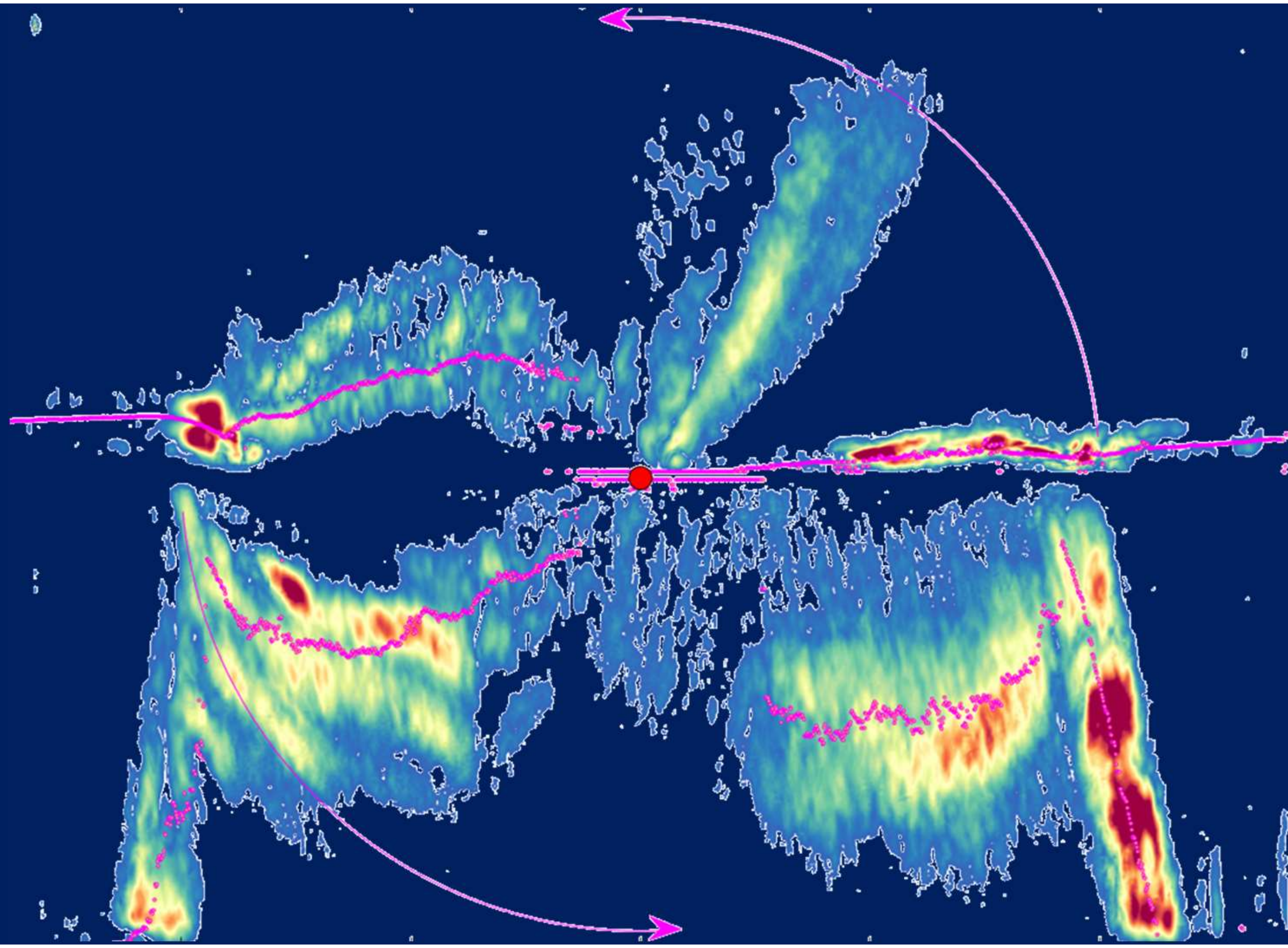

A SKIN-FRICTION ESTIMATION METHOD BASED ON TIME-RESOLVED TSP DATA AND A TAYLOR-HYPOTHESIS DERIVED ALGORITHM

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GERMAN AEROSPACE CENTER

A (NOT SO) SHORT HYSTORY

CNR-INM (Rome, IT) & AS-EXV DLR (Gottingen, GE) cooperative efforts since 2015

Starting rationale: extension of aeronautic TSP to under-water conditions to go deeper inside (below) the inner Boundary Layer.

AKNOWLEDGEMENTS

Christian Klein, Marco Costantini, Lars Koop, Jonathan Lemarechal, Carsten Fuchs, Fabio Di Felice, Alessandro Capone, Lorenzo Fratto

REFERENCES

- Capone, Klein,·Di Felice, Beifuss, Miozzi (2015): **Fast-response underwater TSP investigation of subcritical instabilities of a cylinder in crossflow.** Experiments in Fluids 56:196
- Capone, Klein,·Di Felice, Miozzi (2016): **Phenomenology of a flow around a circular cylinder at sub-critical and critical Reynolds numbers.** Physics of Fluids 28, 074101
- Miozzi, Capone, Di Felice, Klein,· Liu (2016): **Global and local skin friction diagnostics from TSP surface patterns on an underwater cylinder in crossow.** Physics of Fluids **28**, 124101 (2016)
- Miozzi, Capone, Costantini, Fratto, Klein, Di Felice (2019): **Skin friction and coherent structures within a laminar separation bubble** Experiments in Fluids (2019) 60:13
- Miozzi, Di Felice, Klein, Costantini (2020): **Taylor hypothesis applied to direct measurement of skin friction using data from Temperature Sensitive Paint**. Experimental Thermal and Fluid Science (2020), 110: 109913.
- Miozzi, Capone, Klein, Costantini. **Incipient stall characterization from skin-friction maps.** International Journal of Numerical Methods for Heat and Fluid Flow, 31 (2)
- Costantini, Henne, Klein, Miozzi (2021): **Skin-Friction-Based Identification of the Critical Lines in a Transonic, High Reynolds Number Flow via Temperature-Sensitive Paint** *Sensors*, *21*(15), 5106
- Miozzi, Costantini (2021): **Temperature and skin-friction maps on a lifting hydrofoil in a propeller wake** Meas. Sci. and Tech., 32 (11)
- M. Miozzi, G. Dubbioso, R. Muscari, M. Costantini (2022): **Phase-resolved evolution of transition and critical loci on a lifting hydrofoil in a propeller wake.** 34th Symposium on Naval Hydrodynamics. Washington, DC, USA, June 26 – July 1, 2022

WHY ARE WE INTERESTED IN TSP?

Time and space resolved wall temperature T measurements

T statistics (in time)

Max of T standard deviation.
Time and phase-averaged laminar turbulent transition location

Exact theory of steady 3D separation with min and max of T skewness.
Time and phase-averaged separation and reattachment locations

THE EASY, ROBUST WAY

T fluctuations (T') as a passive tracer

Relationship between u_τ and u_T, the celerity of propagation of T'.

Cross-correlation.
Time and phase-averaged quantitative skin friction field.

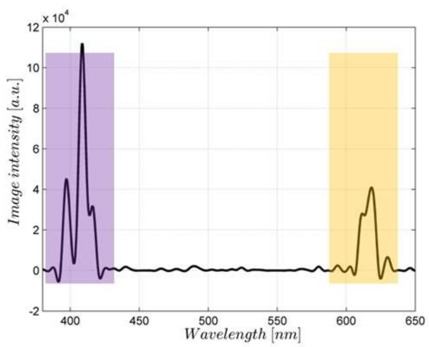
Relaxation of the frozen turbulence condition.
TH algorithm
Time and phase averaged quantitative skin friction field

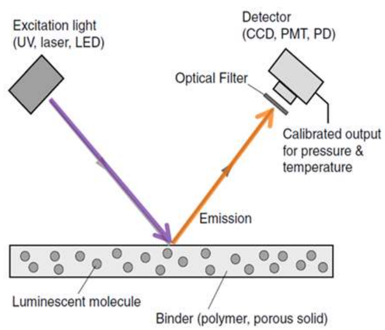
QUANTITATIVE, TIME-AVERAGED, ROBUST

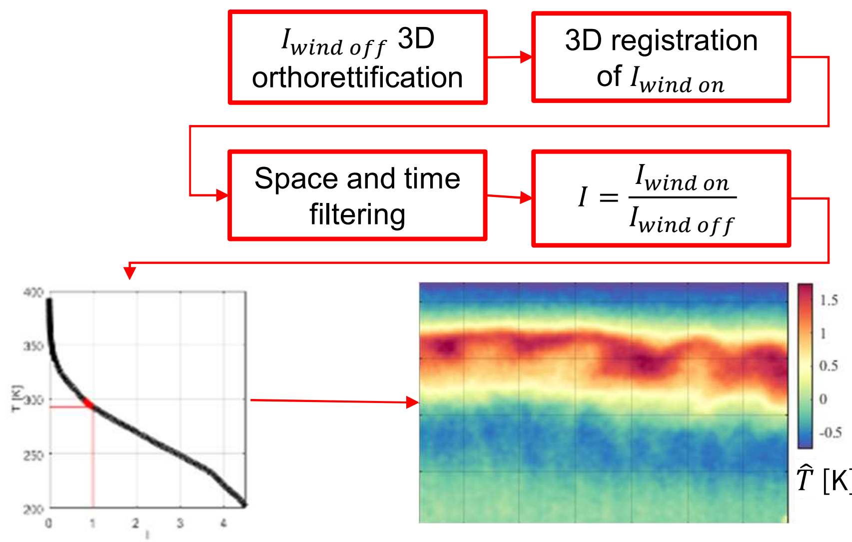
EXPLORE THE FLOW FROM THE POINT OF VIEW OF THE BODY SURFACE

TSP WORKING PRINCIPLE AND PROCESSING CHAIN

- The Europium-based TSP coating (Ondrus et al. 2015), properly excited, emits light whose intensity is directly dependent on the surface temperature: the higher the temperature, the lower is the emission (thermal quenching).
- Wavelength of emission is well separated from excitation (Stokes shift).
- Temperature maps are extracted from the ratio between rearranged wind-on and wind-off images via calibration curve



