

Experimental study of three-dimensional turbulent boundary layers in a simplified wing-body junction

A. Weingärtner^{1,*}, B. Ganapathisubramani¹

¹: Department of Aeronautical and Astronautical Engineering, University of Southampton, United Kingdom

*Corresponding author: a.weingartner@soton.ac.uk

Keywords: Wing-body junction, three-dimensional turbulent boundary layer, particle-image velocimetry, oil-film interferometry

ABSTRACT

To date, the vast majority of fundamental boundary-layer studies have focused on two-dimensional flow cases. In practice, however, such conditions are the exception rather than the norm, as most engineering applications are dominated by three-dimensional (3D) effects that strongly influence the flow physics. As a result, fundamental understanding of 3D turbulent boundary layers (TBLs) is still limited. A typical flow case that gives rise to 3D TBLs is a wing-body junction, which we investigated experimentally here. We present selected data from an experimental campaign, incorporating direct measurements of pressure, two-dimensional skin friction, and all three velocity components in closely spaced crossflow planes. Results show the expected pressure variation around the airfoil at a positive angle of attack and a significant impact onto the wall-shear stress (WSS) magnitude, especially near the wing's leading edge. For the limited data we show, the direction of the WSS is close to the angle of deflection of the free-stream flow, but they are not equal in general. Furthermore, we show the skewed 3D TBL profiles along a spanwise plane near the leading edge. Results show a maximum in the spanwise velocity and hence the flow angle near the wall, which is likely related to the maximum in the WSS amplitude observed in that region. In the future, this combination of pressure, skin-friction, and velocity data is expected to be instrumental for testing and developing models to more generally describe 3D TBLs. Furthermore, it is known that the misalignment of stress and strain across the TBL is a major source of modeling inaccuracies, which we will assess based on the current data.

1. Introduction

Wing-body junctions (WBJs) are a classical example for the occurrence of three-dimensional turbulent boundary layers (3D TBLs). Here, an incoming 2D boundary layer experiences the streamwise and spanwise pressure gradient imposed by the wing and hence develops 3D features. Due to its relevance for engineering applications, this type of flow has been studied previously, investigating both skin friction and boundary layer topology in the vicinity of the WBJ. A commonly used geometry for WBJ research is the Rood wing, which is a NACA0020 airfoil with an elliptical nose of ratio

3:2. For example, Zhong et al. (2015) measured the wall-shear stress (WSS) of a WBJ qualitatively by means of global luminescent oil-film visualization, using a Rood wing at different angles of attack. They describe regions of separation and reattachment of the flow in the vicinity around and on the wing. Their results show that the regions of largest WSS are on the wing near its maximum thickness, besides also visualizing the horseshoe vortex that forms in the junction region.

One of the first studies systematically investigating the 3D TBL around the Rood WBJ is by Ölcmen & Simpson (1995). Measuring several individual velocity profiles around the wing, they report a significant amount of mean-flow deflection that depends on both the streamwise/spanwise location of measurement and the wall-normal distance. This can be quantified using the mean flow angle, $\gamma = \tan^{-1}(W/U)$, where W and U are the mean spanwise and streamwise velocity components, respectively. They observed, for example, that the near-wall flow is most strongly affected and attribute this to the momentum of the fluid being lowest in that region. In addition, they report a significant amount of anisotropy in the turbulence statistics, especially the eddy viscosity, as a result of the misalignment of stress and strain across the boundary profile. This is a direct violation of the Boussinesq approximation, which is a central assumption made for many Reynolds-averaged Navier–Stokes (RANS) closure models. The consequences are discussed for instance by Lynch (2017), who experimentally studied the 3D TBL in a turbine blade passage. They demonstrated that standard RANS models are unable to predict the boundary layer flow affected by lateral pressure gradients, showing significant deviations even in the mean velocity. Models allowing anisotropy in the eddy viscosity perform better overall, but in many cases still not satisfactorily well.

