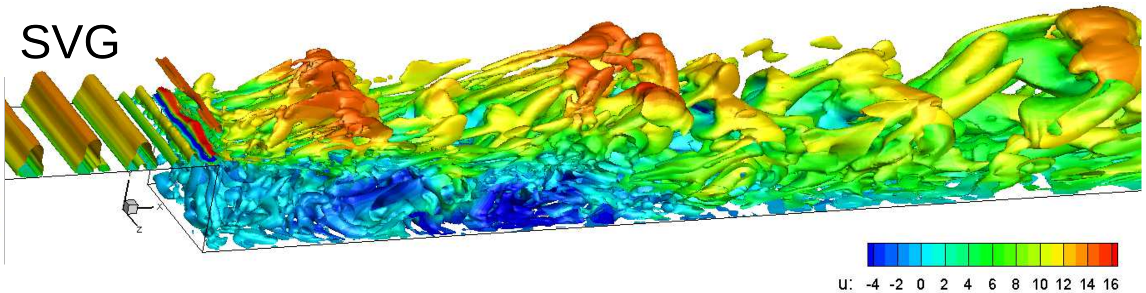
Baseline





SVG





SVG breaks up the rolling vortex shedding from the step and reduces 30%. (From baseline 6.5H to 4.5H.

The University Of Sheffield.

Optimization studies

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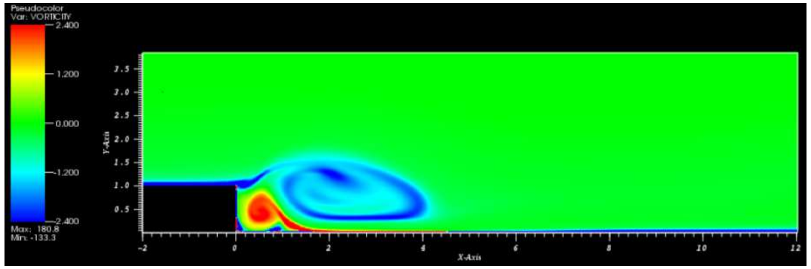
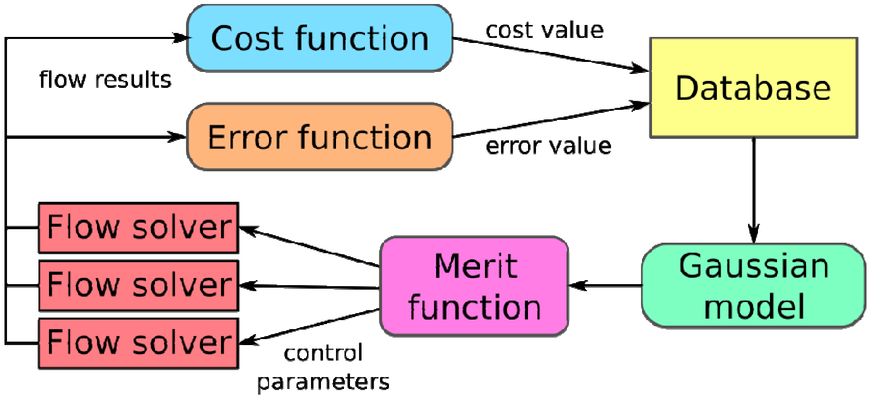
Kriging-based optimization of flow control devices

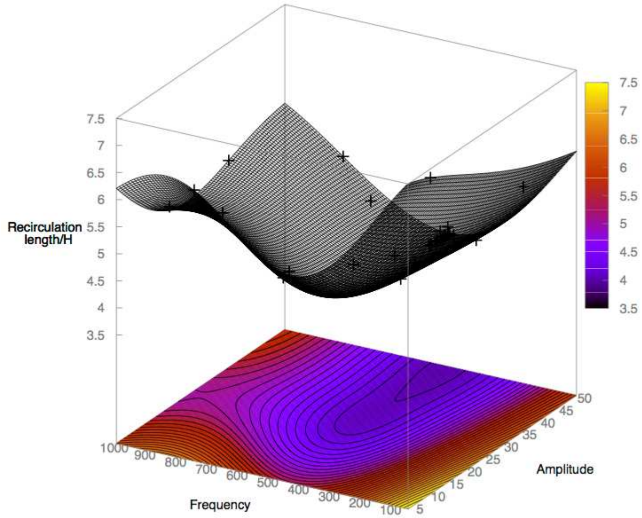
Simulation of controlled flow (RANS models) with actuation coupled with automatic optimization (Kriging-based algorithm)

Quantify impact of :
-Numerical errors
-Modeling (turbulence, actuator)



Vorticity field for BFS case with synthetic jet (RANS)