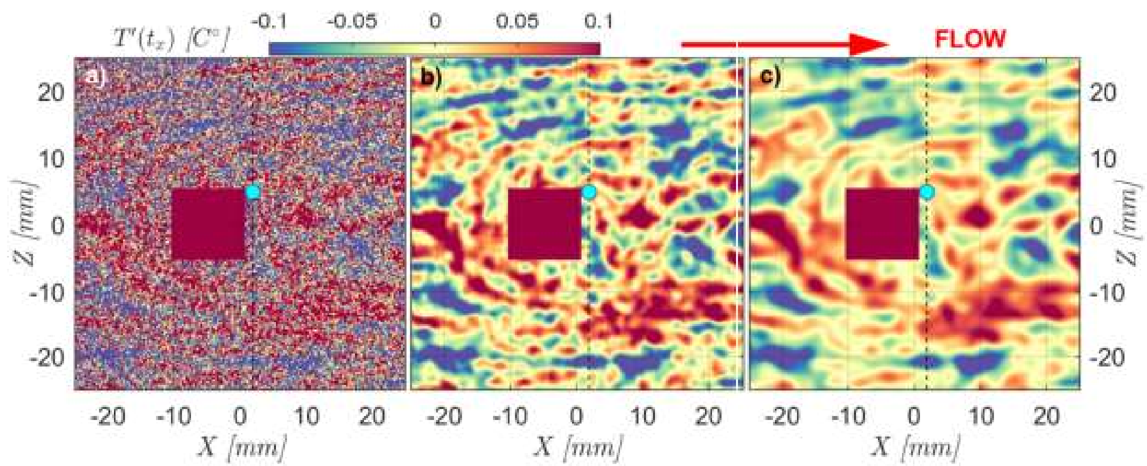




FILTERING IN SPACE AND TIME

The original images are firsly filtered in time, with a spectral features preserving approach.
Tool: Maxpol open-source package.
Hosseini & Plataniotis (2017)

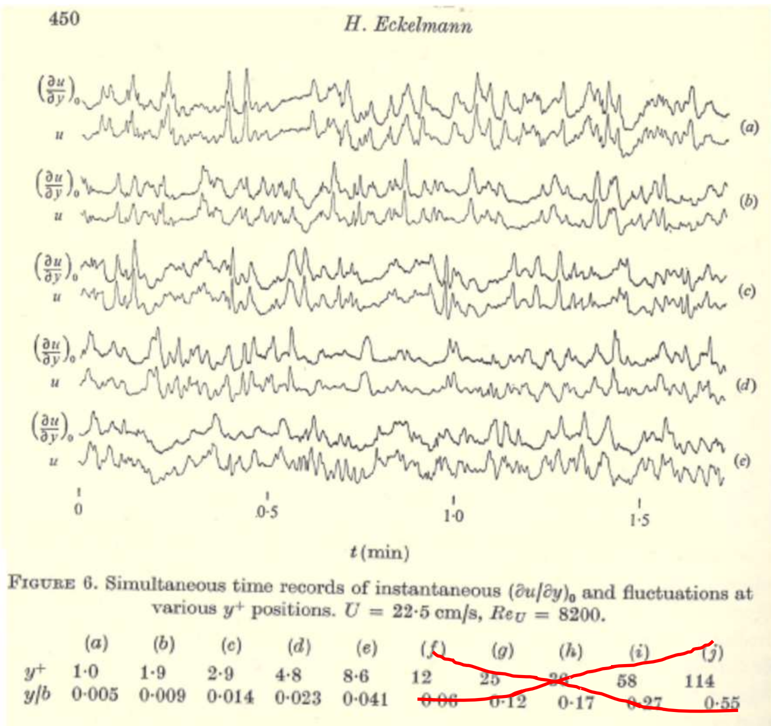
The time-filtered images are filtered again in space, with an edge-preserving approach. Each pixel is convolved with a deformed Gaussian kernel, compressed along the direction of the local maximum gradient and stretched along the normal one.
Tool : OpenCV library.
Miozzi et al. (2019)
Miozzi & Costantini (2021)



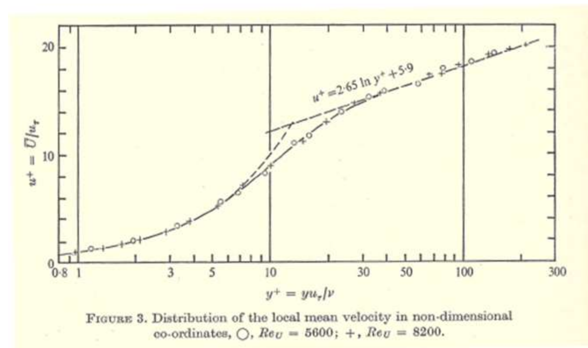
Miozzi, · Capone, Costantini, Fratto, Klein, Di Felice (2019) Skin friction and coherent structures within a laminar separation Bubble. Exp. in Fluids 60:13 (**M19**)
Miozzi and Costantini (2021); Temperature and skin-friction maps on a lifting hydrofoil in a propeller. Wake. Meas. Sci. Technol. 32 114007
Hosseini & Plataniotis (2017): Derivative Kernels: Numerics and Applications. IEEE TRAN. ON IMAGE PROCESSING, 26 (10)

THE STRUCTURE OF THE VISCOUS SUBLAYER

Eckelmann H (1974). The structure of the viscous sublayer and the adjacent wall region in a turbulent channel flow. *Journal of Fluid Mechanics, 65*(3)



Wall-normal propagation of disturbances at wall



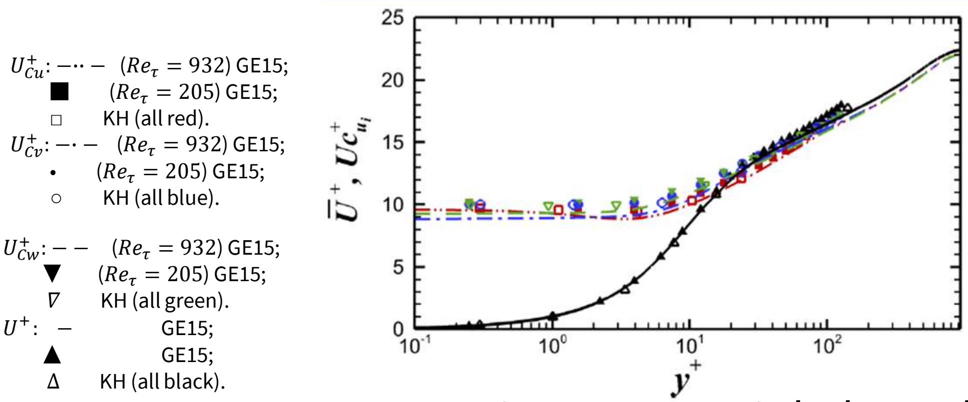
Images from E74

- The instantaneous u'-fluctuations in the region $0 < y^+ < 5$ were very similar to the instantaneous fluctuations of the velocity gradient at the wall $\left(\frac{\partial u}{\partial y}\right)_0$.

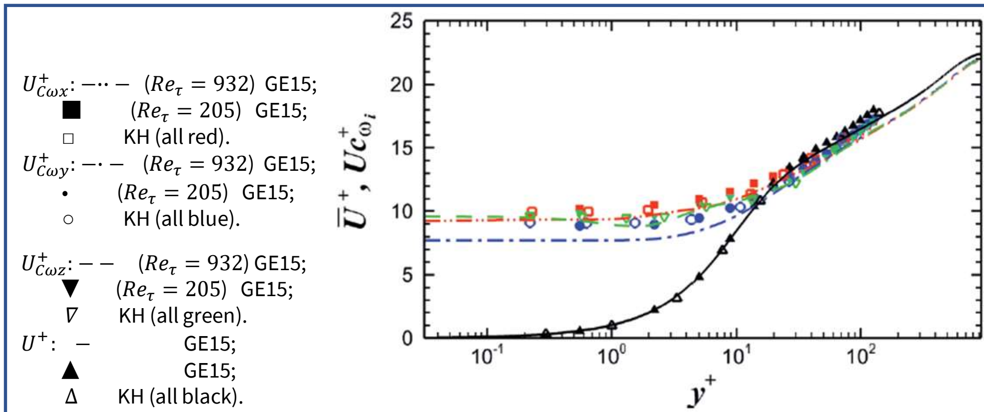
- The u'-fluctuations in the flow, however, lead those at the wall in time. The propagation velocity for the perturbations travelling toward the wall was found to be equal to u_τ.

Images from E74

WAVE PROPAGATION OF KINEMATIC QUANTITIES PERTURBATIONS



Celerity of propagation of u', v' and w'



Celerity of propagation of ω'_x, ω'_y and ω'_z

Skin-friction from TR TSP data and a Taylor-Hypothesis derived algorithm

Del Alamo and Jiménez. (2009): **Estimation of turbulent convection velocities and corrections to Taylor's approximation.** JFM 640, 5–26 (**DJ09**)

Geng et al. (2015): **Taylor's hypothesis in turbulent channel flow considered using a transport equation analysis.** PoF 27, 025111. (**GE15**)

$\boldsymbol{U_{pi}}$: i-th component of the celerity of propagation of the p-th fluid dynamic quantity (velocity, vorticity, pressure, temperature, etc.)

For $y^+ < 10$, $\boldsymbol{U_{pi}}$ is virtually constant, implying that perturbations of all flow variables propagate like waves near the wall.

WAVE PROPAGATION OF TEMPERATURE PERTURBATIONS

Hetsroni et al. (2004)**: Convection Velocity of Temperature Fluctuations in a Turbulent Flume.** J. Heat Transfer, 126 (**HE04**)

DNS of the temperature field in a turbulent flume (at Prandtl 1, 5.4, 54, $Pr = \frac{\mu C_p}{k} = \frac{viscous\ diffusion}{thermal\ diffusion}$). Prandtl effect on U_T and relations with U_U and U_τ .

$$c_u = \frac{u_{pU}}{u_\tau} = 9 \div 10$$

E74, KH73, DJ09, GE15. Does it whort a new experimental check?

$$\frac{U_T^+}{U_U^+} = \frac{1}{Pr^{1/3}}$$ Isothermal b.c.

$$c = \frac{u_T}{u_\tau} = Pr^{-1/3} c_u = 5.54$$

$$\boldsymbol{u_\tau = \frac{u_T}{5.54}}$$

$$\frac{U_T^+}{U_U^+} = \frac{1}{Pr^{1/2}}$$ Const. heat flux b.c.

