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Experimental investigation of active control in turbulent boundary layer using uniform blowing

Gazi Hasanuzzaman[1*], **Sebastian Merbold**[1], **Vasyl Motuz**[1], **Christoph Egbers**[1], **Christophe Cuvier**[2] **and Jean-Marc Foucaut**[2]

[1] Brandenberg University of Technology, Department of Aerodynamics and Fluid Mechanics, Cottbus, Germany

[2] Univ. Lille, Laboratoire de Mécanique des Fluides de Lille Kampé de Fériet, Lille, France

[*] corresponding.hasangaz@b-tu.de

Abstract

SPIV measurements were carried out at Laboratoire de Mécanique des Fluides de Lille Kampé de Fériet (LMLF) boundary layer wind tunnel where turbulent boundary layer (TBL) flow was perturbed with an upstream blowing. In order to identify the changes in the flow downstream, Stereo Particle Image Velocimetry (SPIV) was used to measure the flow fields by varying the magnitude of blowing at different Reynolds number. Two orientations of SPIV arrangements were used to measure the plane parallel and perpendicular to the principal flow direction. Measurements were taken in a wide variation of Reynolds number based on momentum thickness such as $\mathrm{Re}_{\theta,SBL} = 7495 \sim 18094$ using different rates of blowing. Present proceedings discuss the requirement of such experiment, experimental setup and procedure followed by a description of the database acquired with the present measurement. This project was realized using the grant from "European High performance Infrastructures in Turbulence".

1 Introduction

Turbulence is considered as a major barrier problem in fluid driven transportation sector e.g aviation and shipping industry. For subsonic CTOL aircrafts, skin friction drag contributes almost 50% of the total drag (Kornilov (2015)). Therefore, a novel drag reduction technique that can achieve a substantial friction reduction over the wall can contribute a significant fuel cost abatement. In the course of several drag reduction experiments since 1950's, literature review suggested that active control techniques exhibit superior drag reduction effects compared to the passive techniques. Moreover, a general consensus from our cognition of presently available literature indicate that blowing can potentially reduce skin friction about 50% (Hwang (2004)). Besides, several methods are in practice in order to actively or passively manipulate the wall bounded flows with a common goal to reduce the skin friction.

The concept of active manipulation of the boundary layer goes back to early forties of the last century. First documented flow manipulation experiment using blowing was found from Schlichting (1942a) where he used the blowing from upstream slot of a subsonic aerofoil. Subsequently, several other researches about blowing from a transpired surface established the potential of the blowing in reducing friction drag for incompressible TBL. A good review on the experimental research in such flow manipulation technique can be found from Jeromin (1970). Nevertheless, considerable amount of laboratory experiments and numerical simulations regarding blowing has provided ample of data but growing consensus regarding large and very large scale structures in turbulent wall bounded flows has constrained the renewal of such experiments. Beside the engineering application of blowing on aerodynamic and hydrodynamic machines (e.g. aeroplanes, submarines, high speed trains and automobiles) it is also analogous to determine the relevance of such method to the turbulent flows. Therefore, rather looking into the mean parameters of the TBL with blowing, time dependent analysis of valid high Reynolds number measurements are necessary.

Flow manipulation experiments about incompressible TBL primarily focuses on two principle aspects namely amount of friction drag reduction and time dependent study of turbulence parameters. Although reported numerical results at comparatively low Reynolds numbers, incompressible TBL at $\mathrm{Re}_\theta = 700$, Kametani and Fukagata (2011) presented a very interesting outcome that a small magnitude of uniform blowing (0.1% U_∞) can cause significant amount of statistical alteration to the mean flow. In addition, blowing is not only sustainable within the near wall region but can cause significant upsurge of hairpin like structures all the way through the outer region. This happens simultaneously with the reduction of friction drag of the downstream region.

