An integrated FSI analysis of a windsurfer fin

Miguel Afonso Cardoso de Brito
miguelacbrito@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

April 2021

Abstract

This work consists of the development of a design tool that allows the user to investigate the behaviour of a windsurfer fin, made of composite materials, in operation. This project can be divided in three main sections: (i) the development of a structural model (FEA) to study the response of the composite material to the loads applied at the fin. (ii) the development of a hydrodynamic model (CFD) which studies the behaviour of the surrounding fluid and the pressure fields generated by the fluid on the fin. (iii) the coupling of these two models to create a fluid-structure interaction (FSI) model. A parametric analysis was done, using the developed tool, in different operating conditions, with velocities ranging from 10 to 35 knots and angles of attack from 2 to 8 degrees. This work marks an improvement of the knowledge of the structural behaviour of the fin under operating conditions. Also, the developed design tool facilitates the study of fins with respect to parameters such as the composite materials composition, its orientation, fluid velocity and angle of attack.
Keywords: FSI, CFD, FEA, Composite Materials, Windsurf Fin

1. Introduction

The rising popularity of windsurf has been remarkable in the past decades, with the competitive aspect of the sport gaining lots of supporters. The increase in competitiveness has led to big efforts by engineers and designers to build the best equipment possible. The aspiration for a design tool that allows the user to analyse and improve the design of a fin is the main goal of this work.

With the improvement of technology, specifically engineering softwares, it is now possible, through computational analysis, to take into account multiple aspects of the design of a fin simultaneously. These technologies include Finite Element Method (FEM) analysis to study the structural behaviour of complex and, in this case, anisotropic structures. The use of Computational Fluid Dynamics (CFD), which allows a trustworthy analysis of the fluid around the structure, as well as the ability to calculate the load exerted on the structure by the moving fluid. Finally, joining both of these simulations, a Fluid-Structure Interaction (FSI) problem is generated, where both softwares will communicate with each other, sharing fields in order to arrive to a final solution.

Previous research around this topic was made in the University of Exeter and Southampton [1], in the United Kingdom, in 1992, where the effect of platforms and surface finishes of fins on the performance and manoeuvrability of a sailboard was investigated. Uncovering fluid dynamics involved in the design of fins. Afterwards, the effect of the tip flexibility on the performance of a new windsurf fin was also investigated [2]. This fin was better than other fins, especially for high-speed windsurfing and it was found that a slight increase in tip flexibility resulted in higher performance comparatively to using rigid tips.

Two researchers from the University of Bournemouth investigated if changing the geometric cross-sectional shape to one with camber, would lead to an increase of lift on the windsurf fin [4]. Fins on a windsurf board must be able to operate on both directions, or tacks, and because of that a symmetrical cross-section is often used. However, this has the drawback of limiting the amount of lift that the fin is able to generate in a given angle. In this paper, it was shown that the symmetrical cross-section has a lift coefficient with a low ceiling, while the camber can increase this value while maintaining the same thickness to chord ratio. The camber solution has better lift coefficient for a range of angles of attack, while also decreasing the drag coefficient, making it a superior design for some angles of attack. However, this solution has the obvious drawback that it is optimal for one angle of attack, while windsurf fins will operate in very different conditions. The solution to overcome this problem is to use variable fins with mechanically hinged leading or trailing edges, a resource used often in the aeronautical field. This solution was tested afterwards, with one of the researchers coming up with a design solution which consisted of a hinged deck mechanism on the board which would activate flaps on the fin, generating camber [3].

In a more recent paper, from 2007 [5], the maximum velocity of a windsurfer was studied through modelling of the movement of the rider over a finite number of sails with a prescribed shape, with many environmental variables taken into account. The conclusions showed that a larger sail would turn into higher velocities, however the windsurfer needs to be able to withstand the sail with his hands and body weight, in addition the fin will also have to resist the high hydrodynamic loading.

2. Background

In this work a slalom windsurfer fin was studied. The fin in question is manufactured by F-Hot, a leading supplier of fins to professional sailors, and has a 37 centimeter length, or span, 10 centimeters length root chord, and a rake angle of 2°to the aft. The leading edge of the fin being the round front, while the trailing edge is the straight side. A representation of the windsurf fin studied is presented in figure 1.

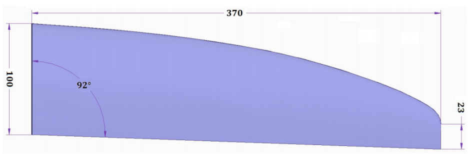

Figure 1: 37cm windsurf slalom fin, produced by F-Hot

The profile of the fin is shown in figure 2. It has a maximum relative thickness of 8.10% and it is located at x/c=40%.

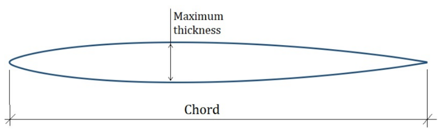

Figure 2: F-Hot windsurf slalom fin profile

As for the composite laminate of this fin, each half is composed of 19 layers of carbon and glass fibres in a matrix of epoxy resin. There are 3 different fabrics that compose this laminate: carbon woven , carbon UD (unidirectional) and E-glass UD. The layup scheme for the laminating process is as follows:

- 3 layers of carbon woven fabric at an angle of 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 fluid used in the simulations completed during the process of this work is seawater with a salinity of 35 g/kg [6], which has the following characteristics, presented in table 1.

