

Experimental Aerodynamic Characterization of a Multi-Element Formula Student Rear Wing using Particle Image Velocimetry

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ABSTRACT

Formula Student competitions require vehicles to operate at relatively low Reynolds numbers while generating maximum downforce to improve cornering speeds. This necessitates the use of aggressive high-lift devices, often resulting in complex flow phenomena such as steep pressure gradients, wake interactions, and potential flow separation. This work presents a detailed experimental investigation of the aerodynamic performance of a multi-element rear wing assembly designed for a Formula Student racing car. The experiments were conducted at the wind tunnel facilities of the National Institute for Aerospace Technology (INTA). A high-resolution Particle Image Velocimetry (PIV) system was employed to quantify the flow field around the suction side of the main plane and the interaction with the flap elements.

The study focuses on the analysis of the velocity vector fields and scalar maps obtained at different spanwise locations. The PIV measurements effectively captured the boundary layer development and the flow turning efficiency of the multi-element setup. Particular attention is given to the flow physics within the gaps between elements and the near-wake region. The experimental results reveal the presence of a coherent recirculation bubble at the trailing edge of the second flap (as seen in the instantaneous and average velocity maps), highlighting the limit of flow attachment in high-angle-of-attack configurations. Furthermore, the PIV data provides a quantitative assessment of the velocity deficit in the wake, offering a robust dataset for the validation of Computational Fluid Dynamics (CFD) simulations typically used in the design phase of these vehicles. The visualization of the streamlines and turbulent structures demonstrates the capability of the PIV setup to resolve flow features critical for optimizing the aerodynamic performances in competitive motorsport applications.

1. Introduction

The aerodynamic design of a Formula Student (FS) vehicle is a critical factor for overall competition performance, directly influencing dynamic events such as skidpad, autocross, and endurance through the generation of downforce (Wordley & Saunders, 2006). To achieve these

demanding aerodynamic targets within restricted bounding boxes, vehicles typically employ aggressive multi-element airfoil cascades, operating at relatively low speeds and high angles of attack. The development of these high-lift devices heavily relies on Computational Fluid Dynamics (CFD) codes, frequently utilizing Reynolds-Averaged Navier-Stokes (RANS) simulations to optimize the aerodynamic package (Zhang, Toet, & Zerihan, 2006).

However, numerical solvers often face challenges in accurately resolving the complex flow phenomena inherent to these devices, such as steep pressure gradients, boundary layer development, wake interactions, and flow separation. Consequently, experimental validation in wind tunnel facilities becomes an essential step in the design cycle. While traditional validation methodologies, such as force balances or surface pressure taps, provide valuable macroscopic data, they either lack detailed spatial flow-field resolution or introduce intrusive physical disturbances into the airstream. To overcome these limitations, Particle Image Velocimetry (PIV) has emerged as a highly effective, non-intrusive technique (Kumara et al., 2010). By tracking small tracer particles seeded into the flow, PIV allows for the simultaneous measurement and visualization of velocity vector fields across complex aerodynamic regions, providing a deeper understanding of the fluid behavior.

This paper presents a comprehensive experimental characterization of a multi-element rear wing assembly designed for a Formula Student racing car. The experimental campaign was conducted at the Wind Tunnel 1 facility of the National Institute for Aerospace Technology (INTA). Through the implementation of a high-resolution PIV setup, the flow field around the suction side of the main plane and its aerodynamic interaction with the subsequent flap elements was quantified. The resulting velocity maps and turbulent scalar fields offer a robust dataset to identify critical flow features, such as trailing edge recirculation bubbles, and serve as a reliable baseline for the validation of CFD turbulence models applied to competitive motorsport aerodynamics (Wengrzyn, 2021).

2. Experimental setup

2.1. Wind tunnel facilities and PIV system

The experimental campaign took place at the low-speed T1 wind tunnel of the National Institute for Aerospace Technology (INTA) (Figure 1a). This facility features a closed-loop architecture with a 2 x 3 m elliptical open test section. The tunnel is capable of reaching flow velocities up to 60 m/s,

maintaining a low turbulence intensity of less than 0.5%. To map the velocity contours of the flow field, a Particle Image Velocimetry (PIV) system was employed (Adrian, 1991; Adrian & Westerweel, 2011; Prasad, 2000; Raffel et al., 2007). This non-intrusive measurement technique, illustrated in Figure 1b, involves seeding the flow with small tracer particles and illuminating them using a pulsed Nd:YAG laser. The particle positions are then recorded by a digital camera equipped with a 2048 x 2048 pixel CCD sensor. The captured image pairs are processed using a Fast Fourier Transform (FFT) cross-correlation algorithm within interrogation windows of 32 x 32 pixels to determine the average particle displacement. By coupling this displacement vector with the precisely adjusted time separation between pulses (25 μ s), the localized flow velocity is calculated. The final velocity maps were generated by averaging 100 image pairs per configuration and were post-processed and visualized using Tecplot 360 software.

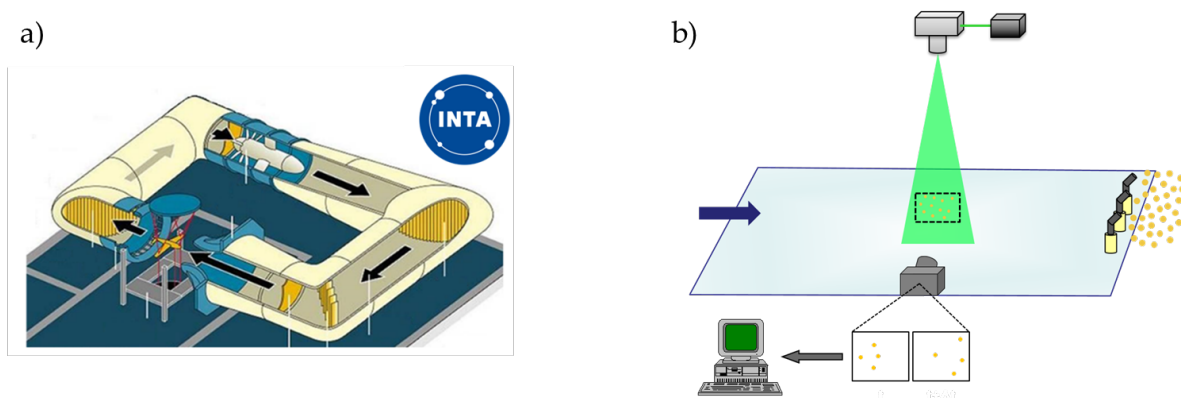


Figure 1. Scheme of Wind Tunnel 1 (INTA) (a) and PIV system (b)

2.2. Rear wing model

The tested model is a full-scale multi-element rear wing assembly designed for a Formula Student vehicle, utilizing FX74-C15-140 airfoil profiles tailored to produce high lift at relatively low operating speeds (Wortmann, 1974). The main cascade has a span of 875 mm and is manufactured from Carbon Fiber Reinforced Polymer (CFRP).