Theoretical models for 3D TBLs have also been developed but there continues to be no consensus on their general validity. For example, Van Den Berg (1975) derived a three-dimensional law of the wall, taking into account variable skewing across the TBL profile, pressure gradients in both streamwise and spanwise directions, and changes in the direction of the WSS. However, several critical assumptions are made that are known not to be generally valid in 3D TBLs, such as the aforementioned alignment of strain and stress. Despite these limitations, Duetsch-Patel et al. (2023) compared experimental data from a boundary layer over a parametrized three-dimensional hill structure to the 3D law of the wall. They found that in regions with mild or negligible stress/strain misalignment, the agreement was good across a considerable range of the boundary layer. However, as mentioned by Devenport & Lowe (2022), additional experimental data on 3D TBLs at high Reynolds numbers are necessary to study mean velocity profile similarity relations depending on local wall-shear stress and pressure gradient.

Given that most previous experiments were conducted using either laser-Doppler velocimetry or hot-wire anemometry, boundary layer data from these studies is generally sparse, offering only limited data for direct comparisons. In the current study, we employ a simplified wing-body junction and perform stereoscopic particle-image velocimetry (stereo-PIV) in several closely spaced

planes normal to the flow. As a result, the data is much more dense and is expected to be highly useful for modeling approaches. In addition, we perform closely spaced direct measurements of the WSS, also allowing the determination of its spatial gradients (as necessary for the model by Van Den Berg, 1975). Furthermore, by varying the angle of attack of the airfoil, we can easily vary the imposed 2D pressure gradient that the boundary layer experiences. In the present paper, we present some selected results from the experimental campaign.

2. Experimental Setup

Experiments were conducted in the Boundary Layer Wind Tunnel (BLWT) at the University of Southampton, Department of Aeronautical and Astronautical Engineering. The BLWT is a closed-loop tunnel with a test-section of $1 \times 1.2 \times 12$ m (height $\times$ width $\times$ length). The tunnel can reach a maximum speed of around 45 m/s but kept at a constant value of $U_\infty = 20$ m/s for the current experiments. A smooth wall aluminum floor of length 9.6 m was installed for the boundary layer to develop upon. It was tripped at the beginning of the test section to ensure 2D conditions and left to develop naturally in zero-pressure gradient conditions, enabled by the wind tunnel's compliant ceiling. After a running length of roughly 7.5 m, a wing was placed perpendicular to the floor, spanning the whole wind tunnel height and therefore acting as a simplified wing-body junction. The employed airfoil is a NACA0012 with a chord length c of 0.3 m. A mechanism to vary the wing's angle of attack was implemented and angles of $\alpha = -10^\circ$, 0° and 10° degrees were tested. In addition, the flap could be deployed. However, the presented data here is exclusively from the $\alpha = 10^\circ$ case.

To measure the static pressure distribution on the wall affected by the airfoil, a floor panel with a total of 128 pressure taps connected to a ScanValve ZOC 33/64 Px pressure scanner by means of silicone tubing were used. The taps were spaced more densely in the main region of interest, as will be shown in the results section (Figure 2). The inner diameter of the pressure taps is 0.8 mm.

The WSS exerted by the TBL was measured by means of oil-film interferometry (OFI). In this method, the deformation of a thin film of oil is related to the local WSS, as the film deforms (thins). The thickness of the oil film over time, and thus its thinning rate, is measured through interferometry. In the current experiments, we employed a monochromatic sodium light with a wavelength of 589.3 nm. Now, as soon as the oil film is sufficiently thin, $\mathcal{O}(10\mu\text{m})$, the deformation of the oil with time can be observed, from which the acting WSS is computed. A special challenge in the current experiments was that the flow is three dimensional, meaning that the WSS is now a vector quantity, $\vec{\tau}_w$, and for the subsequent analysis it is crucial to know both its amplitude and direction. To achieve this, individual oil droplets were placed on the glass floor panel around the airfoil. The droplets were sheared in the direction of the acting WSS and at a rate proportional to its magnitude. This was repeated for a total of eight runs with varying oil droplet locations, to achieve

more continuous coverage of measurement data. The results were analyzed using a (currently unpublished) method that employs a convolutional neural network to determine both direction and magnitude of the WSS from a series of images.