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

Parameter	Value	Units
Temperature (T)	20	ºC
Density (ρ)	1024.9	kg/m^3
Dynamic Viscosity (μ)	1.077E-3	$Pa \cdot s$

Additional conditions for which the fin is numerically tested are related to the fluid continua. The fluid is assumed to have a constant density, to be incompressible and the flow to be steady and turbulent. All these conditions are then inputted into the CFD software for the numerical simulations.

3. Structural Model

The first step towards developing the design tool is to build a structural model in order to being able to assess the fin's behaviour when hydrodynamically loaded. The model here presented was built from scratch, in ABAQUS.

The main steps involved in the development of the FEA model are shown in figure 3:

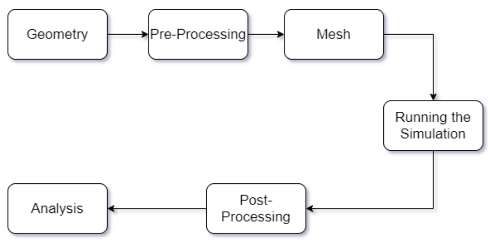

Figure 3: Diagram of a FEA analysis

The geometry of the fin was supplied by the manufacturer, as that used to make the moulds. The next important step is to arrive at the final material properties. The process of obtaining the properties estimation was quite difficult, due to the fin and the composites used being hand-crafted. This signifies that there are no prescribed properties and an iterative process of estimating and validating material properties had to be done. The final composite properties are presented in table 2.

The next step of the FEA process is to build the computational model. In ABAQUS, there is a need to partition the geometry in different "pieces" so the

Table 2: Final Composite Properties

Parameter	E-glass	Carbon UD	Carbon WR
E_{11} [Pa]	2.23E10	5.66E10	2.84E10
E_{22} [Pa]	7.9E9	5.11E9	5.54E9
ν_{xy}	0.29	0.31	0.04
ν_{yz}	0.4	0.42	0.3
ν_{xz}	0.29	0.31	0.3
G_{12} [Pa]	4.12E9	3.26E9	3.3E9
G_{13} [Pa]	3.50E9	3.08E9	2.70E9

software can properly mesh the geometry. In this model, the partitions shown in figure 4, also help to define the position of each ply in the fin. The model is composed by 38 plies of different widths (50 and 70 mm) many different lengths (from 14 cm to 24 cm) and different composite materials, along with a "skin" layer, for the resin used on the mould, and an "epoxy" layer, which defines the paste used to fill the vacant spots between each side of the fin.

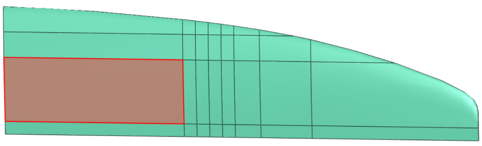

Figure 4: Partitions made in ABAQUS

Having defined all the plies and loads applied to the fin, the next step on the FEA process is to generate the mesh. In this meshing process, the element type chosen was SC8R, a first-order reduced-integration element. Since these types of elements may suffer from hourglassing effects, the generated mesh has to be reasonably fine. A mesh validation study was conducted in order to choose the global size for the FEA mesh. Figures 5 and 6 show the convergence study done on the mesh for the 80% span point load case. The mesh size influence was studied both on the displacement of the fin's tip and on the computational cost, represented by the wall-clock time. Taking into account both parameters, the approximate global size of 4 was chosen, which means that the average cell will have 4 mm as its defining size, this results in a mesh with 13824 elements and 7.23×10^{-5} 1/number of elements. This value was chosen for the global seed due to its accuracy on the displacement of the fin, having a relative difference to the finest mesh studied of under 0.1 %. While not having an excessive computational cost, taking approximately a third of the time of the finest mesh.

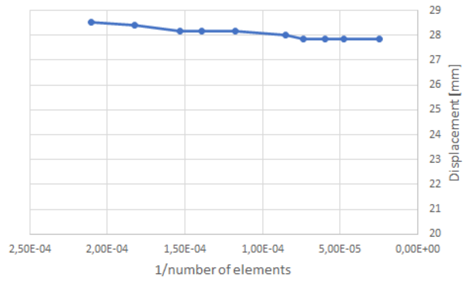

Figure 5: Displacement behaviour with mesh density

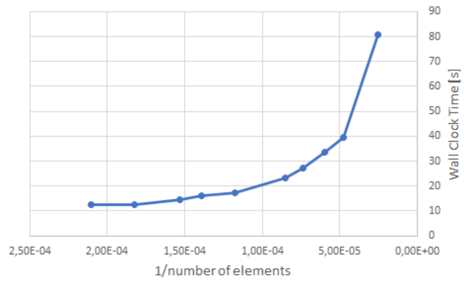

Figure 6: Wall-clock time with mesh density

4. Hydrodynamic Model

The second step in the process of developing the design tool is to build a CFD model in Star-CCM+. In figure 7, the major steps needed to develop this type of model are shown.

