

PIV Investigation of Aerodynamic Flow Interaction between Eppler 61 Wing Sails and a Cargo Ship Deck

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ABSTRACT

The maritime industry is increasingly adopting wind-assisted ship propulsion (WASP) systems to displace fossil fuel dependency, reduce operational fuel consumption, and curtail greenhouse gas emissions in compliance with international environmental mandates. Among these technologies, rigid wing sails offer exceptional potential for enhancing propulsive efficiency due to their high lift-to-drag characteristics. This work presents a comprehensive experimental investigation exploring the aerodynamic flow patterns generated over a simplified mid-sized cargo ship deck equipped with three rigid wing sails arranged in a tandem configuration. Moving beyond traditional marine geometries, the sails are based on the high-performance Eppler 61 aeronautical airfoil, selected for its advantageous characteristics within low Reynolds number regimes. Experimental data were registered through a Particle Image Velocimetry (PIV) system in the T1 low-speed wind tunnel facility at the National Institute for Aerospace Technology (INTA), Spain, using a 1:150 scaled model. Flow diagnostics were performed at a freestream velocity of 15 m/s. The experimental tests evaluated five apparent wind angles ($\beta = 15^\circ, 30^\circ, 45^\circ, 65^\circ, 80^\circ$) under wing-sails angle of attack ($\alpha = 0^\circ, 5^\circ, 10^\circ, 15^\circ$). The PIV analysis characterized the non-dimensional velocity fields and turbulence intensity contours to capture sail-to-sail aerodynamic interactions. The results confirmed that the array contributes positively to propulsive generation, generating velocity peaks on the suction side of the wing-sails. However, some aerodynamic interferences have been founded, resulting in a velocity peak reduction between 2.1% and 13.3% for the second sail. At the highest angle of attack ($\alpha = 15^\circ$), flow detachment and stall were captured on the rear part of the first sail's suction side. These experimental data provide essential information for maximizing multi-sail propulsive efficiency and optimizing future sustainable commercial vessels.

1. Introduction

The maritime transport sector constitutes the backbone of international commerce, facilitating over 90% of global trade volume. However, this massive logistical network heavily relies on the combustion of heavy fuel oils for propulsion, rendering it a major contributor to anthropogenic greenhouse gas (GHG) emissions and atmospheric pollutants. In response to mounting environmental concerns and tightening international regulatory frameworks mandated by the

International Maritime Organization (IMO) to achieve net-zero targets, the shipping industry is under unprecedented pressure to accelerate its decarbonization strategies. Consequently, wind-assisted ship propulsion (WASP) systems have re-emerged as a highly promising technological solution to displace fossil fuel dependency and curtail operational emissions by directly harvesting renewable aerodynamic energy.

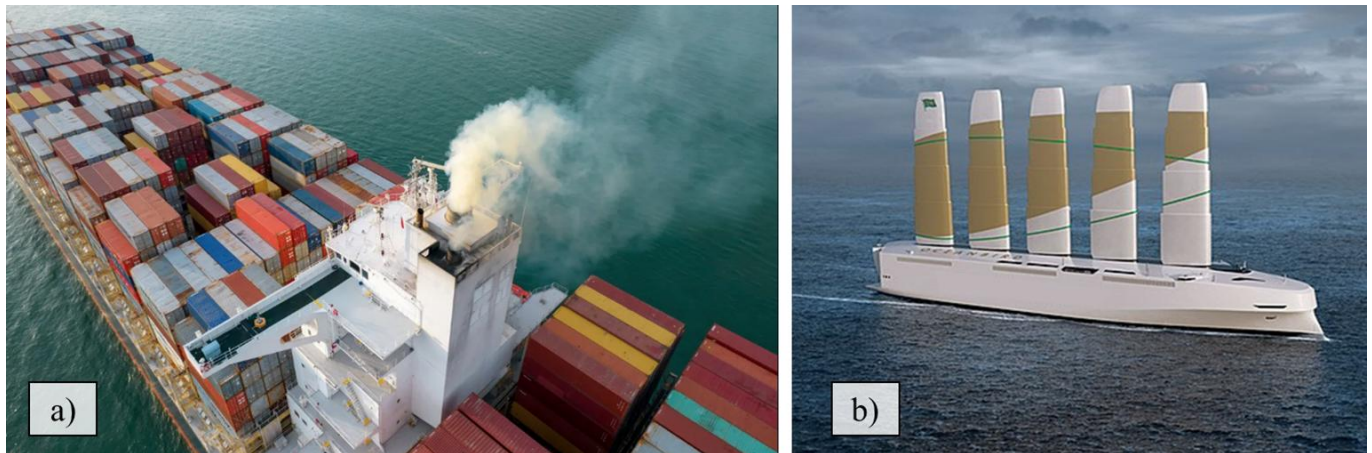


Figure. 1 a) Cargo whips with containers b) Experimental ship with wing sails.

Among the various wind propulsion variants, rigid wing sails have garnered substantial academic and industrial interest owing to their superior aerodynamic efficiency and lift-to-drag characteristics compared to conventional soft sails. The foundational commercial viability of rigid wings was demonstrated in the 1980s with the landmark deployment of the Japan Marine Machinery Development Association (JAMDA), yielding fuel savings approaching 30% under optimal wind regimes (Ouchi et al., 2013). In recent years, researchers have extensively leveraged advanced computational fluid dynamics (CFD) to optimize these structures. For instance, Atkinson and Binns (2018) conducted detailed numerical simulations to evaluate the airflow patterns, drag mechanisms, and wake structures surrounding segmental rigid sails, highlighting the critical influence of the operational angle of attack on overall propulsive efficiency. Furthermore, multi-sail interactions have been explored by Yasuda et al. (2024), whose CFD analysis of multiple rigid wing sails underscored the highly non-linear, complex nature of sail-to-sail aerodynamic interference and its subsequent impact on net thrust generation alongside the ship hull. Similarly, recent investigations on multi-sail arrays have demonstrated that in-line layouts experience substantial thrust penalties due to wake interference, while experimental wind tunnel tests under the presence of representative bulk carrier hull forms have confirmed that sail-hull interactions significantly redistribute aerodynamic loads across the deck.

Numerical and experimental studies on tandem airfoils (such as the NACA 4412 or high-lift biomimetic airfoils) show that the interaction of vortices between the upstream and downstream airfoils significantly alters the wake size and delays or accelerates flow separation. Depending on the horizontal (gap) and vertical (stagger) distances, efficiency can improve or deteriorate drastically due to flow coupling. (Gong et al. 2025). A recent work analyzes interference effects of tandem configurations of rigid sails (Van Reen, 2026). It is demonstrated that an in-line layout can suffer thrust losses up to 6% due to wake interaction compared to isolated sails. Another relevant study of Fujiwara et al. 2005, uses wind tunnel testing to describe the effect of the bulk carrier hullform shape combined with four identical sails. It is concluded that the total comprehension of hull-sail and sail-to-sail interaction is essential due to the effect of longitudinal and lateral forces generated by this effect.

