15^{th} International Symposium on Particle Image Velocimetry – ISPIV 2023
June 19–21, 2023, San Diego, California, USA

Boundary layer tuning using PIV data in an open-jet multi-fan facility for ground-effect research

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Abstract

A finite-span wing is tested for ground-effect aerodynamics in a multi-fan open jet facility over a stationary ground. A multi-fan facility enables a fine control of the ground boundary layer morphology through a suitable modulation of each individual fan speeds. Particle Image Velocimetry (PIV) is used to quantify the boundary layer growth: an iterative process is then used between the PIV measurements and the fan speeds until the desired boundary layer profile is reached. An adequately-shaped plate leading edge has also contributed to a satisfactory boundary layer profile. The open jet configuration makes a proper PIV seeding difficult to achieve. A suitable seeding device and data acquisition methodology has been developed. PIV was finally used to characterize the flow around an airfoil close to the ground. The results give some remarkable insights onto the mechanisms occurring in ground effect.

1 Introduction

When a finite-span wing flies near the ground, it is generally believed that it experiences an increase in lift and a reduction in drag. This ground-effect phenomenon can be used to operate an aircraft with high efficiency (Yun et al., 2010). The study of ground effect in wind tunnels brings additional constraints compared to classical flight studies. In real flight conditions the plane flies in a medium at rest relative to the ground. In a wind tunnel, the air is set in motion and the aircraft is stationary. A proper implementation of the ground effect would require a sliding surface underneath the aircraft, such as a moving belt. Although the moving belt provides the best simulation of the ground, it brings up difficulties. It is expensive and requires a lot of engineering work, especially when it has to reach high velocities. A simpler way to simulate the ground is to use a stationary floor (flat plate) in the test section. If the lifting surface is not too close to the ground for a given upstream flow velocity, a stationary floor and a moving belt are equally performant (Carter, 1961).

However, even when the lifting surface is at relatively large distances from the ground, a boundary layer that starts developing at the leading edge of the plate might affect the large-scale morphology of the flow when the aircraft is in ground effect. A procedure based on PIV and the modulation of individual fans was developed in order to tune the boundary layer. The resulting configuration helped provide insightful results on the phenomena underlying ground effect.

2 Methodology

2.1 Test set-up

Tests were conducted in a multi-fan open jet facility depicted in Figure 1. It is composed of a multi-fan wind generator (windshaper from WindShape), a flow management section, and a test section. The present windshaper is composed of 9 x 18 = 162 contra-rotating fans, which are 8 cm in diameter. The windshaper takes the ambient air in the lab and pushes it through multiple screens and a honeycomb (for turbulence flow management) while allowing the power of each fan unit to be tuned individually to control the entire

