13th International Symposium on Particle Image Velocimetry – ISPIV 2019
Munich, Germany, July 22-24, 2019

Wall Image Velocimetry through deviation of temperature disturbances transport from Taylor hypothesis

Massimo Miozzi[1*], Fabio Di Felice[1], Christian Klein[2], Marco Costantini[2]

[1] CNR-National Research Council, INM-Institute of Marine Engineering, Rome, Italy

[2] DLR, German Aerospace Center, Göttingen, Germany

[*] massimo.miozzi@cnr.it

Abstract

In this paper the feasibility of a strategy to retrieve quantitative estimations of the skin friction $\boldsymbol{\tau}$ is reported. The strategy grounds on the measurement of the propagation speed U_{T} of temperature disturbances T_w very close to the surface of a slender body, as obtained by means of a Temperature Sensitive Paint. Here we shortly report about relationships between speed of convection of disturbances of different fluid dynamic quantities, as retrieved from literature and about a Taylor-Hypothesis-based, physically motivated way to extract an average convection velocity from time histories of T_w maps. Then, results in terms of streamwise component of friction velocity and friction coefficient are presented for the suction side of a NACA 0015 hydrofoil model at a Reynolds number $Re = 1.8 \times 10^5$ and Angles of Attack $AoA = [1°, 3°, 5°, 7°, 10°]$. The profiles of time and spanwise averaged friction coefficient $C_f(x)$ are proposed and commented. Time averaged maps (i.e. streamwise and spanwise averaged distributions) of u_τ are reported and commented as well.

1 Introduction

There is a wide interest in the measurement of the friction velocity $\boldsymbol{u}_\tau = \partial \boldsymbol{U}/\partial z|_{z\to 0} = \sqrt{|\boldsymbol{\tau}|/\rho}$ on the surfaces subjected to the action of the flow, where $\boldsymbol{\tau} = \boldsymbol{\tau}(x, y, z \to 0)$, $\boldsymbol{U}(x, y, z \to 0)$ are the vectors of velocity and skin friction respectively, ρ is the fluid density and x, y and z are the streamwise, the spanwise and the wall normal directions. The friction velocity is a primary scaling parameter for the theoretical treatment of wall turbulence (Schlichting and Gersten (2017)) and non-dimensional counterparts of spatial and velocity quantities are defined on the basis of it, e.g. $x^+ = x|\boldsymbol{u}_\tau|/\nu_\infty$ and $u^+ = u/|\boldsymbol{u}_\tau|$. Moreover, the availability of time resolved maps of $\boldsymbol{\tau}$ enables a physics-based description of the evolution of wall-bounded flows in terms of separation, reattachment and also of laminar/turbulent transition (Lighthill (1963); Hirschel et al. (2014); Miozzi et al. (2019)). The local analysis of these topological details provides also information about sweeps and ejections which support the modeling of the coherent structures embedded in the viscous sub-layer, whose activity is relevant in wall-bounded turbulence (Miozzi et al. (2019)).
A specific feature of the friction velocity concerns its relationship with the propagation speed of fluctuations of fluid dynamic quantities at the wall. As firstly reported by Eckelmann in his seminal paper Eckelmann (1974), a region develops at $0.1 < z^+ < 7$ where the temporal evolution of wall-normal velocity derivatives, measured via hot films is proportional, by a constant factor, with the temporal evolution of velocity fluctuations u measured at the same streamwise location and increasing distance from the wall. The development of numerical techniques made available further information about $U_{\mathrm{U}}(z)$ as a function of the distance from the wall z. Results reported by Kim and Hussain (Kim and Hussain (1993)) in a turbulent channel flow at $Re_\tau = 180$ firstly stated that disturbances of fluid dynamic quantities, like velocity and vorticity components, when convected close to the wall ($0.1 < z^+ < 15$), don't follow the mean flow velocity but propagate at higher, constant speed, thus behaving like waves. They retrieved the convective speed as $U_{\mathrm{U}} = \Delta x_{peak}/\Delta t$ by looking at the peak of the cross correlation R_{uu}, where Δx_{peak} corresponds to the space lag of the peak of R_{uu} for the imposed time lag Δt. The propagation speed was found to be proportional to the friction velocity, i.e. $U_{\mathrm{U}} = 10.6 u_\tau$. These results have been substantially confirmed in more recent studies, with small

differences only in the the magnitude of the coefficient of proportionality (see Geng et al. (2015); Atkinson et al. (2015) among the others).