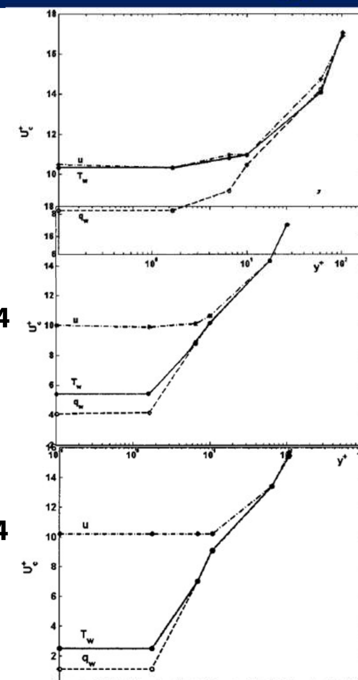
$$c = \frac{u_T}{u_\tau} = Pr^{-1/2} c_u = 4.12$$

$$\boldsymbol{u_\tau = \frac{u_T}{4.12}}$$

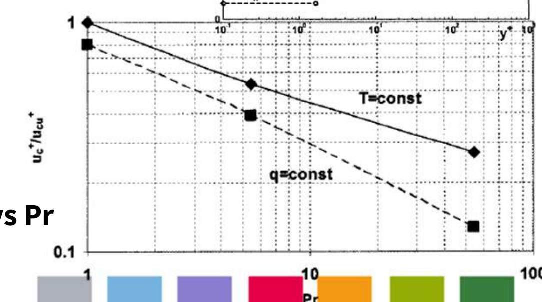
U_T at Pr=1

U_T at Pr=5.4

U_T at Pr=54



U_T vs Pr



Images from HE04

THE "TAYLOR HYPOTHESIS"ALGORITHM: FROM FROZEN TO GRANITA-LIKE TURBULENCE

Definition of convection velocity dependence from spatial scale **requires $k - \omega$ spectrum to associate velocity and wavelength**.
DJ09 proposes a physically motivated definition which depends on spectral information in only one direction (either space or time) and on a local derivative in the remaining direction.
RMS minimization to identify the reference frame in which waves experience the least amount of change.

$$\overline{\frac{DT}{Dt}} = 0$$

RELAX

$$min\left\{\overline{\frac{DT}{Dt}}\right\} \rightarrow \frac{\partial}{\partial \boldsymbol{U}}\left\{\overline{\frac{DT}{Dt}}\right\} = 0$$

Doesn't hold at wall (mainly because of the shear production and large $u'/\overline{U}$)

$$\begin{cases} \overline{U}_1 = -\dfrac{\overline{\partial_1 \partial_t}}{\overline{\partial_1^2}} \\ \overline{U}_2 = -\dfrac{\overline{\partial_2 \partial_t}}{\overline{\partial_2^2}} \end{cases}$$

TH ALGORITHM

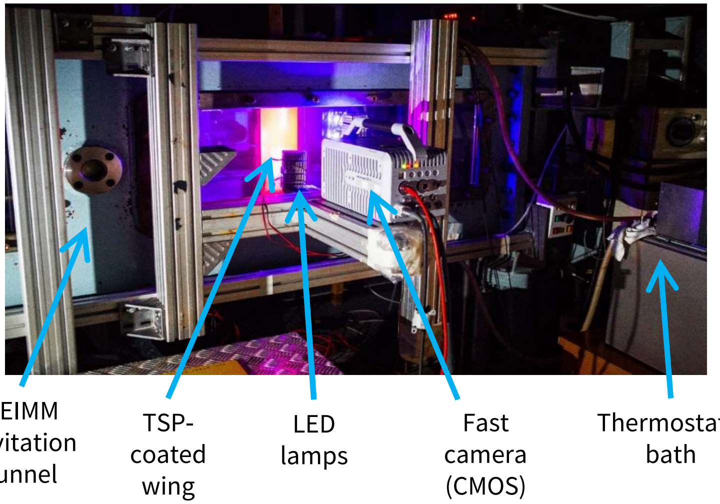
Del Alamo and Jiménez. (2009): **Estimation of turbulent convection velocities and corrections to Taylor's approximation.** JFM 640, 5–26 (**DJ09**)

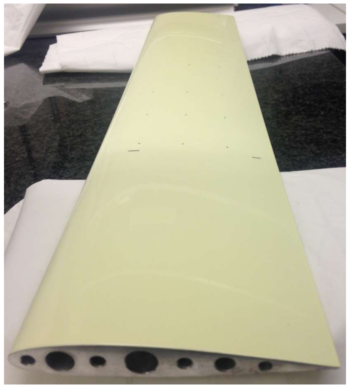
TSP IN FLUID DYNAMIC APPLICATIONS AT CNR-INM (ROME-IT)

Facility: CEIMM water tunnel 0.6%<Tu<1.5%

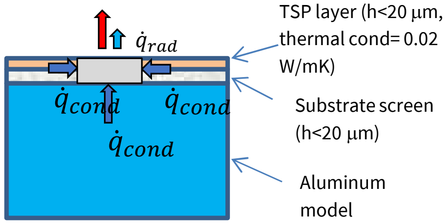
Features of the TSP coated surface

- Surface roughness: 0.09 µm (hydraulically smooth)
- Richardson number below the critical threshold for the existence of convective flows
- Biot number not uniform: T_w data are useful up to x/c<0.65





Hydrofoil with NACA 0015 profile

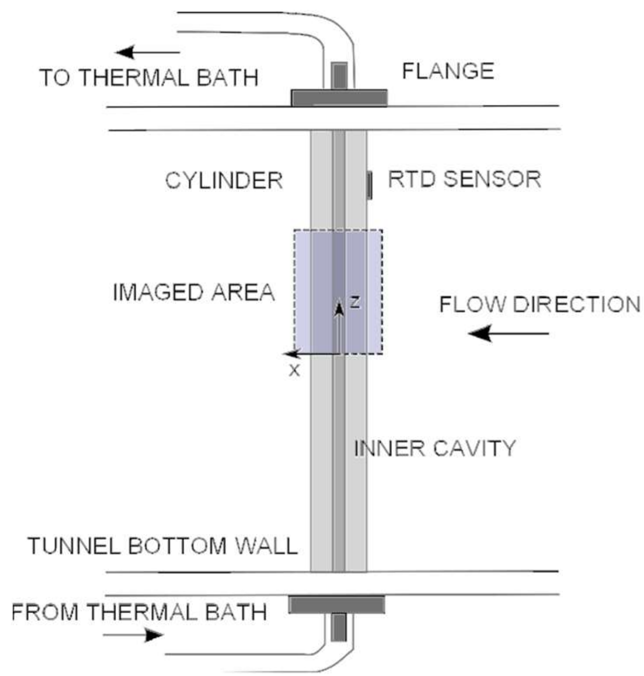


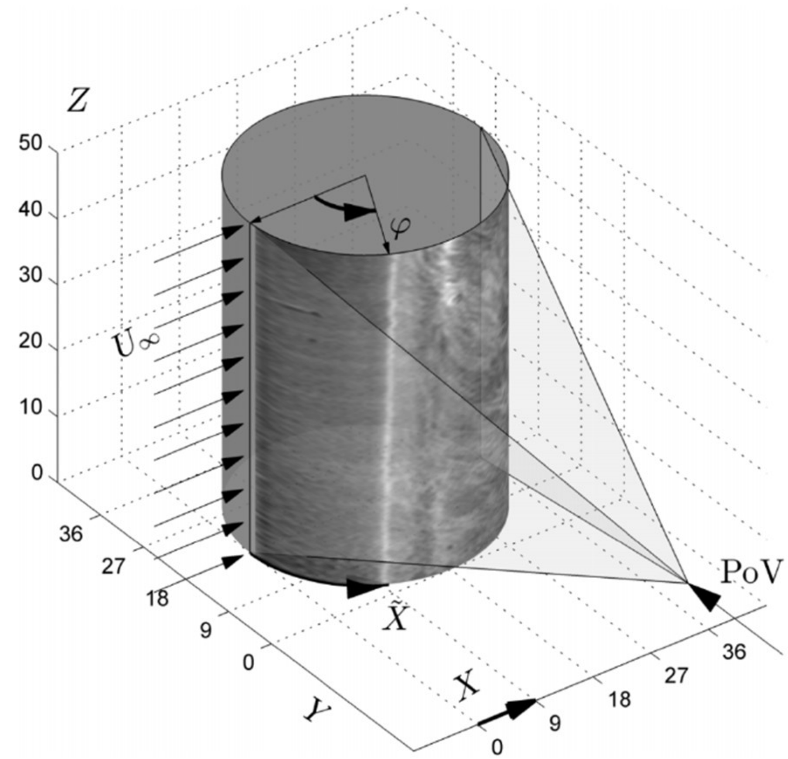
$$Ri = \frac{g\beta(T_w - T_\infty)}{U^2} \ll 0.001$$

Hydrofoil and cylinder in crossflow	Hydrofoil in propeller wake
• TSP acq. frequency: 1 kHz – 3 kHz • Free stream Speed U_∞ :1.5 m/s • Re: (chord=120mm): 1.8×10^5 • PHOTRON FASTCAM SA-X type 324K-M2	• TSP acq. frequency: 1.5 kHz • Free stream Speed U_∞ : 3.4 m/s • Re: (chord=120mm): 4.1×10^5 • 2 PHOTRON FASTCAM SA-X & SA-1 side by side • INSEAN E779 rotation speed: 17 rps • INSEAN E779 advance ratio $J = U_\infty / n_p D = 0.88$