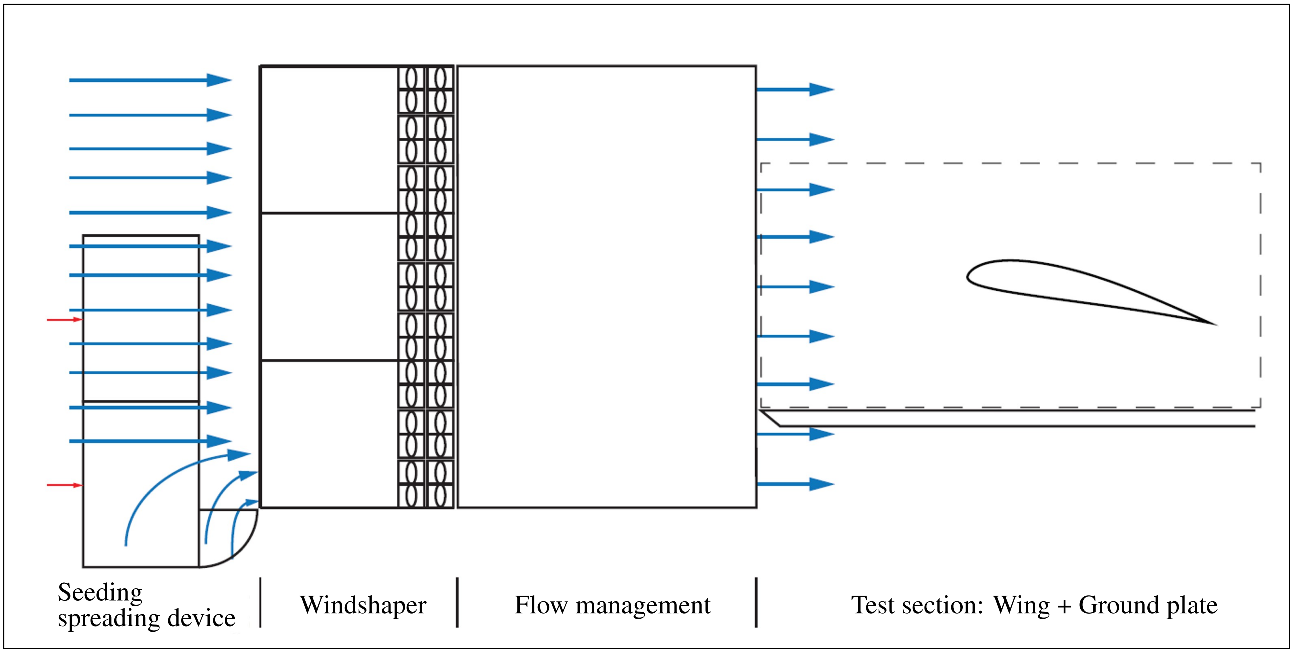


Figure 1: Open jet test facility, composed of a multi-fan wind generator (WindShaper), a flow management section (honeycomb and screens), and a test section. PIV is performed on the plane represented by the dashed rectangle slicing the wing at a specific span location. A spreading device injects seeding droplets at the windshaper inlet.

flow. A half-span model (fuselage and wing) and a removable floor (flat plate) are placed in the test section right downstream of the flow management section. PIV is used to characterize the flow in the test section on a vertical plane parallel to the oncoming flow, represented by the dashed lines in Figure 1. Illumination is provided by an Evergreen YAG200-15-QTL laser, while images are captured with TSI Powerview Plus 4MP camera and processed using TSI Insight software.

2.2 Seeding of an open-jet wind facility

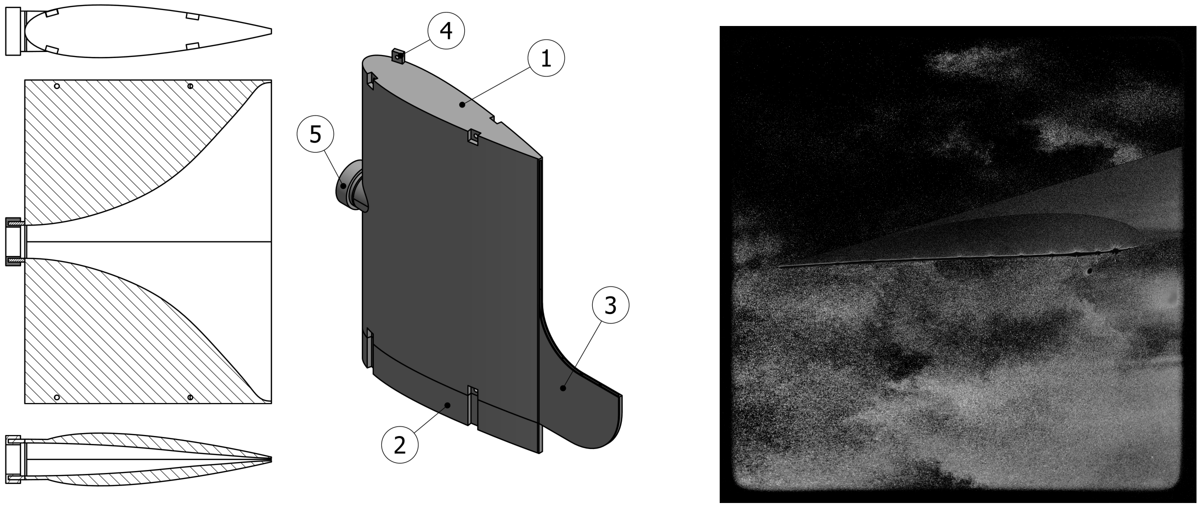
Droplets are generated with PIVTEC seeder based on Laskin nozzles and PIVLIGHT fluid (from PIVTEC).

