Hydrodynamic and Fluid-Structure Interaction analysis of a Windsurf Fin

André Saldanha
arqsaldanha@gmail.com

Instituto Superior Técnico, Lisboa, Portugal

October 2019

Abstract

This work concerns the development of a Multiple Iteration Fluid-Structure Interaction (FSI) model with the purpose of studying the hydrodynamic loads on the composite Windsurf Slalom Fin produced by F-Hot [5], as well as its structural behaviour when in operation. The work develops and subsequently calibrates and validates both structural and hydrodynamic models, which are then finally coupled together to give an FSI analysis. The analysed sailing conditions comprise four different velocities and three Angles of Attack, which cover the various most probable sailing conditions encountered during a Windsurf Slalom event. Regarding the study of the Fin's behaviour, three different parameters are investigated: Lift Force, the maximum deflection and twist angle. The process developed here contributes to a better understanding of the Fin's behaviour, providing more in-depth and accurate numerical results compared to previous work.

The present work is part of an ongoing investigation of a Slalom Windsurf Fin relying on the collaboration between different institutions in Portugal and the United Kingdom.

Keywords: Fluid-Structure Interaction, Computational Fluid Dynamics, Composite Material, Windsurf Fin

1. Introduction

Rising popularity of Windsurf has been observed in the past decades, gaining a lot of supporters in the competitive aspect of the sport. This increase of competitiveness has been observed by designers and manufacturers, hence big efforts have been made to design and create the best windsurfing gear to suit the requirements of each rider. Despite that, few recent scientific works have focused on this topic. The present work wishes to follow these aspirations for a better design and performance of a Windsurf Fin.

To do so, a detailed study of the hydrodynamics and structural behaviour of the Fin was proposed. This report discusses the development of the technology capable of analysing with a considerable degree of accuracy the behaviour of a Fin when in sailing mode.

This work arises with the intention of complementing a sequence of several other recent studies that have been developed in IST concerning the analysis of a Windsurf Fin with the major final objective of doing a Passive Adaptive Composite (PAC) analysis, tailoring the response of the structure by changing the orientation of the composite plies [2]. This is the main objective of all the past, present and future work related to this Fin, to be able to create the technology and necessary tools capable of building a structure that behaves exactly as desired.

An FSI analysis was proposed for this work due to the need for a more exact prediction of the structural behaviour of the Windsurf Fin when in operation. During the development of this FSI model, several numerical simulations were conducted, requiring the use of commercial software: ANSYS Workbench for the Structural analyses and Star CCM+ and XFoil for the CFD part of the project.

2. Fin Design and Simulation Envelop:

A Slalom Windsurf Fin is studied. This Fin is manufactured by F-Hot and has a 37 centimetres length, 10 centimetres chord at the base, 2.3 centimetres chord at the Tip and a rake angle of 2° aft. A general representation of the Windsurf Fin studied in this work is presented in Figure 1 with all dimensions in millimetres and degrees.

The profile of the Fin is represented in Figure 2 and has a relative maximum thickness of 8.25% of the chord located at x/c = 40.20%.

As for the composite laminate of this Fin, it is

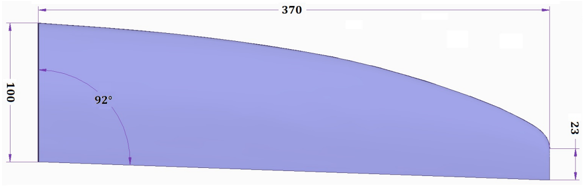

Figure 1: 37cm Windsurf Slalom Fin produced by F-Hot

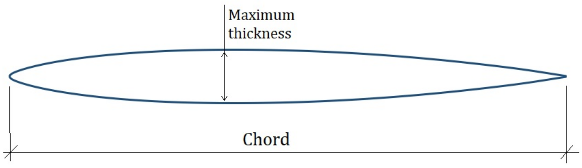

Figure 2: F-Hot Windsurf Slalom Fin profile

composed of 19 layers of carbon fibers and fiberglass fabrics in a matrix of Epoxy resin. There are 3 different fiber fabrics that compose this laminate: Carbon Woven fabrics (interlaced fibers of carbon), Carbon UD fabrics (unidirectional fibers of carbon) and E-Glass UD (unidirectional fiberglass). The layup scheme for the laminating processes is as follows:

- 3 layers of Carbon Woven fabric at about 45 in relation to the trailing edge
- 11 layers of Epoxy Carbon UD fabric at 0 with the trailing edge
- 5 layers of E-Glass UD fabric at 0 with the trailing edge

The working fluid used for the simulations completed during the process of this work is seawater with a salinity of 35 g/kg [7].

The study of the Slalom Windsurf Fin was tested for specific conditions which are presented in Table 1.

Parameter	Value	Units
Temperature (T)	20	C
Density (ρ)	1024.9	kg/m^3
Dynamic Viscosity (μ)	1.077 x 10^{-3}	kg/m.s
Angles of Attack	2, 4, 6	deg
Velocity (v)	10, 15, 20, 25	kn
Average Chord ($\overline{c}$)	8.12	cm
Max Re $(\overline{Re}_{max})$	0.9938 x 10^6	-
Min Re $(\overline{Re}_{min})$	0.3975 x 10^6	-

Table 1: Operating Conditions for the simulations on the Windsurf Fin

The velocities chosen are typical velocities for a Slalom Windsurfer, ranging from 10 knots up to 25 knots, which is considered to be a reasonable average top speed at a Windsurf Slalom event. Accurate data for these slalom velocities is not widely available, so the top speed here considered is based on many riders' opinions and understanding of the sport.