In this type of experimental setup, mitigating optical shadows and optimizing the measurement domain size are crucial considerations. Because placing the laser directly upstream of the rear wing would disrupt the incoming free stream, the laser source must be positioned either above or below the test section. Furthermore, the two-dimensional nature of the PIV system requires the illumination to be constrained strictly to a single plane of study, in this case the central spanwise plane of the wing assembly. To achieve this precise illumination, the laser beam is conditioned

using a specific optical arrangement. Cylindrical lenses are employed to expand the light beam and increase the illumination angle (Paschotta, 2019). Subsequently, spherical lenses are introduced into the optical circuit to compress the expanding conic beam into a thin, 2D light sheet (Dickey, Weichman, & Shagam, 2000).

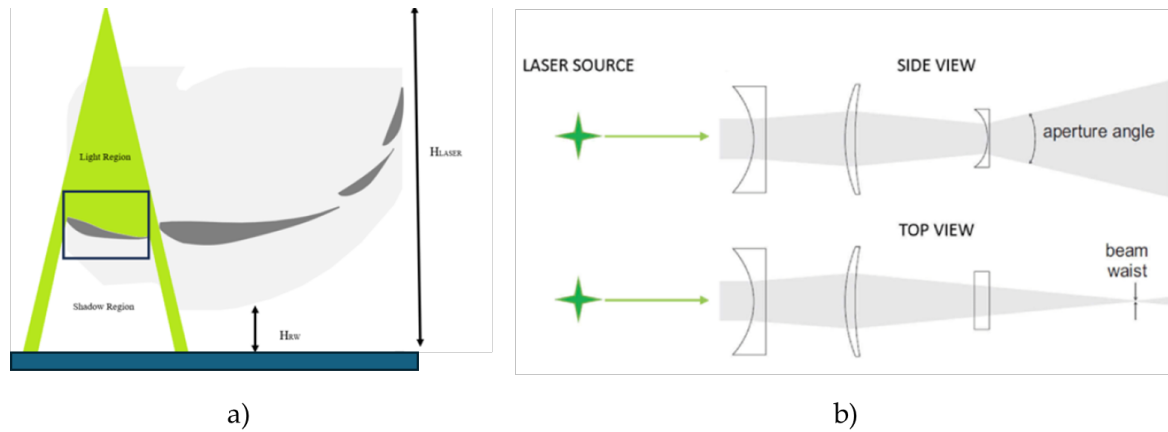


Figure 2. PIV laser phenomena. (a) Sketch of the Shadows created in the experiment (b) Effect of lens in laser beam

Despite this optical conditioning, the width of the light beam depends on the relative distance between the laser and the target body. Moreover, the opaque nature of the carbon fiber airfoils inevitably casts shadows, creating regions devoid of illumination beneath the wing elements. To overcome these limitations and ensure a comprehensive mapping of the flow field, two distinct PIV configurations were utilized: one for mapping the intrados (pressure side) (Figure 3) and another for the extrados (suction side) (Figure 4). For the upper region measurements, a specific structural element (Duplex 1) was temporarily dismantled to prevent excessive shadowing over the cascade. By combining these overlapping fields of view, a complete velocity map around the multi-element wing could be successfully reconstructed.

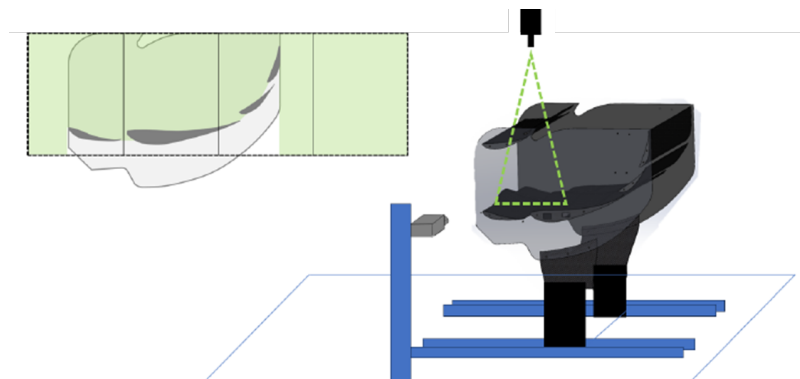


Figure 3. Sketch of the setup for the intrados map.

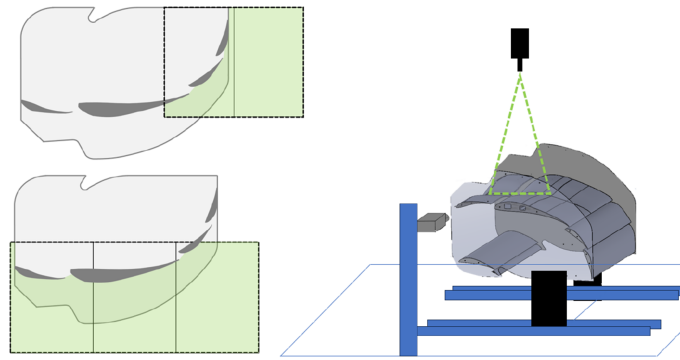


Figure 4. Sketch of the setup for the extrados map.

Finally, Figure 5 shows the experimental setup of the rear multi-element wing in the wing tunnel.

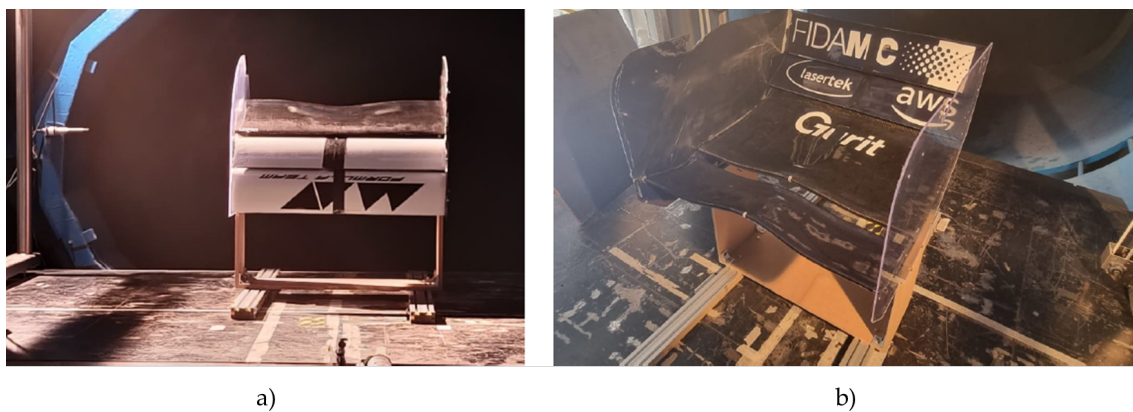


Figure 5. Experimental setup of the rear wing for both configurations: extrados (a) and intrados (b)

3. Results and discussion

After applying the PIV methodology in the previously described setup, the raw velocity data was acquired. The initial processing of the raw PIV data, including the merging of multiple windows and noise filtering, was performed using a custom-developed code. Subsequently, to gain a deeper understanding of the fluid behavior and clearly identify the aerodynamic structures, Tecplot 360 software (Tecplot, Inc., 2023) was employed to extract and visualize the non-dimensional velocity contours and streamlines for both the intrados and extrados configurations. The initial velocity maps of horizontal velocity before post-processing are shown in Figure 6 and Figure 7.