The use of an open-jet wind facility makes the seeding difficult (Raffel et al., 2018). Droplets are lost in the lab after a single pass through the test section. Thus, they have to be injected properly ahead the test section. In order not to disturb the flow, the choice was made to inject the droplets upstream of the windshaper.

PIV had to be performed on a plane parallel to the flow. Since the seeding generator outlet is a simple plastic tube, the seeding had to be properly spread out in order to uniformly seed a plane. To do so, a spreading device has been designed (de Sepibus, 2022). As shown in Figure 1, it is composed of stackable modules having a symmetric NACA airfoil geometry to minimize inlet flow disturbances (see Figure 2(a)). Inside, a diffuser ensures that the incoming droplet cloud transitions successfully from the inlet circular section to the outlet long rectangular slit (at the trailing edge of the airfoil geometry). A bottom layer feeder can be added to the first module to ensure a good seeding in the lower layer of the fan array.

Despite having a good seeding distribution on a vertical plane at the windshaper inlet, the droplets undergo substantial mixing in the fans. The seeding is thus strongly non-homogeneous in the test section. Seeding is then not sufficiently well distributed to provide a complete velocity field with a single PIV snapshot. This problem is clearly visible in Figure 2(b) where the upper part of the snapshot is empty, thus preventing suitable flow velocity determination.

To compensate for the non-homogeneous seeding in the test section, the time-averaged velocity field is evaluated from a batch of images. Each set of images generate velocity vectors in random areas of the plane, so that the batch needs to contain a sufficient number of images to be able to reconstruct the entire field. In addition to solving the seeding problem, the use of a large batch allows a statistical analysis of the flow, which provides information about the steadiness of the flow.



(a)

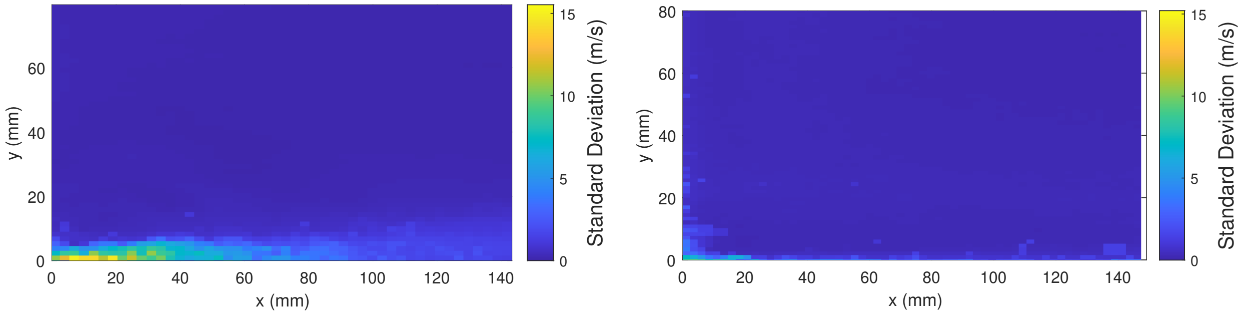
(b)

Figure 2: (a) Spreading device unit: (1) stackable module, (2) base, (3) optional bottom layer feeder, (4) binding piece, (5) seeding inlet/pipe connection; (b) Imperfection of the seeding on a single snapshot: some areas are seedless, in particular in the upper part.

2.3 Tuning of the boundary layer with a multi-fan facility

This methodology has been used to study the boundary layer on the plate simulating the ground. A satisfactory boundary layer on the ground is needed to have a more realistic boundary condition. Figure 1 shows the first plate leading edge iteration with a simple bevel. The standard deviation of the velocity field obtained with the available vectors from each snapshot shows an instability downstream of the leading edge (Figure 3(a)). This is an indication that flow separation occurs right after the leading edge, which is not adequate for a proper study of ground effect. A modification of the leading edge (airfoil shape) provides a cleaner boundary flow condition. The standard deviation shown in Figure 3(b) indicates that the flow is stationary downstream of the leading edge.