Regarding the Reynolds number, as the Fin has a non-constant chord, each section will have a different Reynolds number. For analysis purposes, the average Reynolds number $(\overline{Re})$ is considered for each simulation using the average profile's chord of $\overline{c} = 8.12cm$. The fluid flow is assumed to be incompressible (constant density), steady and turbulent. All these conditions are then implemented into the CFD code.

3. Hydrodynamic Model

A Hydrodynamic model was constructed for a later coupling with the Structural model to create the FSI tool. Before the creation of the model itself, several parameters regarding the properties of the flow and the characteristics of the computational domain's discretization were selected and subsequently validated.

The validation process is of the utmost importance to be able to assess the level of confidence that should be attributed to a CFD simulation. The credibility of CFD results for both academic research and industry-level purposes is only obtained if a concrete and well-defined validation plan is set forth. Therefore, for this work, a validation of the computational results is required in order to be scientifically reliable. With the final purpose of validating the CFD model on Star CCM+, a series of tests were done on 2D aerofoils complying with some verification and validation methodologies [6]. These validation processes include:

1. XFoil validation with experimental data
2. Selection and validation of mesh parameters and turbulence model
3. Validation of final Star CCM+ model with experimental data

All 3 of these validation processes were of extreme importance in the choice of the final Hydrodynamic model to be used in the FSI model. To Select the mesh parameters as well as the turbulence model, a grid sensitivity analysis was done for 4 turbulences models using 4 different mesh configurations. The numerical uncertainty calculation for each of the turbulence models shows which model is more adequate to be used for further simulations. Also, the grid sensitivity study gives an indication of whether the results are independent of the chosen mesh resolution, allowing for the choice of the discretization parameters.

The 4 turbulence models considered are: $K-\epsilon$ Standard, $k-\omega$ SST, $k-\omega\ \gamma - Re_\theta$ and Spalart-Allmaras. After the grid sensitivity analysis, it's clear that the only model that presents adequate results when compared with XFoil data (already validated) is the k-ω turbulence model with the γ-Re$_\theta$ transition model, presenting a relative error of 2.98 % and 3.29 % for the C_L and C_D respectively. This choice is supported by Sørensen [8] that concluded that this model gives promising numerical results with outstanding agreement with experimental data, being an excellent predictor for Lift, Drag and the transition point.

Regarding the discretization of the computational fluid domain, a decision was made not to use the Law of the Wall, which numerically solves the turbulent boundary layer without the need for overly refined meshes. This decision was supported by the work of Firooz [4] that stated that when using turbulent models in low Reynolds simulations (Re $<$ 2 x10^6), the agreement with experimental data will be enhanced if the boundary layer is numerically solved without the wall law. So, not using the Law of the Wall, implies the need for a finer definition of the mesh in the near-wall region so that the boundary layer is properly captured. This better resolution of the mesh is materialised in a $y^+ < 1$, which will significantly increase the simulation time, but at the same time, will enable a good prediction of the boundary layer flow. Figure 3 presents the cross-section of the 3D discretized fluid domain, where 3 different control volumes are presented (Domain, VOR1 and VOR2). Table 2 presents the main characteristics of the selected mesh.

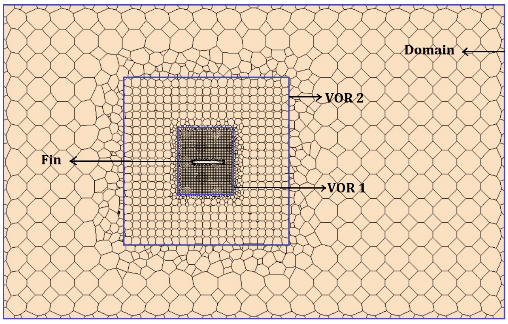

Figure 3: Mesh Discretization of 3D Computational Fluid Domain

Base Size	0.05 m
Number of Prism Layers	30
Prism Layer Thickness	0.002 m
y$^+$	$<$ 1
Domain relative cell size	150 %
VOR 1 relative cell size	8 %
VOR 2 relative cell size	50 %

Table 2: Final mesh main parameters

The Fluid Domain discretized based on the mesh parameters defined in Table 2, are composed of about 3 million cells, maintaining a good mesh definition especially in the near-wall region.

Regarding solution convergence, two criteria were selected: the convergence of residual values and convergence of a specific quantity of interest (Lift force). About the residual values, the lower they get, the more numerically accurate is the solution. For CFD purposes, the solution is considered loosely converged for residuals lower than 10^{-4}. To check the Lift force convergence, a monitor plot is done for this quantity and when the numerical results between iteration i and $i+1$ are negligible, the solution is considered converged. For some simulations, the solution did not satisfy the convergence criteria and in these cases, a practice that proved very effective to arrive at a converged solution, was to change the Relaxation Factors (RF), changing the velocity RF to 0.5, the pressure RF to 0.1 and the turbulence RF to 0.5. The RF is a coefficient frequently used in iterative non-linear solvers that uses the results of iteration i and $i-1$ to define the value that should be used for the next iteration $i+1$, following equation 1.

$$Y_{i+1} = f \cdot Y_i + (1-f) \cdot Y_{i-1} \tag{1}$$

Under-Relaxation (RF $<$ 1) of a CFD simulation reduces the solution oscillations and helps to keep the computation stable. Even though using under-relaxation factors allows to access a converged solution,it generally causes an increase of computation time.