Using experimental results in wind tunnel, and specifically Particle Image Velocimetry (PIV) have become crucial in this field, as demonstrated in recent aeronautical studies for mapping micro-level boundary layer transitions and complex wake topologies that challenge conventional numerical closure models performed by Marciniuk et al. (2024). Despite these critical advancements, a significant gap remains in the literature regarding the geometric profiling of the wings. While historical and contemporary designs have relied heavily on traditional, symmetric, or low-complexity marine profiles, high-performance aerodynamic profiles derived directly from aeronautical applications represent a largely untapped frontier for maritime propulsion. Specifically, geometries such as the Eppler family of airfoils, which are meticulously engineered to maintain high lift coefficients under near-stall conditions and manage boundary layer transition regions, have never been thoroughly investigated in practical maritime contexts. Recognizing this potential, a preceding numerical study performed at INTA by Bardera et al. (2025) was conducted utilizing Unsteady Reynolds-Averaged Navier–Stokes (URANS) simulations to characterize the theoretical propulsive efficiency, boundary layer separation, and wake dynamics of a three tandem Eppler 61 wing sail configuration. The study computed aerodynamic forces under varying apparent wind angles (β) and sail angles of attack (α). The results indicated a potential to contribute positively to ship propulsion, with the case of $\beta = 65^\circ$ providing up to a 60% reduction in drag compared to the bare hull, and $\alpha \in [2^\circ, 6^\circ]$ were selected as the most favourable configuration in terms of drag reduction and lateral force generation, and were therefore proposed for future experimental validation in a wind tunnel.

While the initial numerical investigation using Eppler 61 geometry established a solid theoretical framework and demonstrated the aerodynamic potential of the wing-sails to increase ship efficiency, computational models require rigorous experimental validation. To address this limitation and advance the state of the art, the present study conducts a Particle Image Velocimetry (PIV) investigation of the aerodynamic flow interaction between Eppler 61 wing sails and a simplified cargo ship deck. By capturing velocity and turbulence fields within a wind tunnel environment, this work elucidates the flow topologies and wake structures of the aeronautical type wing-sails.

2. Experimental set-up

2.1. Cargo ship model

The present study is focused on wing-sails that can be installed on a generic prototype of a mid-sized cargo ship, scaled down to 1:150 to fit in the wind tunnel test section. The principal dimensions of the scaled ship model are detailed in Figure 2, with a total length $L_{OA} = 2\,000$ mm, and a beam $b = 300$ mm. Figure 2 also displays the wing-sails placed at the centerline plane of the cargo zone. They are based on Eppler 61 airfoils airfoil geometry, selected due to its advantageous aerodynamic characteristics within low Reynolds number regimes.

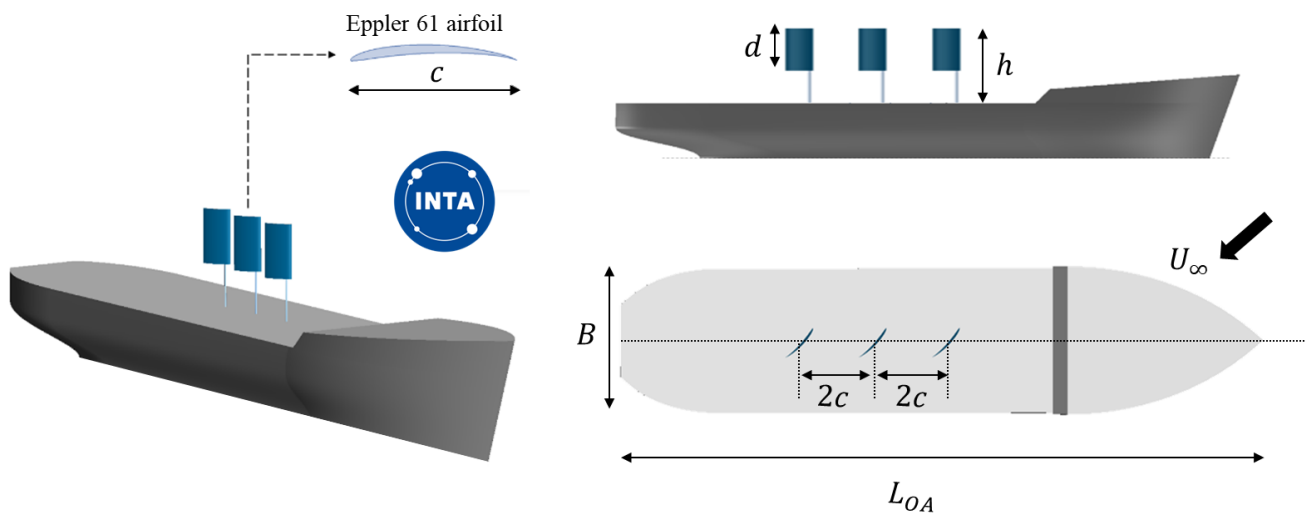


Figure. 2 Schematic representation of 1:150 scaled model dimensions of the Cargo ship with Eppler 61 Wing Sails.

The three sails have a cord $c = 67$ mm, a height $h = 260$ mm and a span $b = 130$ mm. They are separated $2c$ and leave a gap between the deck and the wing-sail to transport up to six vertically stacked containers without interferences with the sails. These dimensions of the scaled model satisfy geometric, kinematic, and dynamic similarity criteria, enabling a dependable extrapolation of aerodynamic performance data to full-scale conditions. Reynolds number associated with the hull and the sails are in turbulent regime ($Re > 10^5$), ensuring that transition effects are appropriately captured during wind-tunnel testing.

