

Experimental and numerical evaluation of hydro-elastically tailored windsurfer fins

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ABSTRACT: The windsurfer fin is a small vertical hydrofoil which produces the high upwind lateral hydrodynamic forces required to balance the aerodynamic upwind side force of the far larger sail. Dynamic fin performance is highly dependent on even very small changes to its longitudinal bending and torsional twisting response, and this is traditionally achieved via the planform of the fin. However, there is unexploited potential to use the internal lay-up of these composite material fins to optimise this behaviour without the drag penalties of a non-optimum planform. In order to verify that the fins' bend-twist behaviour is as designed, extensive experimental and numerical comparisons of three otherwise identical 44 cm span FRP windsurfing fins with different hydro-dynamically tailored laminate orientations to give different bend-twist responses have been completed and reported here. Towing tank and mechanical DIC tests, as well as numerical 1-way FSI results all show that the simple rotation of a small number of plies in the laminate can reliably give the intended fin twist (wash-out / 'twist off' and wash-in) and deflection characteristics. With this successful verification of the method, various further numerical, experimental and sea trial studies are currently underway.

1 INTRODUCTION

One of the three equally critical components of a windsurfer (together with the sail / rig and board), the fin is a small vertical hydrofoil which produces the high upwind lateral, horizontal hydrodynamic forces required to balance the aerodynamic downwind horizontal side force of the far larger sail. Dynamic fin performance is highly dependent on even very small changes to its longitudinal bending and torsional twisting response, and variations in this behaviour for different conditions, sailor weight and style and discipline (e.g. course racing, slalom and wave sailing) is traditionally achieved via variations in the planform of the fin – swept back for twist and hence control, upright for less drag and hence speed (Sutherland, 1993; Sutherland & Wilson, 1994).

However, there is unexploited potential to use the internal lay-up of these composite material fins via changes to the internal layup to give bend-twist coupling and thus optimise this behaviour without the drag penalties of a non-optimum planform, as indicated by work in the aerospace (Krone, Jr., 1975) (Johnsen, 2013; Wansack, 1983)) and wind (Capellaro, 2012; de Goeij, 1999; Fedorov, 2012; Fedorov et al., 2010; Kooijman, 1996; Lobitz et al., 2001; Lobitz & Veers, 2003; Sompong, 2017) and tidal energy

(Nicholls-Lee et al., 2013, 2009) Sectors. The approach has also been investigated for composite marine propellers (Ahmed & Wei, 2012; Blasques et al., 2008; Lin et al., 2010; Liu & Young, 2009; Mulcahy et al., 2010; Young, 2008; Young et al., 2018), and International Moth 'foiling' dinghy and larger surface-piercing sailing hydrofoils (Giovannetti, 2017; Giovannetti et al., 2018, 2017, 2016; Temtching et al., 2021, 2019, 2018; Temtching & Augier, 2019).

Hence, previous work developed by the last author (Bandeira et al., 2024; Cardoso de Brito et al., 2022; Sutherland et al., 2022) has investigated this approach via the combination of numerical Finite Element Analyses (FEA) and computational Fluid Dynamics (CFD) modelling to give a full Fluid-Structure Interaction (FSI) of a commercially available 37 cm span fin. As expected these studies showed that tip deflections were large, and this demonstrated the need for 2-way FSI analyses over 1-way due to these large deflections. Importantly, the work also showed that these deflections were sufficiently large to contribute a significant proportion of the vertical lift required to support the weight of the windsurfer and sailor – and Scientifically showed for the first time that under operational conditions the fin actually works both as a 'centreboard' to keep the craft upwind, and a normal hydrofoil to drastically reduce the vertical lift contribution and hence drag of the inclined planing plate

board. This was not previously obvious since, to avoid aeration and complete loss of control of the fin (a ‘spin out’) the sailor sails to keep the very last part of the board on the water surface, and this ‘hydro foiling’ does not raise the craft out of the water as is

The FSI model was then used to design two alternative fins, one to give extreme Wash-out (feathering) and one to give extreme Wash-in due to different bend-twist behaviours induced via different internal ply alignments.

These designs were adapted to fabricate 3 new 44 cm span fins: ‘Nominal’ (as commercially available), ‘Wash-out’ and ‘Wash-in’, and then, in order to verify that the fins’ bend-twist behaviour is as designed, and as described in this paper, their relative bend-twist behaviours compared via:

1. Towing Tank testing at the Boldrewood facility in Southampton University, UK
2. Digital Image Correlation (DIC) measurements on mechanical cantilever tests
3. 1-way FSI numerical modelling using ABAQUS FEA and STAR CCM+ CFD software

Each of these three programmes showed that the hydro-elastic fibre composite tailoring approach was successful, and gave valuable data enabling the design and planning of further ongoing experimental and numerical work currently underway, which is also briefly outlined here.