The initial captured images were inherently noisy, requiring the application of a pre-filter to limit the maximum possible velocity to twice the free-stream speed. These noisy regions typically manifested close to the reflecting surfaces of the model and at the limits of the PIV windows, caused by surface reflections and a lack of tracer particles, respectively (Cameron, 2022).

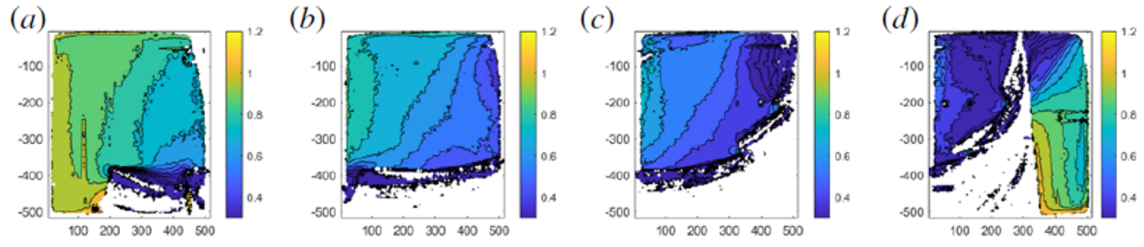


Figure 6. PIV Results for intrados. Horizontal velocity $\frac{u_x}{u_\infty}$. (a) Window 1. (b) Window 2. (c) Window 3. (d) Window 4.

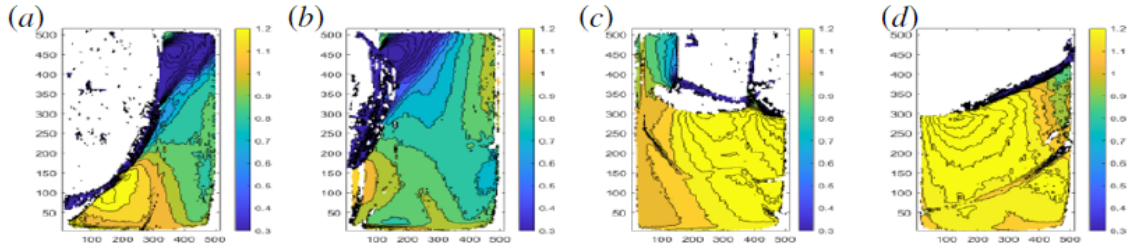


Figure 7. PIV Results for extrados. Horizontal velocity $\frac{u_x}{u_\infty}$. (a) Window 1. (b) Window 2. (c) Window 3. (d) Window 4.

3.1. Window Overlap and Data Merging

The first approach to reconstructing the complete flow field involved accurately positioning the eight PIV images over the airfoil cascade, utilizing reference points such as the leading and trailing edges. Figure 8 shows the final result.

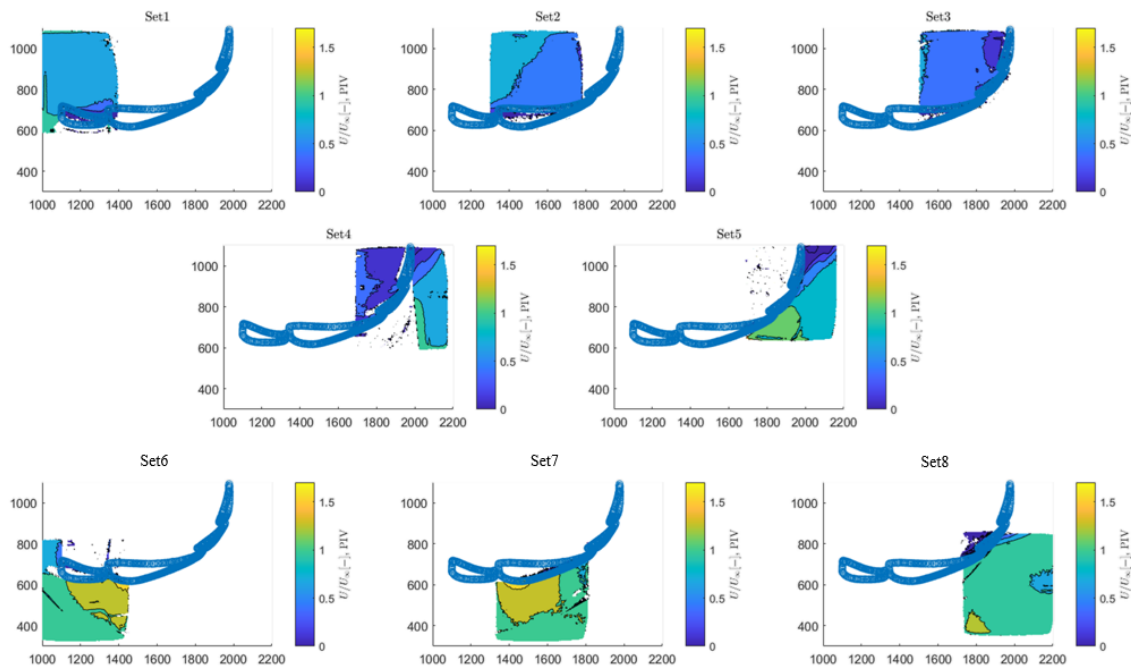


Figure 8. Positioned PIV windows in the airfoil cascade.

A direct superposition of the images from window 1 to 8 resulted in steep gradients and, in certain areas, a loss of high-quality information. This basic overlap approach also generated unfeasible physical phenomena, including discontinuities in flow acceleration at the suction peak of the main airfoil, apparent flow passing through solid structures, and erratic detachment-reattachment sequences at the end of the secondary airfoil.

To fully utilize the available information, the data from each window was interpolated onto a uniform mesh of 1 million cells (with a cell size of 1.2×0.8 mm) using a grid data tool, performing an average of the available data at each position. While this clarified the overall flow field, window margins and physical discontinuities remained visible. Furthermore, mapping the extrados (suction side) erroneously captured flow measurements from the intrados (pressure side).

Figure 9 shows the procedure followed for both overlap and interpolation.