The validity of the Taylor Hypothesis (TH, Taylor (1938)) of frozen turbulence in wall bounded flows has been widely investigated in the past. Since the seminal paper of Piomelli et al. (Piomelli et al. (1989)), one of the most studied topics concerned the limits in using a single convective velocity to reconstruct a spatial field from temporally resolved data, especially for what concerns the turbulence intensity and the distance from the wall. A recent approach has been proposed by del Alámo and Jiménez (Del Álamo and Jiménez (2009))), who introduced a physically justified criterion to extract an averaged convective velocity from their DNS data of a turbulent channel flow. A comprehensive description related to the use of a single convective velocity using the transport equation by expanding this approach was proposed by Geng et al. (2015). They also found that, in good agreement with results of Kim and Hussain (1993), there exists a region below $z^+ < 15$ where the speed of propagation U_U remains in constant relationship with the friction velocity u_τ, i.e.:

$$U_\mathsf{U} = 10 \times u_\tau \tag{1}$$

This will be assumed also in this work. It is to notice that, in spite of the general agreement about the linear structure of the dependency, its dependency from the Re is still an open question which would require further attention in the future. Further investigations are also required to analyze consequences of the lack of homogeneous direction and of variable pressure gradients, i.e. the conditions proposed in the present work. A recent review of further experimental efforts on this topic can be found in Atkinson et al. (Atkinson et al. (2015)).

The main flow quantities investigated in the past with regard to the propagation speed of their disturbances in wall-bounded flows were kinematic and dynamic quantities as velocity, vorticity and pressure(e.g. Kim and Hussain (1993); Del Álamo and Jiménez (2009); Geng et al. (2015)). Hetsroni et al. (Hetsroni et al. (2004)) considered for the first time the temperature disturbances T_w by investigating their speed of propagation U_T as a function of the Prandtl number and of the thermal boundary condition at the wall. Their results confirm the existence of a region close to the wall, whose thickness is $z^+ = 2$, where the propagation speed U_T remains constant with decreasing wall distance and where two different relationships hold, one for constant wall heat flux:

$$U_\mathsf{T}^+ = Pr^{-1/2} U_\mathsf{U}^+ \tag{2}$$

and the other for constant wall temperature.

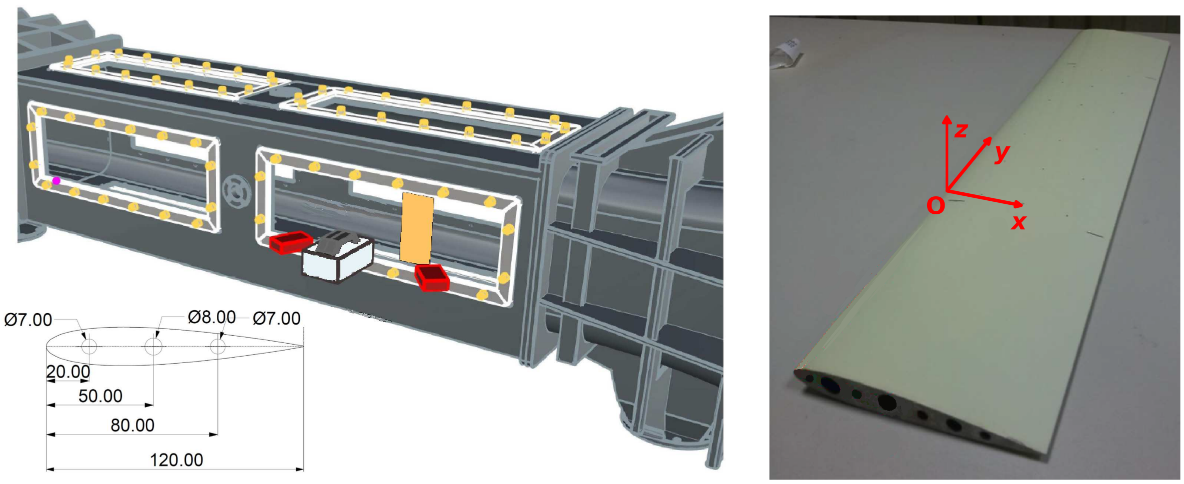
$$U_\mathsf{T}^+ = Pr^{-1/3} U_\mathsf{U}^+ \tag{3}$$