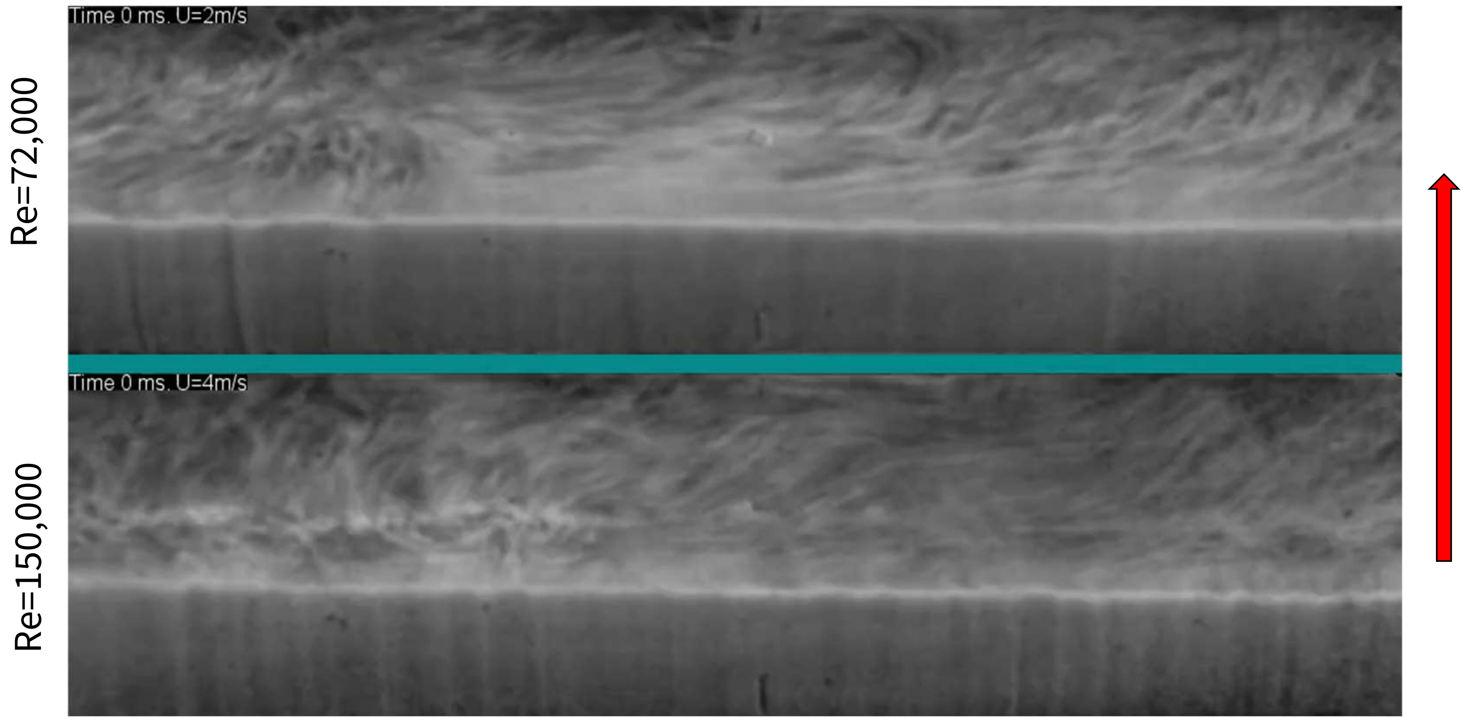
Skin-friction from TR TSP data and a Taylor-Hypothesis derived algorithm

EXPERIMENTAL SET-UP



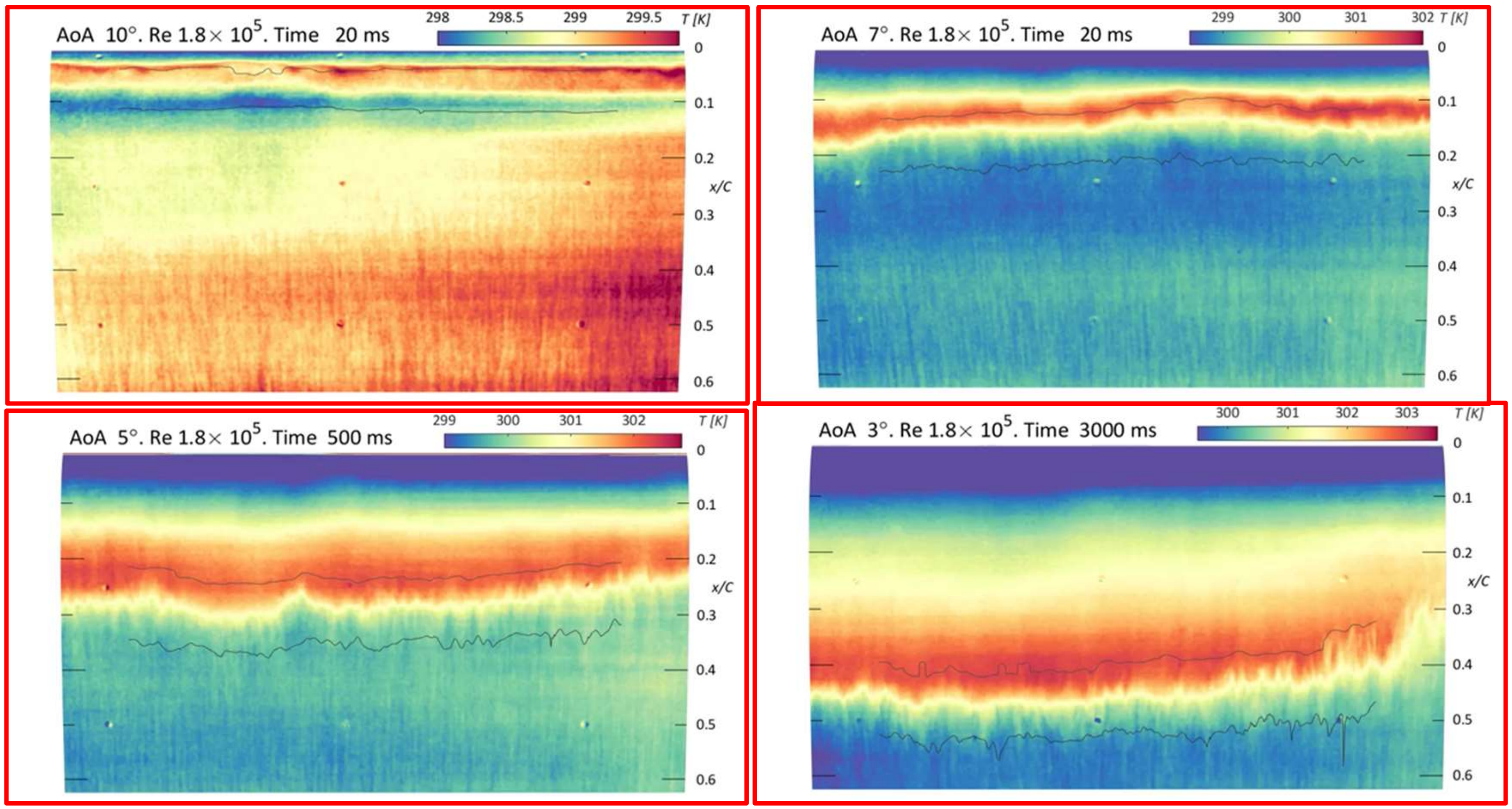


TIME EVOLUTION OF TSP MAPS



TEMPERATURE MAPS AND CRITICAL LINES AT 3°, 5°, 7° AND 10°

Flow

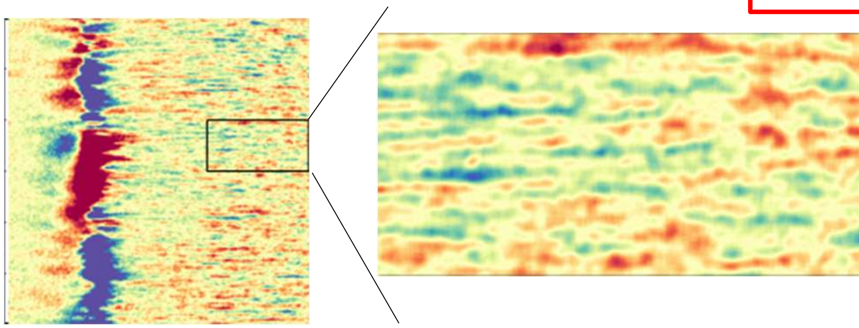


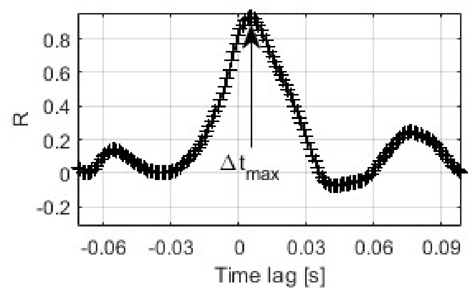
Flow

Note: in this slide critical lines of separation and reattachment are the *loci* of $\tau_x = 0$

C_f PROFILE ON A NACA 0015 HYDROFOIL

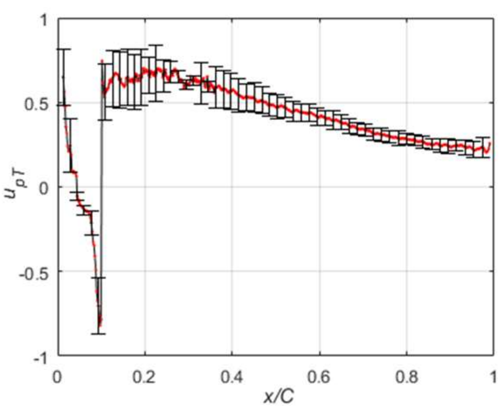
Streamwise distance Δx set to ≈ 3 mm (following **KH93**).



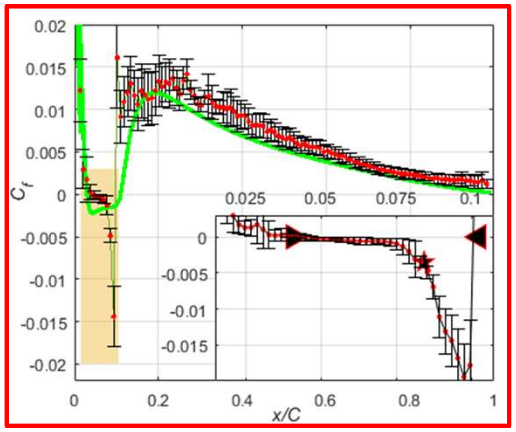


$$u_T = \frac{\Delta x}{\Delta t_{max}}$$

$$C_f = 2\left(\frac{u_\tau}{u_\infty}\right)^2 = 2\left(\frac{u_T/c}{u_\infty}\right)^2$$



u_T [m/s]



C_f and Xfoil profile (green line)

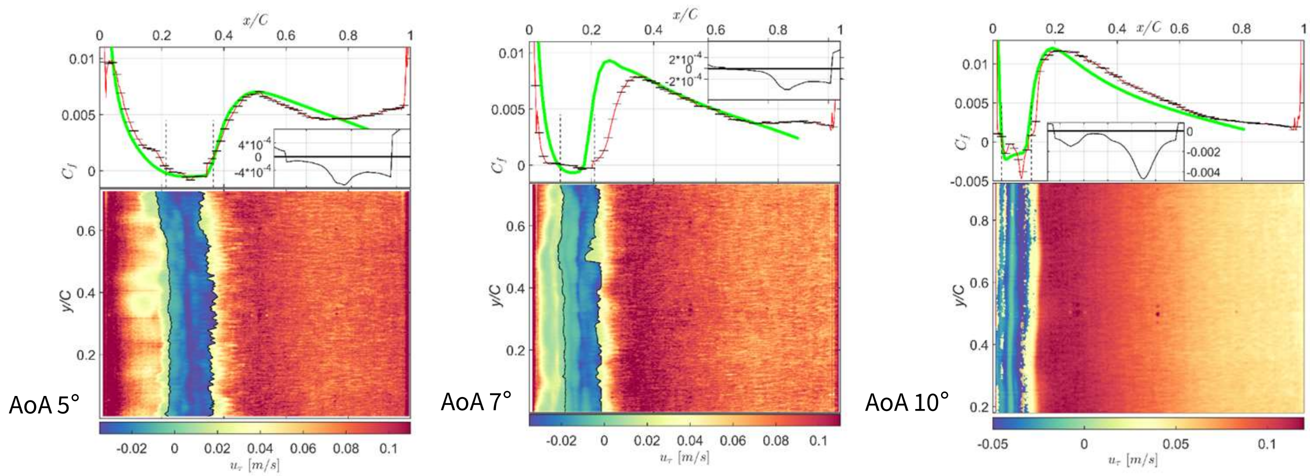
The ratio between distance Δx of two points and peak position Δt_{max} of the cross correlation of their time histories of temperature provides the celerity of propagation of temperature disturbances u_{pT}.

