



Research paper

Experimental and numerical performance evaluation of the Olympic windsurfing class iQFOiL

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ABSTRACT

This work presents an experimental and numerical assessment of the hydrodynamic performance of the Olympic iQFOiL windsurfing class. Full-scale towing-tank tests were carried out at velocities between 3.0 and 7.0 m/s and at angles of attack from -1° to 4° , providing benchmark measurements of lift and drag forces. Preliminary Computational Fluid Dynamics (CFD) analyses revealed that Fluid Structure Interaction (FSI) effects needed to be included to achieve accurate predictions and good agreement with the experimental data. Numerical simulations were therefore performed over the velocity range 1–7 m/s at zero angle of attack. A parametric Computer Aided Design (CAD) model was developed to generate both the undeformed geometry and the deformed configurations obtained through Finite Element Method (FEM) structural analyses. The numerical campaign enabled a detailed investigation of pressure distributions and structural deflections, indicating negligible deformation up to 4 m/s. At higher velocities, neglecting hydroelasticity resulted in a noticeable underestimation of lift. The analysis of the velocity and pressure fields for the undeformed and deformed shapes provided an enhanced understanding of the behaviour of the iQFOiL, particularly in terms of the effective trim angle and the relative variation in the longitudinal position of the centre of pressure.

1. Introduction

A major development in contemporary sail racing has been the widespread adoption of hydrofoil technology. Initially a niche innovation, foiling has found a wide application in extreme racing boats, improving speed, efficiency, and, in some cases, transversal stability. From its debut in the America's Cup, where the AC72 catamarans with wing sails and hydrofoils first demonstrated the unexpected speed and agility of flying above the water, foiling has been applied to different types of sailing craft such as IMOCA, the NACRA Olympic catamaran, the MOTH Dinghy, the kiteboard, and the iQFOiL Olympic Class. This technological leap has been extended to Olympic disciplines, with the introduction of foiling classes that demand a new set of skills and a deep understanding of hydrodynamics.

The design of the current iQFOiL Olympic Class was developed in 2016 by the Starboard® team (2024) (Starboard UK, 2024), in response to windsurfing market requests. In 2024, the iQFOiL became the first windsurfing foiling Olympic class at the Paris Olympic Games. Within this context, the iQFOiL class stands as the pinnacle of Olympic windsurfing, embodying foiling technology in a one-design format. While

instinctive sailing skills, acute tactical awareness, and raw athletic ability remain paramount, the inherent complexity of foiling performance necessitates a complementary scientific approach. In foil sailing, optimum hydrodynamic performance is achieved through the simultaneous optimization of lift and drag. This distinguishes it from traditional displacement or planing hulls, where the primary goal is typically to reduce drag as much as possible. A hydrofoil needs to generate sufficient lift to elevate the hull entirely out of the water, a process essential for effective foiling. While lift is crucial, any unnecessary drag generated by the foils themselves, or by parts of the hull still in the water during take-off or when sailing through waves, will hinder speed. The objective is to produce the required lift with the minimum amount of induced drag (the drag created by generated lift). Thus, the best hydrodynamic performance is not merely the lowest drag, but the optimal balance between generating sufficient lift to sustain flight while keeping associated drag as low as possible. This balance is dynamic, changing with speed, wind conditions, and the apparent wind angle of incidence.

The trim angle, defined as the angle at which the foil horizontal wings are oriented relative to the water flow, directly impacts both the lift and drag generated. The subtle interplay of foil angle, mast rake, sail

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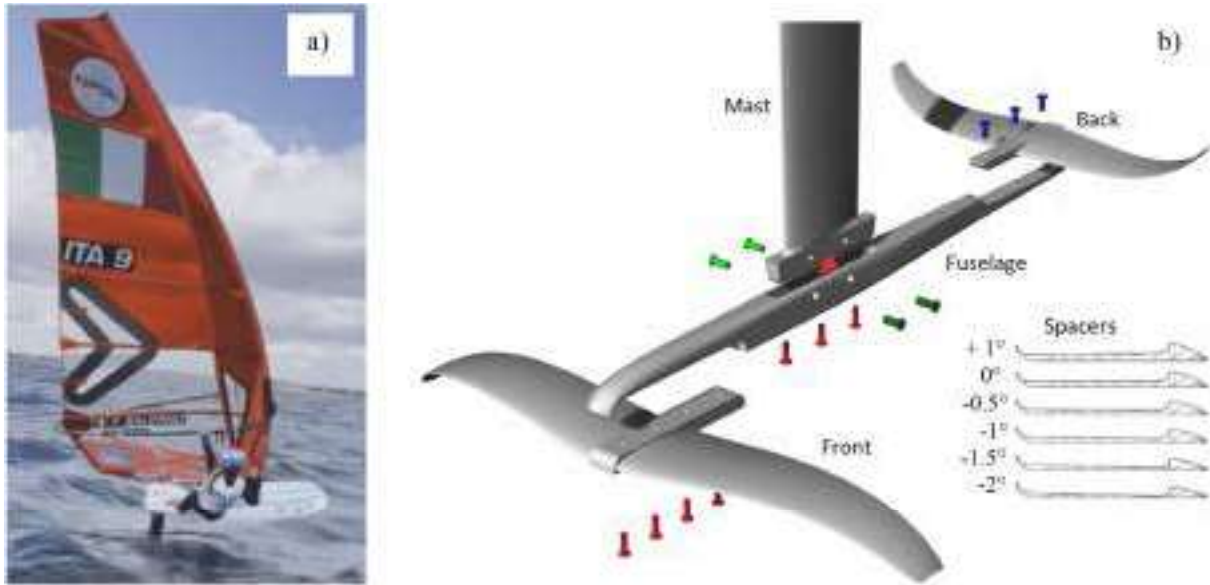


Fig. 1. a) Francesca Salerno during training (photo courtesy of Club Canottieri Roggero di Lauria, Palermo, Italy), b) iQFOiL parts.

trim, and crew input, all influenced by varying wind and sea conditions, creates a multi-dimensional optimization problem. Sailors on foiling racing boats constantly adjust their body position based on their intuitive understanding. Even though these instinctive actions are powerful, they can be refined and optimized through scientific insights. Relying solely on a sailor's intuitive understanding, while crucial, may not unlock the full potential of the equipment. Therefore, a systematic scientific investigation, including both experimental testing and numerical simulations, is fundamental for a comprehensive understanding of the iQFOiL's performance envelope, which depends on the complex interactions between the equipment, the athlete, and the environment.

These trends have attracted the attention of the scientific community, and in recent years, several studies have numerically analysed some performance aspects of this Olympic class. Pernod et al. (2023) have analysed through the 2D Reynolds-Averaged Navier Stokes (RANS) method with volume of fluid interface model, the effect of the free surface on the performance of submerged hydrofoils, showing that drag increases significantly when the immersion to chord ratio decreases below 2.

Mok et al. (2023, 2024) experimentally investigated the sail performance of the Olympic iQFOiL, showing that the sweep-back sail angle is a key element in improving the lift to drag ratio and that the sail could be improved by limiting the recirculation bubble found within a typical range of angles of attack. Bertrand et al. (2025) experimentally investigated the propulsive forces generated by a pitching hydrofoil, simulating the motion of a windsurf foil. The work quantifies lift and drag forces under varying pitching kinematics and mean incidence angles. The findings on thrust generation and stall delay are directly relevant to optimizing the hydrofoil's design and control to maximize propulsion and efficiency in iQFOiL racing, especially under upwind conditions. Bot et al. (2025) experimentally investigated the decrease in lift of the iQFOiL front wing as a function of distance from the free surface, finding monotonic behaviour and observing that the free surface effect is negligible when the immersion-to-chord ratio exceeds 3. Hou et al. (2024) developed a hierarchical velocity prediction program that uses experimental data from wind tunnel tests for both the sail and the hydrofoil. They found that sail orientation is relevant to increasing the board's velocity and overall performance, and that the weight of the sailors is a key factor in achieving the Velocity Made Good (VMG), defined as the speed of a sailboat towards (or away) the direction of the wind. Martínez-Barberá et al. (2026) conducted an extensive experimental investigation of the performance characteristics of a dual-use

hydrofoil (for kitesurfing and windsurfing) as a function of the Froude number and submergence depth. The authors presented a comparison between the experimentally measured aerodynamic coefficients and several numerical results obtained using a RANS solver and a potential flow solver. The discrepancies between experimental and numerical results are highlighted and attributed to several numerical limitations, such as turbulence modelling and the absence of free surface effects. Perali et al. (2024) provided an interesting comparison between RANS results and those obtained using the boundary element method, focusing on a generic hydrofoil like the iQFOiL navigating near the free surfaces. This comparison demonstrates, as shown in Cirello et al. (2025a,b), that low-fidelity methods such as the boundary element method or the vortex lattice method could be used for optimization analysis; however, they present a significant offset in the results due to their inviscid formulation. Consequently, a high-fidelity method like RANS should be used to estimate the device's performance. Yuchen and Horrillo (2021) used numerical simulations and neural networks to predict the hydrodynamic performance of hydrofoils in tandem. While the work focuses on a general tandem configuration, the principles and methodologies for understanding hydrofoil interaction, lift, and drag, particularly in proximity to the free surface, are highly relevant to the multi-element foil system of the iQFOiL and its optimization for stability and speed. Some other studies have highlighted the role of fluid structure interaction (FSI) in the obtained numerical results; these are mainly devoted to cavitation (Jian Hu et al. (2023)), to harmonic response (Ertian et al. (2025)), and to understanding how the large deformations of the foil shape under operating conditions influence its performance (Knudsen et al. (2024)). Matveev (2024) used CFD to analyse the hydrodynamic performance of windsurfing boards with various bottom modifications. The insights into lift, drag, and lift-drag ratio for different board geometries, especially at high speeds, can be helpful for optimizing the iQFOiL performance.

This paper is focused on the assessment of the hydrodynamic performance of the Olympic iQFOiL windsurfing class foil (Fig. 1a) to be used for the identification of optimal foiling settings and the further development of training strategies. Taking advantage of the experimental research in scale 1:1, this work presents, for the first time, the results for lift and drag forces of the iQFOiL in calm water in a speed range from 3 to 7 m/s, and the range of angle of incidence from -1 to 4° . The results, obtained in controlled conditions, can be used as reference values for other researchers for CFD simulations or optimization of training strategies. Unlike previous studies, experimental results have



Fig. 2. Meshes generated from 3D scans of the iQFOiL components: a) Front; b) Back; c) Mast; d) Fuselage.

been compared with CFD simulations with and without Fluid-Structure Interaction (FSI) effects. Deformations of the iQFOiL induced by the pressure field are shown for the tested speed range, revealing for the first time the importance of sound scientific methodologies for the correct interpretation of the experimental results. The paper is structured as follows: in Section 2, the main features of the iQFOiL are highlighted. Section 3 describes the reverse engineering approach from the scan of the surfaces to the generation of the parametric CAD model. The description of the experimental setup, measured results, and data analysis are reported in Section 4. In Section 5, the innovative FSI approach is described, and the main results are discussed. Conclusions and limitations of the presented procedure, as well as future works, are outlined in Section 6.

2. iQFOiL characteristics

The iQFOiL device is composed of a main lifting surface named the *front*, a stabilizer wing named the *back*, connected by a *fuselage*, and an aluminium solid body rigidly connected to a vertical wing, named the *mast*. The front wing, the fuselage, and the mast are connected in a fixed position without the possibility of changing their relative angular position; the back wing, on the contrary, has five different adjustment positions, allowing it to change its relative angle with respect to the fuselage within a range of $+1^\circ$ to -2° (Fig. 1b).