By putting together the relationships in Eq. 1 and Eq. 2, we can close the loop started with Eckelmann (1974) and define a proportionality coefficient between the speed of propagation of temperature disturbances at the wall and the friction velocity. In fact, we can apply a reverse scheme which starts from the measurement of U_T following Del Álamo and Jiménez (2009), moving back to the estimation of U_U according to Hetsroni et al. (2004) and then extracting u_τ (Geng et al. (2015)). The whole procedure is here performed on the basis of the T_w data extracted from TSP (see Liu and Sullivan (2005) for a description of the basic principles of TSP) on the suction side of a NACA0015 hydrofoil model. By adapting and extending the method proposed by Del Álamo and Jiménez (2009) and assessed by Geng et al. (2015) to the temperature fluctuations, the convective velocity is chosen as the value which minimizes the deviation from the Taylor Hypothesis of T_w propagation, which we consider as a passive scalar.

This work extends a previous study by Miozzi et al. (Miozzi et al. (2019)), where the same test model was examined at $Re = 1.8 \times 10^5$ and $AoA = 10^\circ$ to inspect the feasibility of skin friction measurement from the cross correlation of the time histories of temperature disturbances T_w, taken at two streamwise-aligned measurement points. The absence of any homogeneous direction requires the extraction of a local $U_\mathsf{T}(x)$, which evolves along the chord as a function of the pressure gradient. Moreover, at the investigated Re and $AoA = [1^\circ, 3^\circ, 5^\circ, 7^\circ, 10^\circ]$, the flow is subject to separation, transition in the shear layer within a Laminar Separation Bubble (LSB) and turbulent downstream reattachment (Miozzi et al. (2019)).

2 Experimental setup

Experiments were performed in the cavitation tunnel CEIMM at CNR-INM (Rome). A detailed description of the experimental setup can be found in Miozzi et al. (2019), therefore only the most important aspects of the setup are reported here. The facility consists of a closed-loop water tunnel featuring a 1 : 5.96 contraction nozzle and a square test section of side $B = 600\,\mathrm{mm}$ (see Fig. 1(a)). The free-stream turbulence intensity is 0.6% at the mounting position of the hydrofoil model (1.5% on average), whereas the flow uniformity is about 1%. The optical access to the test section is guaranteed from all directions by a set of perspex windows. The model cross-section is a NACA 0015 hydrofoil with chord length $C = 120\,\mathrm{mm}$ (Fig. 1(b)). Its span L equals to test section side B. The model was coated with a TSP to measure the surface temperature. The development and the properties of the TSP used in this work are described in Ondrus et al. (2015). Details about image orthorectification, registration and temperature extraction as well as about spatial and temporal filtering, applied during image preprocessing, can be found in Miozzi et al. (2019).



(a) CEIMM tunnel

(b) TSP coated hydrofoil model

Figure 1: (a) Water tunnel experimental setup and NACA 0015 hydrofoil model (orange, inside the tunnel), LEDs (red) and fast camera (white). Contraction nozzle is on the right. Lower left detail reports the NACA 0015 profile with heating structure. Reference coordinates given (distances in mm). (b) TSP-coated hydrofoil model. Registration markers can be noticed onto the surface.

3 Wall Image Velocimetry and skin friction measurements

The Taylor hypothesis states that the disturbances of velocity u (but also of other flow quantities, such as vorticity, temperature and pressure) behave like waves and thus, in the limit of weak disturbances, that streamwise derivatives $\partial/\partial x$ of velocity fluctuations in turbulent flows can be approximated by $(1/U_U)\partial/\partial t$. The Taylor hypothesis provided a useful tool to experimentalists to extend point-wise, time resolved measurements to the spatial domain and substituted spatial derivatives with a simple time-space derivative transformation. This frozen condition of the flow turbulence is obviously violated by the presence of a rigid wall, where the identification of a speed of propagation U_U becomes an issue, so as its dependency from the spatial scale of the advected flow structures. The approach in Del Álamo and Jiménez (2009); Geng et al. (2015) allows to extract a physics-based average convective velocity of the investigated disturbances by assuming that it is the value which minimizes the discrepancy from the Taylor hypothesis. All existing works report about U_U along a homogeneous direction. On the contrary, the flow investigated here is characterized by a continuous variation of the pressure gradient. Moreover, the presence of a Laminar Separation Bubble rises up the complexity of the flow behavior at the wall and its analysis has to consider the existence of changes in sign of the velocity. For this reason, the original approach in Del Álamo and Jiménez (2009); Geng et al. (2015) is extended to take into account the absence of an homogeneous direction and the existence of a reverse flow region. This is accomplished by moving from the minimization of the RMS error to the minimization of the RMS absolute error, which leads to the Eq. 4 for U_T:

$$|U_\mathsf{T}| = \overline{\left|(-\partial_t T_w)\,\partial_x T_w\right|} \Big/ \overline{\left|\partial_x T_w\right|^2} \tag{4}$$

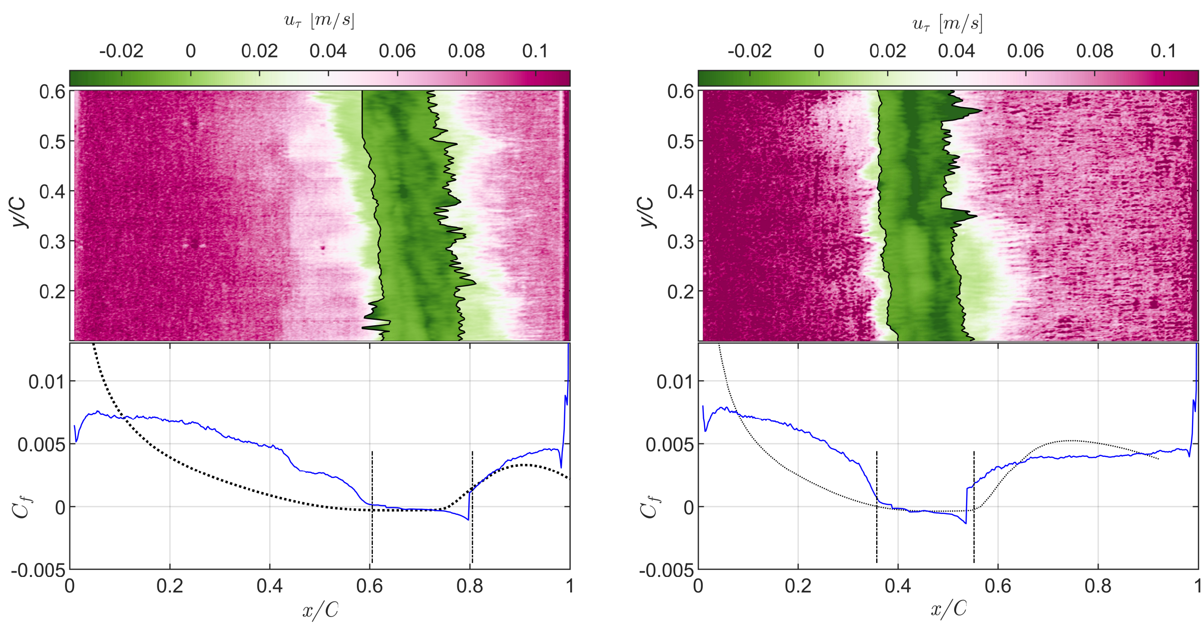
and to a robust criterion to identify a reverse flow region:

$$U_{\mathsf{T}} = \begin{cases} +|U_{\mathsf{T}}| & \text{if } \overline{|(-\partial_t T_w)+U_{\mathsf{T}}\partial_x T_w|} < \overline{|(-\partial_t T_w)-U_{\mathsf{T}}\partial_x T_w|} \\ -|U_{\mathsf{T}}| & \text{if } \overline{|(-\partial_t T_w)+U_{\mathsf{T}}\partial_x T_w|} > \overline{|(-\partial_t T_w)-U_{\mathsf{T}}\partial_x T_w|} \end{cases} \tag{5}$$

The obtained U_{T} provides the initial information to extract U_{U} and then u_τ, by following Eqs. 1 and 2. As a final remark, it is to underline that the present algorithm is fed by kinematic quantities and is not exposed to the influence of factors not related to fluid dynamic phenomena, such as a non-uniformity of surface heating (generally applied to rise up the signal-to-noise ratio in TSP measurements, see e.g. Capone et al. (2015)).