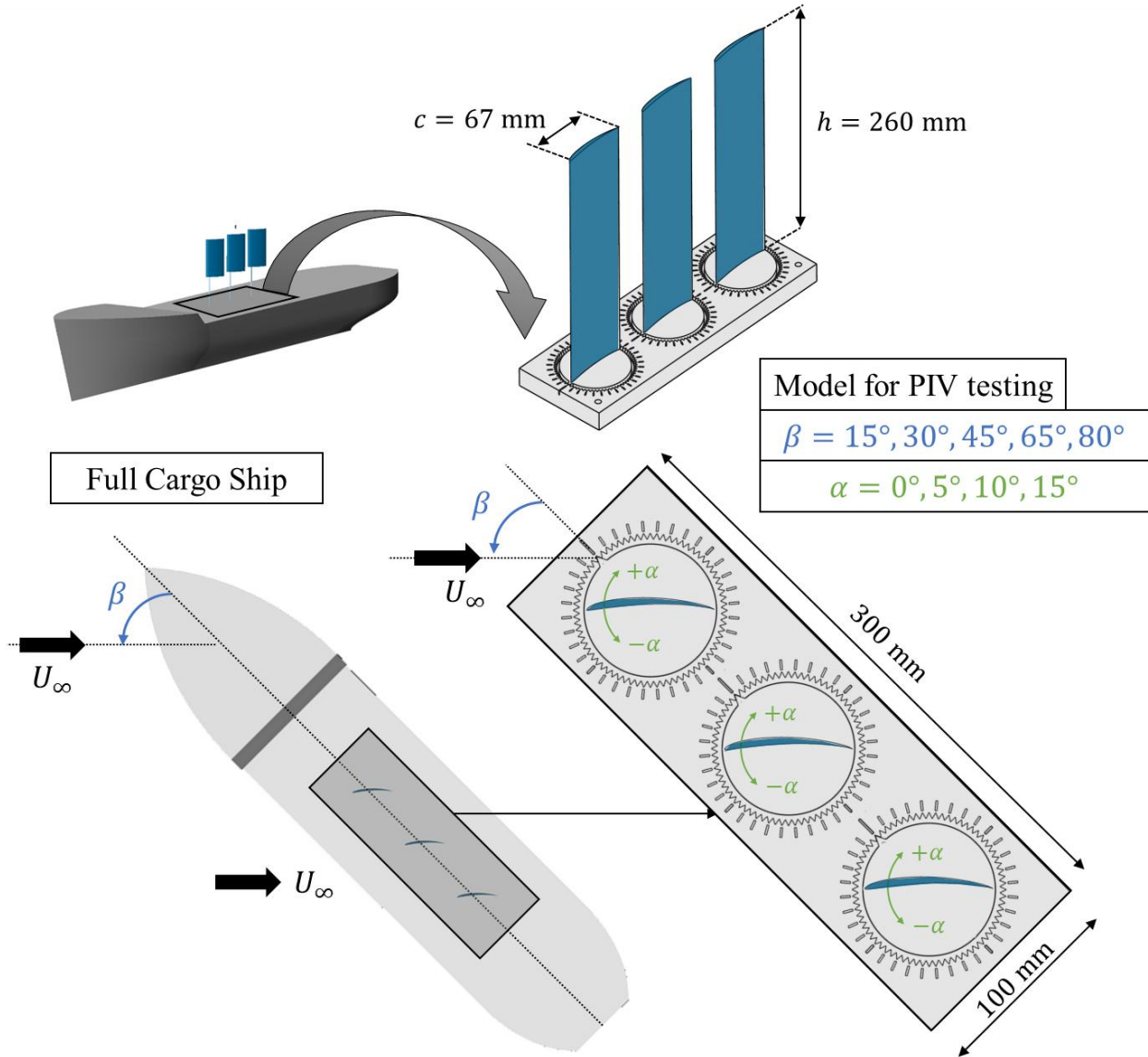


Figure. 3 Simplified model for Particle Image Velocimetry (PIV) wind tunnel testing.

Following the numerical study carried out using the same sails and the vessel (Bardera et al. 2025), a simplified model of the sails (Figure 3) will be tested in this first phase of experimental testing. This model allows to change the angle of attack of each wing-sail (α), and the apparent wind angle

(β) for the whole group. In order to work properly and generate lift, the leading edge of the sails must be oriented towards the relative airflow (U_∞), which is the sum of the ship's forward speed and the atmospheric wind component.

Then, during the experimental campaign, results with $\alpha = 0^\circ$ of the wing-sails and $\beta = 15^\circ, 30^\circ, 45^\circ, 65^\circ, 80^\circ$, will be obtained. After that, the values of the angle of attack of each wing-sail will be modified for $\alpha = 5^\circ, 10^\circ, 15^\circ$. Wind tunnel speed will be fixed to $U_\infty = 15$ m/s, that represents the combination between the forward velocity of the ship (10 m/s) and different lateral wind speeds (6 to 16 m/s) that vary the β angles tested.

2.2. Wind Tunnel and Particle Image Velocimetry (PIV)

The wind tunnel facility employed for the present study is the low-speed wind tunnel T1 of the National Institute for Aerospace Technology (INTA) in Spain (Figure 4 a). It has a closed-circuit with an open, elliptical test section with a cross-section of 2×3 m², in which velocities up to 60 m/s can be reached using a DC 420 kW motor operating at maximum power. The flow in the test section can maintain a freestream turbulence intensity below 0.5 %.

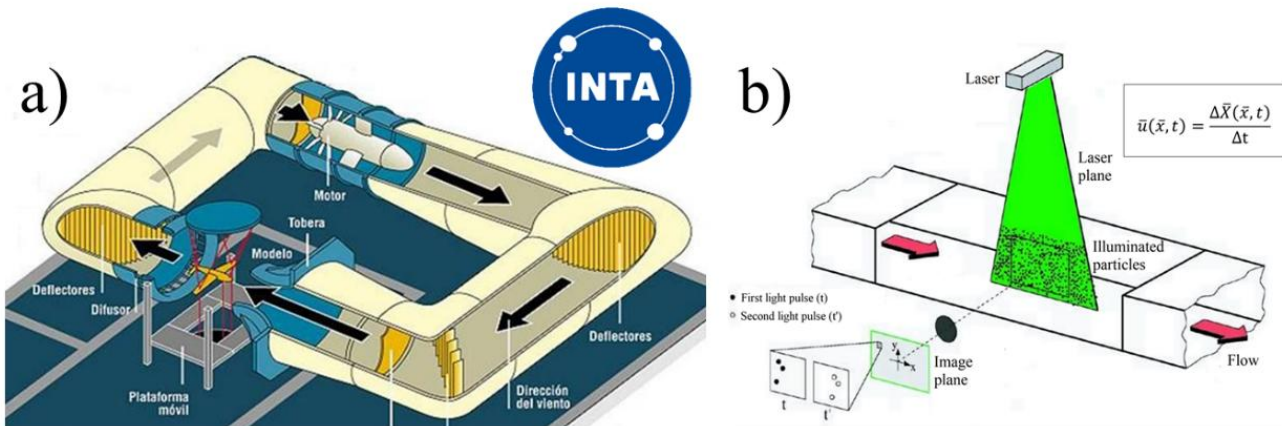


Figure. 4 Simplified model for Particle Image Velocimetry (PIV) wind tunnel testing.

The wind tunnel is equipped with a Particle Image Velocimetry (PIV) system (Adrian & Westerweel, 2011; Prasad, 2000; Raffel et al., 2018) to acquire flow visualizations and velocity fields around the models. For the PIV setup (Figure 5 b), the flow is seeded with olive oil small tracer particles of 1 μm in diameter and illuminated using a dual-cavity, neodymium-doped yttrium aluminum garnet (Nd:YAG) pulsed laser system, with a maximum energy output of 190 mJ per pulse. The laser pulses are synchronized with the captures of the high-resolution digital camera equipped with a $2048 \times$

2048 pixels Charge-Coupled Device (CCD) sensor. Given the precisely controlled time delay ($\Delta t = 25 \text{ us}$) between successive frames, a cross-correlation algorithm based on a two-dimensional Fast Fourier Transform (FFT) was utilized to compute the particle's displacement and the velocity vectors. The processing was performed using interrogation windows of 32×32 pixels with a 50 % spatial overlap. The ensemble-averaged velocity fields presented in this study were derived from 100 pairs of instantaneous images, averaged and processed into non-dimensional velocity contours using Tecplot 360 software.