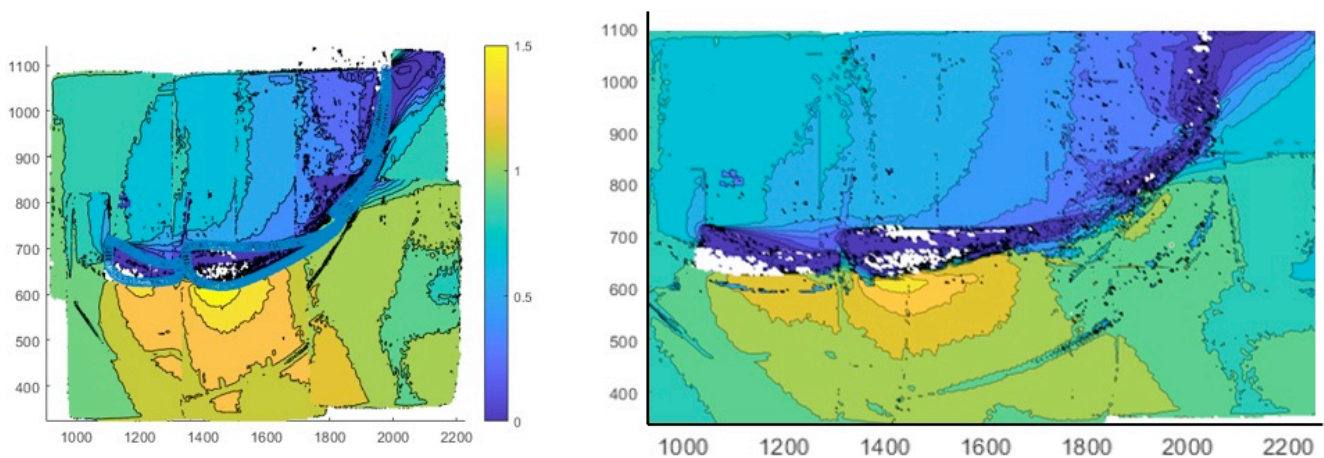


Figure 9. Raw Data horizontal velocity data. (a) Overlapped. (b) Averaged value per mesh point.

To resolve these issues, two targeted procedures were implemented. First, an "Upper Region" mask was created, restricting the intrados mapping from polluting the extrados results. Second, a progressive transition for the overlapped maps was introduced, adapting methodologies standard in multi-FOV PIV analysis (Ryu, Chang, & Mori, 2005). By identifying the intersecting boundaries of the fields of view, the overlapping regions were accurately mapped, as presented in Figure 10.

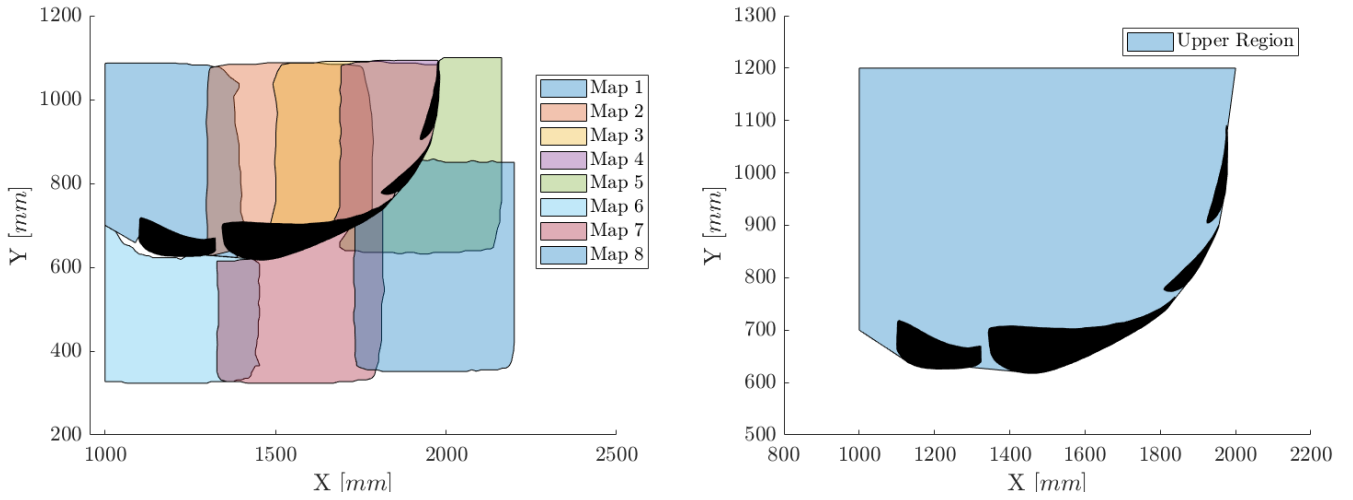


Figure 10. PIV window's region definition (left) and upper region mask (b).

To apply the progressive scaling, a linearly increasing weight system was introduced. The gradient procedure ensures a smooth transition between overlapping FOVs without hard discontinuities. In this system, the value of a studied variable X in cell i, j is obtained by:

$$X_{i,j} = \sum_{k=1}^N X_{i,j}^k W_{i,j}^k \quad (1)$$

where k represents the window number.

Initially, for every window a 0 weight is assigned to all the cells. If the window "A" is the only window containing information for that particular point, then the weight at that position if window "A" is one, whereas the weight at that position for the rest of the windows is 0. If the regions containing information of the point are A, B, C, then these three will have a relative weight of 0.33 in that position, being 0 for the rest of the windows.

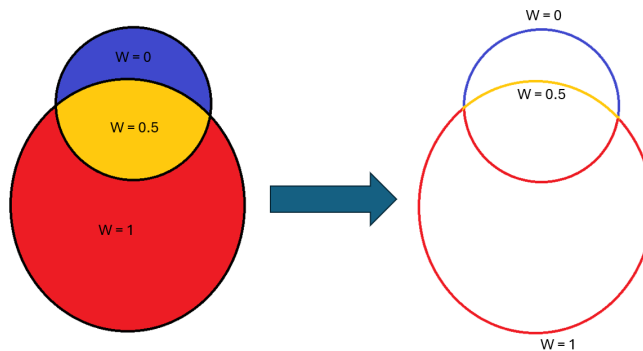


Figure 11. Sketch of the weight distribution gradient procedure.

If no gradient is applied between different weight regions, the procedure is the same as averaging the value of every cell. To introduce the linearly increasing weight, the process sketched in Figure 11 is followed. Per each window, only the boundaries are kept, and data within the eliminated region is interpolated using the boundary values. If the region lies within the ref region, as the only values of the neighbour boundaries is 1, the values of the interpolation will remain 1. If the point lies in the intersection of the red and orange, the value will be linearly interpolated between 0,5 and 1 as a function of its proximity to the boundaries. This procedure allows to create a uniform assignment of the weights based on the distance to the boundaries in every direction.

The resulting weight maps for each of the FOV windows are shown in Figure 12.