3. Reverse engineering approach

3.1. 3D acquisition

The foil analysed in this study is the Olympic class iQFOiL, manufactured exclusively by Starboard, which, due to proprietary

restrictions, does not disclose any technical specifications or construction drawings. Consequently, reverse engineering represents the only viable approach. This method enables high-fidelity reconstruction of foil geometry, supporting both experimental performance evaluations and the initiation of a research programme aimed at identifying the optimal sailing trim and potential design improvements.

A three-dimensional scan was carried out at the University of Palermo using a Hexagon Metrology HP-L 20.8 laser scanner, equipped with an adjustable scan line width and featuring high spatial and temporal resolution, capable of acquiring up to 150,000 distinct points per second. To ensure the highest possible fidelity in reproduction, the scanner was configured to operate at a maximum accuracy of $50\ \mu\text{m}$. To minimize spurious reflections and enhance scan quality, the target surfaces were pre-treated with a thin layer of talcum powder to render them matte.

Each component of the foil assembly (Fig. 1b) was scanned individually to reduce file size and facilitate subsequent data processing. Attention was devoted to maintaining the correct relative positioning among the various parts. To this end, the foil was assembled by a professional athlete, and all the scans were performed on the fully assembled system. Due to the limited reach of the scanner arm, the entire device could not be acquired in a single scan. Consequently, each component was digitized separately in the assembled configuration, including overlapping reference regions that allowed for the accurate reconstruction of the complete assembly. Fig. 2 presents the results of these scans; only one half of the front wing was scanned and then mirrored, while the mast, characterized by a constant cross-sectional profile and a trapezoidal planform, was scanned in discrete parts only; the complete mast was reconstructed by sweeping the three acquired cross-sections along the straight leading edge.

Following data acquisition, the mesh models were converted into

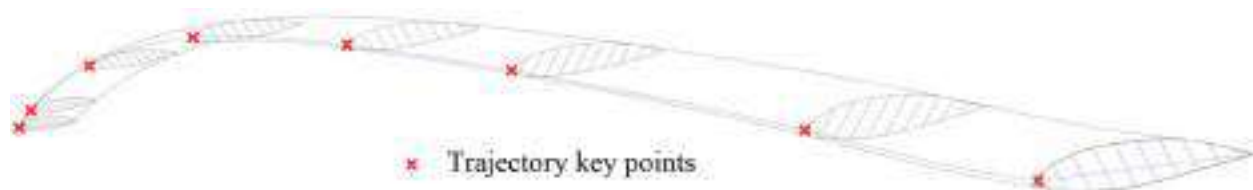


Fig. 3. Sweep of 8 sections along the leading-edge trajectory of the front wing.

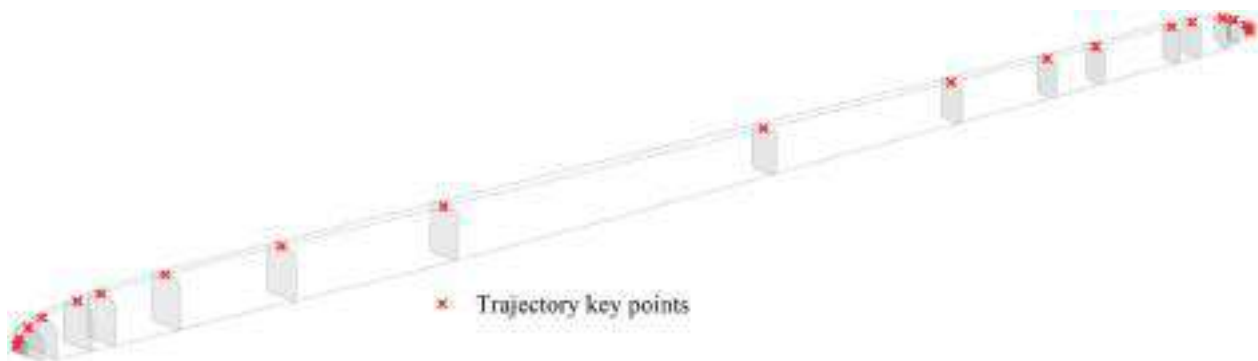


Fig. 4. Sweep of 18 sections along the trajectory of the fuselage.

Table 1

Characteristics of the load cell ME ID/K6D80 2 KN/100Nm/MP11.

	F_x [N]	F_y [N]	F_z [N]	M_x [Nm]	M_y [Nm]	M_z [Nm]
Nominal load	2000	2000	5000	100	100	100
Measurement uncertainty ($k = 2$)	± 1.29	± 2.34	± 6.5	± 0.169	± 0.063	± 0.051

Non-Uniform Rational B-Spline (NURBS) surfaces. This process can be performed using several techniques, such as generative algorithms, as described in Cirello et al. (2025b), or with interactive CAD reconstruction techniques as presented in Zhang et al. (2024), or through a partially manual procedure adopted in the present study.

3.2. Parametric re-design

In the present paper, the file generated using the procedure proposed by Cirello et al. (2025b) was completely rebuilt using the parametric CAD modeller CREO Parametric from PTC (student version 11.0). The main advantage of this approach lies in the versatility of the obtained CAD model. All the components (mast, fuselage, front, and back) were modelled using a single NURBS surface and the same sweep technique. In Fig. 3, the front wing model structure is shown.

These 8 sections have been modelled with third-degree spline curves and swept along the trajectory of the leading edge (Sederberg (2012)). Care has been taken in modelling each section (as well as the leading edge) to match the reconstructed.stl file. The final CAD model is very concise and suitable for shape modification. The back wing has been defined in the same way as the front one (8 sections swept along the back leading-edge trajectory). The fuselage (Fig. 4), although simpler than the wings, has been modelled with a higher number of sections (eighteen) to better replicate the real shape and the subsequent shape

modification induced by structural deformations (see section 5.5 for more details).

As the mast is a tapered solid, three sections were sufficient to accurately define the shape. The final assembly file, with a size of about 2 MB (compared to 100 MB of the.stl file), can be read directly by Ansys, avoiding neutral translator interfaces. Moreover, all the parameters and relations defined in CREO can be imported.

4. Experimental campaign

4.1. Experimental setup

The experimental campaign was conducted at the University of Naples Federico II. The towing tank is 135 m long, 9 m wide, and 4.25 m deep. The tank carriage has a maximum speed of 7.5 m/s. The iQFOiL was tested in scale 1:1 over a speed range from 3 to 7 m/s, with angles of incidence varying from -1 to 4° . The speed range selected for testing was defined based on the recommendations of professional athletes involved in the Italian Olympic team. This speed range, especially from 4 to 6 m/s, is often called marginal speed, indicating a critical condition for initiating foiling. Forces and moments acting on the iQFOiL were measured using a 6-component load cell ME ID/K6D80 2 KN/100Nm/MP11. Measurement uncertainties corresponding to a 95% confidence level are reported in the following Table 1.

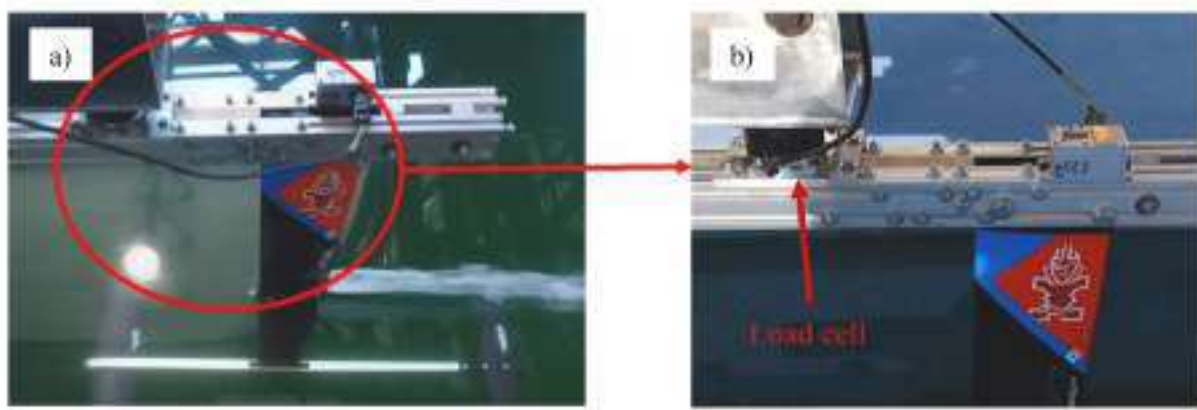


Fig. 5. a) Experimental setup arrangement; b) load cell detail.

Table 2
Experimental setup control for F_z force.

	A	B	C	D	Mean $F_z \pm \text{StDev}$
Test force [N]	55	55	55	55	55
Offset _{Mast} [mm]	350	350	500	500	-
Offset _{Test Force} [mm]	125	475	475	125	-
F_z measured [N]	56.7	57.31	54	52.7	55.178 ± 1.839
M_y measured [Nm]	14.33	31.56	37.65	12.3	-

Table 3
Experimental setup control for F_x force.

	E	F	G	H	Mean $F_x \pm \text{StDev}$
Test force [N]	55	55	55	55	55
Offset _{Mast} [mm]	350	350	500	500	-
Offset _{Test Force} [mm]	540	600	540	600	-
F_x measured [N]	-56.74	-54.72	-53.59	-57.46	-55.532 ± 1.547
M_y measured [Nm]	28.42	60.48	26.83	52	-

The experimental setup was designed to reproduce the full-scale configuration as closely as possible, with the mast fixed rigidly between two Rexroth bars and the load cell at a suitable longitudinal distance from the mast to minimize the moment acting on the foil. This configuration was adopted because, as reported in Table 1, the force measurement range is adequate, but the upper limit for the moment measurement (100 Nm) is critical for the expected moments M_Y . To overcome this limitation, the load cell was mounted offset from the top of the IQFOIL mast. A general experimental setup arrangement is shown in Fig. 5a, with a detail of the load cell in Fig. 5b. The offset distance minimizes M_Y values, bringing them within the cell measurement range.

To ensure that the measurement of the forces F_X and F_Z would not be affected by the distance between the load cell and the mast, a set of F_X and F_Z measurements under known test forces was performed both at rest and at speed. These tests were conducted with mast offsets of 0.35 m and 0.50 m relative to the load cell at different horizontal and vertical distances as reported in Tables 2 and 3. A schematic representation of the test is provided in Fig. 6a, while Fig. 6b shows the two coordinate systems adopted (Oxy and $Ox'y'$), both with the same origin coincident with the load cell coordinate system centre definition.