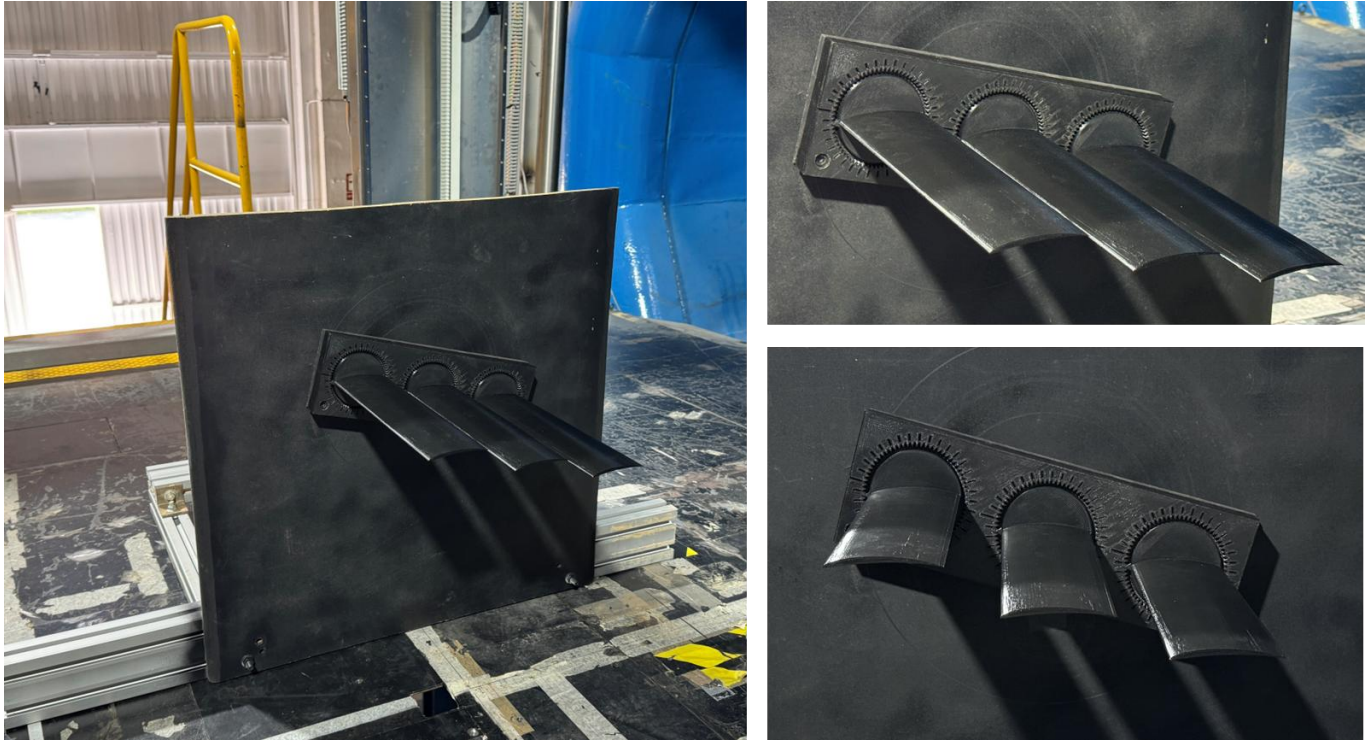


Figure. 5 3D Printed model of wing-sails at the wind tunnel test section.

Figure 5 displays the 3D printed model of the wing-sails placed at the wind tunnel test section for PIV testing. Since the PIV laser generates a vertical plane, the wing-sails were fixed to a vertical wooden board. This way, using the PIV system, velocity contours were extracted at a central section of the wing sails. Figure 6 presents a 3D view of the model and the laser plane right at $h/2$ of the total span of the wing sails. Using an adjustable camera lens, a field of view of $300 \times 300 \text{ m}^2$ was set for PIV data acquisition. The model has a rotation axis under the center sail to rotate the full model and select a specific apparent wind angle (β). Additionally, each wing-sail can also adjust its angle of attack (α), using a graduated scale for each 5° .

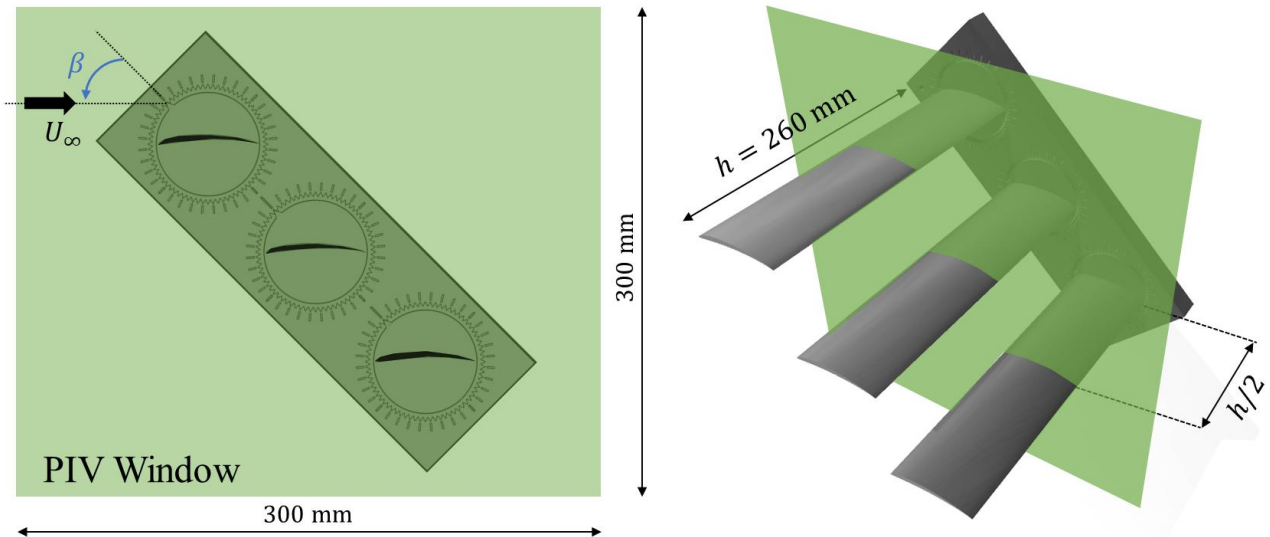


Figure. 6 PIV Plane for obtaining velocity contours of the wing-sails.

3. Results

3.1. Velocity Contours - $\alpha = 0^\circ$

Figure 7 displays the resultant velocity contours obtained con PIV for different apparent winds $\beta = 15^\circ, 30^\circ, 45^\circ, 65^\circ, 80^\circ$, and always maintaining the three leading edges of the three wing-sails aligned with the incident wind ($\alpha = 0^\circ$). In general, all cases presented demonstrate that the three wing-sails work and contribute to the wind-assisted propulsion of the ship. This is because in the five cases tested, the three wing-sails accelerate the flow on the upper part of the profile (suction side) that generates the lift. Additionally, it has been possible to capture the wake generated by each wing-sail, which can be directly correlated to the lift generation of the sails.

The $\beta = 15^\circ$, corresponds to the case where the wing-sails are closer between them. This means that each wing-sail generates acceleration on the upper side (suction side) and a clear interaction of the acceleration generated by the second sail with the wake of the first sail can be observed. The same happens with the third wing-sail with respect to the second one. When the apparent wind angle increases $\beta = 30^\circ$, the same patterns can be observed of flow acceleration and wake interaction along the second and the third sails. Situation substantially changes when $\beta = 45^\circ$ and $\beta = 65^\circ$, in which the suction side of the second and the third wing-sails seems not affected by the previously generated wakes. However, the width of the wake generated behind the first profile is bigger than of the second and the third wing-sail.