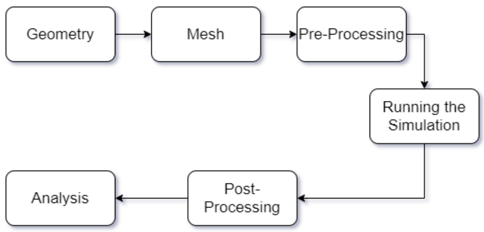

Figure 7: Diagram of a CFD analysis

After generating the appropriate CAD model to represent the fin's geometry, the second major step in developing a CFD model is the mesh generation. In order to generate a mesh, every surface has to be identified, assigned to a specific region and be identified with a type of boundary condition. In this analysis, the boundary conditions used are: *Velocity Inlet* for the Inlet and side surfaces, *Pressure Outlet* for the outlet surface, and *Wall* for the Fin surface.

The mesh is then created using the *Automated Mesh* feature of Star-CCM+, with the characteristics of the grid chosen based on previous research [7]. The used meshers were : *Surface Remesher, Polyhedral Mesher,* and a *Prism Layer Mesher.*

The mesh is not uniform across all the domain because, to have the accuracy needed in the areas of interest, close to the fin, there would be a need for a very large number of cells. In order to save computational space and, at the same time, accurately determine the responses of the fin to the surrounding fluid, Volumes Of Refinement (VOR) were created. The most important VOR is the one closest to the fin, which in this study was constructed to have an approximate geometry of the fin being studied, while being slightly larger so it contains it. The shape used for the VOR is very impactful on the computational cost, as a VOR that closely hugs the shape of the fin allows for more precise analysis when compared with a simple block. These VOR improve the performance of the prism layer meshing, which is useful to analyse the boundary layer, and the performance of the overall mesh, due to a more accurate definition of the fluid around the fin. This marks a significant improvement over the previous work done on this topic.

Figure 8 shows the mesh used in all CFD and FSI simulations, which has the following main characteristics, presented in table 3.

Table 3: Mesh main parameters

Base size	0.05 m
Number of Prism Layers	25
Prism Layer Thickness	0.002 m
Prism Layer Stretching	1.17
Wall y+	approx. 1
Domain Relative Cell Size	150%
VOR 1 Relative Cell Size	3%
VOR 2 Relative Cell Size	10%
VOR 3 Relative Cell Size	50%
Number of Cells	3 M

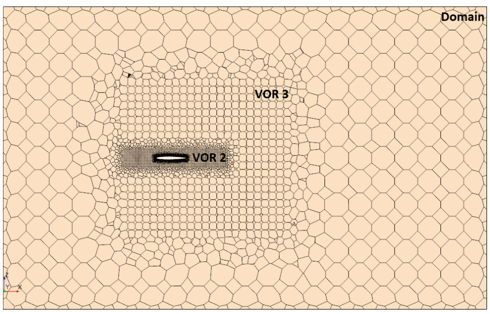

Figure 8: Mesh Discretization of 3D Computational Fluid Domain.

The next step in the CFD process is running the simulation, until solution convergence occurs. The convergence of the numerical results is a fundamental part of the simulation process, as it does not present meaningful results if the residuals do not converge. The criteria used to know if the simulation has converged is usually the residual values and the analysis of a specific quantity of interest. For the specific study of the windsurf fin, the convergence criteria used was the convergence of the residuals.

In some cases, the solution did not satisfy the convergence criteria, usually due to the residuals of the turbulent kinetic energy, which is to be expected due to some very quick phenomena. However, an analysis was made to investigate the influence of these events on the final solution. In this case, this will not affect the results since they occurred away from the fin.

In the search for convergence of the residual values, some parameters of the simulation can be tuned. A small refinement of the mesh can be done, specifically near the fin's surface. Relaxation Factors (RF) can be changed, particularly changing the velocity RF to 0.5, the pressure RF to 0.1 and the turbulence RF to 0.5. Finally, changing the analysis from a steady solution to an unsteady one, especially one with a very small time-step, can get rid of very quick phenomena which would otherwise impact the residuals convergence.

5. FSI Model

The final step in developing the design tool, shown in figure 9, is the coupling of both models into a FSI model.

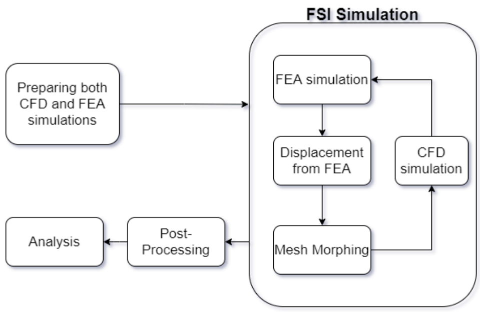

Figure 9: Diagram of a FSI analysis

The FSI analysis can only be initiated after having developed both FEA and CFD models previously, however these simulations have to be slightly altered in order to being able to communicate with one another while running. It is very important to correctly define the co-simulation controls both in ABAQUS and Star-CCM+.