Finally, measurements using PIV were performed to determine the velocity distribution in the 3D TBL around the airfoil. The used laser was an ND-YAG double-pulsed Litron Bernoulli (LPU550) PIV laser with an output power of up to 200 mJ and a wavelength of 532 nm. It was used in conjunction with sheet optics that generated a light sheet of thickness around 1 mm with its waist placed roughly in the center of the measurement region. A stereo-PIV setup was employed to measure all three velocity components in several $y - z$ planes at various streamwise locations. The light sheet entered the test section laterally and at a low vertical angle relative to the glass floor. This ensured total reflection of the light, so that the cameras, imaging from below the glass, could not see the laser-glass contact line (except for imperfections in the glass, such as scratches). Two LaVision CMOS CX3 cameras with a resolution of 25 megapixels, both equipped with Scheimpflug adapters and narrow-band wavelength filters, were placed below the tunnel. They were set up at an angle of around 45° to the vertical, one viewing the light sheet from upstream and the other from downstream. A schematic of the experimental setup is provided in Figure 1, which also shows the used coordinate system. The final combined field of view of the cameras was roughly 200×250 mm (height $\times$ width) in size, ensuring that the height goes beyond the boundary layer edge and captures some data in the free stream while providing a sufficient spanwise range. To calibrate the cameras, a double-sided two-level calibration plate from LaVision (309-15-3) was employed. For processing, the in-house developed software PIVtools (Taylor et al., 2026) was used. Across six passes, the size of the interrogation window was gradually reduced from 128^2 pixels to 8×24 pixels with 50 % overlap to achieve a better resolution in the wall-normal direction. The final vector spacing was around 0.25 mm in y and 0.55 mm in z . Streamwise locations where the PIV data was acquired are highlighted in Figure 2, where the length of the red lines roughly corresponds to the field of view. However, in the present paper, we only present results from a single plane in the leading edge area of the wing ($x = 0$, solid-red line in the figure).

3. Results

The C_p distribution around the airfoil at $\alpha = 10^\circ$ is shown in a bottom-up view in Figure 2. The white markers indicate the locations of the employed static pressure taps and the red lines indicate locations for the stereo-PIV measurements. A continuous C_p contour plot is generated by interpolation, which shows the expected pressure distribution around an airfoil at a positive angle of attack. The data features a clear region of reduced C_p on the suction side of the airfoil that slowly decays with distance, both streamwise and spanwise. From this data, although not shown for reasons of better visibility, the 2D pressure gradient that the TBL experiences can be determined, which is expected to be a major driver of the 3D flow effects. Note that, as per the turbulent bound-

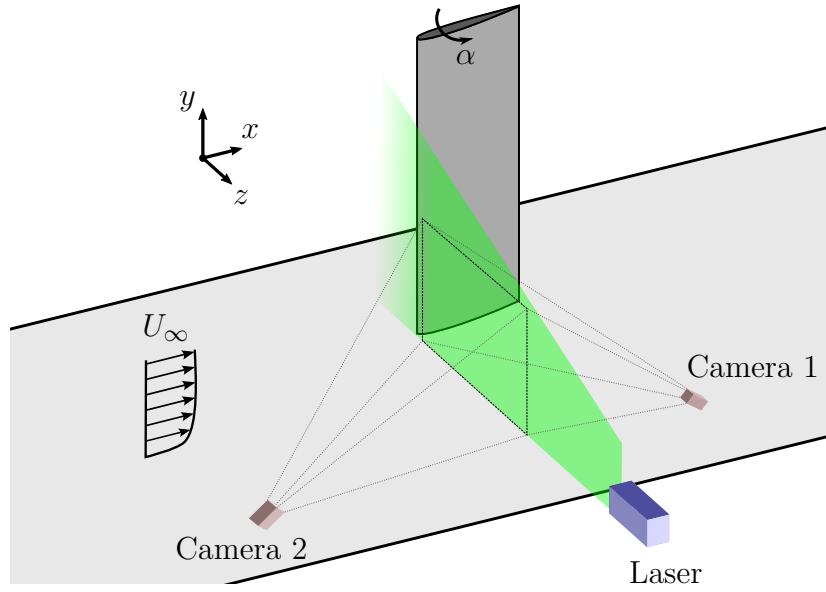


Figure 1. Schematic of the experimental setup for the stereo-PIV measurements, highlighting the field of view of the cameras.