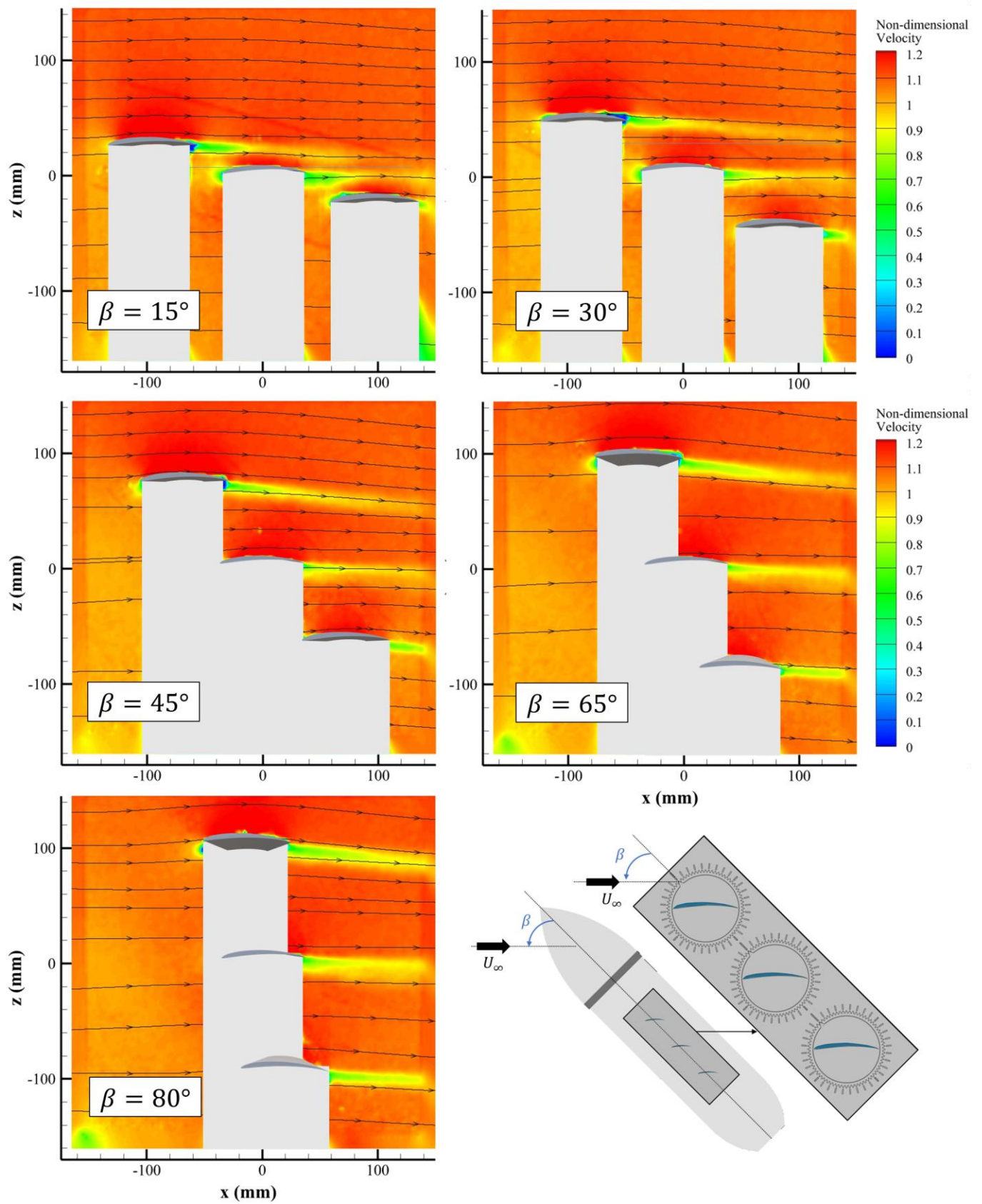


Figure. 7 Non-dimensional velocity contours for Eppler61 wing-sails ($\beta = 15^\circ, 30^\circ, 45^\circ, 65^\circ, 80^\circ$)

This could mean that the aerodynamic interaction between the pressure side (not visible) and the suction side between first and second, and between second and third wing sails has a noticeable effect, and could be reducing the aerodynamic performances of these last wing-sails. Finally, $\beta = 80^\circ$ is the case tested when the wing-sails are more separated. The flow patterns on the upper side of the sails seems not affected by aerodynamic interaction. However, again, the first sail generates a thicker wake whose green area (non-dimensional velocities around 0.7) has more length behind the airfoil in comparison with the second and third wing-sails.

3.2. Velocity Contours - $\alpha \neq 0^\circ$

The following figures display the non-dimensional velocity contours for a fixed apparent wind angle $\beta = 30^\circ$ (Figure 8), and $\beta = 65^\circ$ (Figure 9), for different angles of attack of the wing-sail $\alpha = 0^\circ, 5^\circ, 10^\circ, 15^\circ$. Each case has the same value of angle of attack for the three wing-sails, and the range tested is below the angle of attack where the flow detachment appears on the suction side of the Eppler61 single airfoil.

When the angle of attack is null, the velocity contour is the same as seen in Figure 7, but with a greater scale of non-dimensional velocity (up to 1.5). When $\beta = 30^\circ$ and as the angle of attack of the profiles increases, the velocity contours present more flow acceleration on the upper part of the sails, as a consequence of the lift increase. The wake generated by each sail under $\alpha = 0^\circ$ is similar, but the interaction between them produces different accelerations on the upper surfaces. The first wing-sail clearly produces more acceleration (and lift) than the second and third ones. Similar flow patterns can be observed for the case of $\alpha = 5^\circ$. The three sails have a similar wake behind them but more flow acceleration due to the increase in angle of attack and an aerodynamic performance that is superior for the first sail in comparison with the second and third sails. This aerodynamic interference under $\beta = 30^\circ$ is also present along the cases of $\alpha = 10^\circ$ and 15° . First of them, produces an important flow acceleration of the first wing-sail, but the second and third wing-sails show a degraded aerodynamic performance due to the interference with the first and second sail wakes, and also by the interaction with the flow of pressure sides of the previous wing-sail. Finally, the highest angle of attack tested ($\alpha = 15^\circ$) presents the highest values of velocities on the suction side of the sails. Again, interaction effects can be observed between the airfoils, with the greatest acceleration produced on the first airfoil (and also a flow detachment produced on the last part of the sail), and lower acceleration for the second and third wing-sails. Then, under this apparent angle of the sails $\beta = 30^\circ$, increase angle of attack effectively improves aerodynamic loads on the wing-sails.