4. Structural Model

After the construction of the CFD model, a structural model is created to be able to access how the component behaves when hydrodynamically loaded.

The structural model here presented is based on a previously developed model [3]. A reconstruction of this existing model was conducted in order to be able to import the proper CFD loads into the structural analysis.

This model is responsible for numerically simulating the structural behaviour of the Fin. After assigning the proper composite characteristics to the Fin's structure and creating the numerical laminate composite through ANSYS' ACP system, the pressure distribution is imported from the CFD software into ANSYS. Figure 4 shows a representation of the pressure distribution load acting on the Fin's surface.

After applying the pressure load on the Fin and the adequate boundary conditions (fixed support at the Fin's base), the Fin's structural behaviour is simulated, allowing for the calculation of the 3 parameters to be focused on (Fin's Lift, Deflection

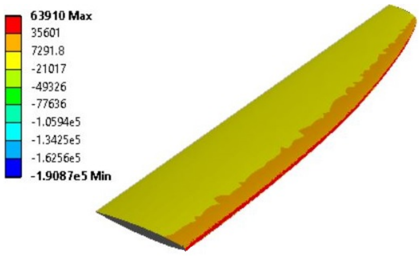

Figure 4: Pressure distribution on Fin's Surface (units in Pa)

and Twist). Figure 5 presents the Deflection behaviour of the Fin with the hydrodynamic loads correspondent to a Fin sailing at 20 knots at an AoA of 6°.

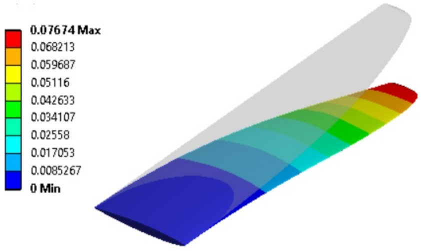

Figure 5: Numerical Fin's Deflection (units in metres)

5. FSI Model

The FSI model development is one of the main achievements of the present work. It comes with the biggest objective of defining and quantifying the structural reaction of the Fin's structure when in use.

The Fluid-Structure Interaction (FSI) is a process that studies the interaction between a deformable structure and the internal or surrounding fluid, consisting of the coupling between the laws that describe fluid dynamics and structural mechanics.

The present work proposed an FSI model that performs a Multiple Iterations FSI analysis, in order to predict with higher accuracy the structural behaviour of the Windsurf Fin. Making a single iteration FSI study provides with a fair estimate of the structural response. But, to study the response with greater accuracy, multiple iterations must be conducted. This is because, after the first iteration, the deformed geometry will constitute a new boundary for CFD calculation, which will result in different pressure distributions. Hence the need for Multiple Iterations, so that a converged result is obtained where the difference of hydrodynamic loads between consecutive iterations is negligible.

The Multiple Iteration FSI model here developed is a manual iterative process, where a dynamic coupling between the structural and the CFD software is done. All this process is done using Star CCM+ and ANSYS Workbench. Firstly, the hydrodynamic loads are calculated in Star CCM+, and are then imported into ANSYS Workbench where a structural analysis is performed. After completed this structural study, the outcome will be the deformed geometry. This will be imported into Star CCM+ for a second CFD analysis where the hydrodynamic pressure distribution is once more calculated and again imported for a second structural analysis. For each structural analysis, the pressure load applied on the deformed Fin is the Δ Load corresponding to the difference between the two latest pressure distribution calculated on Star CCM+. So, this process will repeat itself until convergence, until the difference of hydrodynamic loads between consecutive iterations is negligible which results in a close-to-zero Δ Deformation of the Fin in the last iteration.

In Figure 6, a simplified diagram can be seen, showing the consecutive actions required for this Multiple Iterations FSI analysis.

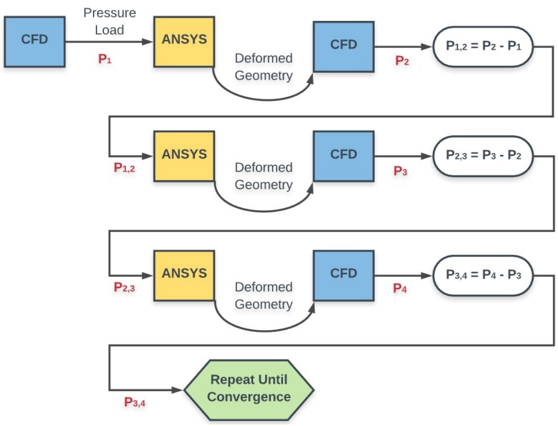

Figure 6: Multiple Iteration FSI model process diagram

The FSI tool developed is meant to perform a static analysis of the Fin. From the observation of experimental tests of the operating Fin in a water tunnel, some fluctuations at the Fin Tip were detected, indicating that some kind of dynamic effects are occurring in this region. This oscillatory behaviour of the Fin Tip is of a very small magnitude, validating the assumption of a static behaviour of the Fin.

5.1. Case Study

As an illustration of the Multiple Iteration FSI model, the results of the iterative process are shown for the specific case of a Fin sailing at 25 knots at an AoA of 6°. A converged solution was obtained after 10 Iterations, meaning that 10 CFD analyses and 10 structural analyses were performed to arrive at a converged numerical solution. To evaluate the iterative process, a plot is done to check the evolution of specific scalars over the 10 iterations, focusing on the 3 main parameters being studied: Lift, Deflection and Twist (Figure 7).