The same surface must be present and defined with the same name in both solvers. In this region, the displacements will be exported from the FEA solver and the pressures normal to the element surfaces, as well as the wall shear stress are imported back [8]. Extra attention has to be given to the simulation's units, due to the fact that ABAQUS does not have an integrated units system. In this case, since the geometry was constructed in millimeters, all units have to be in accordance to this, which, in the case of pressure, for instance, is MPa instead of the SI Pa.

The approach chosen to model the FSI coupling between the structure and the fluid is a dynamic implicit solution, as there is a strong physical coupling, due to the fact that the composite fin is lightweight and highly flexible.

The iterative coupling scheme allows one analysis to lead, highly recommended to be the structural solver, in this case ABAQUS, while the other analysis lags the co-simulation [9]. The structural analysis uses the data from the previous time-step, as the initial prediction of the fluid loads at the end of the current time-step.

Lastly, the coupling step size needs to be specified in both solvers, which will define the period between two consecutive exchanges, in this case 0.1s. This coupling step size was established after many iterations with different time steps were unable to converge, either due to the step-size being too big or too small. Also in this study, it was found that the step size of both softwares should be constant. The coupling step size is established at the beginning of each coupling step and a constant coupling size will be used, allowing both analyses to advance in parallel. In the following equation, δt_c defines the coupling step size, t_{i+1} is the target time, or the next iteration time, and t_i is the current time at the start of the step

$$t_{i+1} = t_i + \delta t_c \tag{1}$$

Finally, a study on the use of a ramping parameter of the pressure was done. It was found that not using a ramping model led to the solution diverging rapidly and the simulation being unable to run, especially for operating conditions where the deflection and expected pressure field on the fin would be higher. The ramping time and the total displacement define the rate at which the fin deflects. Therefore, when expecting more deflection, higher ramping time was used. Otherwise, the simulation cannot withstand the large pressure differences that would occur with a smaller ramping time. This is particularly important at the start of the simulation, since the structure is initially unloaded and the initial flow field is calculated with a rigid structure. The initial parameter was set to 0 in the Co-Simulation Time and the second parameter was increased with the increase of the velocity and the angle of attack, due to an expected higher deflection.

6. Parametric Study

Having developed the design tool, a parametric study will now be done to study the influence of certain input parameters on the behaviour of the windsurf fin, as well as the tool's performance. The changed parameters were the speed and angle of attack. The speeds chosen are typical for a slalom windsurfer. They range from 10 knots to 35 knots, with 35 knots being close to the design limit of the slalom windsurf fin. The angles of attack from 2 to 6 degrees are also thought to be typical of leeway angles experienced when windsurfing. Overall, over 7500 computational hours were spent during this parametric study.

- Speed : 10, 15, 20, 25, 30, 35 (knots)
- Angle of attack: 2, 4, 6, 8 (degrees)

The main aspects of the simulation that will be studied and analysed, from which conclusions will be taken from are:

- Lift Force
- Fin Deflection
- Fin Twist
- One-way vs two-way coupling

The Lift Force is a hydrodynamic parameter, which corresponds to the force acting on the fin perpendicular to incoming flow, when steadily sailing without accelerating nor curving, the fin's lift forces balance with the aerodynamic side force acting on the sail. Fin deflection and twist are related to the fin structural response to the surrounding fluid loads. These two parameters change various behaviours like stall occurrence, the vertical lift forces and, most importantly, the controllability of the fin. They are often coupled together, as the bend-twist effect. Finally, the difference between one-way and two-way FSI coupling will be studied. This is a very important result of this study, because it allows the user of the design tool to know if the use of the two-way coupling is worth the extra computational costs relative to the faster, but less accurate, one-way coupling. The one-way coupling was done by analysing the fluid around the initial rigid undeflected body and calculating the pressure field around the fin. These fields were then exported into ABAQUS, where they were inputted as a loading force on the fin. Finally, the response of the fin to these new loads was calculated and the deflection and twist of the fin's tip was analysed. Two-way coupling was done by using the design tool developed as described in section 5.

6.1. Lift Force

For all the simulations studied, the lift force was calculated in Star-CCM+. The lift force 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, the surface integral of the pressure along the fin's surface area.

$$\vec{L} = \int P d\vec{A} \tag{2}$$

The lift force was evaluated at every operating condition (velocity from 10 knots to 35 knots, AoA from 2°to 6°), with both the multiple iteration model, as well as the single iteration model. The overall behaviour of the lift force is as expected, with the lift force following 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 coefficient and has a quadratic response to the increasing velocity, seen in equation 3.