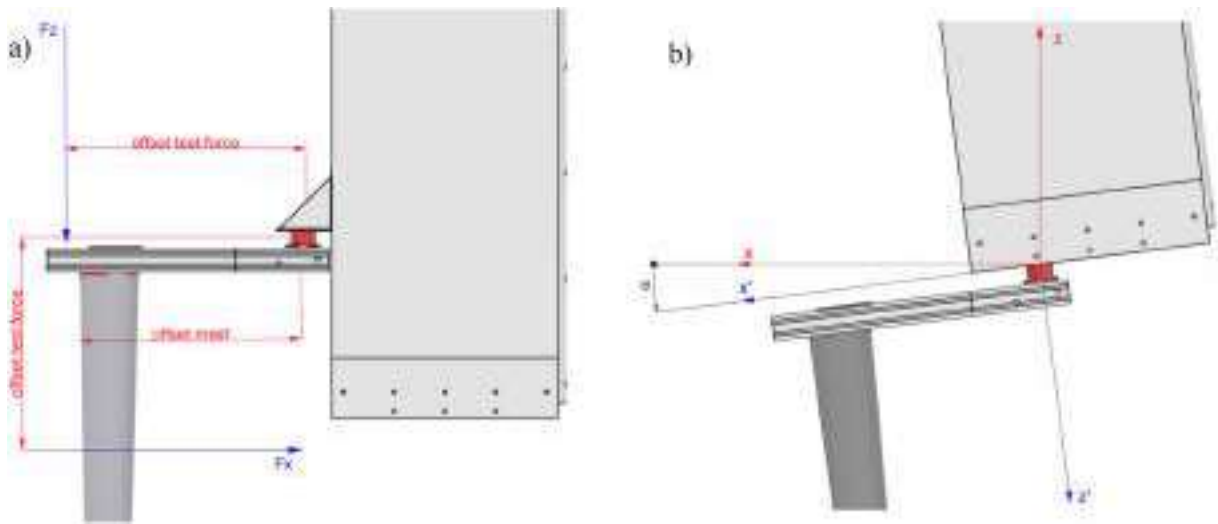


Fig. 6. a) Schematic of the setup for the experimental calibration tests; b) Coordinate systems, xz (in red) aligned to waterplane, $x'z'$ (in blue) aligned to mast leading edge. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

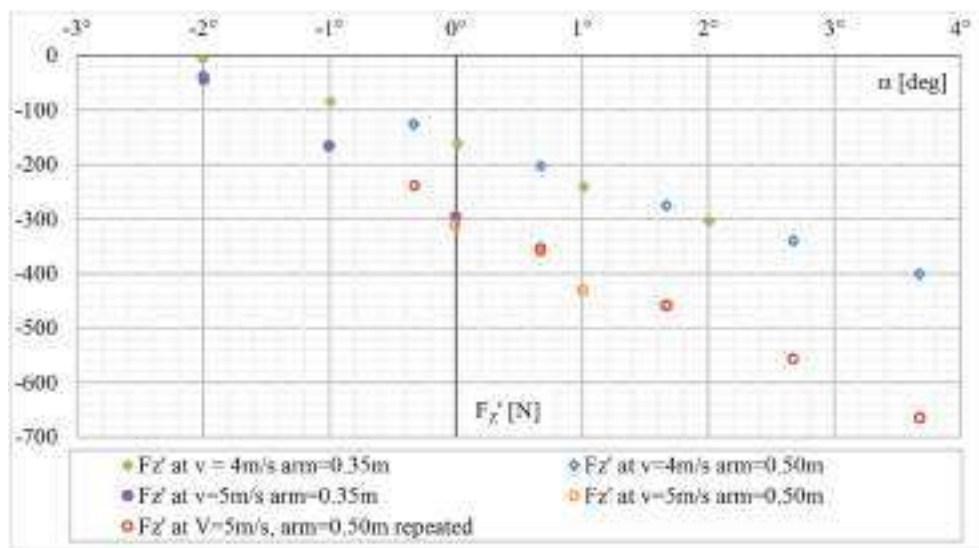
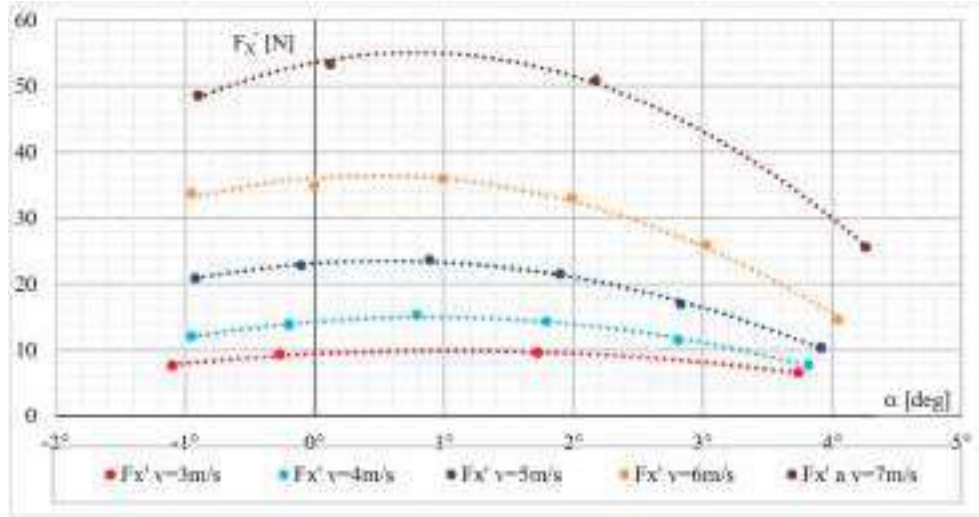


Fig. 7. Dynamic validation of experimental setup: measured F_z' force at 4 m/s and 5 m/s.

Fig. 8. Measured F_x force.

where:

- F_x is the resultant force oriented in the flow direction, positive backwards (drag D);
- F_z is the resultant force oriented in the vertical direction, positive upwards (lift L);
- $F_{x'}$ is the measured force in x' direction, positive backwards, aligned with the load cell;
- $F_{z'}$ is the measured force in z' direction, positive downwards, aligned with the load cell.

The measured results, for the F_z force at speeds of 4 m/s and 5 m/s are shown in Fig. 7. All data were sampled at a frequency of 500 Hz

It can be observed from Tables 2 and 3 that the standard deviations of the measured forces and from the diagram of measured $F_{z'}$, at speeds of 4 m/s and 5 m/s (see Fig. 7), are within the 95% confidence interval declared by the manufacturer and therefore acceptable for the validation of the experimental setup. Finally, the test setup was identified as follows: the height of the iQFOiL above the free surface was 0.6 m,

resulting in 0.393 m of immersion, and the offset of the mast from the load cell was 0.50 m. The inclinometer Schaevitz LSOC-30 was mounted on the top of the Rexroth bar, rigidly connected to the iQFOiL for the trim measurement with a precision of 0.02 deg. From the four repeated tests at a speed of 5 m/s, the standard deviation was calculated as Type – A uncertainty equal to 3.085 N for F_z and 0.145 N for $F_{x'}$. According to the ITTC Recommended Procedures and Guidelines (ITTC, 2014) the total uncertainty is:

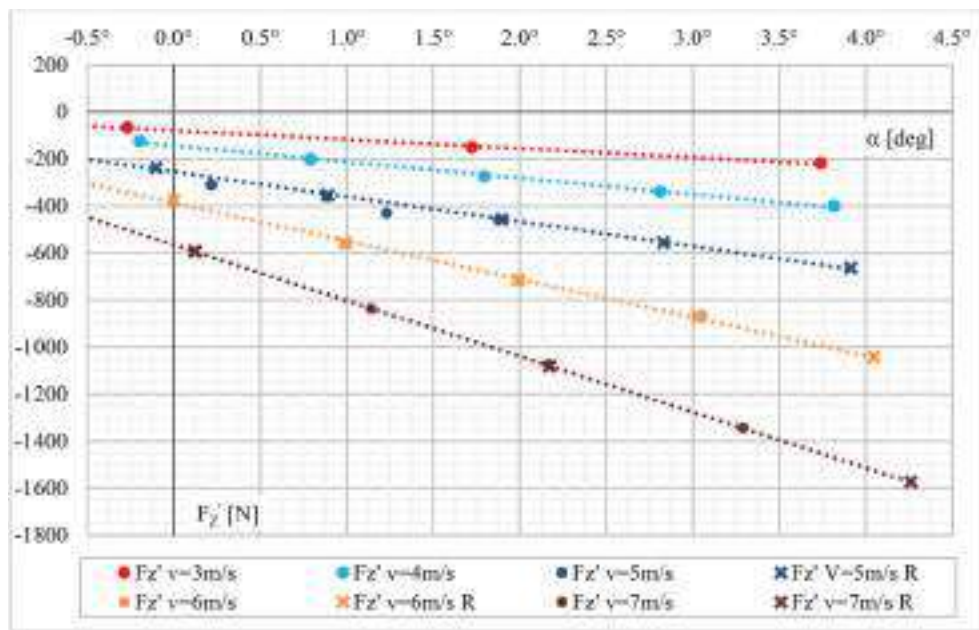
$$U_D^F = \sqrt{U_{Type-A}^2 + U_{Type-B}^2} \quad (1)$$

where Type - B uncertainty corresponds to values reported in Table 1, divided by factor k.

Considering factor $k = 2$ for the expanded uncertainties, we have:

$$U_D^{F_{x'}} = 1.29 \%$$

$$U_D^{F_{z'}} = 1.74 \%$$

Fig. 9. Measured F_z force.

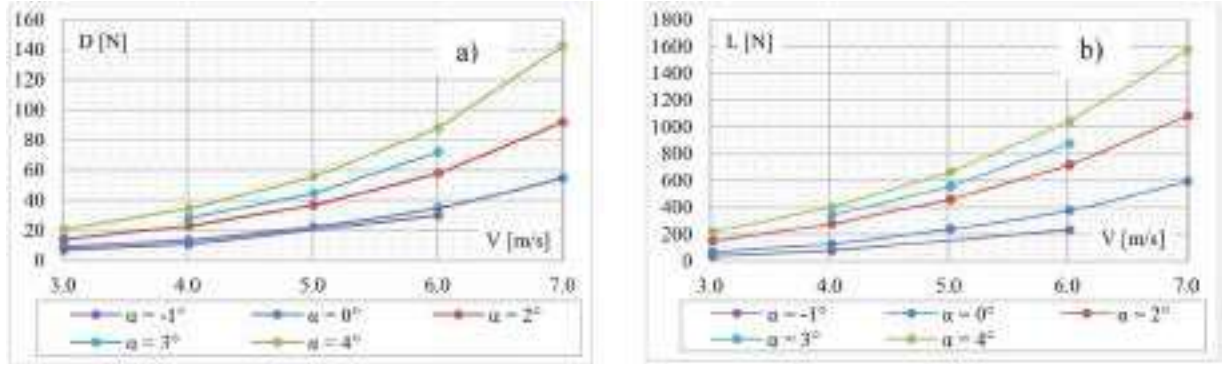


Fig. 10. a) Drag Force and b) Lift Force, for different trim angles.

4.2. Experimental results

The objective of the experimental campaign was to provide the Lift (L) and Drag (D) forces and their corresponding coefficients (C_L , C_D) as a reference for the CFD analysis and to provide results on the actual forces at different speeds and trim angles as the first step towards the engineering optimization to maximize speed and efficiency on the water. Due to the experimental setup, drag and lift values were obtained from the measured F_x and F_z forces by applying the trigonometric transformations of forces between the previously defined coordinate systems, as shown in the following Equations (2) and (3):

$$D = F_x = F_x \cos \alpha - F_z \sin \alpha \quad (2)$$

$$L = F_z = -F_x \sin \alpha - F_z \cos \alpha \quad (3)$$

where α is the trim angle measured according to Fig. 6b.