KH93: Kim J, Hussain F (1993) Propagation velocity of perturbations in turbulent channel flow. Phys Fluids A 5(3)

APPLICATION: THE NACA 0015 HYDROFOIL IN CROSSFLOW

Images from Miozzi et al. (2020)

FLOW

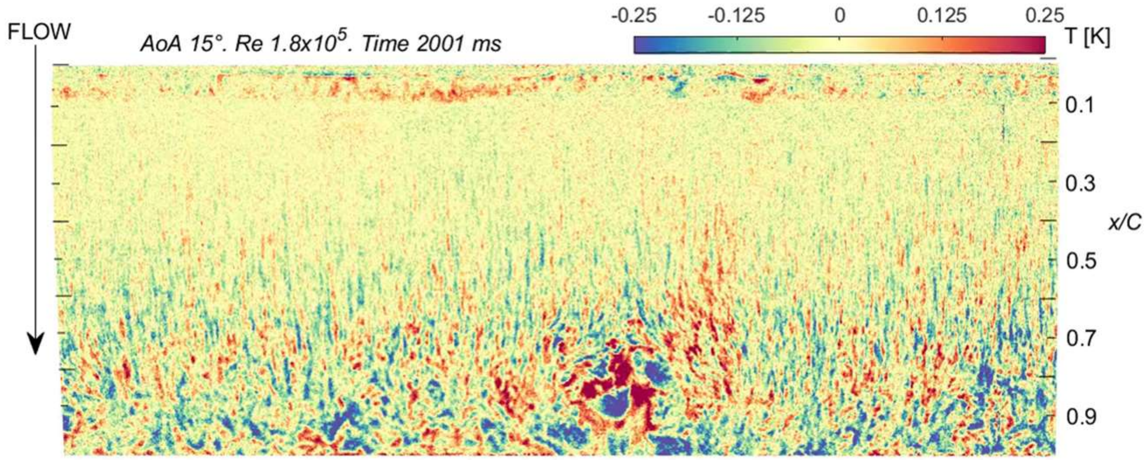


Friction coefficient C_f (top) and friction velocity u_τ (bottom). Green line from Xfoil ($N_{crit} = 9$) for visual comparison.

Original u_τ maps contain only positive values. The u_τ sign is extracted in the aftermath. Details of C_f profile in reverse flow region within the LSB are shown in the inset.

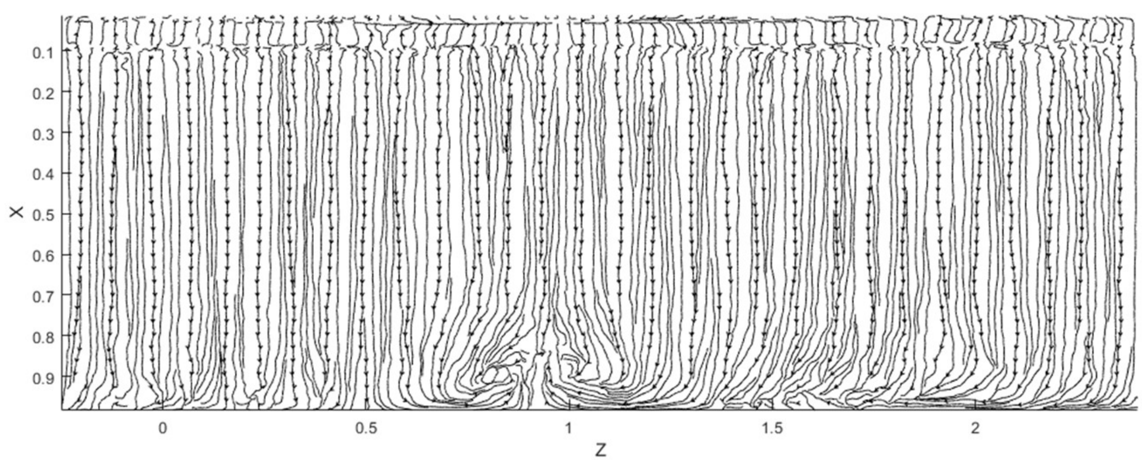
Miozzi, Di Felice, Klein, Costantini (2020): Taylor hypothesis applied to direct measurement of skin friction using data from Temperature Sensitive Paint. Experimental Thermal and Fluid Science 110 109913

NACA 0015, $\alpha = 11.5°$



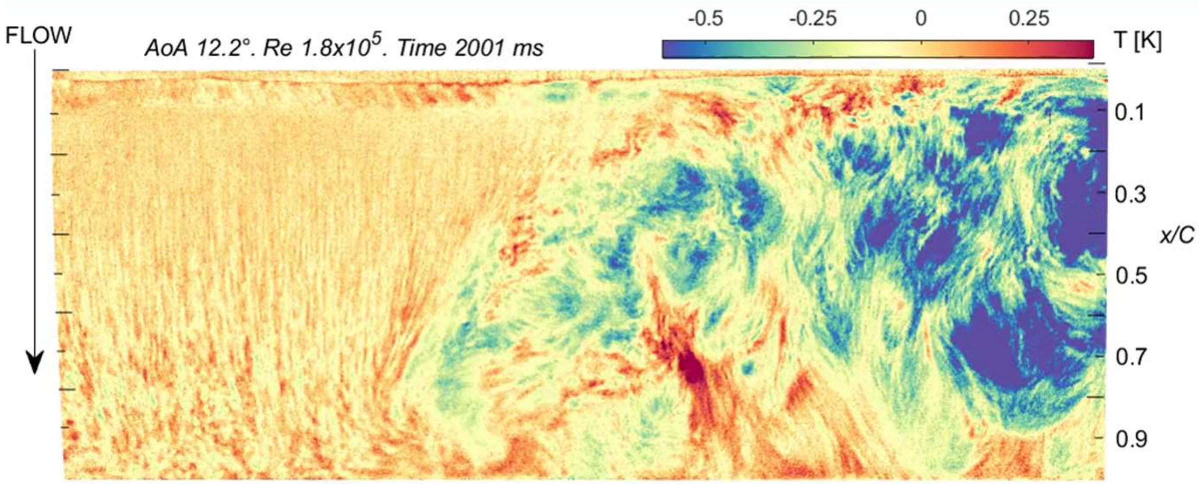
Incipient stall at trailing edge.

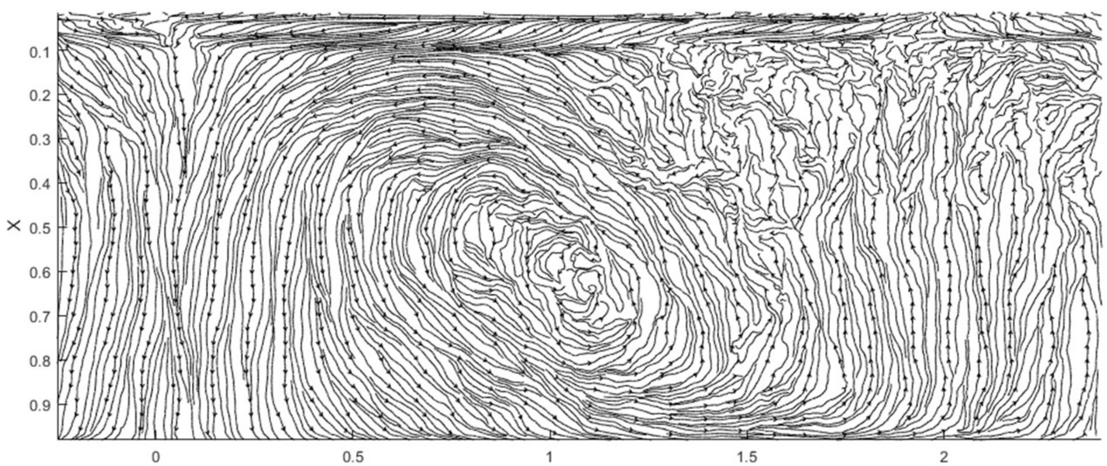
Map of the fluctuating temperature $T_w'(\boldsymbol{x}, \boldsymbol{t})$ over time



Time averaged skin friction topology by TH algorithm. Symultaneous presence of LSB and incipient stall at trailing edge.