2 FINS

The baseline ‘Nominal’ fin of this paper is a 44 cm commercially available production Slalom fin manufactured by F-Hot Fins Ltd, a leading supplier to world class professional sailors. The port and starboard side glass and carbon plies are hand laid up separately using epoxy resin in a split female CNC aluminium mould, which are then bolted together uncured after a final application of a thin layer of epoxy / carbon short fibre paste and cured as a single piece at 50°C for 24 hours. The exact layup schedule is commercially sensitive information, but the laminate of each side consists of 6 full face outer layers of $\pm 45^\circ$ woven and bi-directional, and 0° unidirectional (UD) carbon, followed by 8 internal tape plies of 0° UD carbon and E-glass, giving a 28 ply fin.

The Wash-out and Wash-in fins were fabricated in exactly the same way, using the same mould and identical materials (and amounts thereof) and fabrication methods as for the Nominal fin. The same lay-up schedule as for the Nominal fin was also followed, with the exception that, in order to induce bend-twist coupling (Figure 1), a number of the outer plies were rotated in such a way to ensure that the laminate remained ‘symmetric’ with ply directions above the mid-plane a mirror image of those below the mid-plane. Detailed descriptions of the laminate theory of

fibre composite bend-twist coupling can be found in (Barbero, 2011; Caprino & Visconti, 1982; Fedorov, 2012; Fedorov et al., 2010; Jones, 1999; Ong & Tsai, 1999; Strong, 2008).

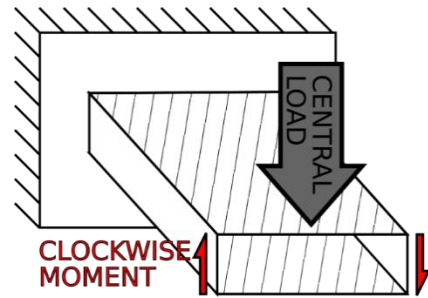


Figure 1: Bend-twist coupling. (Cardoso de Brito et al., 2022), adapted from (Fedorov, 2012))

The three fins (Figure 2) were hence identical in all respects except for the alignment of the rotated outer plies of the Wash-Out and Wash-In fins.



Figure 2: Nominal, Wash-in and Wash-out 44 cm span fins

Figure 3 explains the fin twist directions of ‘Wash-in’ (producing a progressive increase in AoA from base to tip) and ‘Wash-out’ (producing a progressive decrease in AoA from base to tip).

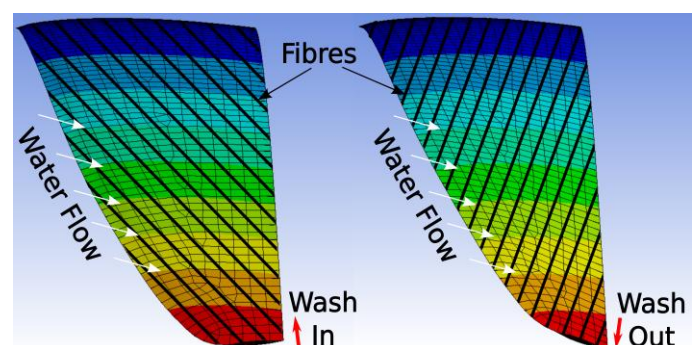


Figure 3: Wash-in and Wash-out

3 TOWING TANK TESTS

Comparative tank testing between the three fins was performed (Howard, 2023) using the rail mounted carriage of Southampton University's 138 m Boldrewood towing-tank (Figure 4).