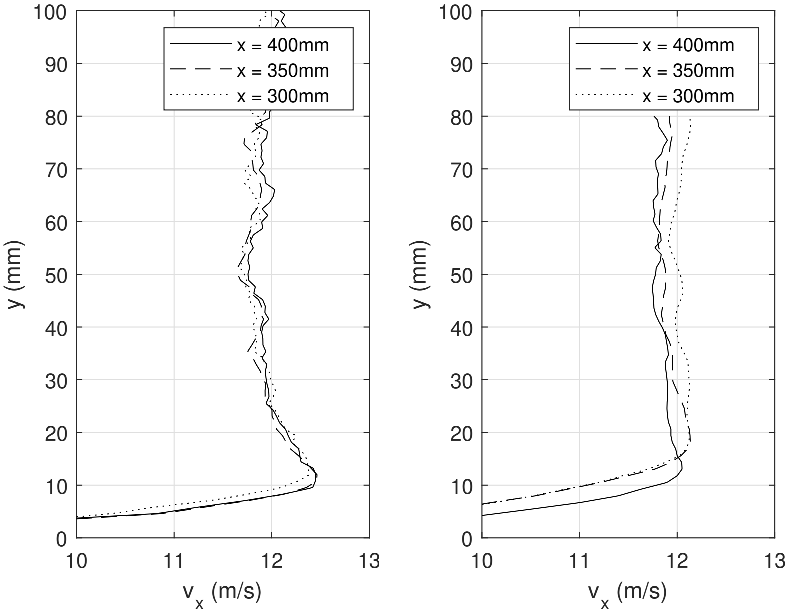
The flow being stationary on the plate, the horizontal velocity along the vertical axis is plotted in Figure 4(a) at different stations along the stream. It shows a speed overshoot 10 mm above the ground, which is in part due to the portion of the flow layer occupied by the plate and being deviated towards the upper face. The windshaper enables the control of each fan individually, and the speed overshoot can thus be reduced by fine-tuning the fan speed near the ground. Figure 4(b) shows the velocity profile obtained reducing the power of the bottom fan row. This final velocity profile is very close to the profile predicted by boundary layer theory.



(a)

(b)

Figure 3: Standard deviation of the horizontal velocity above the ground plate (the origin is placed at the leading edge, the flow comes from the left): (a) bevel leading edge, and (b) airfoil-shaped leading edge.

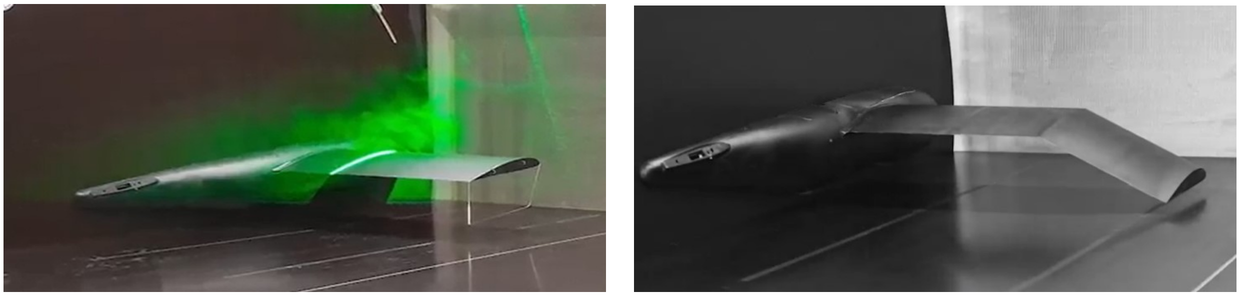


(a) (b)

Figure 4: Horizontal velocity profile above the ground plate equipped with an airfoil-shaped leading edge, with measurements performed at three stations downstream (x is the distance from the leading edge of the ground plate), approximately 10 cm upstream of the *wing* leading edge: (a) windshaper operating at full power and the fans at homogeneous speed, showing a flow-speed overshoot near the plate, and (b) bottom row of fans finely tuned in order to remove the flow-speed overshoot.