4 Results

Results obtained from the procedure described in Sec. 3, are shown in Figs. 2 to 4 for angles of attack $AoA = [1°, 3°, 5°, 7°, 10°]$. Streamwise temperature gradients have been evaluated with central differences on a spatial lag of ± 12 px which roughly correspond to 20 x^+ at $AoA = 10°$, in agreement with the Kim and Hussain suggestion of $t^+ = 18$ (see Kim and Hussain (1993)).



(a) $AoA = 1°$.

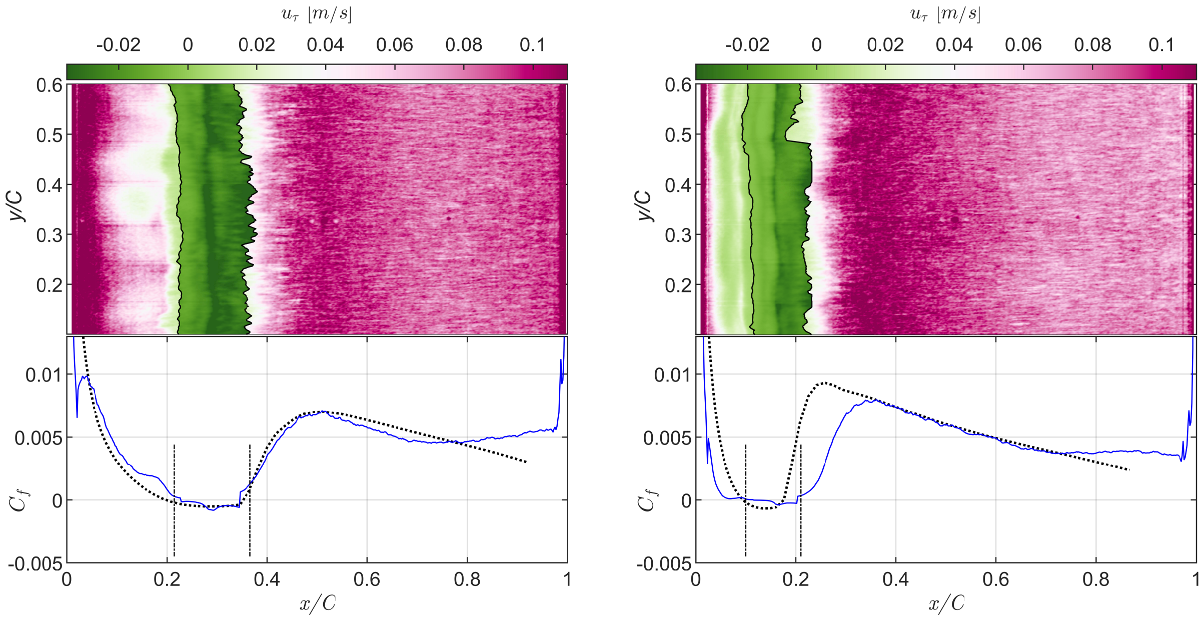
(b) $AoA = 3°$.

Figure 2: Bottom: experimental C_f profile (blue) and Xfoil result (black dashed). Top: map of friction velocity u_τ. The green reverse flow region is found to be confined between the vertical jagged black lines.

The positively definite maps of u_τ are modified following Eq. 5 calculated for each matrix row. The resulting u_τ sign allows for an easy identification of the LSB separation and reattachment borders. Bottom graphs report the corresponding C_f profiles obtained starting from the spanwise average of the u_{tau} maps. Profiles from Xfoil data ($N_{cr} = 9$, Drela (1989)) are also provided in the C_f graphs, neither to validate experimental results nor because Xfoil data can be considered as a *ground-truth*, but in order to provide a visual comparison of the orders of magnitude of the present results.

The comparison of results obtained with cross correlation and Taylor hypothesis based criteria at $AoA = 10°$ is reported in Fig. 5(a), where a fair agreement of the results can be observed everywhere but inside the laminar separation bubble and in its vicinity, where the output of the Taylor hypothesis based algorithm show that after separation the flow exhibit a rise of the negative velocity, not observed with the cross correlation based approach.

As a final remark, comparisons between present data about separation and reattachment locations and data



(a) $AoA = 5°$.

(b) $AoA = 7°$.

Figure 3: Bottom: experimental C_f profile (blue) and Xfoil result (black dashed). Top: map of friction velocity u_τ. Reverse flow region is found to be confined between the vertical jagged black lines.