NACA 0015, $\alpha = 12.2°$



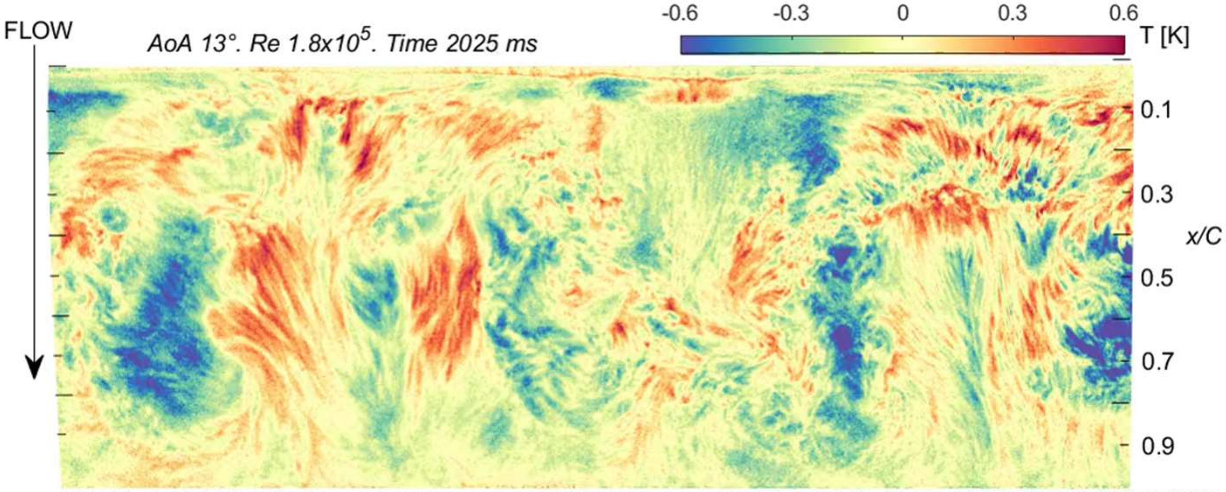


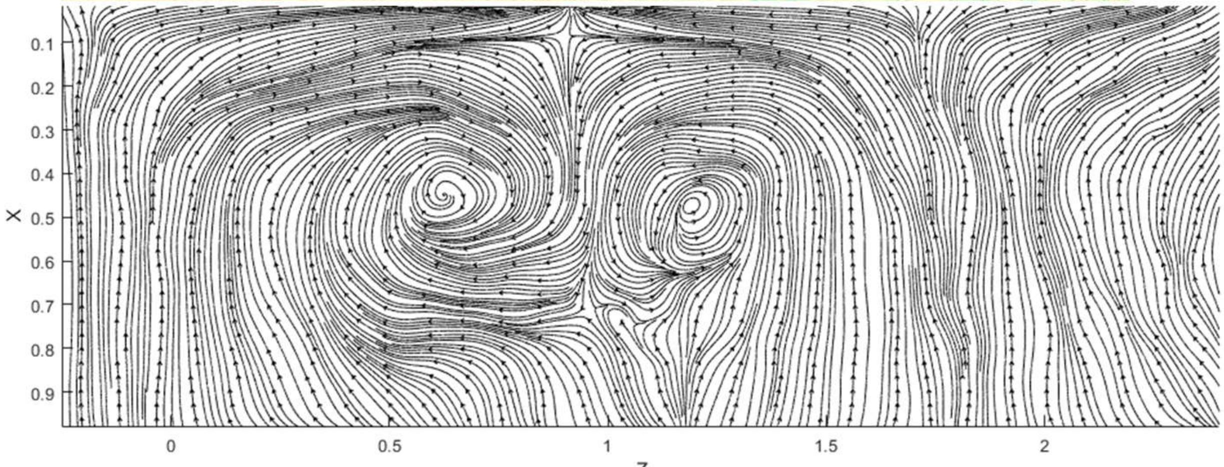
Large aspect ratio $\left(\frac{L}{C} \approx 4:1\right)$ stall cell.

Map of the fluctuating temperature $T'_w(\boldsymbol{x}, \boldsymbol{t})$ over time

Time averaged skin friction topology by TH algorithm. The measurement captured one of the roots of a large aspect ratio stall cell. A symmetric companion is expected on the right, out of the picture.

NACA 0015, $\alpha = 13°$



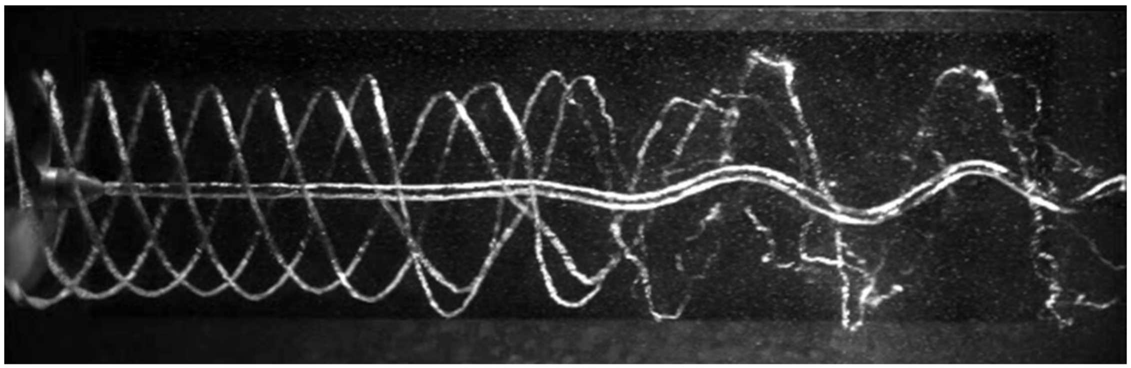


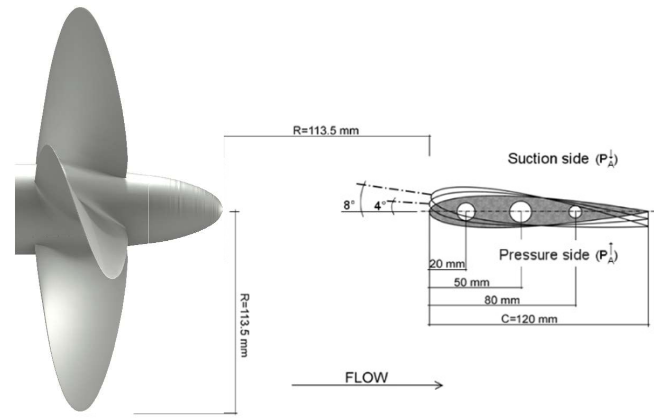
Small aspect ratio $\left(\frac{L}{C} \approx 2:1\right)$ stall cell.

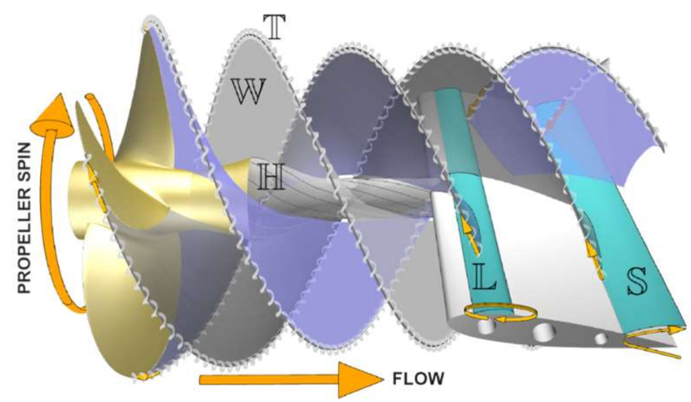
Map of the fluctuating temperature $T_w'(\boldsymbol{x}, \boldsymbol{t})$ over time

Time averaged skin friction topology by TH algorithm. The measurement captured a small aspect ratio stall cell.

APPLICATION: THE NACA0015 HYDROFOIL IN A PROPELLER WAKE



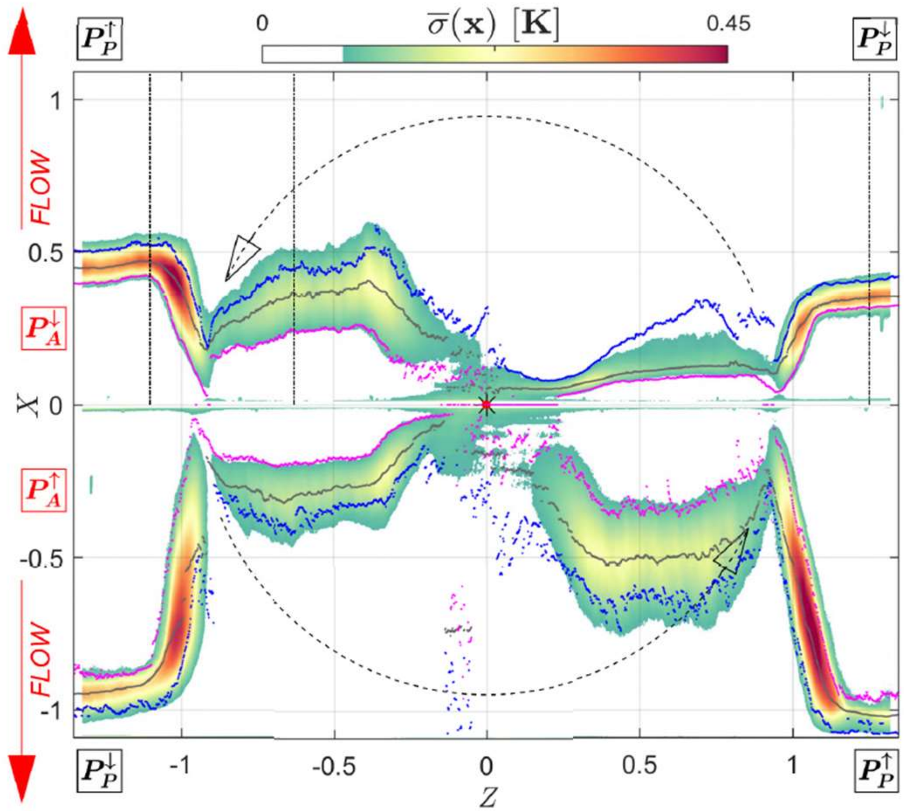




- Three main classes of vortical structures:
  - Hub vortex from propeller hub;
  - Tip vortices from propeller blades tip;
  - Foil vortex from propeller blade trailing edge

The hydrofoil with NACA 0015 profile is placed in the wake of an INSEAN E779A standard model propeller.
The profile is also at incidence (AoA=[0°, 4°, 8°])