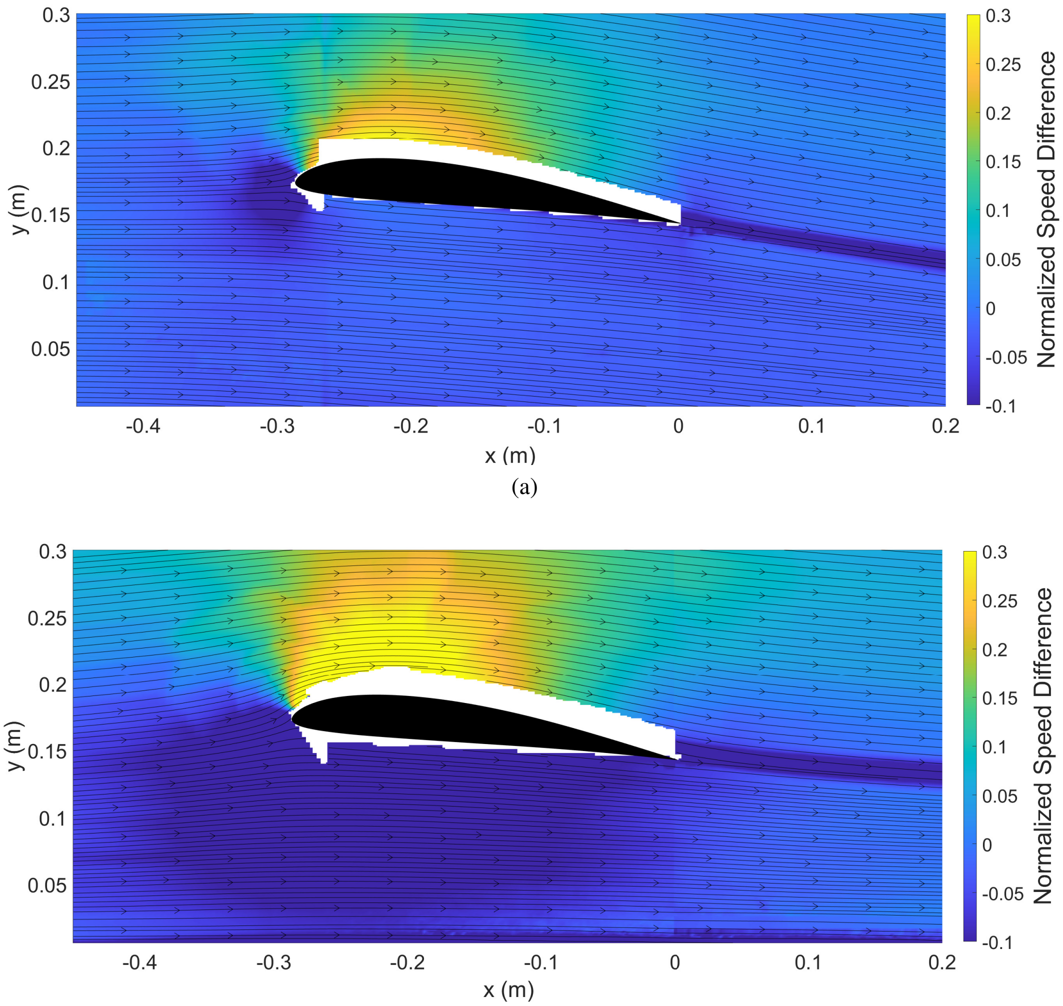
3 Results

PIV was performed on a semi-span model, with a vertically projected *total* wing-span of 1.56 m and a constant chord of 0.29 m, which gives an aspect ratio AR = 5.37. The Boeing Pelican prototype was designed with a 5.4 aspect ratio (Holsignton and Rawdon, 2003). The projected wing length from root to tip is 0.78 m. In the results that are presented here, the illumination plane was chosen inboard (Figure 5(a)), at a distance of 0.2 m from the wing root. The wing is attached to a 6-component force balance. Pressure taps (total of 23) were installed along the circumference of the wing at the illumination plane (de Sepibus, 2022). The present paper only focuses on PIV data at the indicated illumination plane.