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

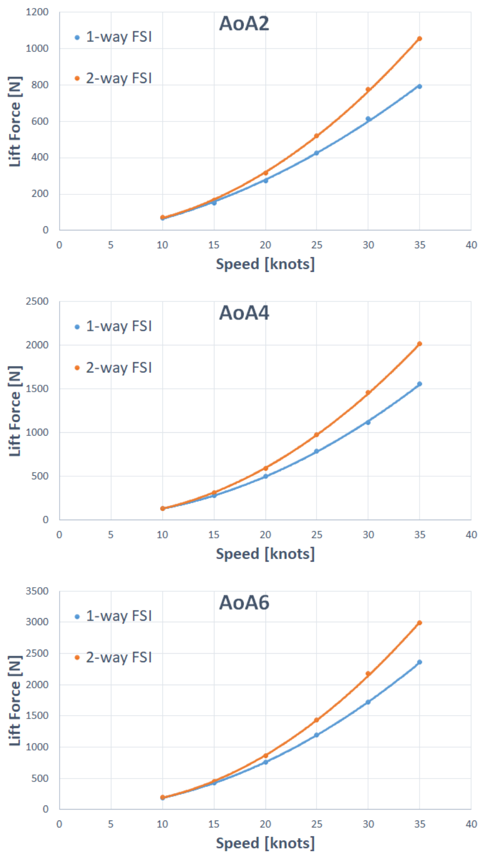

Figure 10: Lift force comparison between one-way and two-way FSI

From figure 10, it is possible to compare the results using both methods of FSI. It is clear that while the fin's behaviour is similar, using two-way FSI leads to higher lift forces overall, which means that the one-way coupling underestimates the fin's lift force response to the incoming flow.

The difference seems to increase with the velocity, up until 35 knots, where the difference in lift plateaus, which is understandable given its near the limit for the windsurf fin and an unrealistic condition for a windsurf board. At the same time, the relative difference between the results seems to be independent from the angle of attack, meaning that the relative error does not change with an increase or decrease in AoA. The difference reaches a maximum of 33% for 35 knots at an AoA of 2°and a minimum of 3.7% for 10 knots at an AoA of 4°.

Observing the results of this comparison, it can be seen that as the relative error between the two coupling modes increases, it becomes too big to ignore. Therefore a compromise must be done between the accuracy of the results and computational costs. Defining the two-way FSI as the accurate analysis and expecting a relative error under 5%, there are only two operating conditions where the one-way FSI analysis meets this criteria. In all other sailing conditions, the relative error is not worth the savings in computational costs or time.

Important findings are summarized below:

- Lift force increases with both velocity and angle of attack for both FSI models
- Two-way FSI increases lift force compared to one-way FSI
- Difference between both models indicates that it is useful to use two-way FSI in almost all simulations

6.2. Fin Deflection

Deflection is a natural behaviour of a cantilever type structure clamped at one end and loaded along its surface. In the particular case of this work, the windsurf fin is fixed by the base to the board and the pressure loads are hydrodynamically induced by the surrounding flow. In all simulations here presented, load oscillations and the dynamic study of natural frequencies were disregarded.

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 "1-way FSI" and "2-way FSI" results, being the results obtained by the single iteration simplification method always lower than the multiple iteration ones. This means that simplifying these simulations by not using the automated FSI model, will again, similarly to the lift force results, underestimate the maximum tip deflection.

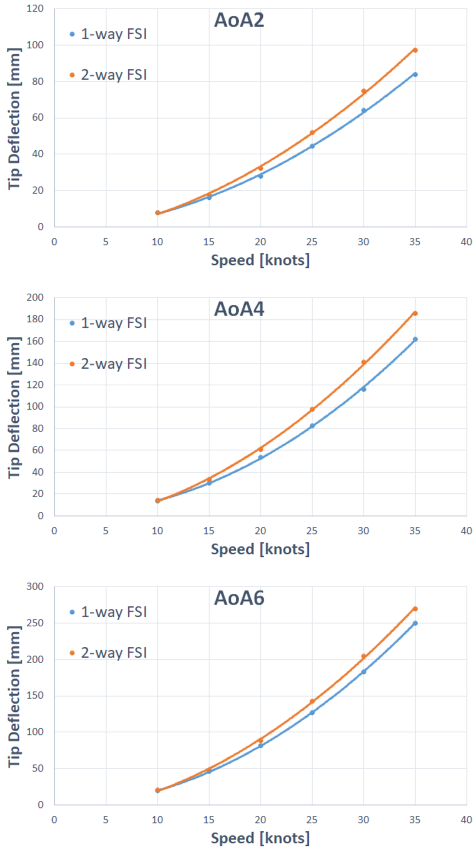

Figure 11: Tip deflection comparison between one-way and two-way FSI

The relative error between one-way and two-way FSI drops significantly, when compared to the lift force graphs, as can be seen in figure 11. The difference increases for higher velocities, reaching a maximum of 21.6%, for 30 knots at an AoA of 4°, and with a minimum value of 2.5%, for 10 knots at an AoA of 2°.

Another conclusion that can be taken is the fact that this discrepancy is highly influenced by the velocity but not so much by the angle of attack, meaning that there is not a clear correlation between the error and the angle of attack.

The most important findings are summarized here:

- Fin deflection increases with both velocity and angle of attack for both FSI models
- Two-way FSI increases fin deflection compared to one-way FSI
- Difference between both models indicates that it is useful to use two-way FSI in almost all simulations

6.3. Fin Twist

The twist parameter, similarly to the deflection, is a natural structural behaviour of the fin when it is being pressure loaded along its surfaces. Contrarily to the previous two parameters studied, twist is very sensitive to small changes in the domain characteristics, which means that it is expected for the value to fluctuate more than lift force and tip deflection. Physically, this can be explained due to small differences in the pressure distribution around the fin, generation of separation bubbles on the boundary layer and the small dimensions of the fin's tip (around 23 mm of chord and maximum thickness of 2 mm). All of this phenomenona are sufficient to alter the tip twist, whilst not being sufficient to change the lift force and tip deflection. Because of this, tip twist was not one of the main convergence parameters opposed to the former two, and this will be clear in the results obtained.