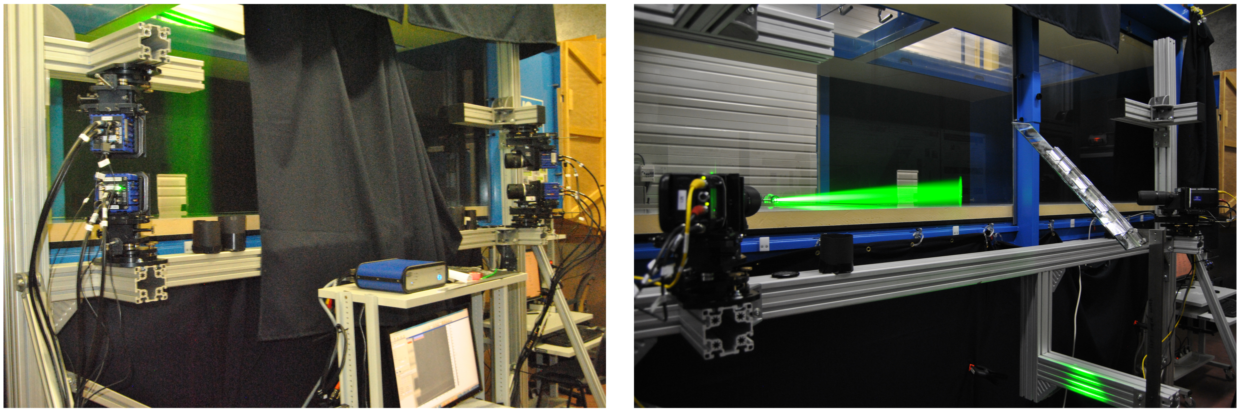
In experiments, general feasibility of uniform blowing in the field of friction drag reduction is mostly considered as a local phenomena. In addition, active methods such as blowing is also characterized as external energy input. Therefore, relative gain in terms of friction drag to the input energy is still one controversial issue in this regard. Recent TBL experiments at moderate Reynolds number from Motuz (2014) has demonstrated the effect of uniform blowing that the changing blowing ratio (see Section-4) has a significant impact on the relative gain calculation. However, such analysis is still unavailable from high Reynolds number TBL measurements. On the other hand statistical description from literature study exhibit a general consensus on the fluctuation increase due to blowing, at least streamwise and wall-normal components of velocity overshoots (depending on the different magnitudes of blowing). Hasanuzzaman et al. (2016) has demonstrated the fluctuation variation as an outcome of blowing. Moreover, 13% friction reduction was possible using 0.4% blowing (% of U_∞) at $Re_{\theta,SBL} = 1788$. But with increased computational capacity, we receive a complete description of the flow field through numerical simulation. Therefore, overall estimation of the friction drag along an incompressible TBL was found possible by Stroh et al. (2016). As such, a detail description of the upstream influence from blowing along the TBL was provided. A significant finding from their result is that the finite length of affected area through a very small amount of uniform blowing can be persistent for the complete spatial growth of TBL.

2 High Reynolds Number Measurement

Since Theodorsen (1952) illustrated the existence and classification of different structures present in the wall bounded shear flows, extensive research effort has been imparted in the study of structures in turbulent flows. In other words, 'Coherent Motions' in the outer layer of wall bounded shear flows has received monumental attention as their dynamical nature was difficult to study due to the limitation of existing measurement technique. It was widely accepted that the dynamics of these coherent motions were relatively similar and independent from the flow Reynolds number. Maximum kinetic energy was believed to be from the influence of the inner layer. Contrary to such belief, using Hot Wire measurements at high Reynolds number TBL flows, Hutchins and Marusic (2007) showed that outer scaled large structures become more influential as the Reynolds number increases. In addition, they have also showed that sufficient scale separation of the fluctuation data is required in order to obtain a distinction between inner and outer layer peak (both fluctuation and spectra). That occurs at a minimum Reynolds number of $Re_{\tau,SBL} = 1700$ (Here, Reynolds number is based on the ratio of inertial and viscous forces, $Re_{\tau,SBL} = \delta u_\tau/\nu$, u_τ is the shear velocity and δ is the boundary layer thickness at $U_\infty = 99\%$).

In connection to the flow control/manipulation experiments in TBL, most often measurement and simulation data available is based on low Reynolds number flows. On the other hand, most of the engineering applications are at very high Reynolds number. General aviation is operated upto and beyond $Re_c = 10^7$ (Chord Reynolds number, $Re_c = U_f c/\nu$, U_f is the flight speed and c indicates the chord number. This is quite similar to the characteristics length based Reynolds number in TBL). Most often low Reynolds number measurements are justified with the fact that most of the turbulent kinetic energy (TKE) is the contribution from viscous layer. As the Reynolds number increases, the share of TKE contribution from viscous layer keep reducing and share from the logarithmic layer keep increasing. Smits et al. (2011) described such phenomena using high Reynolds number HWA measurements where pre-multiplied TKE was used to describe the TKE contribution from different layers. Although, PIV measurement is limited to reach the near wall regions but at sufficiently high Reynolds number overlapping and logarithmic layer becomes more important in terms of turbulent structure analysis.

As a consequence to such hypothesis, an experimental study was designed to verify the idea of energy transfer manipulation using uniform blowing. In addition, suitable scaling parameters for the mean profiles and Reynolds stresses were evaluated. Therefore, flow manipulation using uniform blowing experiments at sufficiently high Reynolds numbers were conducted within the framework of European High-Performance Infrastructures in Turbulence (EuHIT) Project, 'Enhanced Turbulent Outer Peak using Uniform Micro-Blowing (ETOP-MBT)'. The experiment was a joint experiment between Department of Aerodynamics and Fluid Mechanics, Brandenburg University of Technology and Laboratoire de Mécanique des Fluides de Lille Kampé de Fériet (LMLF), University of Lille.