ary layer equations, the pressure in the free stream will deviate slightly from the measurements at the wall, depending on the wall-normal velocity fluctuations. Furthermore, some minor artifacts due to the interpolation of discrete data are visible, such as the apparent double-minimum in C_p . However, these are expected to be small compared to the overall effect of the pressure.

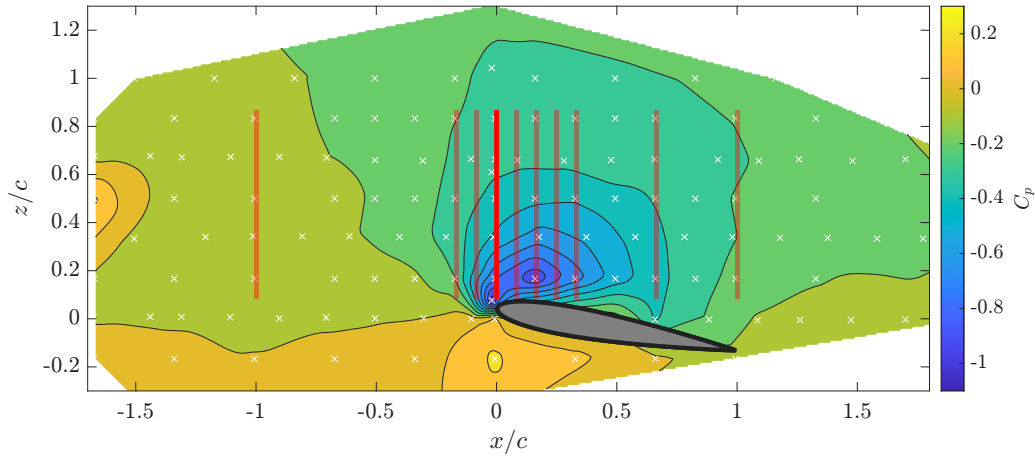


Figure 2. Bottom-up view of the wing-body junction. Data show the pressure coefficient C_p distribution on the wall around the airfoil measured at an angle of attack of 10° . White markers indicate pressure taps and the data is interpolated for a contour plot. The red lines show regions where PIV measurements were performed.

In the next step, 2D OFI was employed to measure amplitude and direction of the local WSS $\vec{\tau}_w$. Measurements were repeated at various locations and, as before, the data was interpolated to get a continuous distribution. The raw $\vec{\tau}_w$ data was strongly affected by the variations in local free-stream speed and therefore resembled the C_p plot in Figure 2. However, using the Bernoulli

equation ($C_p = 1 - (|\vec{U}_e|/U_\infty)^2$) the local boundary-layer edge velocity $|\vec{U}_e|$ can be determined from the static pressure data. Note that, due to the 3D nature of the boundary layer, $\vec{U}_e$ is generally a vector quantity. Now, we can compute the non-dimensional friction coefficient:

$$C_f = \frac{|\vec{\tau}_w|}{\frac{1}{2}\rho|\vec{U}_e|^2}, \quad (1)$$

which is shown in Figure 3. As before, the individual measurement locations are indicated with white markers and the contour map is the result of interpolating the data onto a grid. In addition, the streamlines show the direction of the local WSS, likewise determined from the 2D OFI measurement and interpolated. It is notable that the wall streamlines appear to resemble the expected free-stream streamlines of the flow around an airfoil in the majority of the investigated region. A more in-depth comparison is performed in Figure 5. The C_f data reaches a clear maximum near the leading edge, where $\vec{\tau}_w$ is deflected the strongest and the WSS is increased by a factor of roughly three, compared to the surrounding flow. Furthermore, there is a streamwise elongated region of elevated C_f along the suction side of the airfoil, which could be a result of the horseshoe vortex that forms in the junction of wing and wall. Further downstream, a local minimum in C_f can be observed. Moving away from the wing in the spanwise direction, the elevated friction coefficient decreases and likely approaches the undisturbed value of a canonical 2D TBL, along with a decrease in the acting pressure gradient.