The results for the measured F_x and F_z are presented in the following Figs. 8 and 9. For each speed, the trend lines given in equations (4) and (5) of forces as a function of trim angles are added in Figs. 8 and 9. Equation (4) represent the interpolating curves (shown as dotted lines in Fig. 8) fitted to the experimental data of F_x , and Equation (5) represent the interpolating curves (shown as dotted lines in Fig. 9) fitted to the experimental data of F_z . For all cases, the coefficient of determination (R^2) is higher than 0.988, indicating a very good data fitting.

$$F_x = -0.4674\alpha^2 + 0.9751\alpha + 9.4113; \quad R^2 = 0.9876; \quad v = 3 \text{ m/s}$$

$$F_x = -0.8681\alpha^2 + 1.5567\alpha + 14.294; \quad R^2 = 0.993; \quad v = 4 \text{ m/s}$$

$$F_x = -1.1868\alpha^2 + 1.3348\alpha + 23.112; \quad R^2 = 0.9974; \quad v = 5 \text{ m/s}$$

$$F_x = -2.007\alpha^2 + 3.1042\alpha + 34.888; \quad R^2 = 0.9998; \quad v = 6 \text{ m/s}$$

$$F_x = -2.7346\alpha^2 + 5.399\alpha + 52.194; \quad R^2 = 0.999; \quad v = 7 \text{ m/s} \quad (4)$$

$$F_z = -38\alpha - 79.707; \quad R^2 = 0.9956; \quad v = 3 \text{ m/s}$$

$$F_z = -69.108\alpha - 143.4; \quad R^2 = 0.9974; \quad v = 4 \text{ m/s}$$

$$F_z = -105.73\alpha - 254.97; \quad R^2 = 0.9993; \quad v = 5 \text{ m/s} \quad (5)$$

$$F_z = -162.44\alpha - 386.77; \quad R^2 = 0.9991; \quad v = 6 \text{ m/s}$$

$$F_z = -236.99\alpha - 566.05; \quad R^2 = 1; \quad v = 7 \text{ m/s}$$

For the correct interpretation of the measured values, and to provide benchmark reference data, the calculated lift and drag forces obtained using equations (2) and (3) are reported in Fig. 10a and b. As expected, the greater the trim angle is, the higher the forces are. Both lift and drag increase with the trim angle, highlighting the importance of considering both forces simultaneously to achieve the maximum speed.

Final data elaboration is relative to drag and lift coefficients at different velocities as a function of the incident angle α , according to the following expressions (6) and (7):

$$C_D = \frac{D}{\frac{1}{2}\rho V^2 S_{PA}} \quad (6)$$

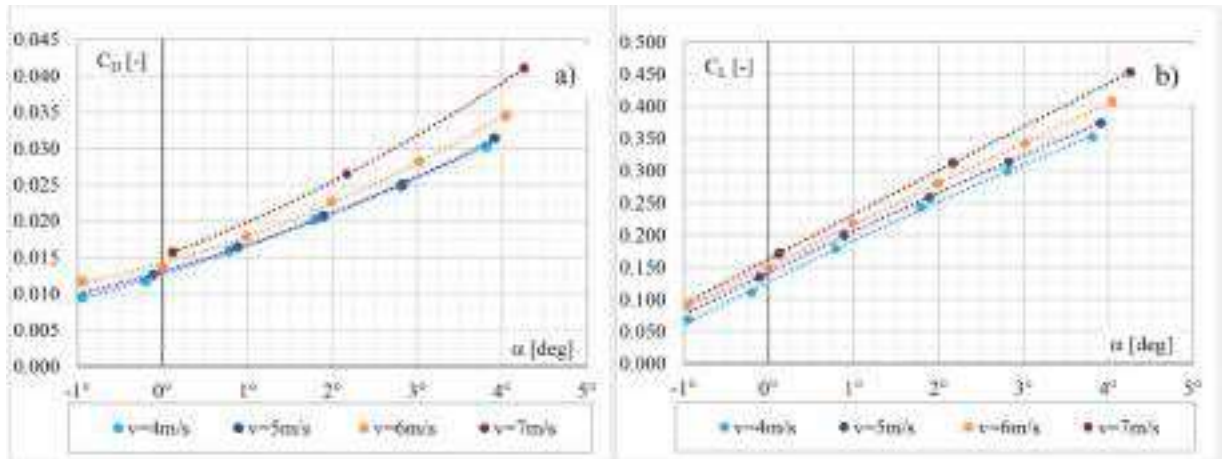


Fig. 11. Experimental a) drag, and b) lift coefficients.

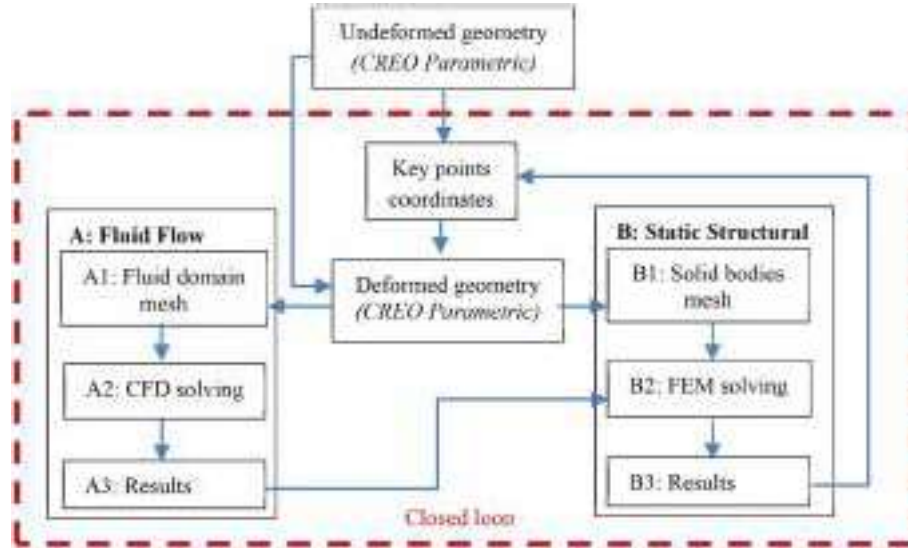


Fig. 12. Generalized structure of the iterative one-way FSI.

$$C_L = \frac{L}{\frac{1}{2}\rho V^2 S_{PA}} \quad (7)$$

where V is the foil speed, ρ is the density of the fresh water, and S_{PA} is the projected area of the front and back foils and of the fuselage, in total equal to 0.1419 m^2 . The same area has been chosen for both C_D and C_L .

For the purposes of this work, the forces are of interest. The coefficients C_D and C_L are shown only for visual control of data and possible future comparison with similar studies. The obtained values are given in Fig. 11.

Considering Fig. 11b, an approximately linear trend of C_L vs α can be observed. In principle, according to Equation (3) and the nonlinear behaviour of F_x , a nonlinear variation of C_L would be expected. However, analysis of Figs. 8 and 9 shows that the values of F_x are approximately one order of magnitude lower than those of F_z , which instead exhibits a strongly linear trend. Consequently, the nonlinear contribution does not significantly emerge in the C_L values, at least within the investigated range of angles of attack.

5. Numerical campaign

The procedure described in the following has been implemented in the ANSYS Workbench environment, and all the simulations have been run on an 8-core notebook with 64 GB RAM. Fig. 12 shows the procedure flow chart with the two main components. Component “A” is aimed at solving the fluid flow problem, while component “B” solves the static structural one. They are linked to each other, giving rise to the generalized fluid structure interaction scheme.

With reference to Fig. 12, the undeformed geometry of the assembled iQFOiL represents the main input. At the beginning of the iterative procedure, the undeformed and deformed shapes are identical. Their input parameters are the coordinates (x, y, z) of each point of the swept surfaces (i.e., 8 points for both front and back surfaces, 3 points for the mast, and 18 points for the fuselage). Moreover, to simulate all possible scenarios of real sailing conditions (as depicted in Fig. 1), other parameters to be considered are the flying height (z-axis displacement), the trim angle (rotation around the y-axis), and the roll angle (rotation around the x-axis). The yaw angle (rotation about the z-axis) will be controlled by component A2.

At the first step, the deformed geometry represents the input for the fluid domain mesher (A1), solved with CFD (A2). The same geometry is transferred to B1 for the solid bodies meshing, and the pressure map on the geometry surface obtained by the solution (A3) is imported into the

static structural FEM solver (B2). Finally, the solution B3 returns the key point coordinates of the deformed shape, closing the loop fluid-structure depicted with a dashed red line in Fig. 12.

5.1. Components outline

Several parameters must be defined for both components A and B of Fig. 12, as outlined in the following.

5.1.1. A1: Fluid domain mesh

The meshing phase is a crucial step and requires several attempts before reaching a stable and robust mesh. The parameters adopted are the size of edges, surfaces, and solids. In particular, all the edges, the corresponding surfaces, the interface surface between water and air (the free surface), and the maximum element size have been parameterized. This allows the generation and testing of several meshes by simply adjusting these parameters.

5.1.2. A2: CFD solving

The Fluent setup, other than the definition of the numerical model, which will be detailed in Sec. 5.2, requires the far fluid flow velocity and the yaw angle (the so-called leeway).

5.1.3. A3: results

The main output parameters of this component are the forces in the global reference frame and the pressure map on the wall surfaces. Of course, several additional quantities can be extracted from the Fluent solver.

5.1.4. B1: solid body mesh

This component requires the definition of mesh, load, and constraints. The curves and surfaces mesh parameters are the same as in A1, so that the pressure load imported from the fluid flow solution can be applied to the structural surfaces, avoiding unmapped nodes. Finally, the mast head is considered clamped to the towing tank carriage.

5.1.5. B2: FEM solving

To associate the material with the geometry, mechanical properties must be defined. The mast, front and back are made of High Modulus pre-preg carbon fibre, while the fuselage is made of an aluminium alloy (<https://www.iqfoilclassofficial.org>, accessed 22/10/2025).

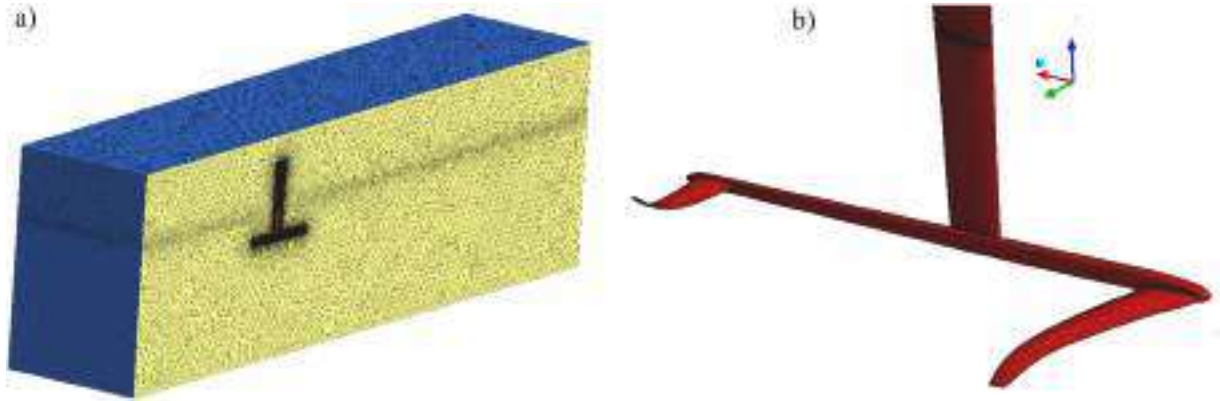


Fig. 13. a) Computational domain; b) close-up of the wall surface mesh.

5.1.6. B3: results

The output parameters of this component are the deformations in the global reference frame of each point of the swept surfaces, as well as the equivalent stresses and the force reactions.

By replacing the initial key points coordinates (i.e., the undeformed shape) with the corresponding output parameters from B3, the new deformed shape can be automatically rebuilt in CREO, closing the iterative approach described above.