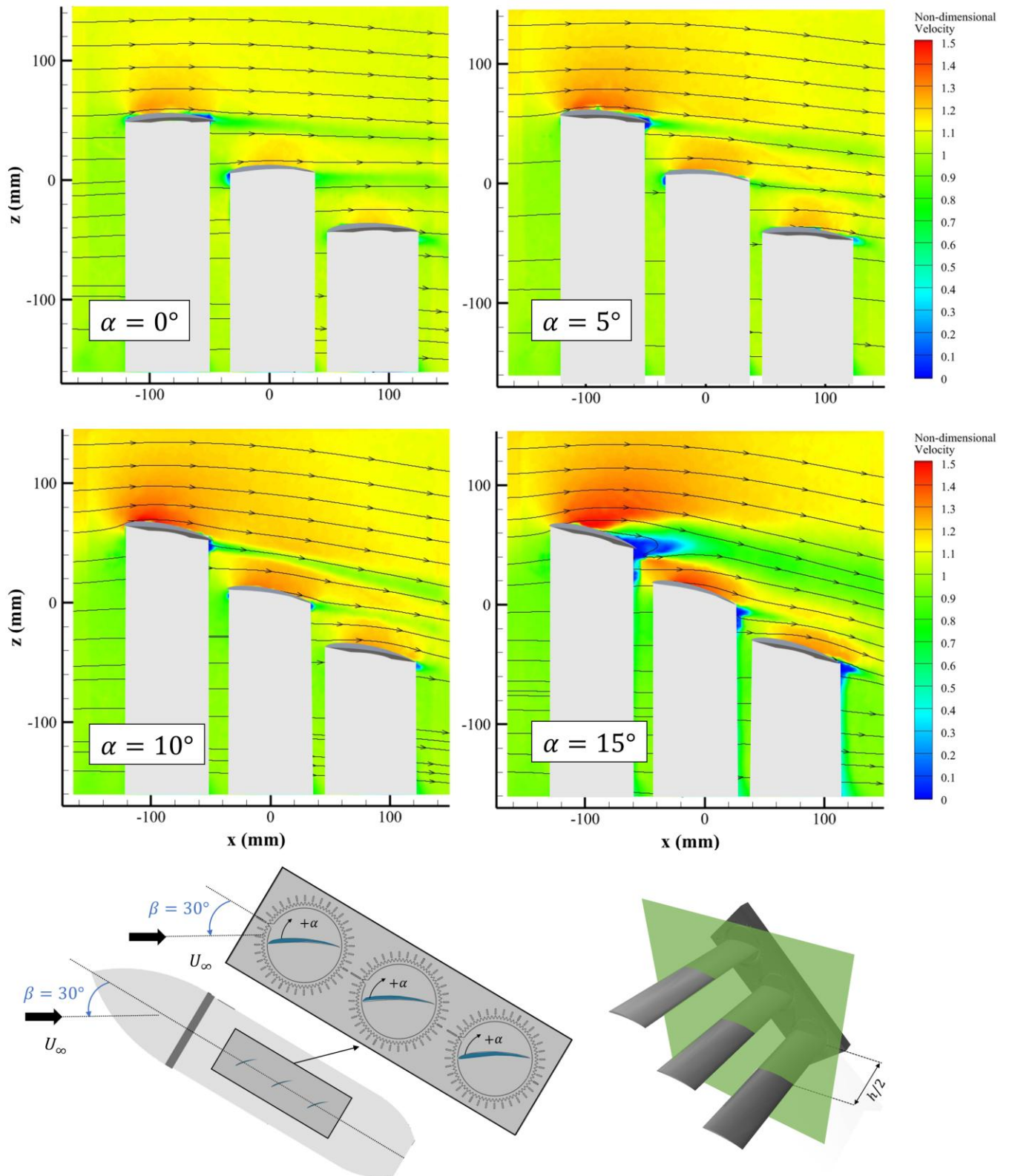


Figure. 8 Non-dimensional velocity contours for Eppler61 wing-sails for different α ($\beta = 30^\circ$).

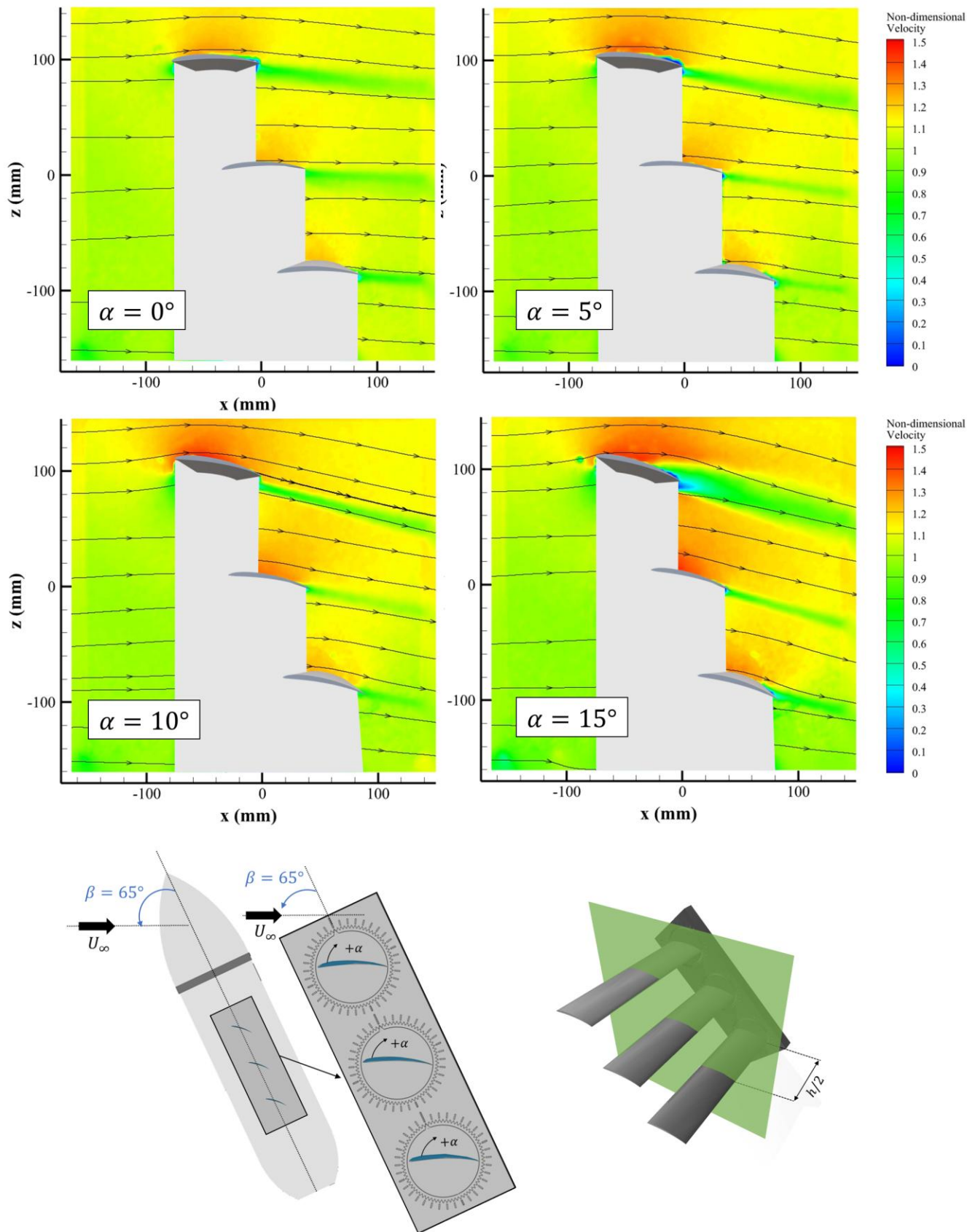


Figure. 9 Non-dimensional velocity contours for Eppler61 wing-sails for different α ($\beta = 65^\circ$).

However, interaction effects are important, and the first wing-sail always produces higher acceleration on the suction side (lift) compared to the second and third wing-sails.