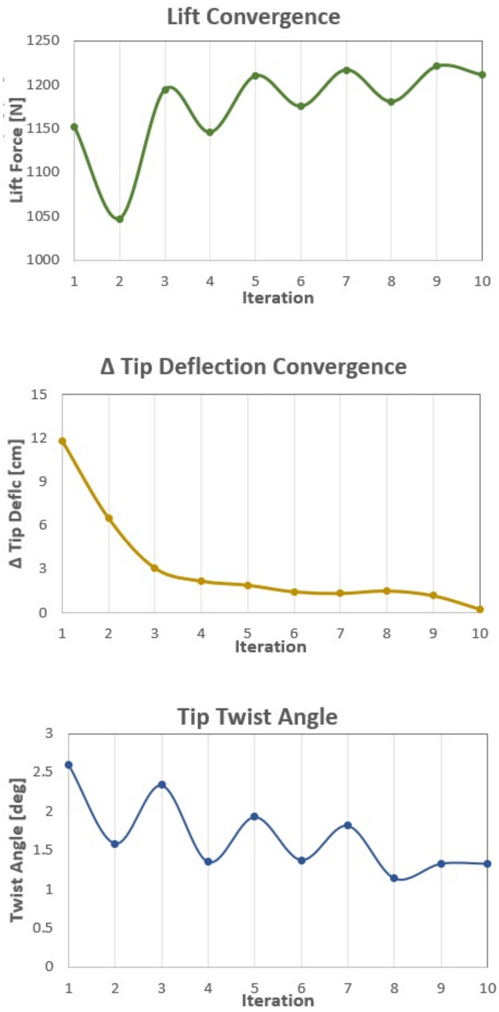

Figure 7: FSI solutions monitor for 3 parameters for conditions of 25 knots and AoA 6°

This is only 1 example out of the 12 different sailing conditions considered along this work (3 angles of attack simulated at 4 different velocities). Looking at the plots of the 3 parameters, it can be observed that a solution convergence was reached. The convergence criteria defined are related to the Lift and Deflection of the Fin. In order for the process to be considered converged, the Δ Lift should be below 2% of the first iteration value, and the maximum deflection at the last iteration must be inferior to 4 mm. The decision not to use the Tip Twist angle as a convergence criterion is because it takes much longer to converge, due to the fact of being a very sensitive parameter, which means that it fluctuates a lot with slight load changes.

It is worth mentioning that all the 12 conditions studied on the FSI analysis have a converged solution for the Lift and Deflection parameters. Regarding Twist, for some sailing conditions, it did not converge, and this is because of the already mentioned oscillatory behaviour at the Fin Tip, that can be physically explained by the appearance of a Laminar Separation Bubble (LSB) and its oscillatory variation of dimensions. It could also be justified by the appearance of significant 3D effects causing complex flows at the Tip of the Fin, varying the pressure distribution in this region, and consequently changing its structural behaviour.

Moreover, due to this Twist fluctuations and convergence issues, it was decided for further analyses to consider the Tip Twist angle calculated in the first iteration, the same as if not using the developed FSI model. This simplification for the Tip Twist angle calculation is only acceptable to identify trends and orders of magnitude and not absolute values for this parameter, given the big relative differences between using and not using the FSI model, reaching over 50%.

6. Results & Discussion

After several FSI analyses for each of the proposed cases in Table 1: Velocity of 10, 15, 20 and 25 knots and an AoA of 2°,4° and 6°, some conclusions start to be drawn in regards of the Fin's behaviour when in operation. These conclusions and observations are in regard to 3 main parameters:

- Lift Force
- Fin Deflection
- Fin Twist

The first parameter to be analysed is the Lift Force, which in the case of a windsurfer, is the horizontal hydrodynamic force acting on the Fin perpendicular to the incoming flow. The two other parameters are related to the structural behaviour of the Fin when hydrodynamically loaded. In Figure 8, a representation of the Fin's behaviour is shown. Here, it can be seen the deflection and the twist of the Fin provoked by the hydrodynamic forces generated by the moving fluid flow around it.

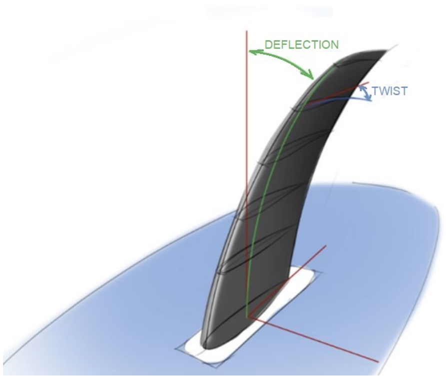

Figure 8: Fin's structural bend-twist behaviour

6.1. Lift Force

The Lift force here evaluated is the most significant hydrodynamic force acting on the Fin. It is the component of the resultant force which is perpendicular to the incoming flow direction. When steadily sailing without accelerating nor curving, this Fin's Lift force balances, in opposite direction, with almost all of the aerodynamic side force acting on the sail, being the biggest responsible for the directional stability.

The Lift force is calculated in Star CCM+. This Lift calculation is possible by knowing the pressure distribution along both surfaces of the Fin. The Lift force is the vector sum of the pressure times the surface area around the entire Fin, in other words, is the surface integral of the pressure along the Fin's surface area (Equation 2).

$$L = \sum_{surf} \overrightarrow{P} \Delta A = \oint \overrightarrow{P} dA \tag{2}$$

Furthermore, several Lift forces were calculated for each of the proposed sailing conditions (V = 10, 15, 20, 25 knots with AoA = 2°, 4°, 6°), and for each of these cases, a few iterations were done until the solution converged.