In figure 12, both models are compared with each other for each sailing condition, in order to further understand the fin's behaviour.

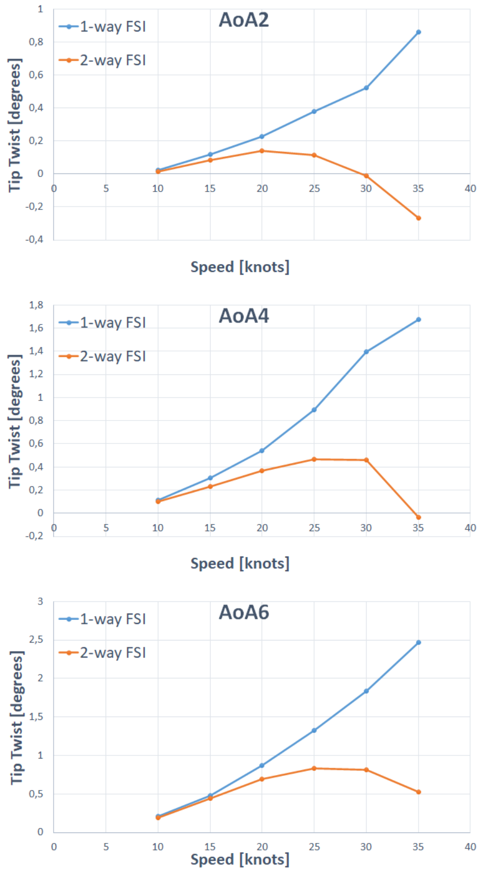

Figure 12: Tip twist comparison between one-way and two-way FSI

Looking at figure 12, it is obvious the difference between the prediction of the fin behaviour for each model. While the one-way FSI clearly predicts an increase in the twist with the increases of both velocity and angle of attack. This translates into an increase of the angle of attack of the fin's tip which, subsequently, should increase the lift force and tip deflection in the next iterations. This was seen in the previous results, where the two-way FSI, with multiple iterations, increased both of those parameters with the rise of velocity and angle of attack. The two-way FSI predicts a low angle of twist across all operating conditions, making the single iteration method a clear over-prediction. It can also be seen that the gap between both values increases with the increase in velocity across all AoA. With this difference in mind, it is clear that more research has to be done, especially investigating why the twist behaves as it does in both models, and what is the fin's behaviour throughout the multiple iterations of the two-way FSI that leads to the final results.

The twist of a composite aerofoil shaped structure, like the fin, may come from two main effects: the hydrodynamic forces on the fin's profile and twisting moments resulting from bending moments due to the coupling between these two effects. The hydrodynamic forces acting on the fin's profile may cause a pitching moment considering that the elastic axis of the fin does not coincide with the pressure centre (point at which the hydrodynamic forces are applied). Considering that the fin is not a 2D aerofoil but a finite wing, with a non-constant chord and is built from composite materials, this pitching moment should exist. It is however very difficult to determine the location of these points, and due to that, difficult as well to determine this moment. Therefore it falls out of the scope of this work. The coupling between bend and twist can come from three main effects: the layup of an anisotropic material; the shape of the structure, for example a swept back fin; and the section shape of the structure. In this fin the effect most likely to be more dominant is the effect due to the shape of the fin, particularly, having a 2 °rake to the aft. Given that the ply layup is totally symmetric and therefore should give no bend-twist coupling by itself if perfectly applied. A combination between these effects appears to be the origin of the difference between the one-way FSI and the two-way FSI, with no clear indicator as to which one is the predominant one without further work.

6.3.1 Two-way FSI iteration analysis

Further research into the twist behaviour, during the multiple iterations, was done. Figure 13 shows the evolution of the twist angle throughout the multiple iterations needed for the two-way FSI to converge. Two cases with 4°AoA are here analysed: 25 and 35 knots.

While the deflection and the lift force, which behave similarly, are increasing, due to numerical ramping, the twist angle increases resembling the

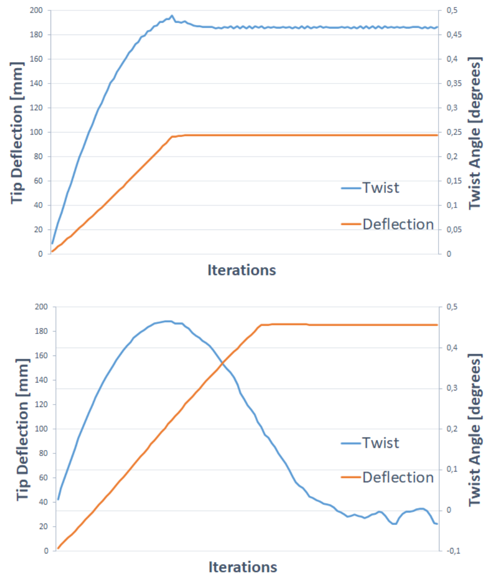

Figure 13: Twist angle and deflection evolution through iterations

one-way FSI model. However, once the deflection reaches a value closer to its final value, or equilibrium state, the twist seems to have two different responses, one for lower velocities and one for higher velocities.