Figure 9 presents cases for different angles of attack of the sails when the apparent wind angle is fixed to $\beta = 65^\circ$. When there is no angle of attack of the wing-sails, flow patterns generated by the three airfoils are similar, with slight differences in the width of the wake and higher values of flow acceleration for the first sail. These differences are more noticeable when the angle of attack increases. At $\alpha = 5^\circ$, the velocity reached on the suction side of the sail increases. As a result, the wake thickness and the lift generated related to this effect increase, especially for the first sail. For the $\alpha = 10^\circ$ and $\alpha = 15^\circ$, flow patterns are similar, with the direct consequence of angle increase in higher suction peak (and velocity) and wake thickness. Although there is some interference for the aerodynamic performance of the second and third wing-sail, this interference is lower than in the previous case presented of $\beta = 30^\circ$ due to the increased distance between wing-sails under this wind condition. As observed in the previous case, under $\alpha = 15^\circ$ the first wing-sail receives clean air, and produces the highest flow acceleration. As a consequence, the flow can not withstand adverse pressure gradients and produces flow deatchment on the last part of the suction side. This effect is not observed in the second and third sails, due to the reduced velocity peak produced by aerodynamic interference between sails.

3.3. Turbulence Intensity

From PIV data, it is possible to obtain turbulence intensity contours surrounding the wing-sails. Figure 10 displays the results obtained using PIV data for the case of $\beta = 65^\circ$ and different angles of attack of $\alpha = 0^\circ, 5^\circ, 10^\circ$. Turbulence intensity was computed as,

$$TI (\%) = \frac{\sqrt{\frac{1}{2}(\sigma_u^2 + \sigma_v^2)}}{U_{mag}} \times 100 \quad (1)$$

where σ_u and σ_v are the standard deviation of horizontal and vertical velocity components and $U_{mag} = \sqrt{u^2 + v^2}$ is the velocity magnitude calculated with horizontal and vertical mean velocity from PIV data.

In Figure 10, turbulent wakes generated behind the three wing-sails are registered. For $\alpha = 0^\circ$, the first sail generates greater turbulence intensity compared with the second and third one. Increasing the angle of attack also increases the turbulent intensity produced. However, the first wing-sail

produces lower turbulent intensity behind than the second and third airfoils for both cases ($\alpha = 5^\circ$, and $\alpha = 10^\circ$). This could be a consequence that the first wing-sail works in clean air and the second and third are affected by aerodynamic interferences.

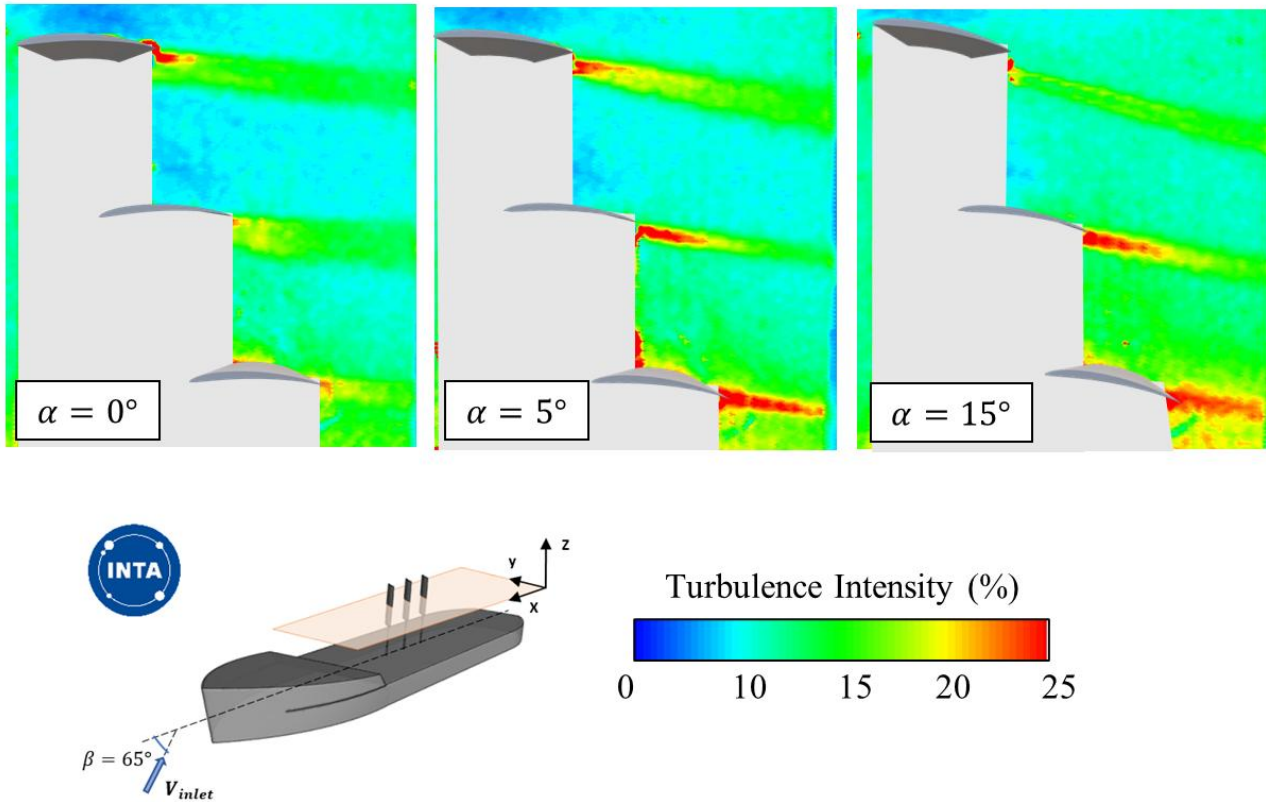


Figure. 10 Turbulent Intensity (%) with experimental PIV data for Eppler61 wing-sails for different α ($\beta = 65^\circ$).

3.4. Velocity peaks

Figure 11 displays the maximum non-dimensional velocities registered at the suction side of the wing-sails for all cases tested with PIV. This velocity reduction is a direct consequence of aerodynamic interaction between the sails and lift generation by each airfoil. Starting with the fixed $\alpha = 0^\circ$ cases for the different apparent wind angles ($\beta = 15^\circ, 30^\circ, 45^\circ, 65^\circ, 80^\circ$), the velocity peak reached at the wing sail 1 is the same for all cases, corresponding to 29 % higher than the free-stream velocity. Interference effects reduce the velocity peak for the wing-sails 2 and 3, with reductions of velocity for the second sail with respect to the first one between 5.9 % and 2.1 %, depending on the apparent wind angle tested. Velocity reduction is again produced for the third wing-sail with respect to the second one, with variations in a range around 0.3 % and 1.8 %. Then, interference effects decrease acceleration, especially on the suction side of the wing-sail 2. The

third sail also experiences a reduction in its velocity peak, but it more or less maintains the same values as the second sail.