An analysis can be performed to conclude the significance of this extra-work doing the Multiple Iterations FSI analysis, comparing its results with the results from the simplification of a single iteration not using the developed FSI model. These two sets of data are presented in Figure 9, allowing for a conclusion about the relevance of this Multiple Iterations FSI approach for the Lift force calculation. In this Figure, it's presented, for each of the AoA, the behaviour of the Lift force with the increasing velocity.

Examining Figure 9, it is clear and expected the increase of the Lift force with the increasing velocity. Higher the velocity, bigger is the associated Reynolds number and higher will be the hydrodynamic forces acting on the Fin.

It can be seen that the Lift follows a parabolic path with the increasing velocity. This is supported by the theory that states that the Lift force is directly proportional to the Lift coefficients and has a quadratic response to the increasing velocity. Equation 3 shows the Lift variation with the velocity, being C_L a constant coefficient dependent on the Fin's profile geometry.

$$L = C_L \frac{1}{2} \rho V^2 A \tag{3}$$

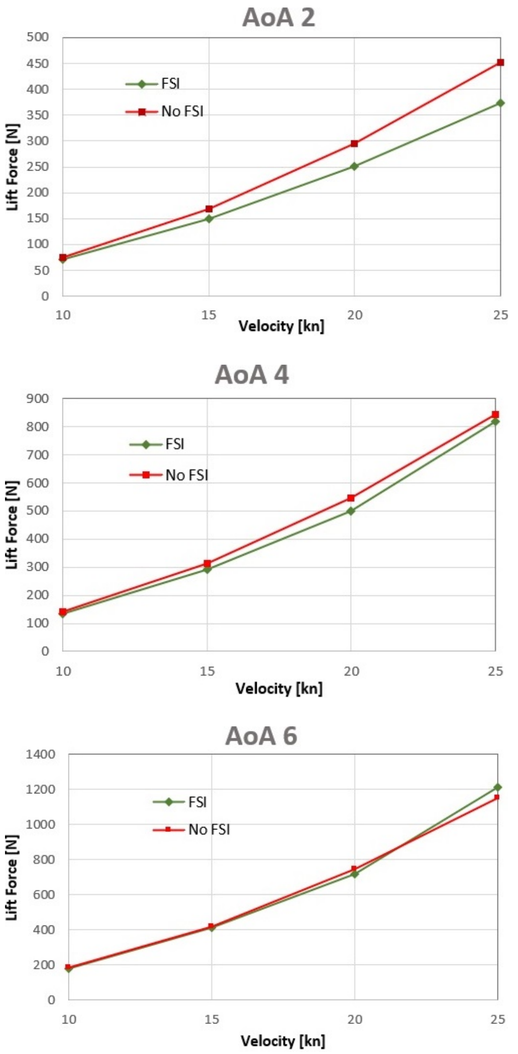

Figure 9: Lift Force vs. Velocity for 3 AoA with and without Multiple Iteration FSI analysis

From Figure 9 it is also possible to compare the results with and without the Multiple Iteration FSI model. In most cases, not using FSI will result in higher Lift forces, which means that in general, simplifying these simulations by not using FSI, will create an excess in the estimation of the Fin's Lift force. This difference between using FSI and not using FSI differs for the different conditions, presenting bigger differences for smaller angles of attack and higher velocities, reaching a maximum relative error of 21% for an AoA of 2° and 25 knots of velocity.

For a higher angle of attack, the results obtained with and without the FSI model, present very similar values, being almost coincident for 6° AoA, with a maximum relative error of 4.8%.

The decision not to use the Multiple Iteration FSI model will generate less accurate results, but at the same time, this simplification is significantly less time-consuming. So, a compromise between simulation time and result accuracy must be done. For the calculation of the Lift force, it can be concluded that it only makes sense to employ this simplification for AoA between 4° and 6°.

6.2. Fin Deflection

The deflection is a natural behaviour of a structure simply fixed on one side and loaded along its surfaces. For all the simulations done, the assumption of a static loading was assumed, disregarding possible load oscillations and the dynamic study of natural frequencies and resonance occurrence.

The Deflection here analysed refers to the Fin's Tip total Deflection between the undeformed and the final deformed geometry. Figure 5 shows a representation on ANSYS of both the deformed and undeformed geometries of the Fin's first iteration simulation sailing at 20 knots at an AoA of 6°.

This Deflection is calculated using ANSYS structural features, simply by applying the pressure load distribution, previously calculated in the CFD analysis, to the Fin's surface and setting the fixed support boundary condition. ANSYS computes the deformation of the structure using a Finite Element Method (FEM) analysis.

Finally, for each of the 12 sailing conditions considered in this work, the deflection was calculated in order to be able to conclude about the structural behaviour of the Fin when in operation.

In Figure 10, it is presented the numerical results for the Fin's Tip Deflection for all the 12 different conditions. In these graphs, two sets of results are presented: the numerical results from the Multiple Iteration FSI model and the results from the simplification of a single iteration analysis not using the developed FSI model. The comparison between these 2 sets of data will allow for a reflection on the relevance of the Multiple Iterations FSI approach for the Tip Deflection calculation.

Looking at Figure 10, a possible direct observation is related to the increase of the Deflection with the increase of velocity. Also looking at the Deflection values, it is clear that with an increase of the AoA (until 6° before stall occurrence), the Deflection will also increase. This behaviour was already expected as the increasing velocity and increasing AoA are related to an increase of the hydrodynamic loads acting on the Fin which, according to Euler-Bernoulli structural beam theory [1] , provoke a higher deflection on the structure.