5.2. CFD setup

Fig. 13a shows the mesh of the computational domain, while Fig. 13b shows a close-up of the wall surface mesh. An unstructured mesh with a prismatic boundary layer has been chosen. It should be noted that the static water plane has been refined to better capture the spray and wave effects on the free surface. The inlet and outlet boundary conditions are a velocity inlet and a hydrostatic pressure outlet, respectively. Turbulence intensity, defined as the percentage ratio of the flow rate variation with respect to the average flow rate (root mean square), and turbulent viscosity ratio, a quantity directly proportional to the turbulent Reynolds number, have been set to 0.01 and 10, respectively, considering we are dealing with towing tank tests in calm water (Fluent manual (2025)). Since the yaw angle (rotation about the z-axis) is zero, only half of the model has been solved with a symmetry boundary condition (yellow surface of Fig. 13a). The domain extension has been related to the fuselage length, l_f . After several attempts, a domain size of $10 l_f$, $2 l_f$, and $3 l_f$ in the x, y, and z directions, respectively, has been chosen. For the solution of the RANS equations, the k- ω SST turbulence model, first developed by Menter (1994), and the implicit scheme of the Volume Of Fluid (VOF) method to capture the free surface effect have been adopted. The spatial discretization has been modelled with the second order accuracy, and all the simulations have been run under steady state conditions. The wall y+ value of the first cell has been chosen close to 30. In principle, the evaluation of the viscous component of the forces in the x and z directions (the leeway is not considered so that the y component of the force is zero) requires the solution of the viscous sub-layer with ideally the wall y+ values of the first cell lower than 1, as in (Saporito et al., 2020) where a 2D systematic analysis of foil sections has been carried out with meshes ranging from 0.4 to 6.5 million cells and y+ close to 0.1. In the present 3D study, however, the number of cells would increase dramatically beyond the available hardware resources, and no grid independence study could be carried out. Although the experimental tests cover a wide range of trim angles, in the present investigation the trim angle has been set to zero. With zero trim, the leading edge of the mast is perpendicular to the board, which represents the default fitting (mast-to-board) and in this configuration, both the front and back wings generate positive and negative lift, respectively. As noted previously, the speed range (marginal speed) indicates a critical

Table 4

Mesh element size (component A1).

max element [mm]	Wall [mm]	Edge [mm]	water plane [mm]	N. of cells [-]
70	2	1	12	1.36E+07
80	5	1	18	6.72E+06
90	10	1	40	3.47E+06
120	15	1.5	80	1.72E+06

condition for initiating foiling, and knowledge of the generated lift for each speed is crucial for racers.

5.3. Verification and validation (V&V)

Roache (1998) introduced the V&V in a very clear way: The Verification step answers the question: “are we solving the equations, right?”, whereas Validation answers the question: “Are we solving the right equations?” During Verification, the problem is faced from the numerical point of view (numerical errors/uncertainties estimation), while during Validation, the problem is faced from the engineering point of view (modelling errors/uncertainties estimation). In this paper, the V&V process following the ITTC guidelines (ITTC, 2017) has been applied at the lowest investigated speed. The methodology is based on the definition of the simulation numerical uncertainty, U_{SN} , which mainly depends on the grid discretization uncertainty, U_G , and on the iterative uncertainty, U_I , with the following eq. (8):

$$U_{SN} = \sqrt{U_G^2 + U_I^2} \quad (8)$$

Since well-converged solutions have always been achieved with residuals of the order of $O(10^{-5})$, iterative uncertainty can be neglected in the formulation (Eca and Hoekstra, 2006), so a systematic grid refinement, according to Zou and Larsson (2014), has been carried out. Once the coarsest grid providing a stable solution is solved, three other similar grids have been generated, each time doubling the number of cells. With a minimum of four grids, the more efficient Least Square Root (LSR) method can be used to perform the fitting of the numerical solution (Eca and Hoekstra, 2014).

The validation of the model requires that the error, E, between experimental, D, and numerical, S, values be lower than the validation uncertainty, U_{val} , according to the following eq. (9):

$$|E| = |D - S| < U_{val} \quad (9)$$

where U_{val} depends on the experimental, U_D , and numerical, U_{SN} , uncertainties:

$$U_{val}^2 = U_D^2 + U_{SN}^2 \quad (10)$$

Table 5
Uncertainty of resistance and vertical lift at different grid resolutions.

N cells	h _i	F _x	U (F _x)	U%(F _x)	F _z	U (F _z)	U%(F _z)
[-]	[-]	[N]	[N]	[-]	[N]	[N]	[-]
1.36E+07	1	13.65	0.10	0.8%	81.32	1.40	1.7%
6.72E+06	1.27	13.71	0.16	1.2%	81.30	1.31	1.6%
3.47E+06	1.58	13.78	0.26	1.9%	81.26	1.61	2.0%
1.72E+06	1.99	13.88	0.38	2.8%	82.50	3.08	3.8%

The next Table 4 shows the adopted meshing parameters (according to the definition previously given in component A1) and the corresponding number of volume cells.

Table 5 shows the result of the verification process, and Fig. 14 shows the corresponding regression curves according to the LSR method. S_i is the solution of the i -th simulation and $h_i = \sqrt[3]{N_1/N_i}$.

Although the grid uncertainty is low for both resistance and lift, the model is validated for lift only. In fact, according to equation (10), and considering the grid with 3.47 M cells, one can write:

$$|E| = |-1.95\%| < U_{val} = 2.65\% \quad (12)$$

5.4. Mechanical properties

The official website of the iQFOIL association gives information about the materials and properties of the wings, mast, and fuselage. The latter is made with an aluminium alloy whose mechanical properties are well known. The mast (<https://iqfoil.star-board.com/equipment/iqfoil-class>) “is built with 44 layers of ultra-high modulus pre-preg carbon fibre”. More information on the mechanical properties of the carbon wings is unavailable. For that reason, preliminary experimental tests were carried out on the front wing by fixing the central connecting section of the wing in a perfectly horizontal position and applying

Table 6
Deflection and standard deviation for point 1 (at 1/2 span position).

Load [N]	10	20	37	50	75
Deflection (mean value) [mm]	0.112	0.247	0.469	0.616	0.926
Standard deviation [mm]	0.002739	0.010954	0.007416	0.01084	0.0251

increasing vertical loads to both wing tips within the purely elastic regime, as shown in Fig. 15a).

Each load level, ranging from 10 to 75 N as reported in Table 6, was tested three times. The resulting deflection at the wing tips was measured using a micrometer with a precision of one hundredth of a millimetre at two different points on each side, as illustrated in Fig. 15 b). The mean values of the deflections were calculated along with their standard deviations and reported in Tables 6 and 7.

The experimental results were then replicated numerically by varying the Young's modulus (E) of an isotropic material with a Poisson's ratio (ν) = 0.25 until a value that accurately matched the experimental data (with a difference in displacement less than 5% between numerical and experimental results) was found. The estimated E was 67 GPa, which is close to the nominal value for a high-modulus carbon composite laminate in the Ansys materials database. Fig. 16 shows a comparison between the experimental and numerical deflection values for the considered points with the numerical values obtained using $E = 67$ GPa and $\nu = 0.25$.

5.5. Numerical results

All the analyses have been run with the medium mesh size

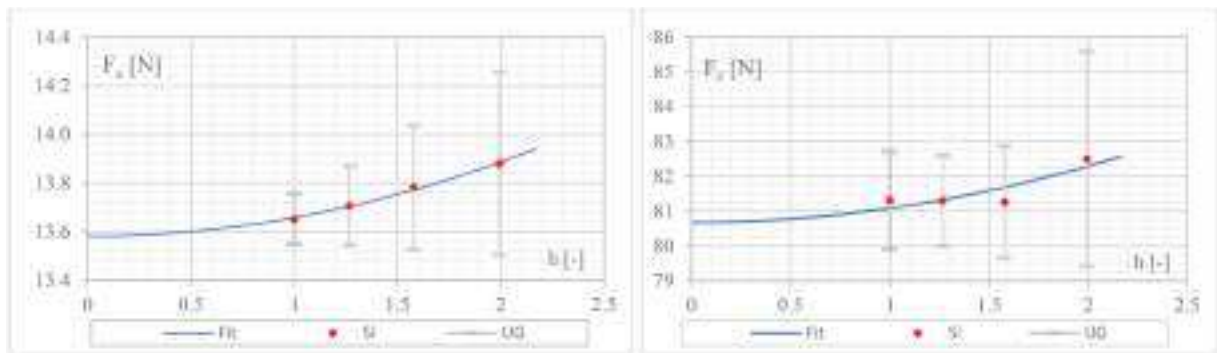


Fig. 14. Regression curves of resistance F_x (left) and vertical lift F_z (right).

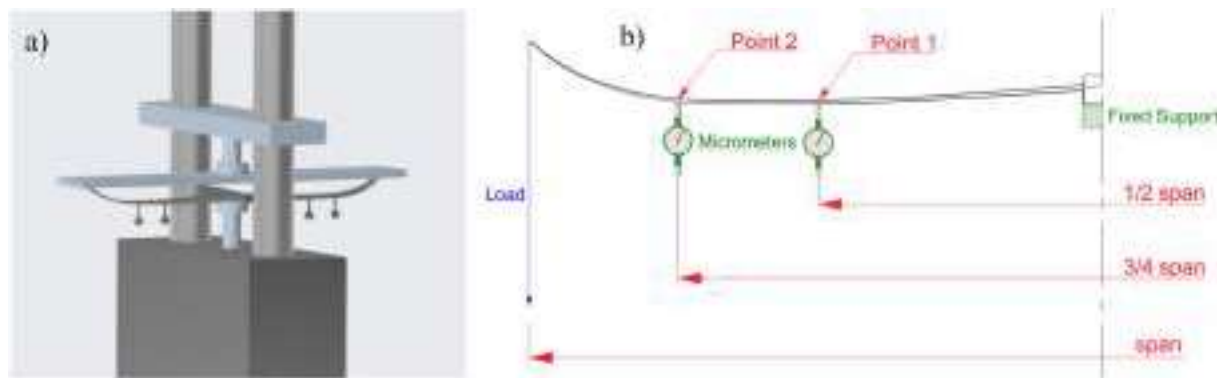


Fig. 15. Experimental test scheme. a): General arrangement; b): scheme details.

Table 7Deflection and standard deviation for point 2 (at $\frac{3}{4}$ span position).

Load [N]	10	20	37	50	75
Deflection (mean value) [mm]	0.305	0.655	1.255	1.648	2.432
Standard deviation [mm]	0.020817	0.023805	0.01291	0.020817	0.023805

(3.47E+06 cells) since the grid uncertainty is low enough to compare results. At each speed, starting from 1 m/s to 7 m/s (with a step of 1 m/s), the resulting deformed shape has been rebuilt with the CAD modeller and analysed with CFD and FEM, closing the loop described in Fig. 12. To achieve a fully coupled and stable solution, three inner iterations (exchanging loads and deformations between CFD and FEM solvers) have been enough to obtain differences between the calculated forces well below 1%.

The following Fig. 17a–b shows the drag F_x and the lift F_z force components obtained experimentally (see Equations (4) and (5)) and numerically estimated, for both the undeformed and iteratively deformed models. It is interesting to note that the undeformed and the iteratively deformed resistances are practically overlapping (Fig. 17a). A different behaviour can be observed in Fig. 17b, for which the experimental and iteratively deformed vertical lift (F_z) are in excellent agreement.

Similar results in terms of aerodynamic behaviour were reported by Martínez-Barberá et al. (2026); however, the observed differences in lift and drag were attributed to limitations of the numerical model, particularly the turbulence modelling approach and the absence of free surface effects. The authors did not account for foil deformation, which may instead help explain the discrepancies, especially regarding the lift force. As expected, the mean difference between experimental and numerical resistance, shown in Fig. 17a, is about 30%. As noted earlier, the reason for that difference lies in the unresolved boundary layer that mostly influences the viscous component of the forces, hence the resistance F_x . From a practical point of view, this difference does not affect the meaning of the results. In fact, Table 8 shows the comparison of the resultant forces developed by the front and back wings for both deformed and undeformed shapes at all the simulated speeds. The forces have been split into their main components: pressure and viscous, and it

can be observed that the viscous component of the force F_z has been neglected, being close to zero for all surfaces. The increased values of drag and lift of the deformed shape are mostly due to pressure effects; in fact, the viscous components of both shapes are almost identical. Moreover, there is always an order of magnitude difference between the z and x components of the forces. From the data in Table 8, the vertical lift F_z shows that the higher the speed, the more the deformed front wing pushes up, and the less the deformed back wing pushes down.