COUPLING OF PROPELLER WAKE AND HYDROFOIL LSB AT THE WALL. AOA=4°



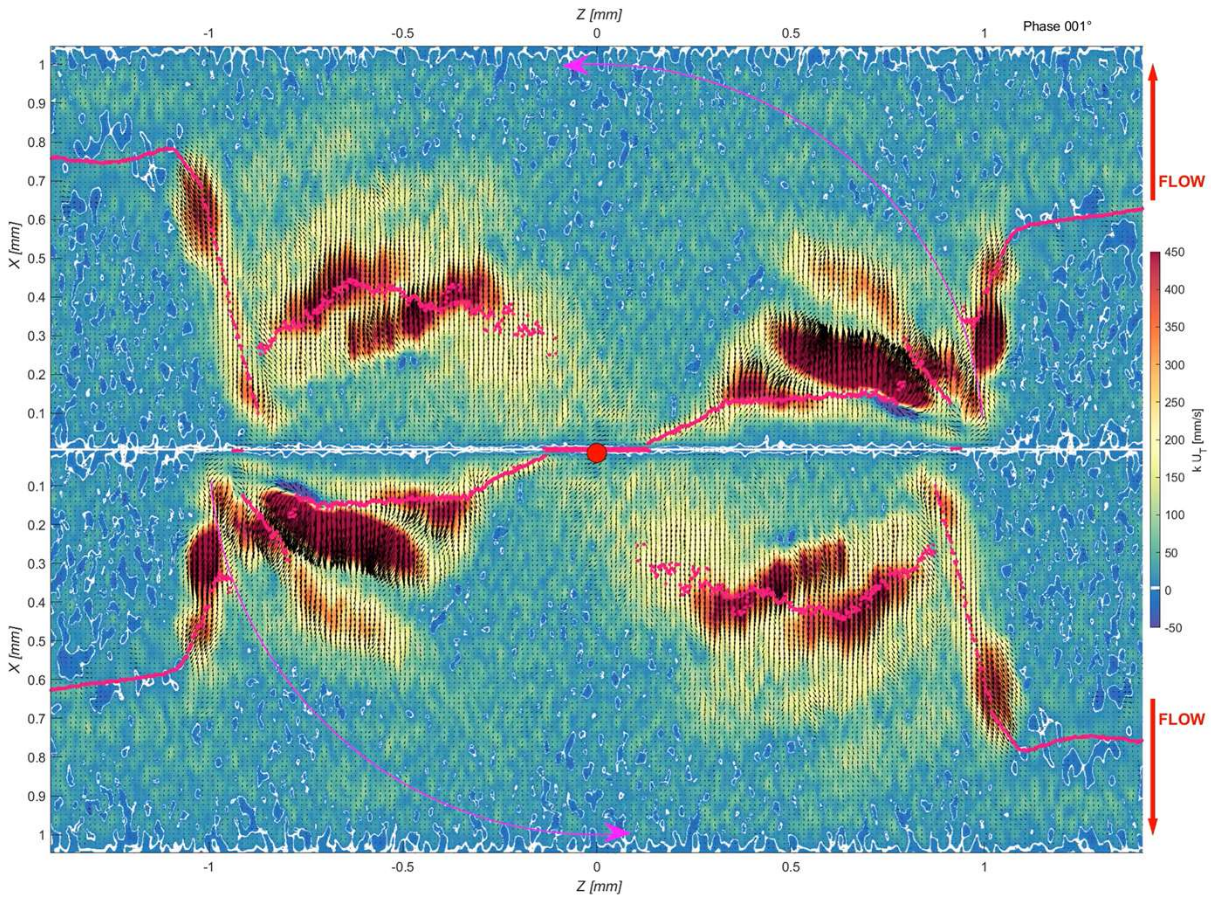
Two types of contributions to pressure field:

1. Due to the propeller spin
   - $P_P^{\uparrow}$: rise of pressure
   - $P_P^{\downarrow}$: decrease of pressure
2. Due to the hydrofoil's APG (incidence, shape)
   - $P_A^{\uparrow}$: rise of pressure
   - $P_A^{\downarrow}$: decrease of pressure

Map of $\overline{\sigma}(\boldsymbol{x})$ on suction (top) and pressure (bottom) hydrofoil's sides.
Values of $\overline{\sigma}(\boldsymbol{x})$<0.08 are blanked

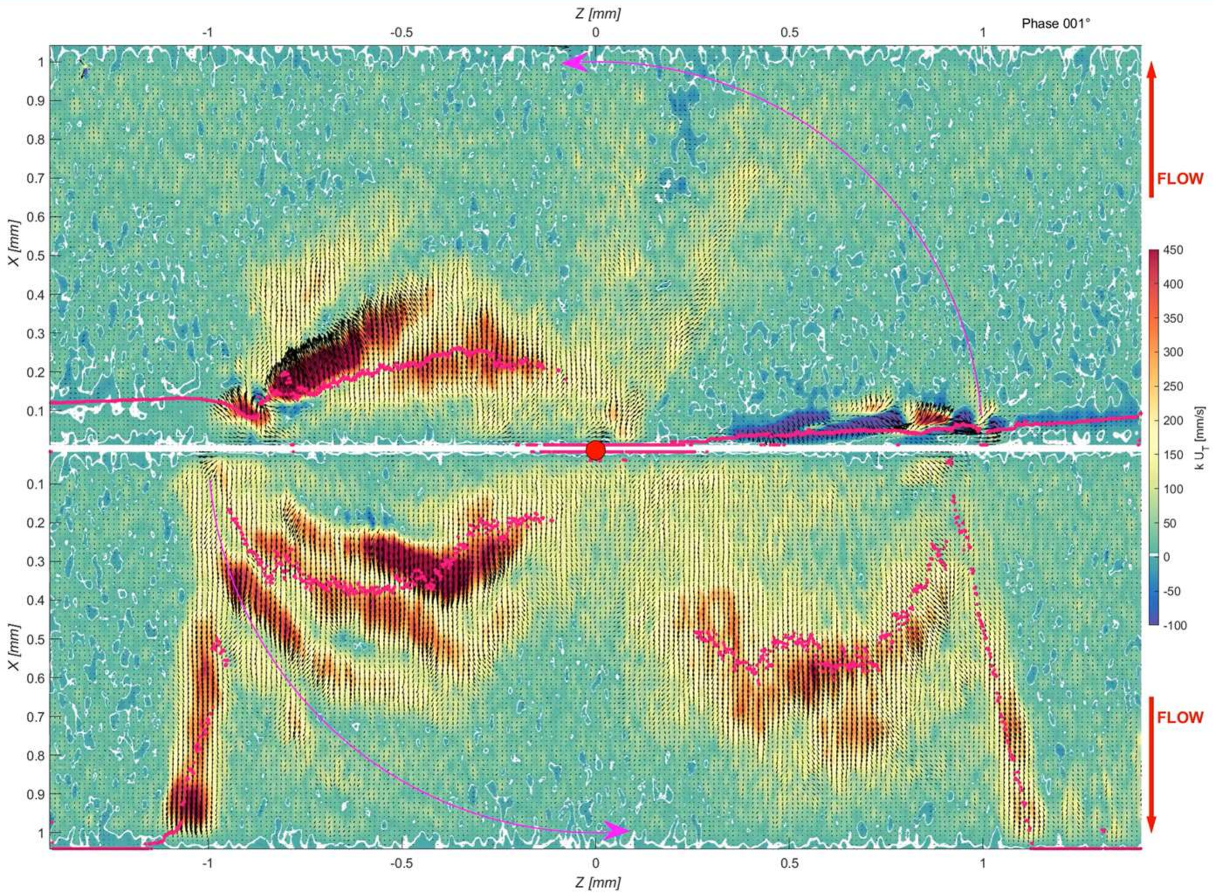
Eight different sectors can be identified, four within the streamtube, four out of the streamtube

FRICTION VELOCITY ON A HYDROFOIL IN A PROPELLER WAKE. AOA=0°



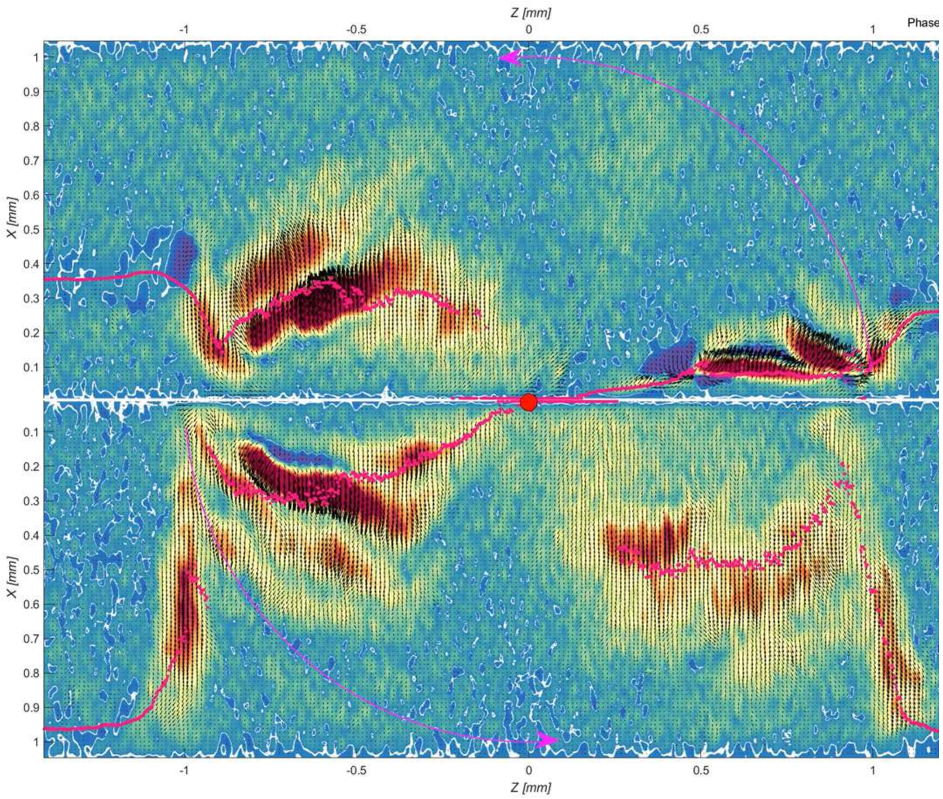
Skin-friction from TR TSP data and a Taylor-Hypothesis derived algorithm