A comparison between the numerical results obtained by using the Multiple Iteration FSI model and using the simplification of a single iteration analysis is possible. For every condition analysed, a significant difference is clear between the "FSI" and "No FSI" results, being the results obtained by the single iteration simplification method ("No FSI") always higher than the converged results ("FSI"). This means that simplifying these simulations by not using the developed FSI model will create an excess in the estimation of the Tip Deflection.

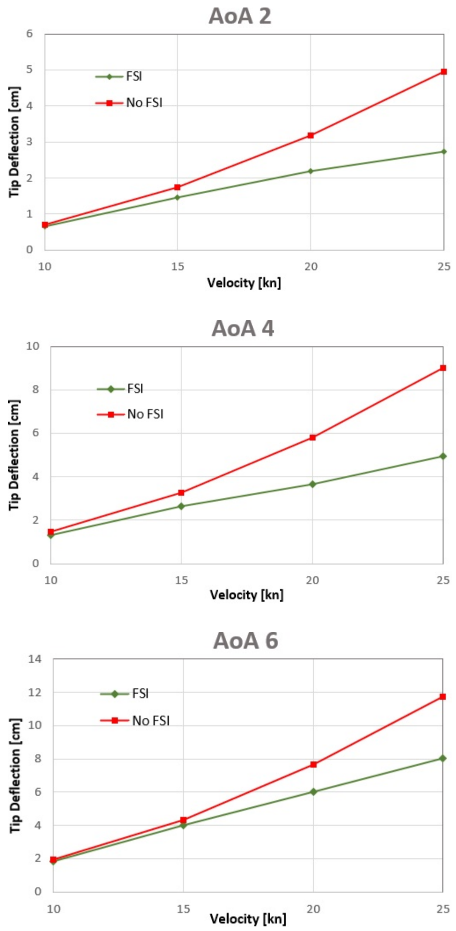

Figure 10: Tip Deflection vs. Velocity for 3 AoA with and without Multiple Iteration FSI analysis

The relative error associated with simplifying the simulations, not using the FSI model, becomes larger for higher velocities, reaching a maximum of 82.6% and a minimum value of 7.6%.

As previously stated, a compromise must be done between result accuracy and computation time, therefore a decision must be taken regarding the use of the developed FSI model or not. The fact that simplifying the simulations, with a single iteration analysis, present such considerable errors, it can be concluded that the Multiple Iteration FSI model must be employed to give reasonable results despite the significant increase of running time.

6.3. Fin Twist

The Twist, unlike the other two parameters, is a very sensitive parameter, which means that its value fluctuates a lot with small load changes. Even though the other parameters converged, it is understandable that the Tip Twist values are still fluctuating. This is because it is possible that between "converged" iterations, the pressure distribution is still slightly varying. This minor variation of pressure distribution along the Fin's surfaces is not significant to alter the results of Lift and total Deflection, but it is enough to change the results of a much more sensitive parameters as the Tip Twist. The fact that the dimensions of the Fin's Tip are extremely small (about 23 mm of chord and a maximum thickness of 2 mm), it makes the calculation of the Twist angle much more susceptible to small pressure distribution changes, which justifies the fact that this parameter might take longer to converge than the other two. These fluctuations at the Fin tip together with the sensitivity of the twist angle are responsible for some convergence issues on the calculation of this parameter.

The fact that in some cases the convergence of the Tip Twist was not achieved, it complicates the analysis of these parameters. In Figure 11, it is presented the Twist angle solutions for all the studied cases calculated using the Multiple Iteration FSI model.

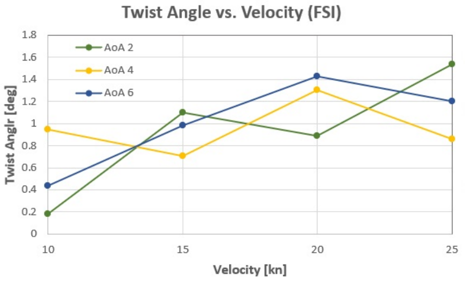

Figure 11: Tip Twist using the Multiple Iteration FSI model

As can be seen from Figure 11, the results are highly inconclusive, giving only a general idea of the twisting behaviour of the Fin. From this analysis, one valuable observation that can be made is the tendency for the twist to increase with the increasing velocity and especially that the twisting of the Fin is in the direction which decreases the effective AoA. This reduction of AoA at the tip, for 25 knots, is significant reaching up to 50% in relation to the incident AoA. This significant twist at the tip, will not produce such a significant alteration of the hydrodynamic forces due to the Fin's tip small dimensions.

As previously stated, in order to get a better understanding of the twisting behaviour, the results of the first FSI iteration can be taken into consideration. These values present a significant relative difference in relation to the ”converged” solution, but it provides interesting insights on how the twist behaves with the increasing velocity and AoA, and also gives a good understanding about the Twist angles magnitude. Despite giving interesting data, these results obtained from the simplification of a single iteration FSI analysis, should not be subjected to a literal interpretation of the absolute values. In Figure 12, the results obtained from the first FSI iteration are presented for each of the conditions considered.