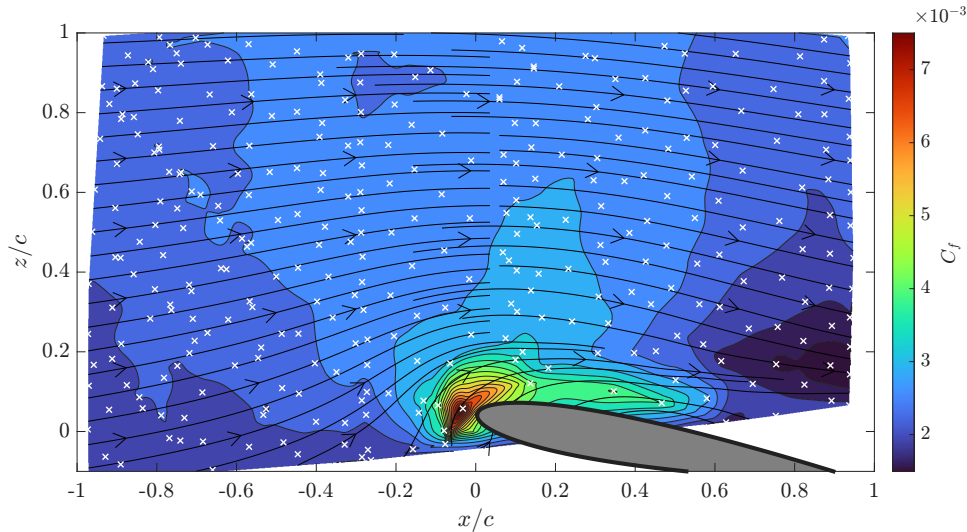


Figure 3. Friction coefficient C_f in the boundary layer around the airfoil. White markers indicate individual measurements of $\vec{\tau}_w$ and the data is interpolated to generate a contour plot. The streamlines indicate the direction of the local WSS (wall streamlines).

A selected wall-normal velocity profile from the PIV data is shown in Figure 4. The displayed profile is located at $(x, z)/c = (0, 0.25)$. When analyzing this data, the selection of the coordinate system is critical. Here, data is displayed in wind tunnel coordinates (subscript tc), so that the flow

angle approaches the free-stream deflection sufficiently far away from the wall. It can be observed that the spanwise velocity component reaches a peak near the wall and then relaxes towards the constant spanwise velocity in the free-stream, while the streamwise profile resembles that of a 2D TBL. The velocity profile is complemented by the local flow angle $\gamma_{tc} = \tan(W_{tc}/U_{tc})$ that varies with the wall-normal location. The flow deflection increases from the free stream exponentially to reach a peak of around 18° near the wall, before decreasing again. The red dashed line indicates the direction of $\vec{\tau}_w$, which the flow angle should approach. Note that the fact that the angles of the WSS and the free stream are approximately equal is not generally true in 3D TBLs, as can be seen for example in the review by Devenport & Lowe (2022). For the present data, as will be shown later, the two angles are different but the observed deviation is small compared to the peak in γ_{tc} .