When the β angle is set to $\beta = 30^\circ$ or $\beta = 65^\circ$, and the angle of attack of the airfoils (α) is changed, the non-dimensional velocities increase significantly for wing-sail 1 at $\alpha = 5^\circ$ and $\alpha = 10^\circ$, and remain constant at $\alpha = 15^\circ$. For the $\beta = 30^\circ$ case, the reduction in speed is greater for the second sail (7.4 % for $\alpha = 5^\circ$ and 13.3% for $\alpha = 10^\circ$). The reduction is less pronounced for the third sail compared to the second, with a decrease of just 1.9% and 4.6%. In the case where $\alpha = 15^\circ$, as the first wing experiences flow separation, the second wing exhibits a similar peak, but the third wing experiences a significant drop in velocity (13.1%). Finally, for the case where $\beta = 65^\circ$, the interference patterns are similar, with speed reductions for $\alpha = 5^\circ$ in the second and third sails of 5% respectively. In the case of $\alpha = 10^\circ$, the reductions are 9.4% and 6.3%. And in the case of $\alpha = 15^\circ$, the same effect occurs again, with similar speed peaks for sails 1 and 2, and a sharp reduction in the third of 7.4%.

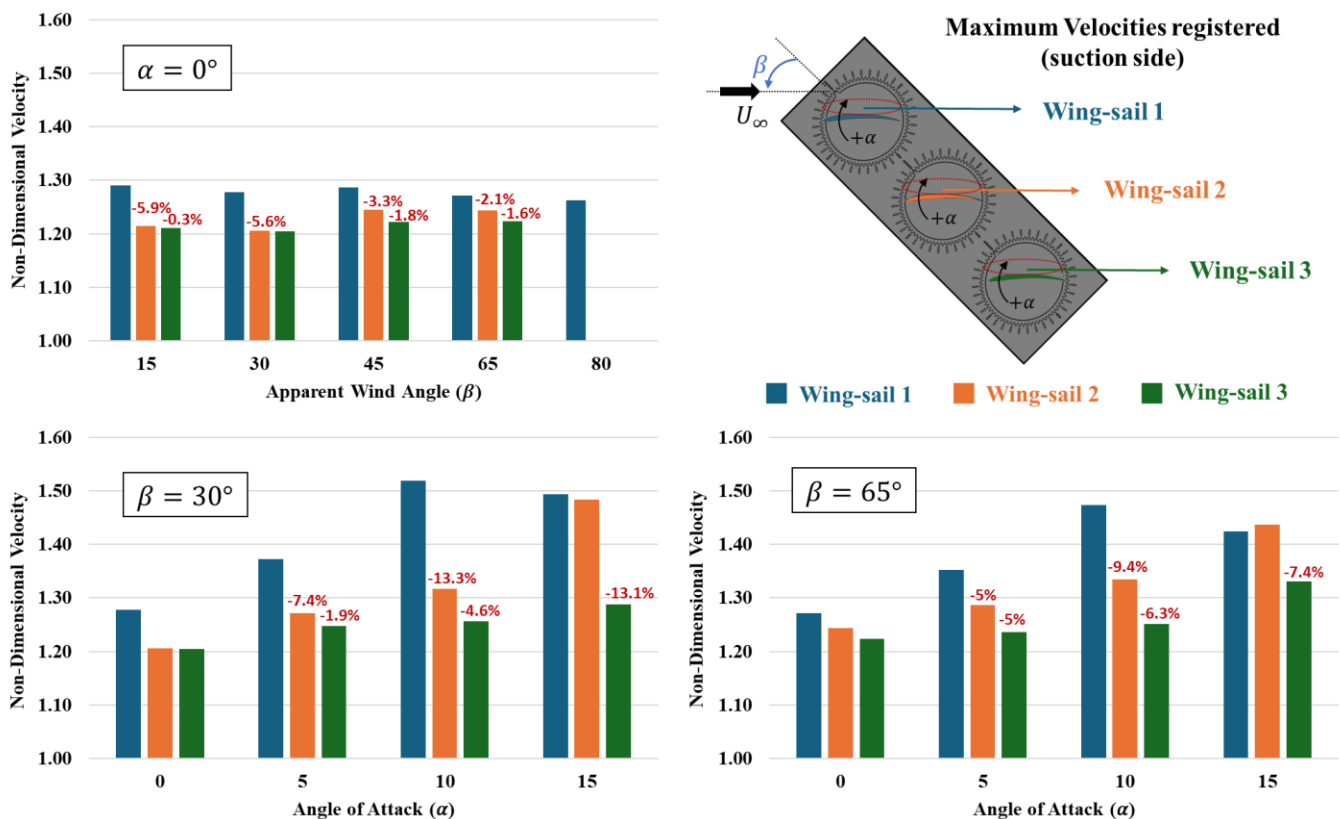


Figure. 11 Maximum velocities registered at the suction side of the wing-sails for all cases tested.

4. Conclusions

This study presented a comprehensive experimental campaign using Particle Image Velocimetry (PIV) in a low-speed wind tunnel to evaluate the aerodynamic flow interactions of a tandem three-rigid-wing-sail configuration. Using Eppler 61 aeronautical airfoils, integrated into a 1:150 scaled cargo ship deck, experimental velocity contours, turbulence fields, and velocity peaks have been analyzed.

The experimental results successfully validate that the aeronautical Eppler 61 airfoil configuration contributes positively to wind-assisted ship propulsion (WASP) across all tested apparent wind angles ($\beta = 15^\circ$ to 80°). The profiles effectively accelerated the flow on the suction side, generating a localized velocity increase of up to 29% above the freestream velocity even at a null angle of attack ($\alpha = 0^\circ$). However, there is a clear aerodynamic interaction between the tandem sails. The first wing-sail consistently operates in clean air, having the highest flow acceleration, suction peaks and then lift generation. Due to wake interactions and pressure side interferences from preceding profiles, the second wing-sail experiences velocity peak reductions between 2.1% and 13.3%, while the third sail faces additional velocity drops, though it tends to stabilize closer to the performance of the second sail. The magnitude of the aerodynamic interference is strongly dependent on the apparent wind angle. At low angles ($\beta = 15^\circ, 30^\circ$) the sails are geometrically closer along the flow direction, leading to a direct coupling between the wake of an upstream sail and the suction side of the subsequent one. At higher angles ($\beta = 45^\circ, 65^\circ, 80^\circ$), the wings are more separated, reducing suction-side interference. Increasing the wing-sail angle of attack (α) effectively boosts flow acceleration and lift generation. However, at the highest angle tested ($\alpha = 15^\circ$), the upstream wing-sail reaches its aerodynamic limit, experiencing flow detachment (stall). This flow separation was not observed on the second and third sails, as the velocity peaks were inherently reduced by the aerodynamic interference of the sail array. Turbulence intensity contours confirmed a tendency of broaden turbulent wakes behind the wing-sails with increasing angles of attack. At $\alpha = 0^\circ$, the first sail generates the greatest turbulence intensity; however, at higher angles ($\alpha = 5^\circ, 10^\circ$), the downstream sails exhibit larger turbulent wake structures due to their operation within the highly disturbed velocity fields generated by the preceding airfoils.

Future work will involve conducting force measurements in a wind tunnel to determine the lift generated by the profiles in the configuration shown and to identify which portion of that lift effectively contributes to the vessel's wind-assisted propulsion. Furthermore, Eppler 61 profiles

offer significant aerodynamic advantages derived from aeronautical engineering. However, as they are not symmetrical, they present problems at negative apparent wind angles ($\beta < 0$); consequently, new geometries based on the same profile are being designed that can be used across the entire range of incident wind angles.

Acknowledgments

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