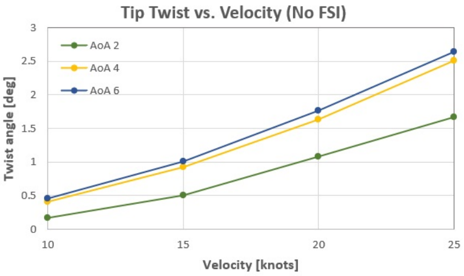

Figure 12: Tip Twist angle results using the simplification of a single iteration analysis

From the analysis of Figure 12, it can be seen that the Tip Twist angle increases with the increasing velocity, as already concluded from the analysis of Figure 11. Another possible observation is the fact that the Twist values for the AoA of 4° and 6° present a very small difference between each other. To better observe this behaviour, Figure 13 shows the variation of the Twist angle at the tip versus the increasing AoA for the 4 different velocities. It was established a zero-twist for 0° AoA.

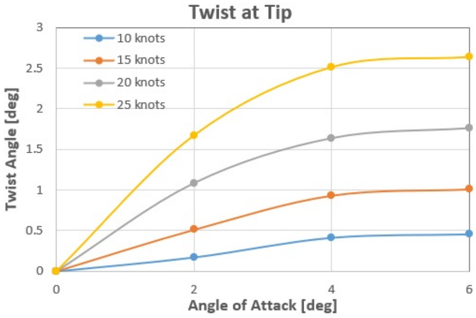

Figure 13: Tip Twist vs. AoA Not using the FSI model

From Figure 13, it can be observed that for AoA higher than 4° the twist stops increasing at the Tip. This Twist angle is in the direction of decreasing the effective AoA, meaning that, when in operation, the twist of the Fin will result in a decrease of the hydrodynamic loads acting on it.

The Twist at an aerofoil shaped structure might come from two main effects: the pitching moment of the Fin's profile and the anisotropic behaviour of the structure's materials.

The anisotropic nature of the Fin composite materials means that there is the possibility of interaction between longitudinal deflection and tip twist. In this case, it appears that the Fin lay-up leads to an interaction where the effective AoA is reduced at higher AoA and velocities. This supports the theory of the Twist angle correlation with the structural composition of the Fin.

The pitching moment of the Fin's profile, when associated to the windsurf Fin, it can be interpreted as a yawing moment once the lift produced is in the horizontal direction, however, the ”pitching” term will continue to be used to describe the moment acting on the Fin, perpendicular to its section and in the direction that decreases the effective AoA ("nose-down" direction in aviation terms).

Despite being a symmetric Fin, which theoretically presents a zero-pitching moment, due to the Fin's deflection and variation of the Fin's section profile parallel to the incoming flow, a non-zero pitching moment appears at the Fin's fixed base. Also, the 3D effects at the Fin's tip will generate a complex pressure distribution on this region, responsible for the appearance of a complex and difficult to evaluate pitching moment. A clear correlation between the pitching moment and the twisting angle can be observed in Figure 14.

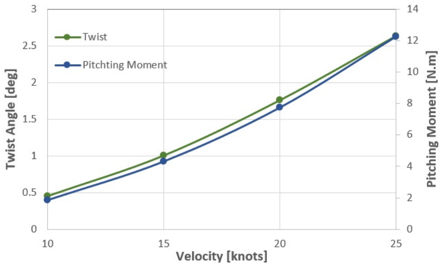

Figure 14: Twist and Pitching Moment vs. velocity (6 AoA)

Analysing Figure 14, it is clear the similarity of behaviour between these two parameters with the increasing velocity. When the pitching moment increases, it will provoke an increase of the twisting angle. As such, it can be concluded that the pitching moment acting on the Fin contributes for the appearance of this twisting angle, together with the bend-twist coupling effect created by the composite laminate lay-up scheme.

This increase of twist angle is in the direction which decreases the effective AoA, and it happens when the Fin is being overloaded and a decrease of the hydrodynamic forces is desirable.

Regarding the fluctuations of the Twisting angle, from observation of water tunnel experimental tests, the Fin's behaviour is not exactly static, presenting small structural oscillations when in operation. These oscillations are very small though, validating the simplification of the static analysis approach done to evaluate the Fin's behaviour. These fluctuations can be observed in the successive iterations of the FSI analysis, mostly affecting the Twist angle, the most sensitive parameter. These Twist angle fluctuations should have a physical explanation that could involve the appearance of Laminar Separation Bubbles (LSB) on the vicinity of the Leading Edge and the oscillatory variation of its dimensions.

The dimensions of the LSB are known to have some influence on the pressure distribution of the hydrodynamic loads over the Fin and consequently interferes with the Lift, Drag and Moment acting on it.

To evaluate the correlation between the size of LSB and the twist oscillations, a monitor of these two parameters is done through the several iterations of the FSI study. For this correlation study, only 2 sailing conditions were selected: 6 ° AoA and a velocity of 25 and 20 knots. The twist calculation was evaluated at the Fin's middle section (20 cm from the base). Figure 15 presents the results of these two parameters for the two sailing conditions.