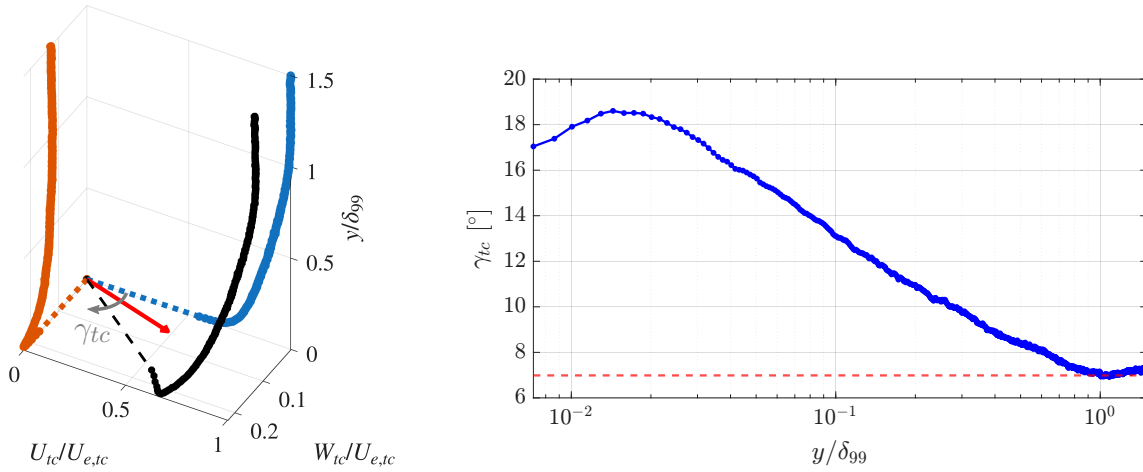


Figure 4. Left: selected three-dimensional velocity profile in tunnel coordinates at $(x, z)/c = (0, 0.25)$. The blue line shows the U_{tc} component and the orange line W_{tc} . Black is the resulting velocity and the red arrow indicates the direction of the WSS. Note that the scale of the W_{tc} component is adjusted for better visibility. Right: corresponding flow deflection γ_{tc} as a function of the wall-normal distance. Red dashed line indicates direction of the WSS.

Moving away laterally from the wing, the overall amount of flow deflection is expected to decrease which is shown in Figure 5, where the flow angle γ_{tc} at constant values of y/δ_{99} is plotted against the spanwise coordinate z . One observation that can be made is that for $y/\delta_{99} \gtrsim 0.8$, the difference in deflection is negligible, regardless of the lateral location. Towards the wall, the flow angle increases for all spanwise locations, as the spanwise velocity component increases. This is consistent with previous observations that the near-wall region is generally more strongly affected by 3D effects due to it containing less inertia (e.g. Ölçmen & Simpson, 1995). A maximum can be identified close to the wall and close to the wing, where there is a strongly accelerated flow around the wing's nose that results in significant flow deflection and is likely related to the maximum in $|\vec{\tau}_w|$. As per the previously shown flow deflection profile (Fig. 4, right), the angle is expected to decrease again even closer to the wall. This is not drawn in the given figure for the sake of clarity.

For $z/c > 0.25$, the free-stream angle γ_{tc} agrees closely with the WSS angle, although the latter switches sign and becomes slightly lower for $z/c > 0.6$. For locations close to the wing, $z/c < 0.25$,

the current WSS results are affected by lack of data. However, for future modeling efforts, the region further away from the wing surface is expected to be more well-behaved and valuable.

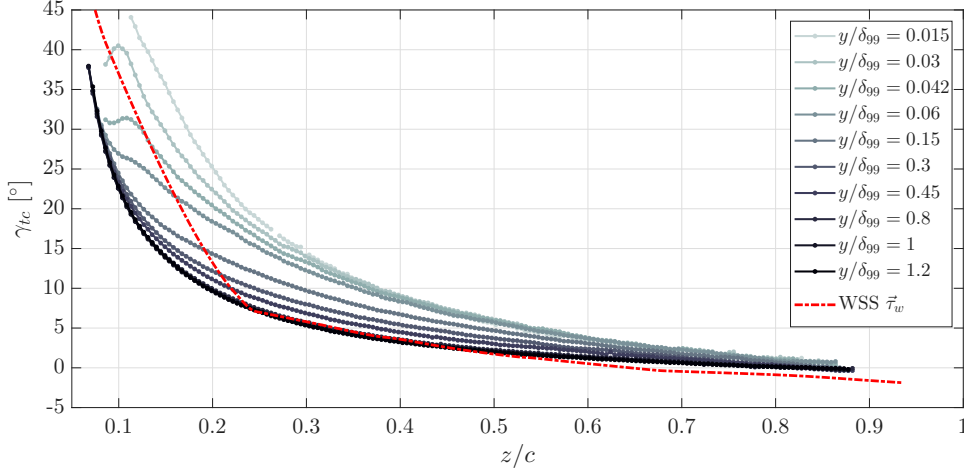


Figure 5. Flow deflection γ_{tc} as a function of the spanwise distance from the airfoil. Colors indicate different wall-normal locations, normalized with the local boundary layer thickness δ_{99} . The red line indicates the WSS angle.