In low velocity cases, the twist stabilizes at an angle close to its maximum value, seen just before the deflection converges. However, at higher velocities, the twist decreases dramatically after this maximum value for all angles of attack, as illustrated in figure 13. This sudden drop in twist angle may be caused by the appearance of separation bubbles during the FSI iterations, which dissipate as the flow field reaches a final state. In order to investigate this assumption, the flow field after one iteration, was compared with the flow field at the end of the multiple iteration FSI, as shown in figures 14 and 15. Where the vectors define the flow direction and the scalar values are defined by the colour.

In figure 14, for 25 knots, there does not appear to be any big difference between the two fields displayed. This corroborates the twist angle results, since the twist angle after the numerical ramping is very similar to the final twist value. However, in figure 15, for 35 knots, differences in velocity near the leading edge can be seen between the two plots. This difference in velocity can be explained by a bigger angle of attack after one iteration than in the final step.

Overall, the multiple iteration FSI leads to a decrease of the angle of twist, when compared with the single iteration FSI, with very small angles of twist across all operating conditions. Using the same criteria as before, although the low velocity cases seem

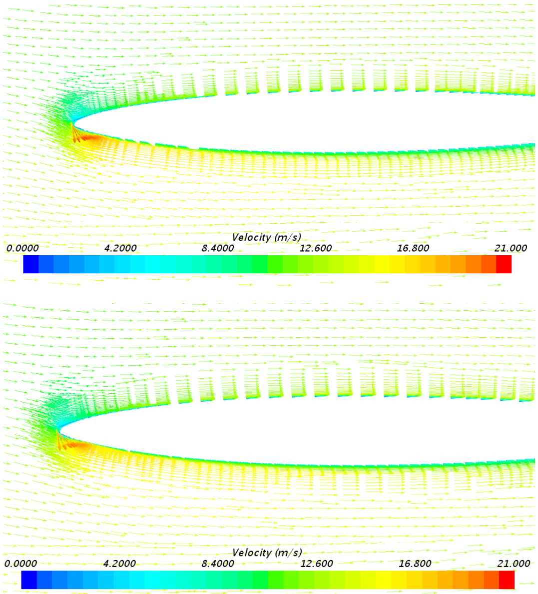

Figure 14: Velocity fields for 25 knots and 4° AoA (Single iteration FSI above; Two-way FSI below)

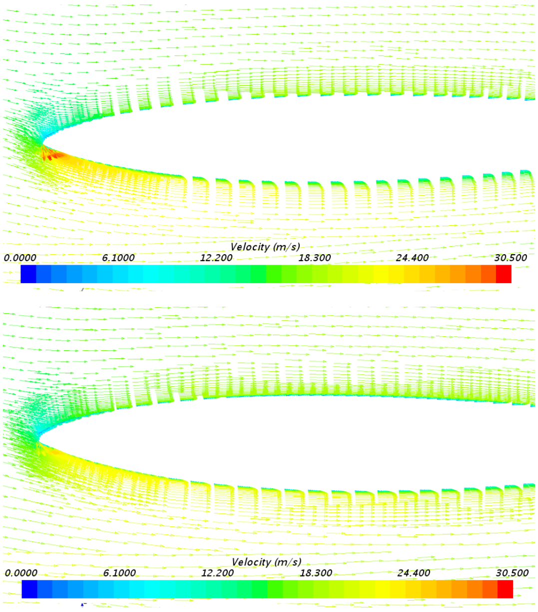

Figure 15: Velocity fields for 35 knots and 4° AoA (Single iteration FSI above; Two-way FSI below)

to have very similar angles of twist, the relative difference between results is larger than 5%. Therefore the multiple iteration FSI should be used for all simulation conditions. Most significant findings regarding fin twist are summarized here:

- Fin twist increases with both velocity and angle of attack for one-way FSI
- Fin twist for two-way FSI is overall lower than one-way FSI, reaching negative angles for some conditions
- There are two main effects responsible for the fin twist: bend-twist coupling due to the specific layup of the anisotropic composite materials used, which decreases the twist, and pitching moment due to the force applied on the fin, which increases the twist
- Two-way FSI should be used for all operating conditions

6.4. Case Study: Stall

Finally, to investigate the influence of a separation bubble on the FSI model, a single test with 8 degrees of AoA at 20 knots was done.

In figure 16, the velocity field around the fin is shown at 10 cm from the root of the fin. As shown in figure 16, a separation bubble appears near the leading edge of the suction surface of the fin.