This phenomenon can be appreciated in Fig. 18, which shows the contours of the pressure coefficient (C_p) at different velocities. The upper views show the contour of the upper surfaces of both wings, while the lower views show the contours of the lower surfaces. Both the undeformed (left side) and deformed (right side) contours are shown for a better visual comparison. At 3 m/s (Fig. 18a), there are no appreciable differences between the shapes. At 5 m/s, the suction effect of the front wing becomes evident in the deformed contour. At the higher speed of 7 m/s (Fig. 18b), both suction and pressure effects are more relevant in absolute values in the deformed shape of both wings.

Although these differences can be visually appreciated from the previous contours, Fig. 19a–b shows the pressure coefficients C_p at the speed of 7 m/s along the normalized chords (x/c) at $y = 0.15$ m. The continuous lines refer to the upper side of the sections, while the dashed lines refer to the lower side. The red lines are for the iteratively deformed geometry, while the grey ones are for the undeformed configuration. The pressure coefficient of the front wing (Fig. 19a) decreases on the upper surface, while increasing on the lower one. This phenomenon starts from the leading edge, and it is visible for about 60% of the chord. As noted earlier, the back wing is mounted upside down, so that the opposite behaviour, with respect to the front one, can be observed in Fig. 19b.

At low speed, the structural deformation induced by the applied pressure field is very low, but as the speed increases, the deformation increases too. In fact, in the following Figs. 20, 21a and 21b, the deformations induced by the pressure field at all surface key points, obtained by FEM static structural results, are presented for two speeds and compared to the results of the one-way FSI analysis. Fig. 20 shows the fuselage deformations (as defined in section 3.2).

The blue line of Fig. 20 shows the deformation of the fuselage at 1 m/s, which is practically zero at all points, while the red line shows the one corresponding to the iteratively deformed shape at 7 m/s (the curves at intermediate speeds lie in between). It can be observed that the forward point of the fuselage (at $x = -460$ mm) moves up by about 13 mm while

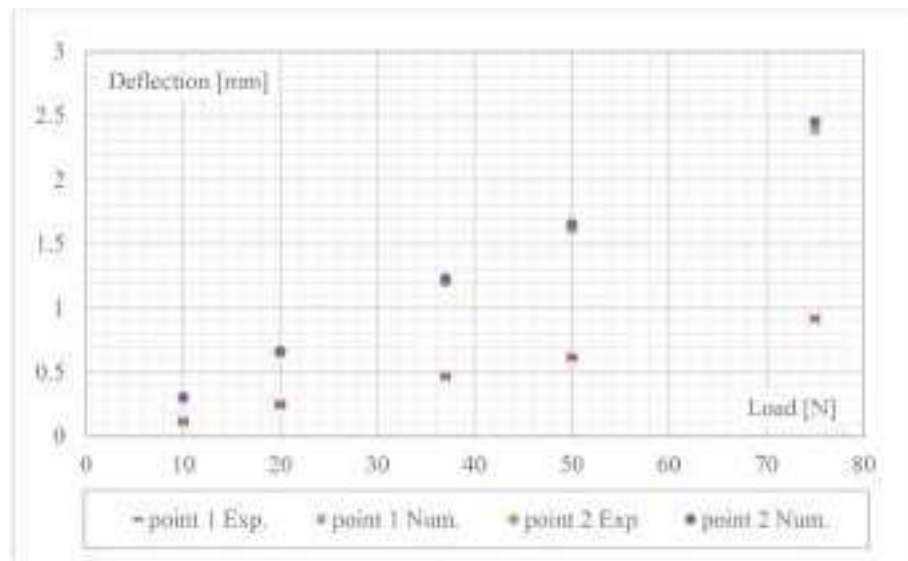


Fig. 16. A comparison between deflection obtained with the experimental campaign (mean values) and numerical values obtained with $E = 67$ GPa $\nu = 0.25$, for point 1 and point 2.

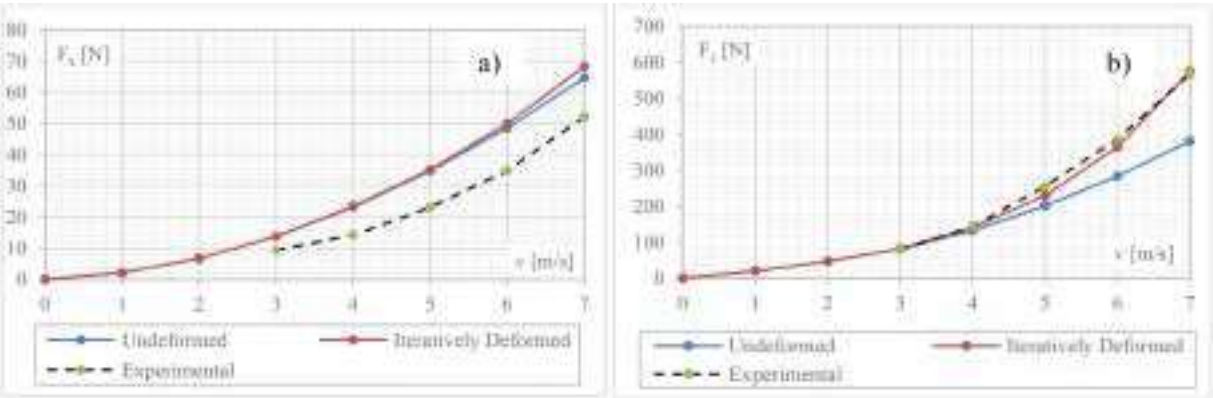


Fig. 17. Experimental and numerical a) drag (F_x) and b) lift (F_z) at different velocities.

Table 8
Pressure and viscous components of the forces.

		Undeformed				Iteratively Deformed			
		Fx [N]		Fz [N]		Fx [N]		Fz [N]	
		pressure	viscous	pressure	viscous	pressure	viscous	pressure	viscous
3 m/s	Front	2,2	4,4	83,4	0	2,2	4,4	84,6	0
	Back	0,6	1,4	-16,6	0	0,4	1,4	-16,8	0
4 m/s	Front	5,4	7,4	150	0	4	7,4	158,6	0
	Back	1,4	2,4	-32	0	0,8	2,4	-33,2	0
5 m/s	Front	7,4	11	239	0	6,4	11	263,8	0
	Back	1,6	3,6	-55,8	0	1,2	3,6	-53,6	0
6 m/s	Front	9,8	15,2	346,8	0	10	15,2	419	0
	Back	2,2	4,8	-83,4	0	1,4	4,8	-77,6	0
7 m/s	Front	12,8	20,2	474,6	0	17,8	19,6	645,4	0
	Back	2,6	6,4	-116,8	0	1,8	6,4	-101,8	0

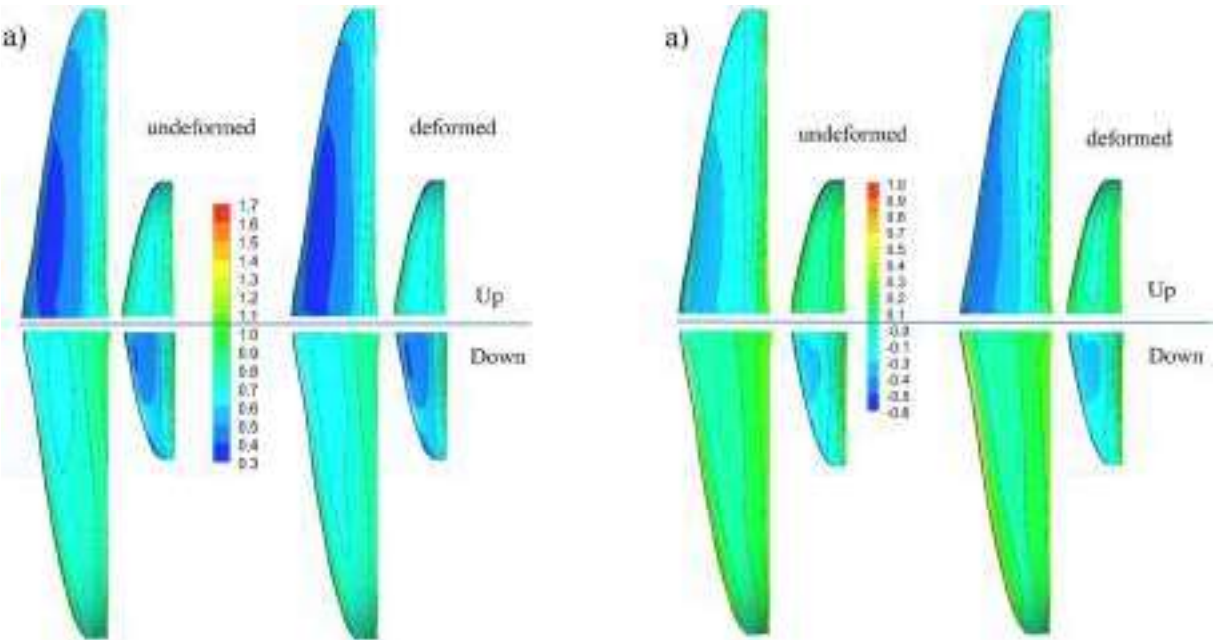


Fig. 18. Pressure coefficient at a) 3 m/s and b) 7 m/s, for front and back wings both undeformed and deformed.

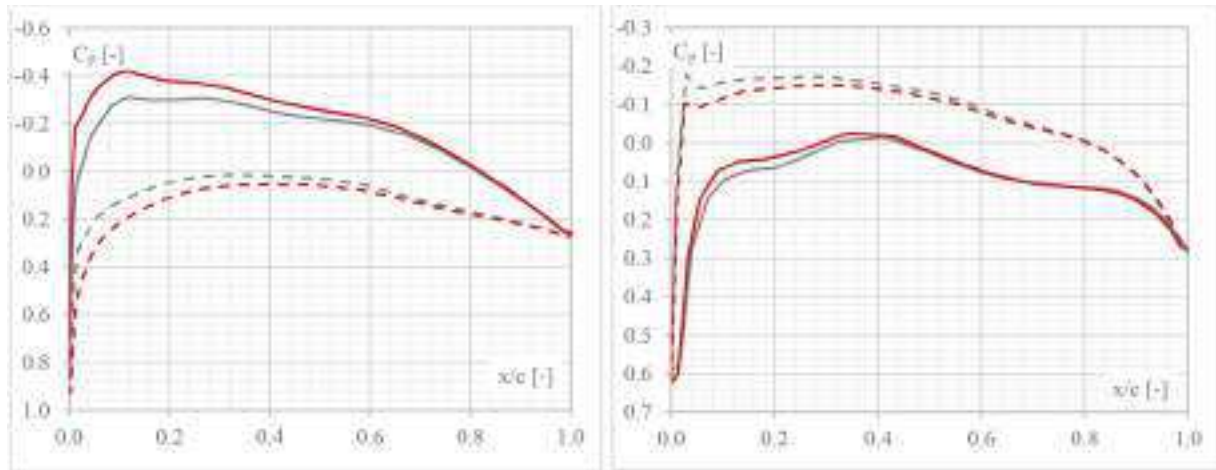


Fig. 19. Pressure coefficient at a section plane, at $y = 0.15$ m, with 7 m/s, of the a) front wing and b) back wing. Continuous lines for the upper side, dashed lines for the downside, red lines = iteratively deformed shape, grey lines = undeformed shape. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