(a) XY plane (b) YZ plane

Figure 1: (Left) SPIV arrangement for XY plane, (Right) for YZ plane, in both cases flow is coming from left to right relative to the reader

3 Boundary Layer Wind Tunnel

LMLF boundary layer facility is particularly suitable for high resolution measurements at high Reynolds numbers of turbulent boundary layer over flat plate. The wind tunnel used for this experiment has a closed loop configuration which is particularly suitable for non-intrusive optical measurements such as Particle Image Velocimetry (PIV).

Test section of the wind tunnel is 20.6 m long with a cross section of 1×2 m^2 e.g. in vertical and transverse length. As the test section has an optical access from all sides along the complete length of it, therefore, non-intrusive optical measurement can be performed. Longitudinal axis (streamwise) is parallel to the bottom wall and to the incoming flow where boundary layer develops. Transverse and vertical axis is referred as spanwise and wall-normal axis respectively. Incoming air to the plenum chamber was passing through an air-water heat ex-changer in order to provide a near iso-thermal flow where efficiency is kept within $\pm 0.15^\circ C$. Subsequently, air through the guide vanes undergoes a relaminarization process via honeycomb screens and grids. Thereafter, contraction takes place with a ratio of 5.4 : 1. Cuvier (2017) provides a detailed description of the experimental facility.

4 Uniform Blowing Experiment

Upstream blowing with uniform velocity in a flat plate TBL was established with a perforated plate where 4514 holes with uniform diameter of 3.6 mm were constructed with staggered arrangement following the designs proposed by Hwang (2004). Although this experiment was designed for compressible flows, therefore, viscous length scale was way too small compared to the present experiment. In order to use the similar blowing surface design for incompressible TBL with larger length scales, necessary modifications of the blowing assembly was done compared to the design data from Hasanuzzaman et al. (2016). In order to provide wall normal blowing, a solid wind tunnel wall was replaced with a perforated (blowing surface) one as described earlier. Streamwise length of the blowing surface was at wind tunnel characteristics length X = 18.424 $\sim$ 18.845, keeping the width center equidistant from both side walls of wind tunnel. Blowing rate is expressed as blowing fraction (F), is a ratio between the magnitude of the incoming air through the perforated surface to the $U_\infty(= V_{blowing}/U_\infty$ in %) was applied at a very low velocity (0, 1, 3 and 6%) for each Reynolds number being measured.

Stereo Particle Image Velocimetry (SPIV) was used as the measurement technique for Reynolds number, Re_θ = 7,495, 12541 and 18,095 (Subscript $_{SBL}$ refer to the cases without blowing). Reynolds number is based on the free stream velocity (U_∞), momentum loss thickness (θ) and Kinematic viscosity (ν). For each Reynolds number, two particular Fields of View (FoV) were realized. In order to acquire uncorrelated SPIV data for statistical analysis over the entire height of boundary layer, a plane parallel in the direction of principle flow (streamwise-wall normal) was measured at 22 cm downstream from the end of perforated surface. This set of measurements are indicated with 'XY' in the section-6. 4000 independent velocity fields

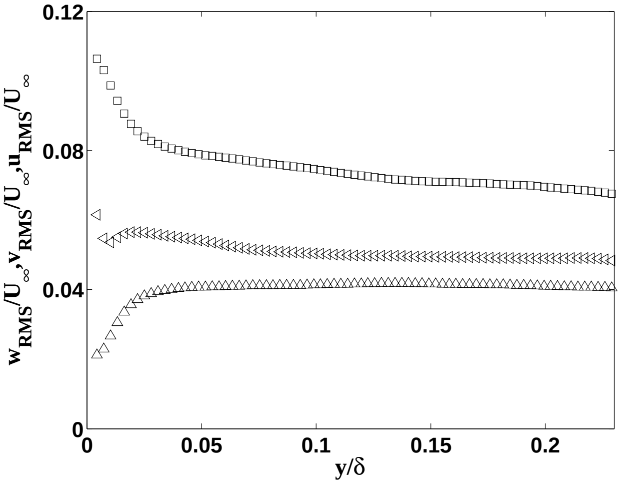


Figure 2: At $Re_{\theta,SBL}$ = 7495 RMS values of fluctuations normalized with U_∞ along different wall normal height scaled with δ (measurements from YZ plane), □ : u_{RMS}/U_∞, ◁ : v_{RMS}/U_∞, △ : w_{RMS}/U_∞

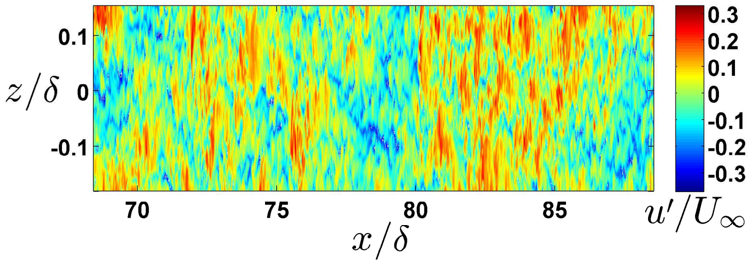
with all three components were obtained.