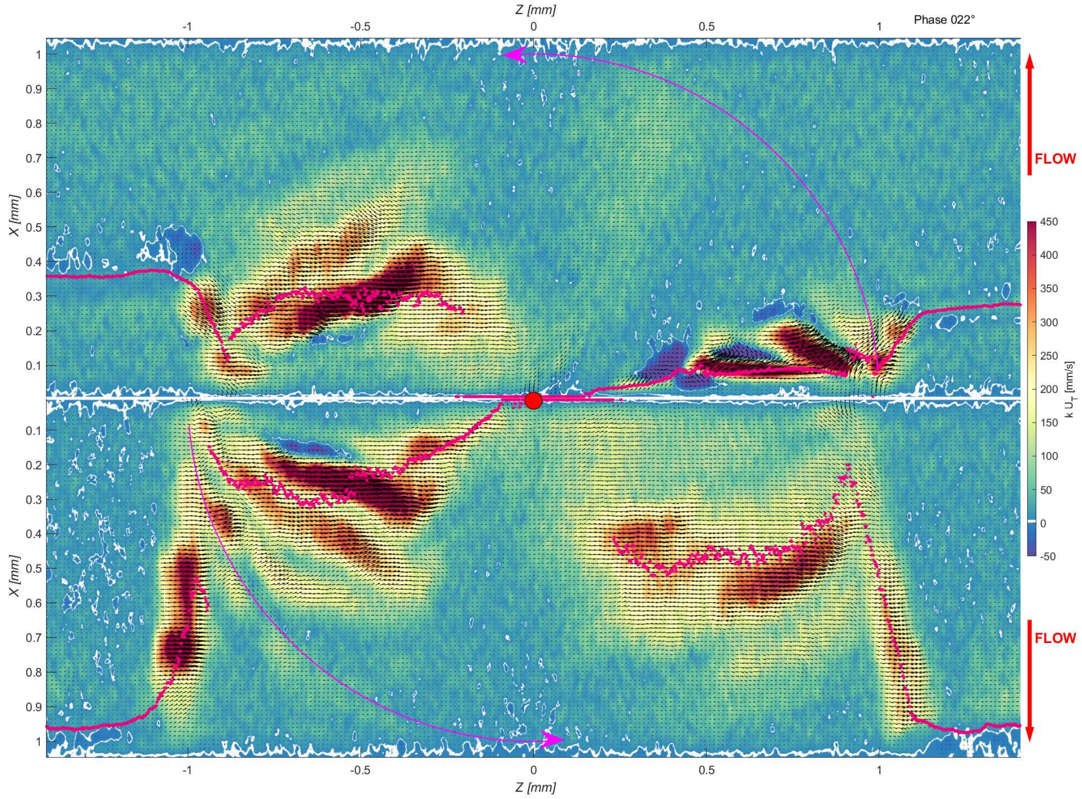
FRICTION VELOCITY ON A HYDROFOIL IN A PROPELLER WAKE. AOA=8°



Skin-friction from TR TSP data and a Taylor-Hypothesis derived algorithm

PROPELLER WAKE SIGNATURE ON A NACA 0015 RUDDER SURFACE AT AOA=4°



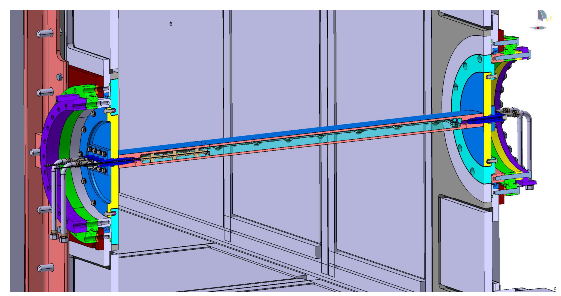


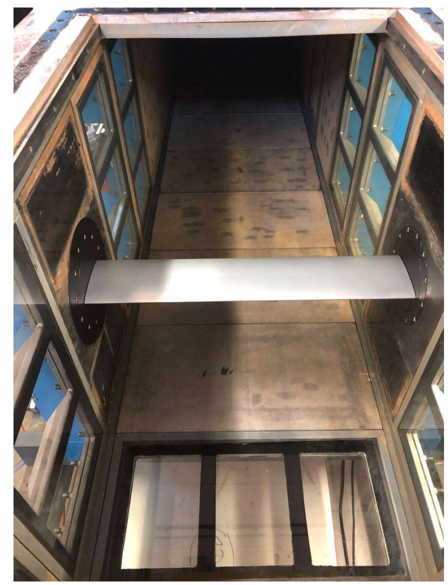
Skin-friction from TR TSP data and a Taylor-Hypothesis derived algorithm

CURRENT ACTIVITY

INM and DLR are developing a common application to study the flow over the surface of an elliptic profile (16% thickness) placed in a uniform cross-flow.
Dimensions: **span 1000mm** **chord 200mm**.

- The experiments have been conducted in the GWB water tunnel of the **Technical University of Braunschweig** (TU BS) in the framework of the DLR project ***ADaMant***.
- Measurements of pointwise pressure and time resolved surface temperature (TSP) at different angles of attack and Re =240k and 500k.
- The GWB tunnel has laminar incoming flow conditions. A double set of measurements with and without a turbulence tripping system on the model has been performed.
- Incoming turbulence levels are unknown at present. Free-stream time-averaged quantities are available, including boundary layer conditions at the tunnel walls.
- RANS and URANS numerical tests are running at INM in Rome. LES activities are still pending



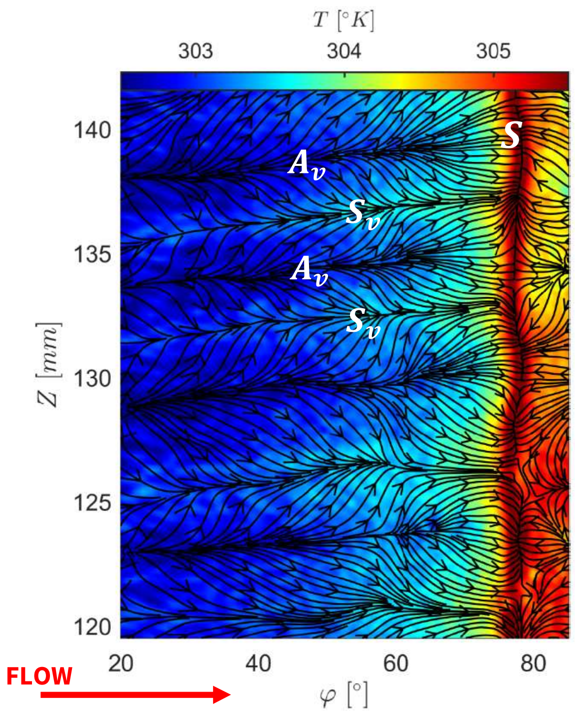


CONCLUSIONS

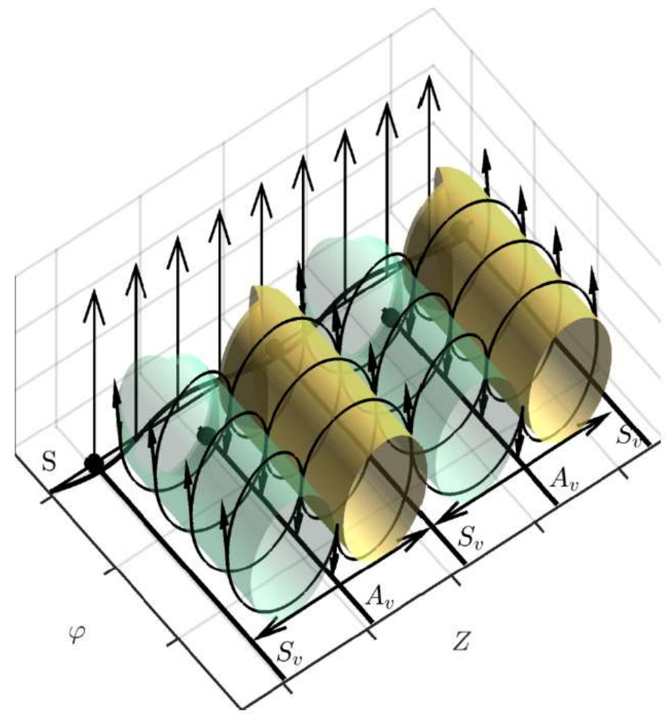
- Application of new methodologies allows 2D TSP measurements to describe coherent structures in remarkably complex flow conditions, like the flow on the surface of a hydrofoil embedded in a propeller wake or around a cube pierced at the wall and embedded in a turbulent boundary layer
- Skin friction from TSP criticisms: lack of experimental support on the relationships between U_T, U_U and U_τ. Dependency of the U_T estimation from the stencil adopted for differences.
- TSP highlights (i.e. molecular sensors potential):
  - Wide spatial extension
  - Impressive sampling frequency available in the future (up to 20 kHz, and even more…)
  - Potential player with leading role in wall flow analysis, also in choosing what to investigate, where, and when.
  - Candidate to became a powerful tool effective in scientific and industrial flow investigations

WHY WE WILL BE INTERESTED IN TSP? (continuing…)

"Distress not yourself if you cannot at first understand the deeper mysteries of Spaceland. By degrees they will dawn upon you."
– **Edwin A. Abbott, Flatland: A romance in many dimensions**



From temperature maps to 3D, near-wall flow structures



Miozzi, Capone, Di Felice, Klein,· Liu (2016): **Global and local skin friction diagnostics from TSP surface patterns on an underwater cylinder in crossow.** Physics of Fluids **28**, 124101 (**M16**)

Skin-friction from TR TSP data and a Taylor-Hypothesis derived algorithm

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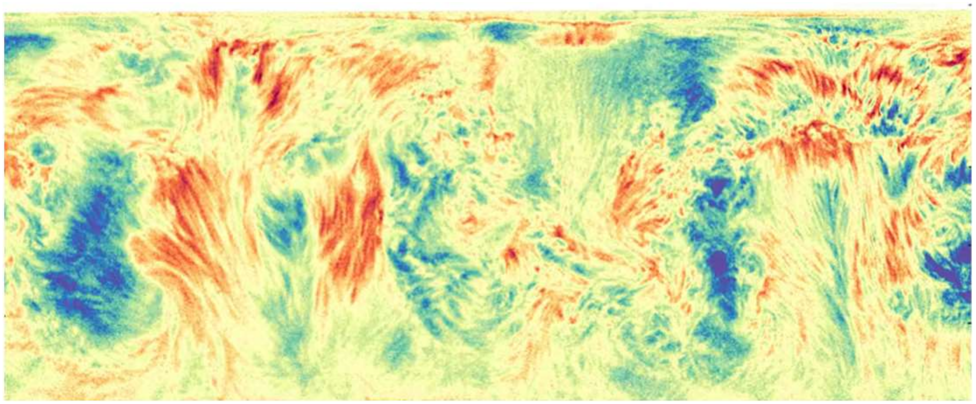

Thank you for your attention.
Questions?

Massimo Miozzi