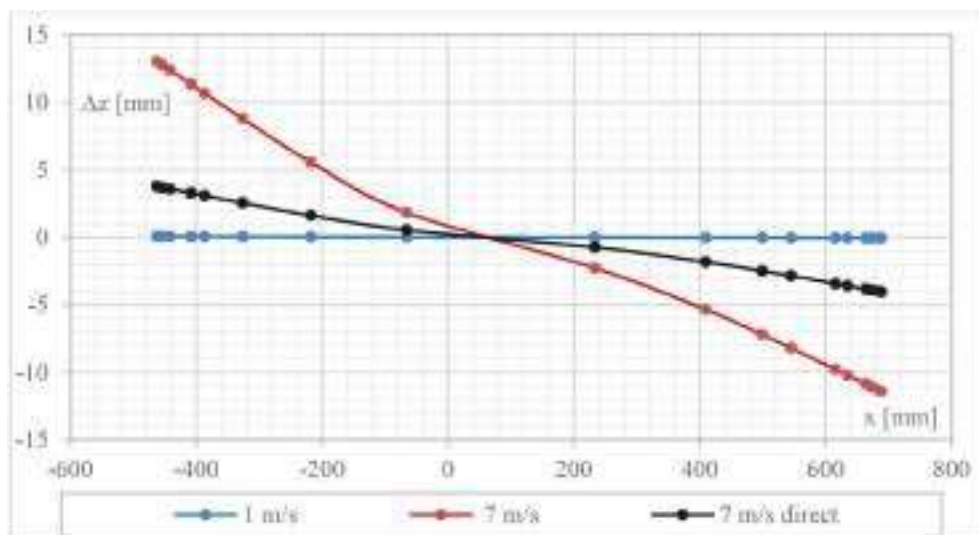


Fig. 20. Deformations of the fuselage key points at 7 m/s.

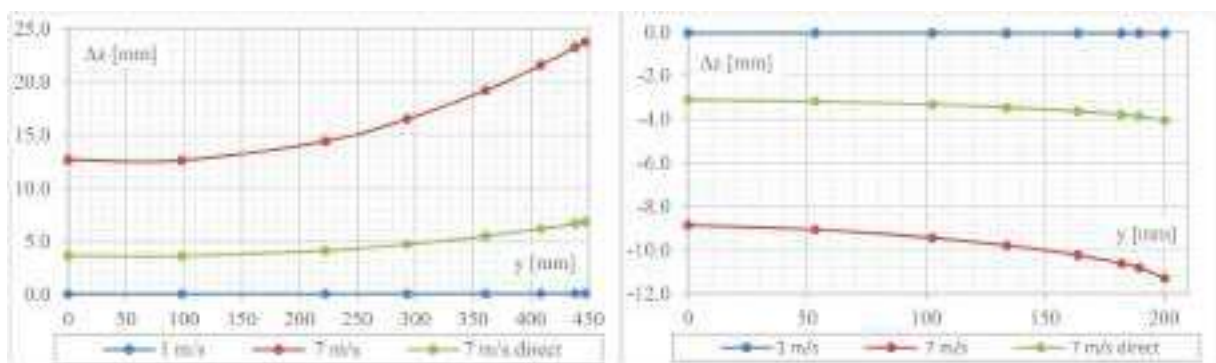


Fig. 21. Deformations of the a) front wing and b) back wing, key points at 7 m/s.

the backward point (at $x = 688$ mm) moves down by about 11 mm. Note that the black line represents the deformed fuselage obtained by loading the undeformed shape directly with the pressure field estimated at 7 m/s

(straight one-way FSI). It shows a very different behaviour with respect to the one obtained with the iterative procedure, giving rise to an underestimation of the actual deformation. Similar considerations can be

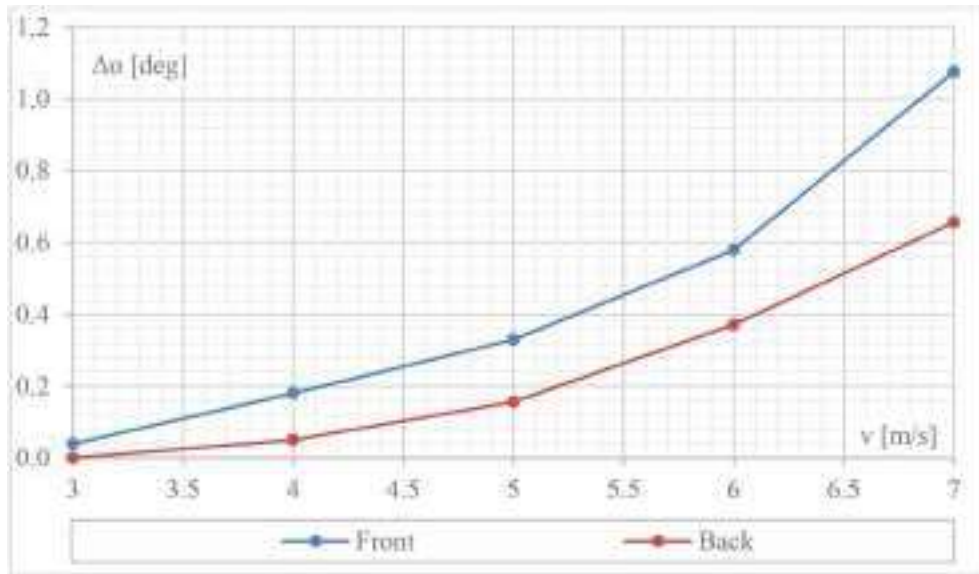


Fig. 22. Variation of the trim angle of the iteratively deformed wings.



Fig. 23. Undeformed shape (grey) and iteratively deformed shape in true scale (red) at 7 m/s. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

made as far as the front and back wings, as shown in the following Fig. 21a–b.

Concerning Fig. 21a, from the root of the front wing (which is fixed to the fuselage) to its tip, a continuous deformation can be observed with a maximum deflection of about 11 mm (from 13 mm at the root to 24 mm at the tip). Being the span of the back wing and the related pressure load lower than the front ones, the behaviour in Fig. 21b is the same as Fig. 21a, but with lower absolute values. Because of these deformations, the actual trim angle is quite different from the theoretical one, by a $\Delta\alpha$ as can be observed in Fig. 22. This variation, which is always positive, causes an increase in the actual trim angle of the front wing and a decrease in that angle for the back one (being mounted upside down). This trim variation scarcely influences the resistance

curves of the deformed and undeformed shapes, as can be seen in Fig. 17a. This is not a surprise, since the sections of both the front and back wings work in the so-called laminar bucket for which the resistance is scarcely influenced by the angle of attack (the trim angle). On the contrary, the vertical lift is largely influenced by the trim angle, and this is the reason why the experimental and iteratively deformed lift curves shown in Fig. 17b are in good agreement.

This effect can be appreciated in Fig. 23, which shows, at full scale, the undeformed and the iteratively deformed shapes obtained at the final speed of 7 m/s. It is evident that the trim angle for the front wing increases, while that of the back wing, being mounted upside down, decreases.

Figs. 24 and 25 show the velocity contour at 7 m/s on a plane at $y = 0.15$ m for both the undeformed and deformed shapes. The spray surrounding the mast is also shown. Some differences can be visually appreciated, particularly from the close-up of the wings. The alteration of the velocity flow field of the deformed shape is more relevant for the front wing, in agreement with the increased actual trim angle, as shown in the previous Fig. 22.

Finally, Fig. 26 shows a qualitative comparison of the experimental and numerical wake and wave patterns. It can be observed that the rooster tail created by the mast, shown in a picture from the towing tank test at a speed of 7 m/s, is of almost equal length as the numerical one, and the shape seems well captured. The wave formation around the mast and in the faraway region are very similar qualitatively, but it is not possible to compare the exact values of the surface elevation from these experiments. In this respect, the numerical simulations are a preferable tool to analyse all flow properties and partial results (pressure field, velocity field, etc) and not only the final forces acting in one direction.

Concerning the stiffness of the foil, the equivalent stress (von Mises), defined as:

$$\sigma_{eq.} = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}} \quad (12)$$

where σ_i are the principal stresses ($i = 1, 2, 3$), has been mapped in Fig. 27 at the maximum speed of 7 m/s.

The maximum value occurs close to the leading edge of the mast to fuselage joint, and its value (120 MPa) is approximately 6 times lower than the typical carbon composite yield stress (~ 800 MPa). It is interesting to note that the actual deformation also influences the equilibrium behaviour. In fact, the x coordinate of the projected centre of

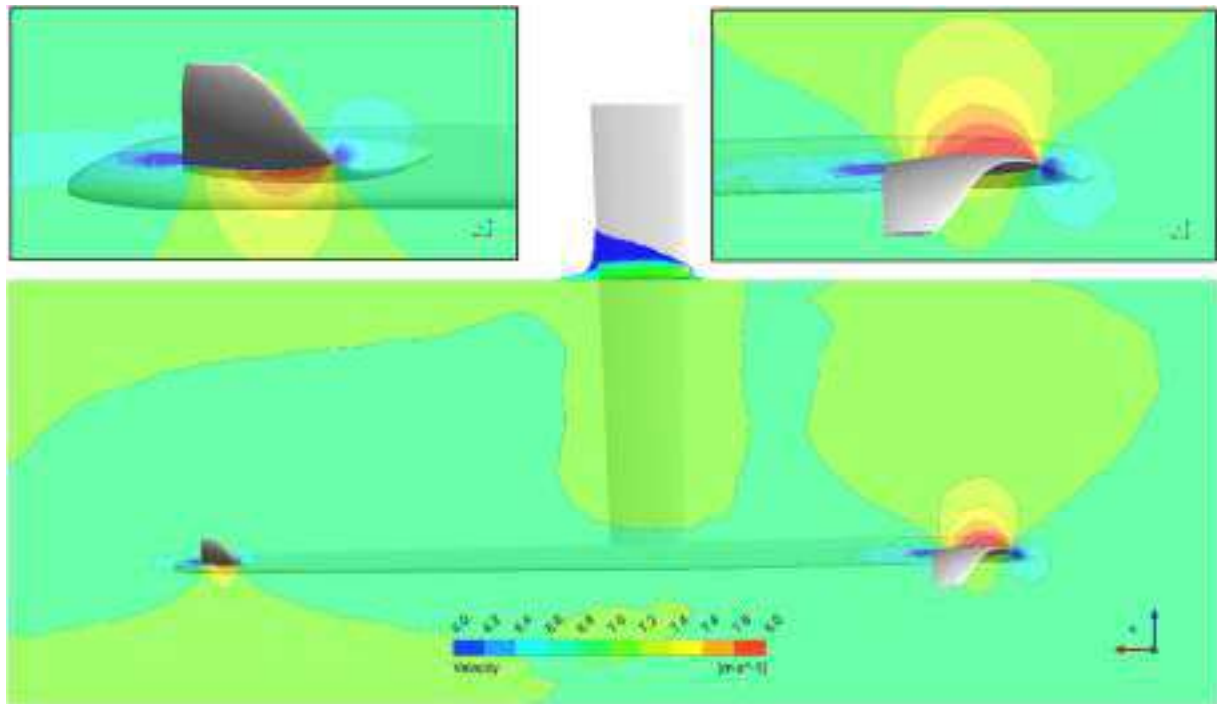


Fig. 24. Velocity contour at the section plane $y = 0.15$ m. Undeformed shape at 7 m/s.