Similarly, for each set of Reynolds number, a plane perpendicular in the direction of principle flow (spanwise-wall normal) was also measured. Second FoV was set immediately over the perforated surface at 25% downstream from the beginning. This is termed as 'YZ' plane. In YZ plane High speed SPIV acquisition was realized in order to obtain time correlated data with sufficiently high frequency (f_{acq} = 2 kHz). For each Reynolds numbers and blowing ratios, 4 runs were acquired. RMS of the different velocity components scaled with the free stream velocity along ascending wall normal height as a fraction to δ is presented with Figure-2 at $Re_{\theta,SBL}$ = 7495. We can observe that v_{RMS} is maximum at y = 0.0044 m or y/δ = 0.016, which is the location where natural peak value is found at the measured Reynolds number. Blowing as an active method, is expected to add energy to the wall normal component. The addition of energy is dependent on the blowing fraction (F). At the same time, wall normal component is expected to curtail the magnitude of the streamwise velocity changing the mean gradient (du^+/dy^+) of u at the near wall region ($y^+ \leqslant 5$). Figure-3 indicate the contour plots of streamwise fluctuation following the space time conversion procedure from Monty et al. (2007). Here, streamwise fluctuations are normalized with U_∞ and cartesian co-ordinates along z and x axis were normalized with δ.

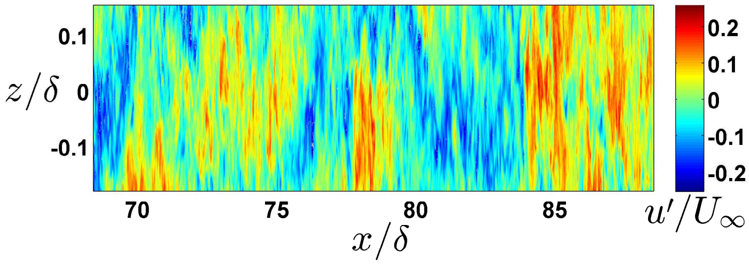
Images were obtained using an SPIV setup of translation orientation (Prasad and Jensen (1995)). Afterwards, SPIV images were evaluated using an in house version of MatPIV code developed at LMLF. This was a multiple grid and multiple pass cross correlation algorithm described in Westerweel et al. (1997) and Soria et al. (1999). In order to avoid the error due to misalignment between laser light sheet and optical plane of the camera, a calibration process called safe calibration was followed (Soloff et al. (1997)). In order to avoid inherent image deformation and outlier detection Westerweel and Scarano (2005) was applied.

5 Conclusion

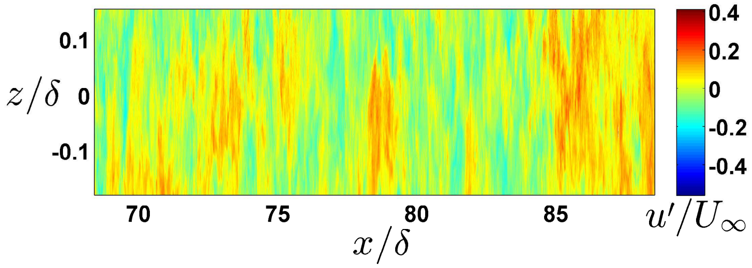
In order to obtain spatial distribution of the streamwise velocity fluctuations presented in Figure-3, Taylors frozen turbulence hypothesis has been employed to infer the spatial velocity field from the temporal SPIV data. The blue low-speed regions surrounded by red high-speed regions are the signature of the Coherent motions in TBL. Corresponding wall normal height is within the logarithmic and the beginning of the wake. In some cases, spanwise length of such motions exceed the length of FoV. Accuracy of the results are in good agreement with literature values. Although, accuracy of the data is strongly depending on the accuracy of the images. Therefore, PIV error was not more then 0.1 pixels.



(a) y/δ = 0.016



(b) y/δ = 0.1492



(c) y/δ = 0.2230

Figure 3: Contour plots of streamwise fluctuations at $\mathrm{Re}_{\theta,SBL} = 7495$.

6 ETOP-MBT Database

Experimental boundary condition and technical details of the measurement campaign can be found in the project completion report in addition to the details of the data repository in the following link: `https://turbase.cineca.it/init/routes/#/logging/view_dataset/82/tabfile`

Access to the data in the above mentioned link is still under embargo period till September 2018.

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