To analyze the influence of the wing on the TBL, velocity profiles at various spanwise locations are plotted in Figure 6. It shows the streamwise and spanwise velocity components across the boundary layer at various distances to the wing in the plane. Note that the data is presented in a coordinate system aligned with the local free-stream direction now. Hence, per definition, W_{fc} approaches zero in the free stream. The streamwise components U_{fc} show the expected shape of a TBL, featuring a wake region, logarithmic region and beginning of the buffer layer. The two profiles closest to the wing feature significantly attenuated wakes, which is likely a result of the strong local favorable pressure gradient in that region (Devenport & Lowe, 2022). With increasing distance to the wing, the profiles appear to approach the shape of a standard zero-pressure-gradient TBL. The velocity component lateral to the free stream, W_{fc} shows a strong 3D effect due to the presence of the wing. Especially at the lowest $z/c = 0.09$, a strong lateral jet close to the wall around $0.015 y/\delta_{99}$ is dominant, which seems to also affect the U_{fc} component. Moving further towards positive z , the peak broadens and decreases in amplitude. At the same time, it moves slightly away from the wall, while still remaining at the lower end of the logarithmic region of the streamwise velocity.

4. Conclusions

In this paper, we presented some selected results from an experimental campaign featuring a wing-body junction where an incoming canonical turbulent boundary layer experiences a 2D pressure gradient and hence develops 3D effects. For the presented case, where the wing is placed at an angle of attack of $\alpha = 10^\circ$, we show both pressure coefficient C_p and friction coefficient C_f mea-

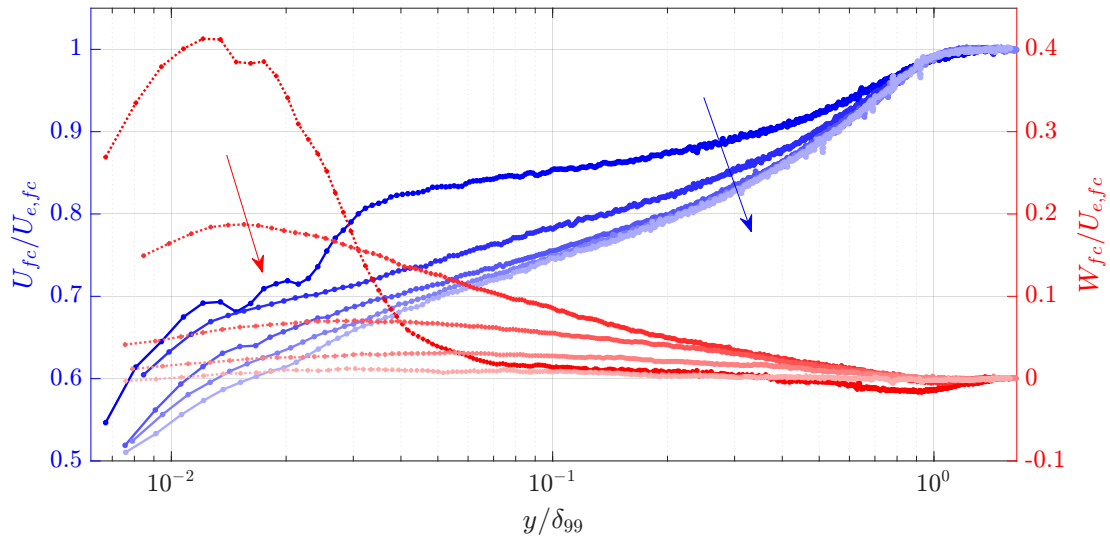


Figure 6. Velocity profiles of the streamwise (blue) and spanwise (red) velocity components, shown in free-stream coordinates and scaled with local δ_{99} . Paler colors indicate an increase in lateral distance to the wing, emphasized by the arrows. Drawn locations are $z/c = (0.09, 0.2, 0.4, 0.6, 0.8)$, with decreasing hue in this order.