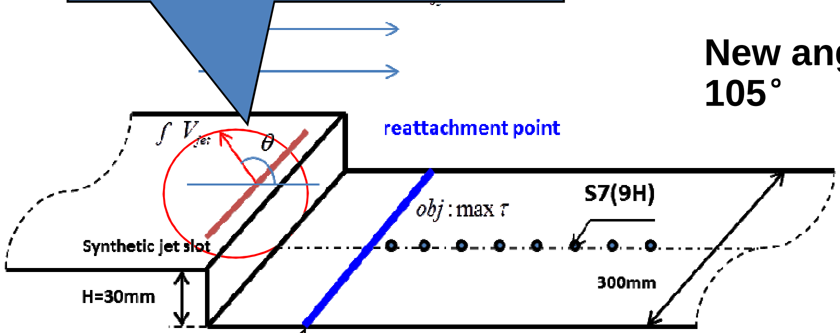




Kriging model of recirculation length w.r.t. actuation parameters

Surrogate-based model optimization for NUAA Test Case based on Wind Tunnel Test with SJ

The new experimental scheme design



Excellent flow control effect

Initial angles:

90° , 120° , 150°

New angle: 135°

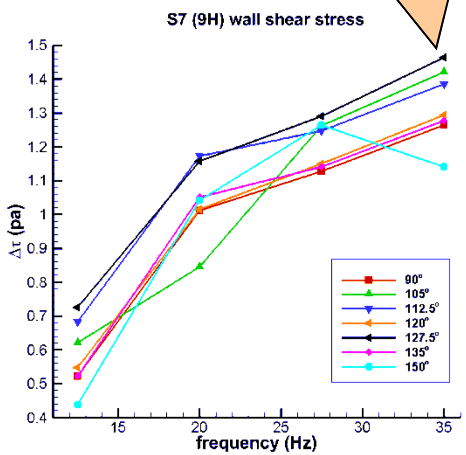
New angle: 105°

New angle: 112.5°

Final angle: 127.5°

The Optimization Strategy Based on the In-Looped Update Surrogate Model with Wind Tunnel Test

$f = 35Hz$
$\theta = 127.5$



As a conclusion:

- Innovative flow control devices proposed and investigated experimentally and computationally in the project:
  - Spanwise pressure wave driven synthetic jets (NUAA/USFD/NPU)
  - Piezo driven oscillating surfaces (UniMan/USFD/ZJU)
  - Spanwise oscillating strip vortex generator (NUAA/USFD)
  - Satisfactry IDDES computation

- Optimisation strategies on the BFS test case (not presented here)
  - Innovative methodology by directly coupling optimisation algorithm to drive the experimental design parameters (CIMNE/Poitiers)
  - Optimisation directly based on experimental output (NUAA/NPU)

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GA Optimization Based on Experiment with Plasma

HPRM OP

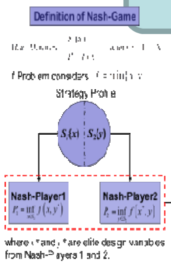
Individual Generation by:
- GA Strategies
- Hybrid Games

LabVIEW: GA-WT interface

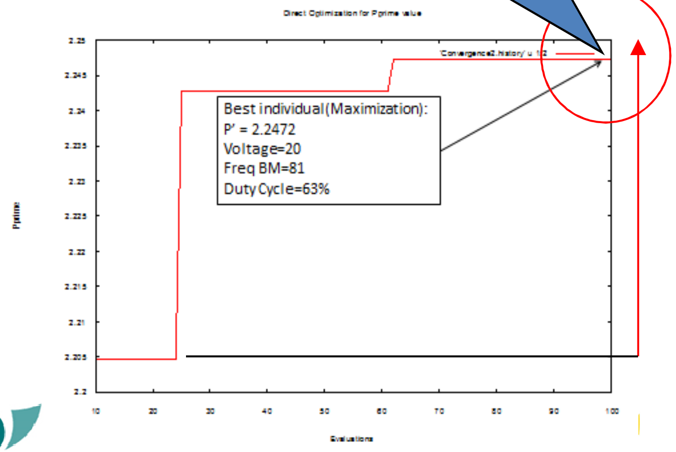
Individual Evaluation:
- Wind Tunnel

LabVIEW: WT-GA interface

Optimal Configuration of the Wind Tunnel:
- maximize P'
- minimize Reatt. lenghth



Improves the control of the flow



The innovative approach with LabVIEW for experimental optimization is built up.

Collaboration

Chinese and EU partners

- Close collaboration has been demonstrated throughout the project between EU and Chinese partners
- This is particularly demonstrated in the DLR experimental effort for plasma and synthetic jets to obtained detailed flowfield Re stresses in the DLR tunnel (DLR, ARI, NUAA, Poitiers)
- Substantial collaboration on the numerical investigation regarding proper turbulence modelling, meshing and boundary conditions through cross-comparison

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Limitations and future work

- Conflicting requirement in design optimization between the required flow resolution for flow control and the huge computation cost (>many weeks) when compared to experiments
- Larger volume detailed flow-field tomographic measurement to reveal the turbulent flow structures to understand and validate
- Differentiation of u tilda and u prime in the triple decomposition and phase averaging the data processing
- Lack of information on the effects of flow control devices on skin friction drag reduction, although their effects on flow separation are better demonstrated

→ MARS is followed by the DRAGY programme devoted to skin friction drag reduction

Thank you

for your attention !