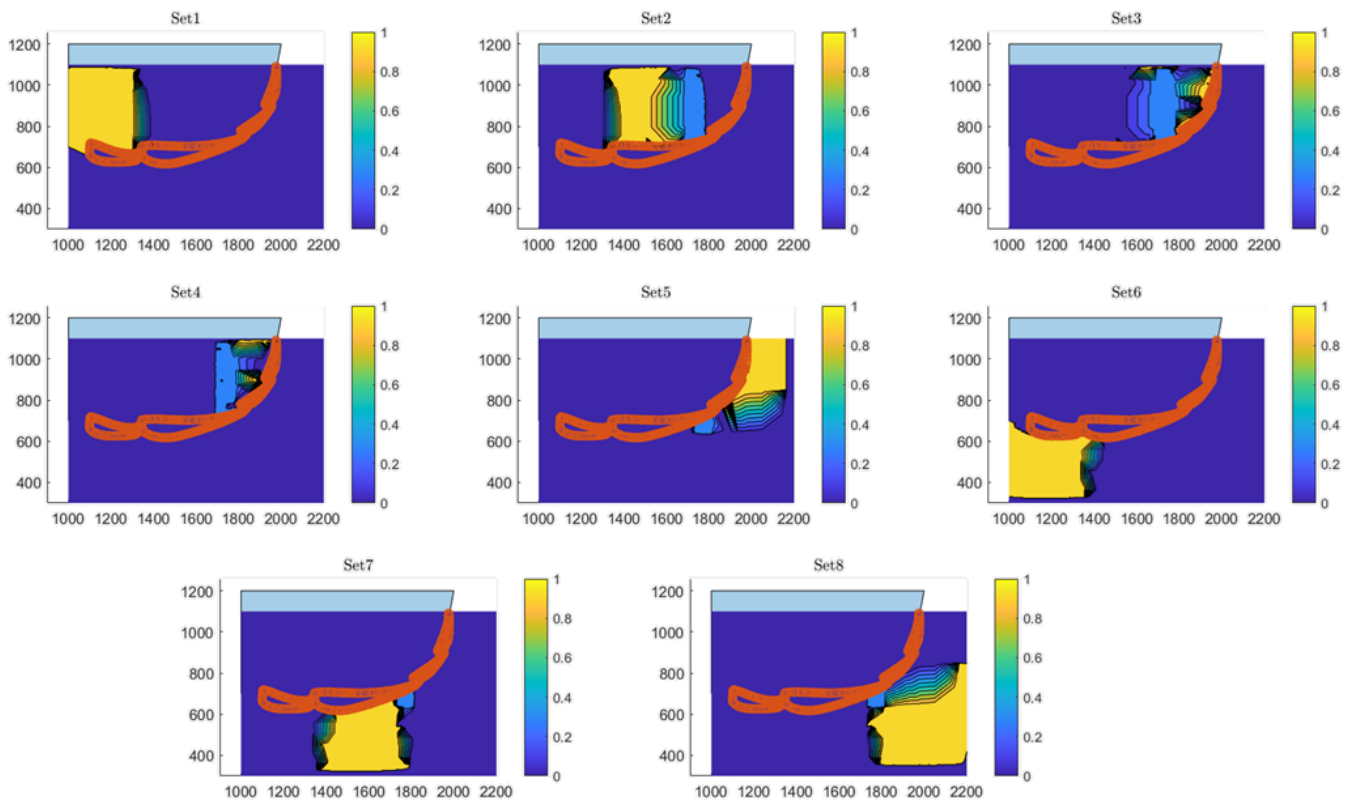


Figure 12. Weight distribution maps per individual window.

Finally, the weight system is applied to the data and a final image of the flow can be obtained. The results are shown in Figure 13. Data is substantially smoother, but the overall picture can still be improved through further data analysis techniques. The corrected data consistently demonstrates flow separation at the leading edge slat (Aparicio, Raiola, & Bardera, 2024). Suction peaks can be identified in the extrados of the airfoils, and the distribution of the horizontal and vertical velocity is consistent with the high angles of attack present in the cascade of the profiles.

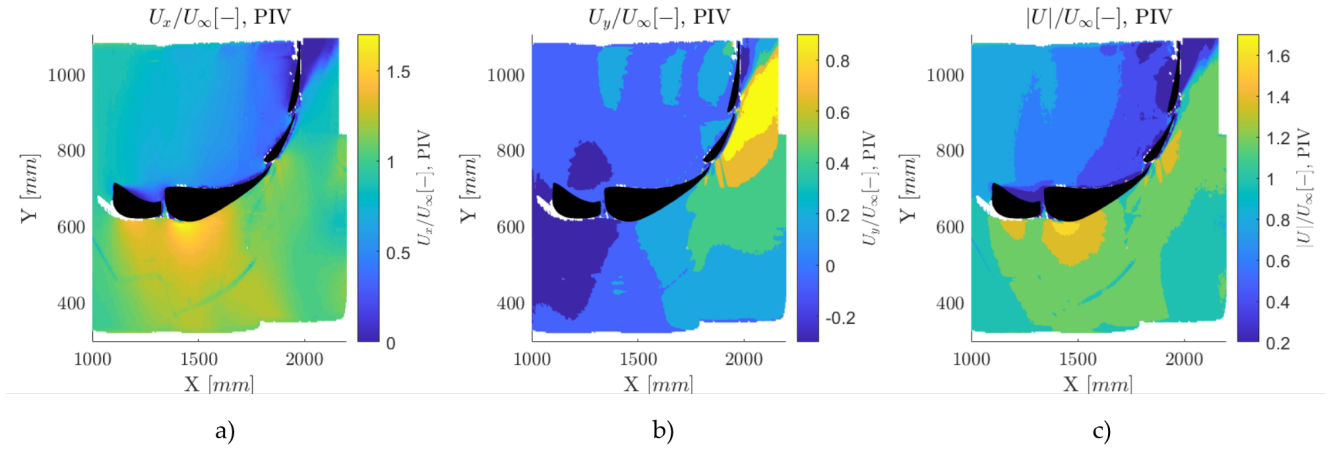


Figure 13. PIV results after linear transition between regions. (a) Horizontal velocity U_x . (b) Vertical velocity U_y . (c) Velocity magnitude U .

3.2. Smoothing of data

Although the overlapping procedure greatly improved the overall quality of the flow maps, further data smoothing was required to eliminate experimental noise residuals. To achieve a higher quality representation, several two-dimensional filtering techniques were evaluated: Moving Mean, Moving Median, Gaussian-weighted average, Lowess (linear regression), and the Savitzky-Golay (Sgolay) filter. Results are shown in Figure 14.