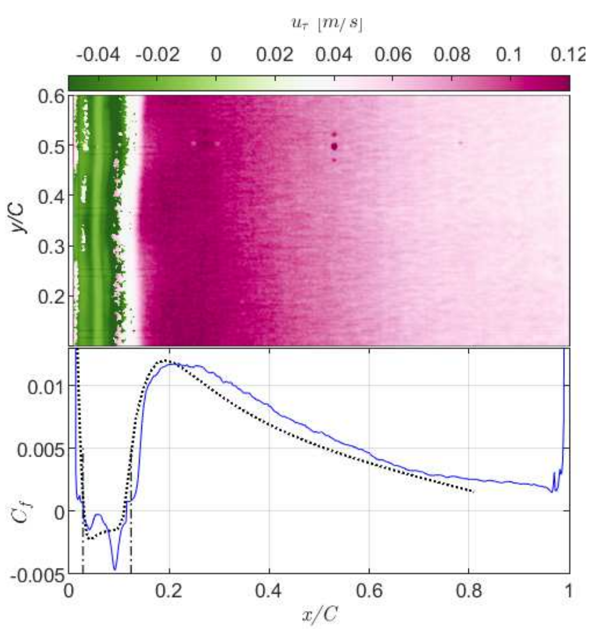


Figure 4: $AoA = 10°$. Bottom: experimental C_f profile (blue) and Xfoil result (black dashed). Top: map of friction velocity u_τ.

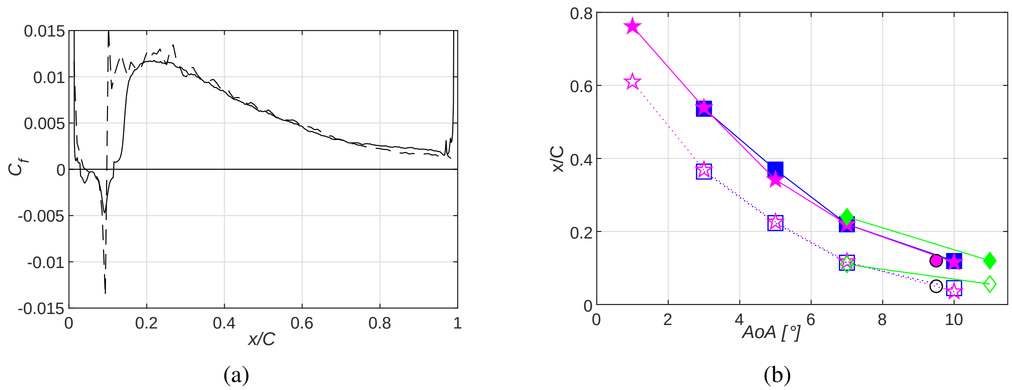


Figure 5: (a): Comparison between C_f evaluated at $AoA = 10°$ with the proposed method (continuous line) and with cross correlation between streamwise-aligned locations (dashed line, from Miozzi et al. (2019))). (b): Separation (empty symbols) and reattachment (full symbols) locations at different AoA. Comparison between present results (magenta ⋆), Miozzi et al. (2019) (blue ■, same flow conditions), Lee and Su (2011)(⧫, $Re = 2.5 \times 10^5$, NACA0015) Sharma and Poddar (2010) (•, $Re = 2x10^5$, NACA0015)

from literature are reported in Fig. 5(b) from Lee and Su (2011); Sharma and Poddar (2010) and Miozzi et al. (2019). The formers were obtained for a NACA0015 profile at $Re = 2x10^5$ and $Re = 2.5x10^5$, which are the most similar conditions to the investigated ones we found in literature. The latter came from the same dataset as that of the present work, but were obtained by applying an algorithm inspired to an Optical Flow analogy starting from the energy equation which involves, though not explicitly available, the heat flux between the surface and the fluid (Liu and Woodiga (2011)). It is interesting to note the excellent agreement over the whole range of investigated angles of attack, with a slight discrepancy for the reattachment location at $AoA = 5°$. It is clear that this agreement doesn't demonstrate the correctness of the methods, but it shows the consistency of the results obtained via different approaches.