(a) (b)

Figure 5: Semi-span setup, with PIV plane at about 26% wing-length from the root. Various wing tips were used, among which (a) a vertical plate, and (b) an anhedral section (keeping the vertically projected wing area constant).



(a)

(b)

Figure 6: Streamlines around the airfoil in laboratory-fixed frame, with density plot of velocity magnitude minus freestream speed ($V - V_\infty$) normalized by freestream speed (V_∞): (a) out-of-ground, and (b) in-ground effect, at a half-chord above the ground.

In Figure 6 the streamlines are displayed in a laboratory frame. The colors represent the flow speed minus the freestream speed normalized with the incoming flow speed. The velocity is higher on the suction side and lower on the pressure side when the wing is close to the ground. The wake is also different: its downward deflection is less in ground effect. Out of ground effect, the flow deflects downward as soon as it approaches the lower portion of the leading edge (Figure 6(a)). In ground effect, at a height h equal to half the chord c ($h/c = 0.5$), the flow remains parallel to the ground, where the boundary layer is visible (Figure 6(b)). Another notable feature has to do with the dividing streamline, which separates the flow going to the upper and lower side of the wing. In ground effect it originates from a much lower upstream location than in the out-of-ground case. This implies that a part of the flow that normally passes under the wing is deviated to the upper side where it is accelerated.