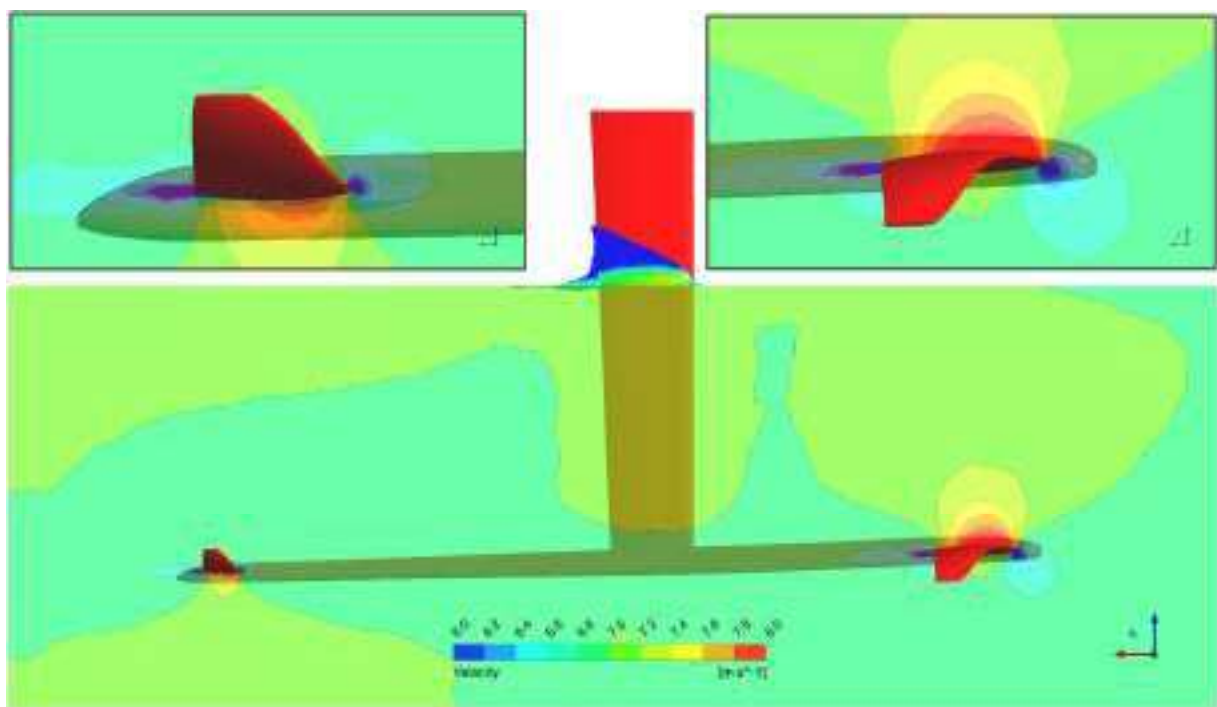


Fig. 25. Velocity contour at the section plane $y = 0.15$ m. Iteratively deformed shape at 7 m/s.

pressure on the water plane ($z = 0$) moves differently between the undeformed and deformed shapes, as shown in the next Fig. 28.

While the undeformed centre of pressure moves monotonically toward negative values of the x coordinate (i.e., toward the front wing), as expected, the deformed one shows a minimum value at approximately 5 m/s. This effect is strictly related to the variation of the actual trim angle and should be considered in the whole aero/hydro equilibrium.

6. Conclusions

The integrated experimental and numerical investigation presented in this work provides a comprehensive assessment of the hydrodynamic performance of the iQFOiL Olympic-class foil system. The full-scale (1:1) experimental campaign yielded reliable lift and drag measurements over a range of trim angles and speeds representative of the marginal conditions for initiating foiling, establishing a robust benchmark for future CFD validation and the development of athlete training strategies. The

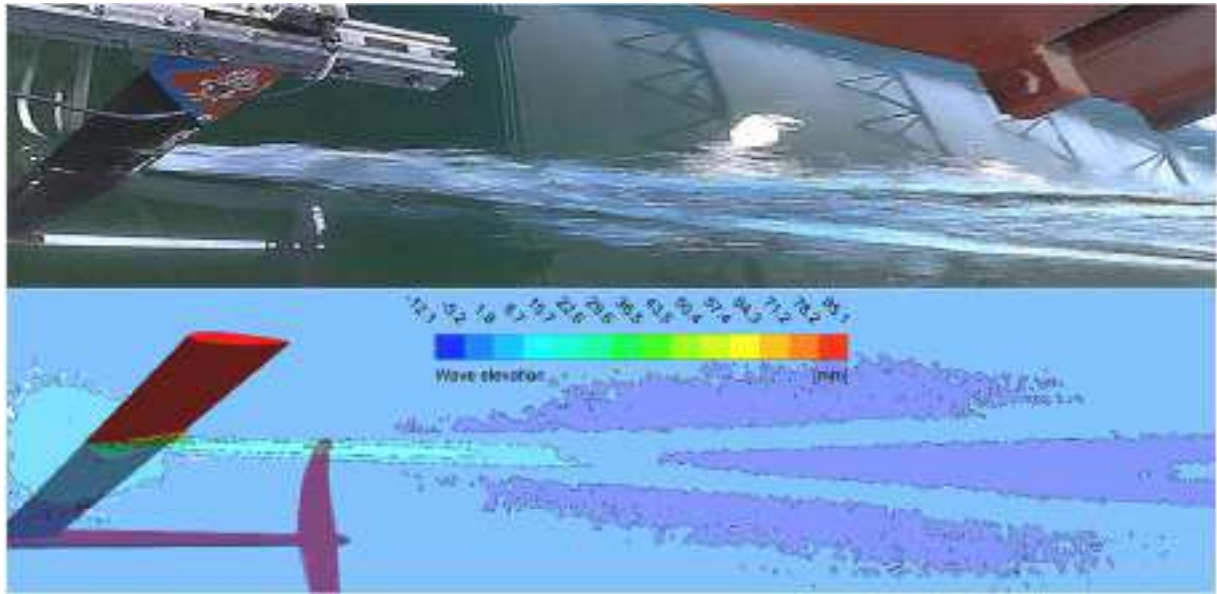


Fig. 26. Wake and wave pattern, by experimental test (up), CFD simulation (down) at 7 m/s.

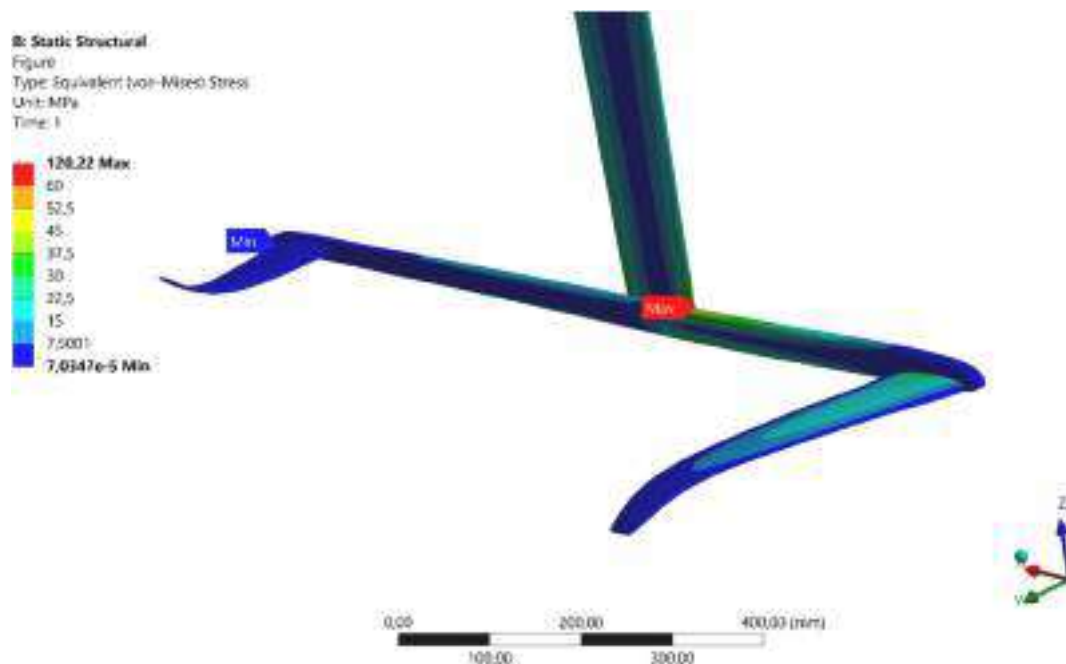


Fig. 27. Equivalent von Mises stress of the deformed shape at 7 m/s.

repeatability of the measurements confirms the reliability of the proposed experimental methodology despite the limitations imposed by the towing tank maximum speed and the characteristics of the six-component load cell.

The agreement between the experimental measurements and the fluid structure interaction simulations demonstrates that structural deformation plays a key role in the accurate prediction of lift and should therefore be accounted for in numerical analyses of hydrofoil performance. Conversely, the results indicate that the influence of structural deformation on drag is negligible for the investigated operating conditions, whereas the accuracy of drag prediction is mainly controlled by the resolution of the computational mesh. While the adopted numerical setup successfully reproduced the overall drag behaviour, a finer mesh would be required to achieve quantitative agreement with the

experimental measurements.

Although the investigation was limited to zero heel and zero leeway conditions, the methodology can be readily extended to more realistic sailing conditions. Future work will therefore focus on a systematic numerical investigation including heel angle, leeway angle and foil immersion depth, aimed at identifying optimal sailing configurations.

CRedit authorship contribution statement

E. Begovic: Data curation, Methodology, Validation, Writing – review & editing. **C. Bertorello:** Conceptualization, Data curation, Methodology, Supervision, Writing – review & editing. **A. Cirello:** Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **A. Mancuso:** Conceptualization,

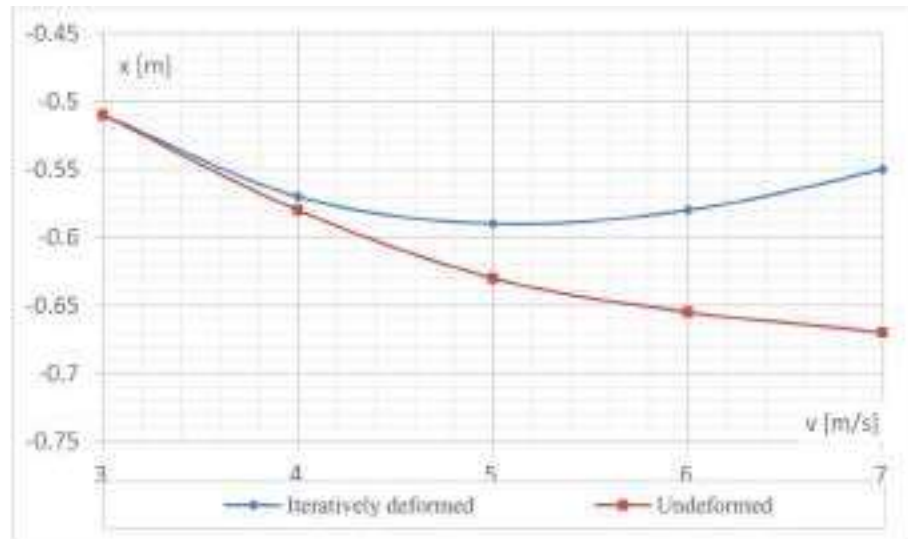


Fig. 28. Longitudinal distance of the centre of pressure from the origin (x) vs velocity.

Formal analysis, Investigation, Methodology, Writing – review & editing. V. Ricotta: Data curation, Software, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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