5 Conclusions

This paper reports about the feasibility of a new method to quantitatively estimate the skin friction τ starting from the speed of convection of thermal disturbances at the wall U_T, obtained by means of TSP. The method assumes as best value for the speed of propagation the one which minimizes the discrepancies between the real behavior of the temperature disturbances, considered as passive scalars, and the Taylor Hypothesis, whose assumption about frozen turbulence fails close to the wall. Reported results concern the suction side of a model with a NACA 0015 hydrofoil, where the absence of an homogeneous direction and the continuous variation of the pressure gradient rise the complexity of the flow and make more challenging the analysis. By means of relationships established in previous work, magnitude and direction of U_T allow to obtain both the speed of propagation of velocity disturbances and the friction velocity, thus providing a direct link with the skin friction.

Acknowledgements

This work has been supported by the Flagship Project RITMARE, The Italian Research for the Sea, coordinated by the Italian National Research Council and funded by the Italian Ministry of Education, University and Research. Dr. Alessandro Capone is acknowledged for his support during setup design and measurements. Carsten Fuchs (DLR) is acknowledged for TSP surface treatment.

References

Atkinson C, Buchmann NA, and Soria J (2015) An experimental investigation of turbulent convection velocities in a turbulent boundary layer. *Flow, Turbulence and Combustion* 94:79–95

Capone A, Klein C, Di Felice F, Beifuss U, and Miozzi M (2015) Fast-response underwater TSP investigation of subcritical instabilities of a cylinder in crossflow. *Experiments in Fluids* 56:1–14

Del Álamo JC and Jiménez J (2009) Estimation of turbulent convection velocities and corrections to Taylor's approximation. *Journal of Fluid Mechanics* 640:5–26

Drela M (1989) Xfoil: An analysis and design system for low reynolds number airfoils. in TJ Mueller, editor, *Low Reynolds Number Aerodynamics*. pages 1–12. Springer Berlin Heidelberg, Berlin, Heidelberg

Eckelmann H (1974) The structure of the viscous sublayer and the adjacent wall region in a turbulent channel flow. *Journal of Fluid Mechanics* 65:439–459

Geng C, He G, Wang Y, Xu C, Lozano-Durán A, and Wallace JM (2015) Taylor's hypothesis in turbulent channel flow considered using a transport equation analysis. *Physics of Fluids* 27:025111

Hetsroni G, Tiselj I, Bergant R, Mosyak A, and Pogrebnyak E (2004) Convection velocity of temperature fluctuations in a turbulent flume. *Journal of Heat Transfer* 126:843–848

Hirschel E, Kordulla W, and Cousteix J (2014) *Three-dimensional attached viscous flow: Basic principles and theoretical foundations*. Springer

Kim J and Hussain F (1993) Propagation velocity of perturbations in turbulent channel flow. *Physics of Fluids A* 5:695–706

Lee T and Su YY (2011) Lift enhancement and flow structure of airfoil with joint trailing-edge flap and Gurney flap. *Experiments in Fluids* 50:1671–1684

Lighthill M (1963) Attachment and separation in three-dimensional flow. *Laminar boundary layers* 2:72–82

Liu T and Sullivan JP (2005) *Pressure-and Temperature-Sensitive Paints*. Springer

Liu T and Woodiga S (2011) Feasibility of global skin friction diagnostics using temperature sensitive paint. *Measurement Science and Technology* 22:115402

Miozzi M, Capone A, Costantini M, Fratto L, Klein C, and Di Felice F (2019) Skin friction and coherent structures within a laminar separation bubble. *Experiments in Fluids* 60:13

Ondrus V, Meier R, Klein C, Henne U, Schäferling M, and Beifuss U (2015) Europium 1,3-di(thienyl)propane-1,3-diones with outstanding properties for temperature sensing. *Sensors and Actuators A: Physical* 233:434 – 441

Piomelli U, Balint J, and Wallace JM (1989) On the validity of Taylor's hypothesis for wall-bounded flows. *Physics of Fluids A* 1:609–611

Schlichting H and Gersten K (2017) *Boundary layer theory*. Springer-Verlag Berlin Heidelberg. 9th edition

Sharma DM and Poddar K (2010) Experimental investigations of laminar separation bubble for a flow past an airfoil. in *Proceedings of the ASME Turbo Expo*. volume 6. pages 1167–1173

Taylor GI (1938) Production and dissipation of vorticity in a turbulent fluid. *Proceedings of Royal Society A* 164