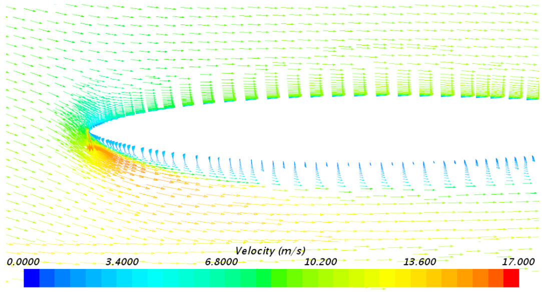

Figure 16: Velocity field for 20 knots and 8° AoA, two-way FSI

Figure 17 not only shows the pressure around the fin, but also shows the wall shear stress isolines. Two different behaviours of these isolines can be seen, in the suction surface the lines are sometimes perpendicular to the flow direction, this indicates where the turbulent flow reattaches to the fin's surface. On the other side of the fin, the pressure or lower surface, the lines are parallel to the flow's direction, which indicates that the flow does not separate.

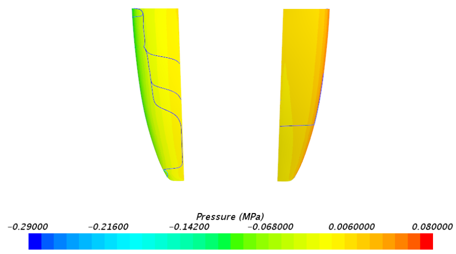

Figure 17: Pressure field for 20 knots and 8° AoA, two-way FSI

Some differences are observable when comparing the FSI results of this case with a separation bubble with all the other previous cases. For all previous operating conditions, the deflection was greater for the multiple iteration method than for the one-way solution, but since here the fin has stalled, the same behaviour is not expected. In fact, the deflection is approximately the same here for both methods, the 2-way value being 2.5% less than the one-way value. Similarly, the increase in lift force from 1-way to the 2-way solutions was small (4.1%) compared with previous, non-stalled, scenarios. However, twist angle change between 1-way and 2-way solutions was similar to that for non-stalled operation, decreasing from 1.23 degrees to 0.86 degrees.

The differences in behaviour seen for this stalled case compared to the previous cases both confirms that an AoA of 8 degrees would not occur under regular sailing conditions, and also gives confidence that the model behaves as expected even under extreme conditions.

7. Conclusions

The main objective and accomplishment of this work was the development of a design tool using an integrated fluid-structure interaction analysis model, in order to have a more accurate knowledge of the behaviour of the fin in operation. Some achievements during this project were: the selection of the material properties to do the structural study; the generation of a FEA model in ABAQUS; the development and improvement of a CFD model in Star-CCM+; and perfecting the coupling process between FEA and CFD into a fluid-structure interaction model. The FSI model created is a multiple iteration, automated FSI model which is easy to use and can be applied easily in other applications and parametric studies.

Three parameters were studied in depth: the fin's lift force, the fin's tip deflection and the fin's tip twist. A solid understanding of the response of the lift force and the tip deflection in operating conditions was achieved, both of which increased with the increase in velocity and angle of attack, and were higher for the two-way FSI when compared to the one-way FSI model. The behaviour of twist was not as simple, and hence required further research regarding its evolution throughout the multiple iterations of the model. Two main effects causing twist angle were identified: bend-twist coupling of the composite material and pitching moment. The influence of these two effects was isolated and it was found that the bend-twist coupling led to a decrease in the angle of twist, while the pitching moment increased the twist. Overall, a lower twist was predicted by the multiple iteration FSI model than was by the one-way FSI. Finally, the study of a operating situation with 8 degrees of angle of attack was done, in order to investigate stall conditions. As expected, stall condition was achieved for 20 knots with 8 degrees AoA, and the output results changed accordingly, with the lift force and tip deflection not changing compared to one-way FSI, while fin's tip twist maintained the same behaviour, decreasing compared to one-way FSI.

It was found that the two-way FSI model improves the results across all operating conditions and should be used in any analysis of the fin's behaviour while in operation.

References

[1] C. Broers, T. Chiu, M. Pourzajani, and D. Buckingham. Effects of fin geometry and surface finish on sailboard performance and manoeuvrability. *Manoeuvring and Control of Marine Craft*, pages 275–289, 1992.

[2] T. Chiu, T. Van den Bersselaar, C. Broers, and D. Buckingham. The effect of tip flexibility on the performance of a blade type windsurfer fin. *Manoeuvring and Control of Marine Craf*, pages 261–274, 1992.

[3] S. Fagg. *The development of a reversible and finitely variable camber windsurf fin.* PhD thesis, Bournemouth University, 1997.

[4] S. Fagg and X. Velay. Simulating the operation of a novel variable camber hydrofoil. In *1996 IEEE Aerospace Applications Conference. Proceedings*, volume 3, pages 261–271, Aspen, CO, USA, 1996.

[5] A. Kunoth, M. Schlichtenmayer, and C. Schneider. Speed windsurfing: Modeling and numerics. *International Journal of Numerical Analysis and Modeling*, 4(3-4):548–558, 2007.

[6] 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 Treatmen*, 2010.

[7] A. R. Q. Saldanha. Hydrodynamic and fluid-structure interaction analysis of a windsurf fin. *Master's Thesis, Instituto Superior Técnico*, 2019.

[8] A. Simulia. Abaqus analysis user's guide, 2013.

[9] Star-CCM+. Star-ccm+ user guide, 2018.