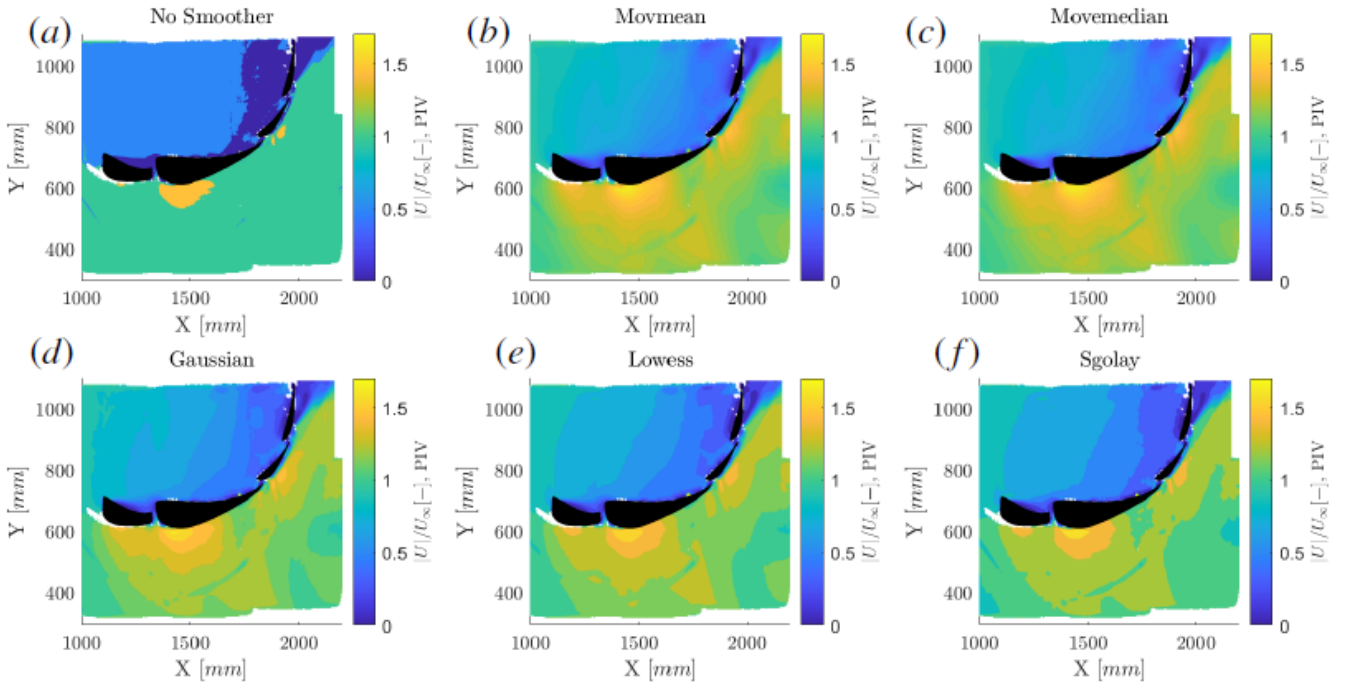


Figure 14. Data smoothing techniques. (a) Raw data. (b) Moving Mean. (c) Moving median. (d) Gaussian Weighted Average. (e) Linear regression. (f) Savitzky-Golay filter.

The evaluation revealed distinct behaviours for each method. The Lowess filter successfully reduced discontinuities but generated an unphysical, independent flow region within the domain (specifically around $X = 1700 - 1800 \text{ mm}$ and $Y = 300 - 500 \text{ mm}$). Conversely, the Moving Mean, Moving Median, and Gaussian filters diffused the data excessively. These filters overly smoothed the velocity peaks and artificially softened the transitions to stagnation points, which is highly detrimental when attempting to resolve sharp aerodynamic features.

The Sgolay filter was ultimately selected for the final processing. As described by Gallagher, this filter performs a local quadratic polynomial regression that adapts effectively to rapid, sharp changes in velocity. This allows for the preservation of critical physical features, such as suction peaks and flow detachments, despite being computationally more demanding than moving average methods.

To optimize the Sgolay filter, a sensitivity analysis on the sampling window dimensions was conducted, systematically varying the width, height, and aspect ratio of the interrogation area (Figure 15).

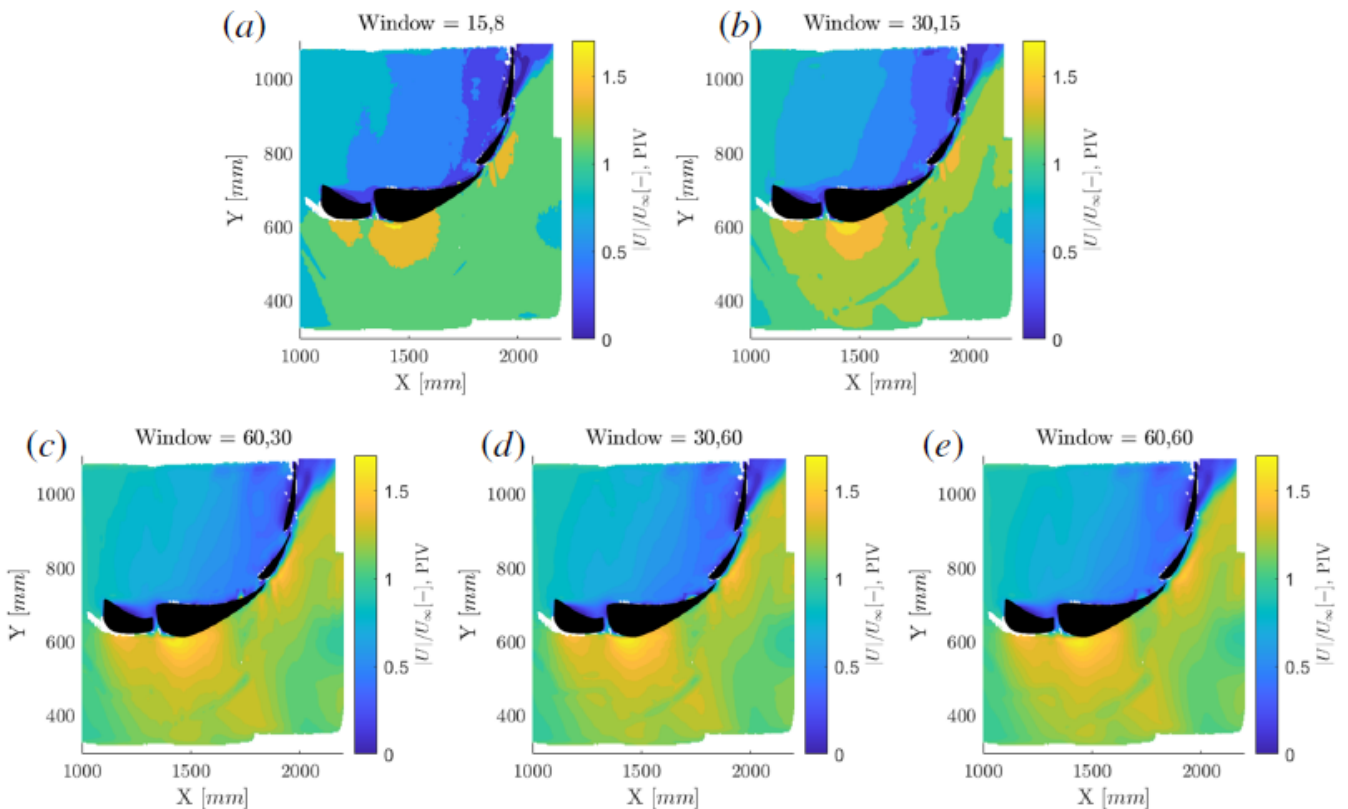


Figure 15. Savitzky-Golay filter sample window analysis. (a) 15x8 window. (b) 30x15 window. (c) 60x30 window. (d) 30x60 window. (e) 60x60 window

The analysis demonstrated that preserving the aspect ratio while increasing the window size increases overall smoothness, but altering the aspect ratio changes the directional bias of the filtering. For instance, in the recirculation bubble of the main wing's intrados, wider windows caused the bubble to become artificially slender (excessive x -direction smoothing), while thinner windows distorted it vertically. Since the noisiest data was concentrated in regions dominated by the horizontal velocity component ($U_x \gg U_y$, specifically where $X < 1800 \text{ mm}$), a smoothing window biased toward the streamwise direction was required. Consequently, a sampling window of 60×30 pixels was chosen to ensure optimal noise reduction while retaining the physical integrity of the flow structures.