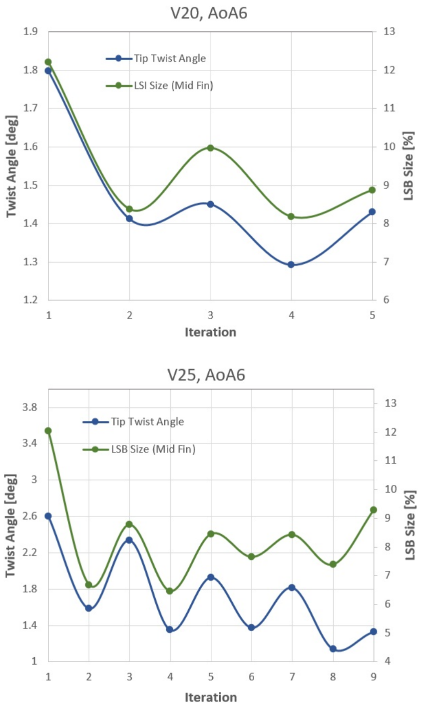

Figure 15: Monitor plots of Tip Twist and LSB size for two sailing conditions

It can be observed that the behaviour of the Twist angle follows the same trend as the size of the LSB. With the increase of the LSB size, the twisting angle also accompanies this increase and vice-versa. So, it can be concluded that these oscillatory variations of LSB size between iterations are in some way responsible for the Twist fluctuations observed during the Multiple Iteration FSI analyses.

It is important to know that these observations are only related to the 6 ° AoA conditions and an extrapolation of these results for different AoA could result in erroneous assumptions. Simulations with different AoA have different pressure distributions and so, the appearance of a LSB and the variation of its dimensions will have different effects on the hydrodynamic parameters and consequently different effects on structural behaviours of the Fin. For lower AoA, the twist angle fluctuations are not as intense and a possible explanation for this might be due to significantly smaller LSB, being these fluctuations, mostly affected by small dynamic effects caused by the moving fluid flow around the Fin.

7. Conclusion

The main objective and achievement of this work was the development of a Multiple Iteration Fluid-Structure Interaction Model, and with that, be able to make a more accurate hydrodynamic analysis of the F-Hot Slalom Windsurf Fin as well as a study of its structural behaviour when in operation.

Results, regarding the structural behaviour of the Fin, were calculated for 12 different sailing conditions, including 3 Angles of Attack (2°, 4° and 6°) and 4 different velocities (10, 15, 20 and 25 knots). With the numerical simulation of the Fin, it was possible to better understand, in a more detailed way, how the Fin behaves when being used. For the characterization of the Fin's behaviour, 3 parameters were selected: The Fin's Lift, Deflection and Twist.

The FSI model here created is a Multiple Iteration FSI model, which means that several iterations were done for each FSI analysis until a converged solution was arrived at.

As for the behaviour of the Fin, it was possible a general understanding of its performance as well as the calculation of concrete values for its behaviour.

The Fin's Lift force was a parameter that easily converged and a correlation between this parameter and the sailing conditions was possible, concluding that the Lift force increases with the increasing velocity following a parabolic path.

The Fin's Tip Deflection is a structural behaviour of the Fin and was also a parameter that converged allowing for a good understanding of this parameter's behaviour for the different sailing conditions. It was observed that, similarly to the Lift force, the Fin's deflection also increases with the increasing velocity.

Regarding the Fin's Twist, unlike the other two parameters, for higher velocities, a convergence was difficult to achieve, mostly due to small variations of the pressure distribution on this region between iterations, creating Tip fluctuations affecting the convergence of this parameter. To understand the Twist behaviour for the different sailing conditions, a simplification of a single iteration FSI analysis was done to calculate these values, creating clear data defining the twist behaviour of the Fin, but providing results that should not be directly interpreted as absolute values of the Twist angle. Also, a possible explanation for the Twist fluctuations was provided for 6° AoA, being related to the appearance of Laminar Separation Bubbles (LSB) and their oscillatory variation of dimension.

Another conclusion derived from this study, is regarding the relevance of the developed Multiple Iteration FSI model. For this, only the Fin's Lift and Deflection are considered due to the observed convergence issues calculating the Fin's Twist angle. It was concluded that not using the developed FSI model to calculate the Lift and Deflection, would result in an excess in the estimation of these parameters.

Not using the Multiple Iteration FSI model, will generate less accurate results, but at the same time, this simplification is significantly less time-consuming. As a consequence, a compromise between simulation time and result accuracy must be done. Regarding the Lift force calculation, it was concluded that the use of this simplification is only adequate for AoA between 4° and 6°. As for the calculation of Fin's Deflection, as the relative error, when using the simplification of a single iteration analysis, is considerable, with a minimum of 7.6%, it can be concluded that the Multiple Iteration FSI model must be used for all sailing conditions.

References

[1] F. P. Beer and E. R. Johnston. *Mecânica dos Materiais*, chapter 5, pages 327–390. McGraw Hill, 5 edition, 2011.

[2] Chesapeake Sailing Yacht Symposium. *Impact of Composite Layup on Hydrodynamic Performance of a Surface Piercing Hydrofoil*, volume 23, Annapolis,Maryland, March 2019.

[3] F. de Albuquerque Marcão Ramos do Nascimento. Windsurf fin - numerical and experimental analysis of ultimate strength. Master's thesis, Instituto Superior Técnico, 2017.

[4] A. Firooz and M. Gadami. *Turbulence flow for naca 4412 in unbounded fow and ground effect*. International Conference on Boundary and Interior Layers, 2006.

[5] F. hot Mouldings. F-HOT RWS SLALOM FINS, 2019.

[6] P. J. Roache. *Verification and Validation in Computational Science and Engineering*. Albuquerque, New Mexico: Hermosa Publishers, 1998.

[7] M. H. Sharqawy, J. H. Lienhard, and S. M. Zubair. Thermophysical properties of seawater: A review and new correlations that include pressure dependence. *Desalination and Water Treatment*, 16:354–380, 2010.

[8] N. Sørensen. Cfd modelling of laminar-turbulent transition for airfoils and rotors using the gamma-re-theta model. Technical Report 12:715-733, Wind Energy, 2009.