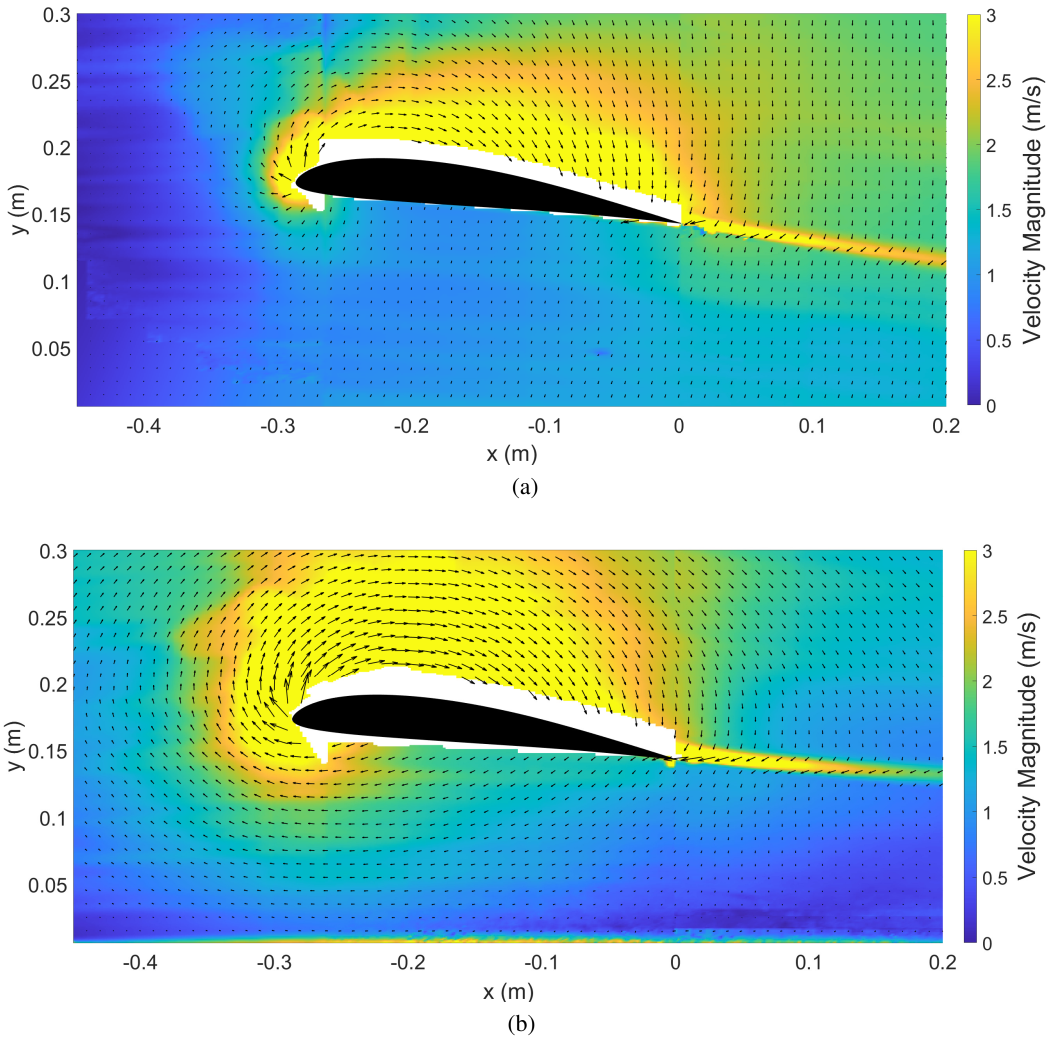


Figure 7: Flow velocity in body-fixed frame, with density plot of velocity magnitude, showing an increase in circulation when the wing is near the ground: (a) out-of-ground, and (b) in-ground effect, at a half-chord above the ground.

In Figure 7 the velocity field is displayed in a body-fixed frame. The colors represent the magnitude of flow velocity. Increase in circulation in ground proximity is visually evident. A quantitative estimation of the circulation from PIV data (de Sepibus, 2022) has shown that sectional circulation is 80% higher in ground effect, with only a minor influence from wingtip geometry. However, wingtip geometry does have a major effect on overall lift and drag forces measured with force balances (de Sepibus, 2022). Slight upstream flow is also detectable below the wing. This reverse flow may indicate that in actual flight above ground or water, boundary layer effects may be important, and, thus, that a proper replication of these surfaces may need to be implemented in future work.

4 Conclusions

Although PIV in an open-jet multi-fan facility may seem forbidding at first glance, a combination of a good seeder and a proper methodology does yield satisfactory results. The boundary layer on a flat plate simulating the ground is a key factor when studying ground effect, and is highly dependent on the plate leading edge. The boundary layer can be finely tuned by the use of a windshaper. The fact that the velocity profile can be adjusted by modulating each fan speed opens up new perspectives in controlling flow quality in wind tunnels. PIV was used to determine the velocity field around an airfoil in and out of ground effect, and clearly showed the change in the entire flow morphology between these two flight conditions.

Acknowledgements

The work is being performed with PhD thesis support from the Swiss National Science Foundation (SNSF) project number: 200021_204827, to elucidate the flight physics of pelicans and albatrosses in ground effect (2022-2025). Research work is being performed within the Center for Hydro & Aero `https://chachacha.ch/` of the Aero-Nautical-Space group `https://www.hesge.ch/hepia/en/group/aero-nautical-space` at the Haute école spécialisée de Suisse occidentale (HES-SO).

Preliminary research work on a ground-effect drone ("Drhône" 2019-2021) received support from Haute école spécialisée de Suisse occidentale (HES-SO) and was led by Haute école du paysage, d'ingénierie et d'architecture de Genève - HEPIA (Thierry Bujard, Cyprien de Sepibus), in collaboration with HEIG-VD (Prof Joël Cugnoni, Nima Pakpoor, Raphaël Nardin), College of Engineering and Architecture of Fribourg (Prof Wolfgang Berns, Claudio Panizza, ROSAS), and HES-SO Valais-Wallis (Prof Fariba Moghaddam, Mael Forestal).

References

Carter AW (1961) *Effect of Ground Proximity on the Aerodynamic Characteristics of Aspect-Ratio-1 Airfoils With and Without End Plates*. National Aeronautics and Space Administration TN-D-970

de Sepibus C (2022) *Ground effect aerodynamics for fixed-wing drones*. Master's thesis. Swiss Federal Institude of Technology (EPFL). Lausanne, Switzerland

Holsignton ZC and Rawdon BK (2003) Ground effect wing having a variable sweep winglet. Technical report. Boeing US Patent 6,547,181

Raffel M, Willert CE, Scarano F, Kähler CJ, Wereley ST, and Kompenhans J (2018) *Particle image velocimetry: A practical guide*. Springer International

Yun L, Bliault A, and Doo J (2010) *WIG Craft and Ekranoplan*. Springer