surements. The pressure data exhibits the expected features of the flow around an airfoil at the given angle including a clear pressure minimum on the suction side. The friction coefficient is generally increased on the low pressure side and features a notable maximum at the nose of the airfoil, where the flow is strongly deflected and thereby accelerated. Furthermore, we present mean-flow data at the leading edge of the wing. They show that the 3D TBL is strongly affected by the acting pressure gradient. Near the leading edge of the wing, a strong spanwise jet can be observed close to the wall, but even further away skewing of the boundary layer profiles is present.

For more in-depth analysis, viscous scaling will be employed in the future to get insights into the near-wall dynamics of the TBL. This can then be used to test the results against existing models, such as the 3D law of the wall by Van Den Berg (1975). This model requires information on both, pressure gradients and WSS gradients, in both spatial directions, which can all be determined from the current experimental data. The complete set of results of the study includes several stereo-PIV planes at various streamwise locations, which will provide a large amount of data for this. Additionally, a total of four wing configurations at different angles of attack were tested, which will give a large variety in pressure gradient strengths and shapes. This will, for example, enable the assessment of history effects on the mean flow profiles, which are not taken into account in the previously mentioned model. Finally, the PIV data also gives access to turbulence statistics. These are known to be the driving factor that leads to the failure of many commonly used turbulence models in 3D TBLs. Analysis of the data will highlight regions where the stress/strain misalignment is the strongest and predictions can be expected to be inaccurate.

Acknowledgements

We gratefully acknowledge the financial support from EPSRC (Grant Ref no: EP/W026090/1).

Nomenclature

x, y, z	Spatial coordinates (streamwise, wall-normal, spanwise) [m]
U, V, W	Mean velocity components in x, y, z [m/s]
γ	Mean flow angle [°]
$\vec{\tau}_w$	Wall-shear stress vector [N/m ²]
α	Wing angle of attack [°]
c	Wing chord length [m]
C_p	Pressure coefficient [-]
C_f	Friction coefficient [-]
δ_{99}	99 % boundary layer thickness [m]
U_∞	Global wind-tunnel free stream velocity [m/s]
$\vec{U}_e$	Local boundary-layer edge velocity [m/s]
tc	Subscript to denote wind-tunnel coordinates
fc	Subscript to denote free-stream coordinates

References

- Devenport, W. J., & Lowe, K. T. (2022). Equilibrium and non-equilibrium turbulent boundary layers. *Progress in Aerospace Sciences*, 131, 100807.
- Duetsch-Patel, J. E., Gargiulo, A., Borgoltz, A., Roy, C. J., Devenport, W. J., & Lowe, K. T. (2023). Boundary layer flow over a bump and the three-dimensional law of the wall. *Journal of Turbulence*, 24(3-4), 2202404.
- Lynch, S. (2017). Three-dimensional boundary layer in a turbine blade passage. *Journal of Propulsion and Power*, 33(4), 954–963.
- Ölçmen, S. M., & Simpson, R. L. (1995). An experimental study of a three-dimensional pressure-driven turbulent boundary layer. *Journal of Fluid Mechanics*, 290, 225–262.
- Taylor, M., Lawson, J., & Ganapathisubramani, B. (2026). Pivtools: A comprehensive open source software for particle image velocimetry. Available at SSRN 6661397. Retrieved from <https://dx.doi.org/10.2139/ssrn.6661397>

- Van Den Berg, B. (1975). A three-dimensional law of the wall for turbulent shear flows. *Journal of Fluid Mechanics*, 70(1), 149–160.
- Zhong, H., Woodiga, S., Wang, P., Shang, J., Cui, X., Wang, J., & Liu, T. (2015). Skin-friction topology of wing–body junction flows. *European Journal of Mechanics-B/Fluids*, 53, 55–67.