3.3. Final PIV maps

After the application of the data smoothing and treatment methodologies, the final PIV velocity maps of the flow around the multi-element airfoil cascade were generated (Figure 16). The resulting data exhibits a significantly smoother transition between flow phases, and the upward velocity trajectory is entirely consistent with the high angles of attack of this aerodynamic setup.

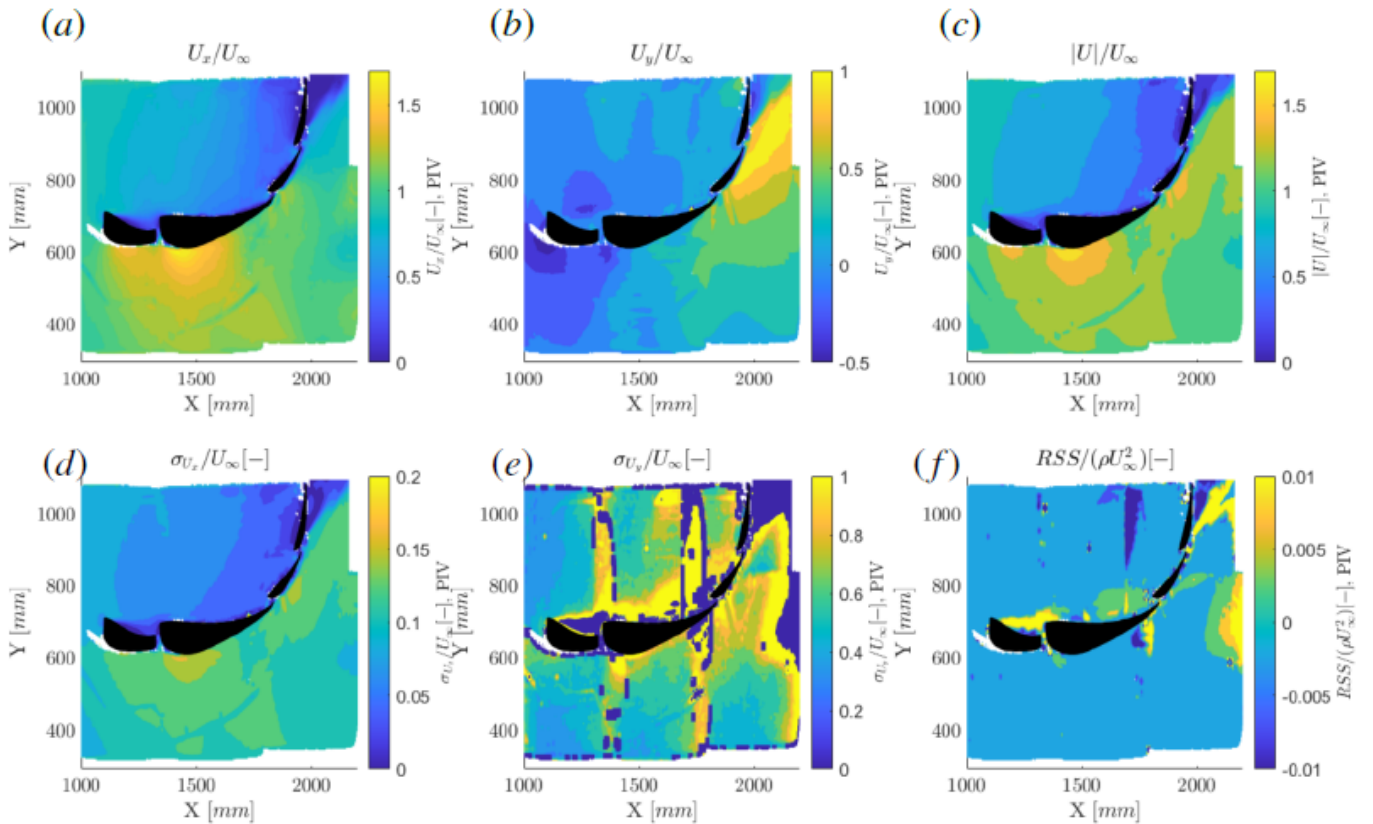


Figure 16. Final PIV results. (a) Horizontal Speed U_x . (b) Vertical Speed U_y . (c) Velocity Magnitude U . (d) Horizontal velocity variance. (e) Vertical velocity variance. (f) Reynold's Shear Stress

Despite the rigorous smoothing process, the velocity fields clearly preserve critical aerodynamic features. Specifically, flow detachments can be easily identified in the tertiary airfoil and the leading-edge slat, being particularly prominent in the vertical speed distributions.

These separation events are further corroborated by analysing the Reynolds Shear Stress (RSS). This parameter represents the random velocity fluctuations that are highly characteristic of turbulent flows; therefore, higher RSS values correlate directly with increased local turbulence. The RSS maps reveal distinct peaks at the leading edge of the slat and the extrados (suction side) of the tertiary airfoil, confirming that active flow separation is occurring in these regions and subsequently affecting the aerodynamic performance of the main wing.

On the other hand, the standard deviation of the horizontal speed aligns consistently with the observed velocity magnitudes. The highest deviations are localized within the higher-speed regions. This behaviour is expected because PIV measurement errors generally have a fixed relative value tied to the pixel resolution within the sampling window. Consequently, for a constant relative error margin, the absolute standard deviation inherently scales up in regions of accelerated flow.

After the application of the custom data smoothing and treatment methodologies, the final PIV data was imported into Tecplot 360 to generate high-fidelity non-dimensional velocity maps of the flow around the multi-element airfoil cascade.

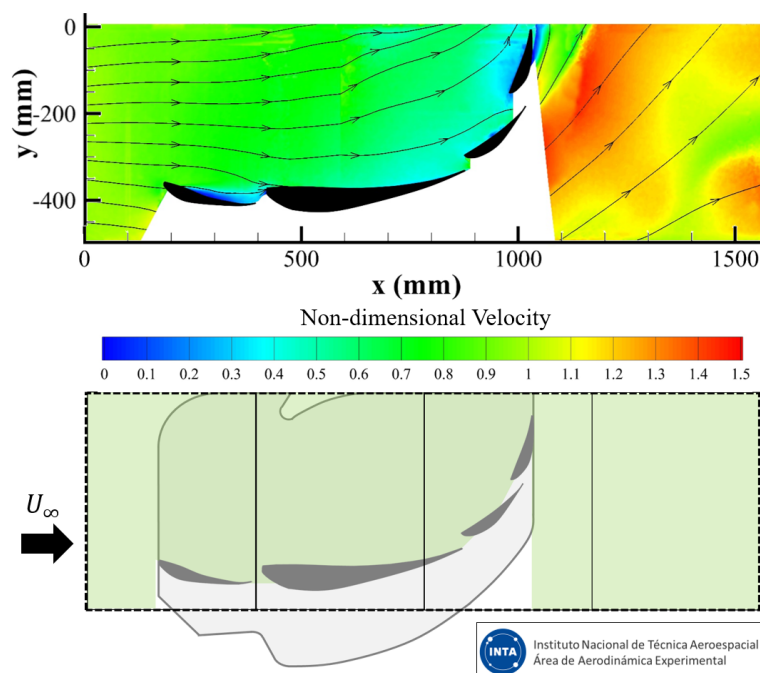


Figure 17. Non-dimensional velocity contours and streamlines for the intrados region obtained with Tecplot 360. Figure 17 illustrates the flow behavior underneath the main plane and the secondary elements (intrados). The streamlines demonstrate a smooth, attached flow trajectory, with clear flow acceleration through the gaps between the staggered airfoils. This interaction is essential for injecting high-momentum air into the boundary layer of the subsequent flaps, preventing premature stall.

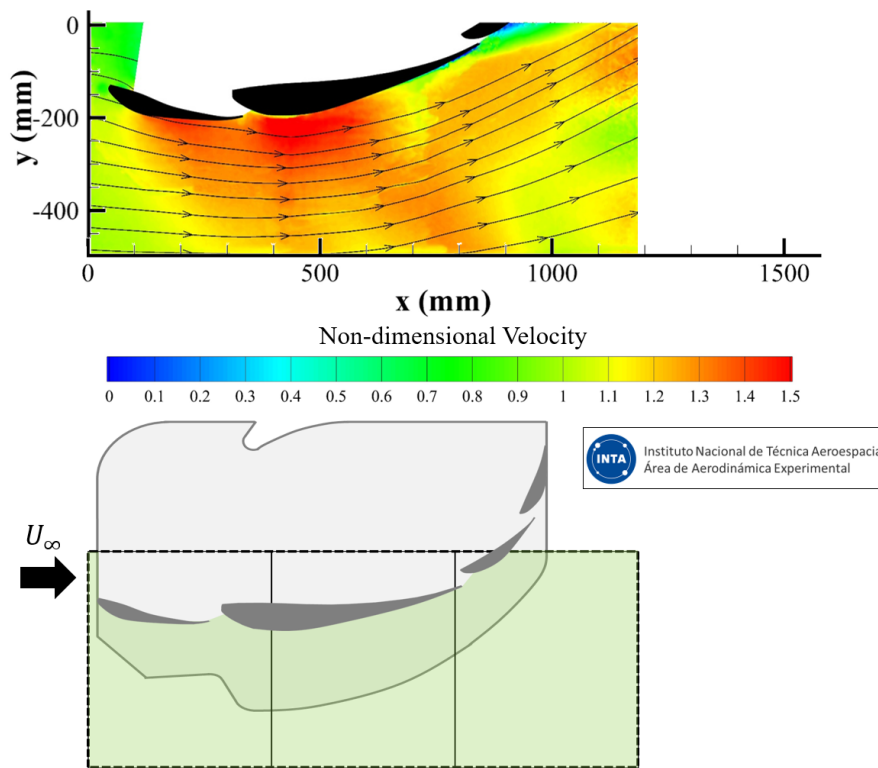


Figure 18. Non-dimensional velocity contours and streamlines for the extrados region obtained with Tecplot 360.

Figure 18 presents the flow field over the suction side (extrados). The upward velocity trajectory is entirely consistent with the high angles of attack characteristic of this aerodynamic setup. The contour maps effectively capture the strong suction peaks near the leading edges and the boundary layer development along the upper surfaces.

Despite the rigorous smoothing process, the processed velocity fields clearly preserve critical aerodynamic features. A closer examination of the near-wake region, shown in Figure 19, reveals a prominent and coherent recirculation bubble at the trailing edge of the tertiary flap. The streamlines in this specific detailed view mark the physical limit of flow attachment, visually confirming the stall characteristics of this aggressive high-lift setup.

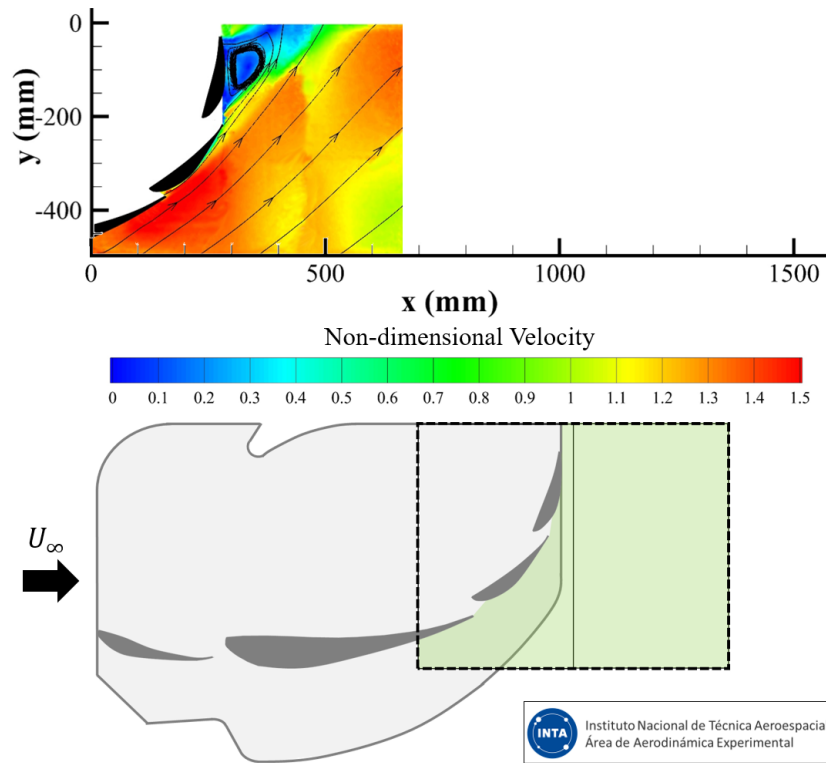


Figure 19. Detailed non-dimensional velocity contours highlighting the trailing edge recirculation bubble.

4. Conclusions

The experimental aerodynamic characterization of a multi-element Formula Student rear wing was successfully conducted using a high-resolution Particle Image Velocimetry (PIV) system at the INTA T1 wind tunnel.

A robust data processing methodology was implemented to overcome the spatial limitations of a single Field of View (FOV) and the optical shadows cast by the complex staggered geometry. By interpolating the raw data and applying a linearly increasing weight system, eight individual FOVs were seamlessly merged into a single, continuous flow map. Furthermore, the application of a directionally biased Savitzky-Golay filter proved highly effective in reducing experimental noise and reflection artifacts, preserving critical sharp aerodynamic features that standard moving-average filters tend to obscure.

The processed horizontal and vertical velocity maps, alongside the Reynolds Shear Stress fields, provided a detailed quantitative visualization of the aggressive flow turning and boundary layer development. Critical aerodynamic phenomena, including the turbulent flow separation at the

leading edge of the slat and the trailing edge recirculation bubble on the tertiary flap, were accurately identified and quantified. Overall, this methodology demonstrates the capability of advanced PIV post-processing to resolve the complex flow physics inherent to high-lift motorsport applications. The resulting high-quality experimental dataset serves as a reliable benchmark for the future validation and tuning of Computational Fluid Dynamics (CFD) setups, particularly for assessing numerical schemes and turbulence models in regions of adverse pressure gradients and flow detachment. Future work may explore three-dimensional or time-resolved PIV techniques to further investigate the unsteady characteristics of these aerodynamic structures.

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