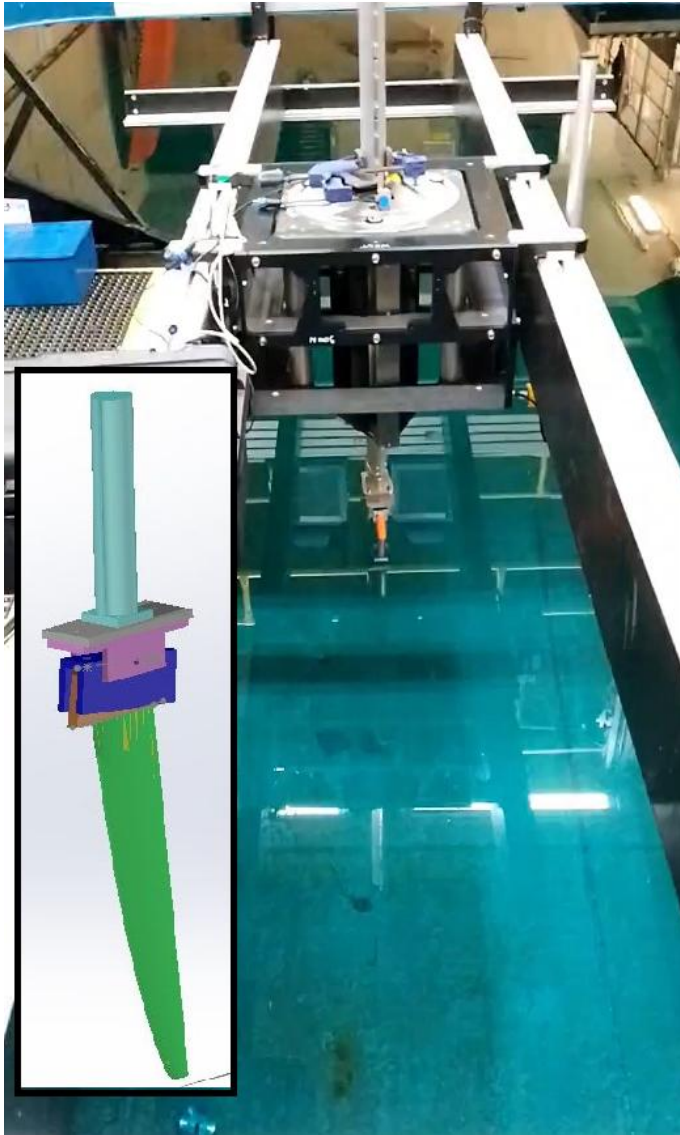


Figure 4: Bolderwood Towing Tank and test setup

The top speed of approximately 20 knots, as a respectable speed for a windsurfer, avoided all of the difficulties or even impossibilities, involved in trying to scale the microstructure of these FRP fins by allowing testing of the fins themselves.

Fins were attached to the towing post via a custom-made fixing allowing variation of the fin's lateral angle of attack (AoA) to the direction of movement. The towing post was clamped to the carriage to ensure no vertical or lateral movements. Dynamometry measured the side force and drag.

In order to try to estimate tip deflection, a strain gauge was attached to the high pressure side of each fin, and the gauge both calibrated using laboratory mechanical cantilever tests and using a "Go-Pro" video camera placed behind the fin, but these approaches were not found to be a successful and are

not considered in this paper. In this sense, the test programme was a preliminary one to evaluate measurement methods of tip deflections. The presence of strain gauges, although they were protected with extremely thin layers of silicon and applied close to the fin root to minimise the lengths of wires in the water, could have influenced the flow at the fin root. Hence the results, although allowing valid comparisons between the three fins, should only be interpreted as representative of the in-service loads developed by the fins under actual sailing conditions.

Over 80 test runs were undertaken, including:

- i. 5 identical repeatability runs at 2° AoA and 2 m/s on the Wash-in fin.
- ii. 2 runs with no waiting time between runs.
- iii. 60 runs on all 3 fins at varying AoA and speeds.

Tests were performed at 2, 4, 6 and 8 m/s (up to 16 knots, limited by the dynamometry) and AoA of 0, 2, 4, 6 and 8° . In practice, a fins would typically operate at 0 to perhaps 6° AoA under steady state conditions on flat water, depending on the point of sail. 8° was included to consider the transient effects of gusty, overpowered and choppy conditions.

The runs of i. above showed that repeatability was excellent for both lateral side force and drag coefficient C_l and C_d , (Figure 5), with a variability of approximately 5%.

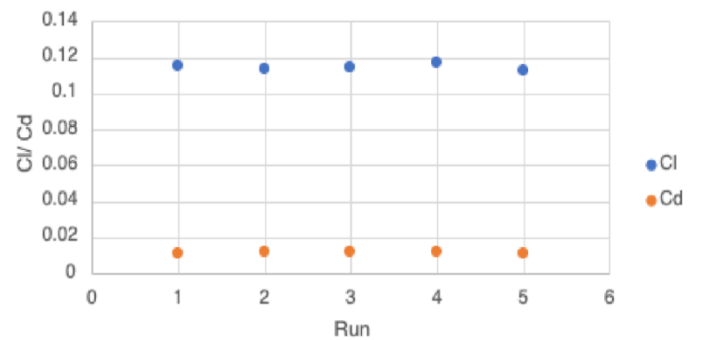


Figure 5: Lift and drag variability (2° AoA, 2 m/s, Wash-in fin)

Since a large number of runs was to be completed and the water surface required a significant amount of 'dead time' after every test to settle to the flat water state, and as the fins operated below this water surface, the tests of ii. above were performed with just the minimum test set-up time between runs to see if this process could be speeded up. However, by reducing the waiting time, lift and drag forces were seen to increase by 30 and 25%, respectively, and so all further tests were performed under flat water conditions.

3.1 Towing Tank Results

In the next two sections, the results of tests iii. above, in terms of side force or foil 'lift' and then drag are summarised.

3.1.1 Lift

The variations of lift coefficient with AoA and speed seen for the Nominal, Wash-in & Wash-out fins are shown in Figure 6, Figure 7 and Figure 8, respectively.

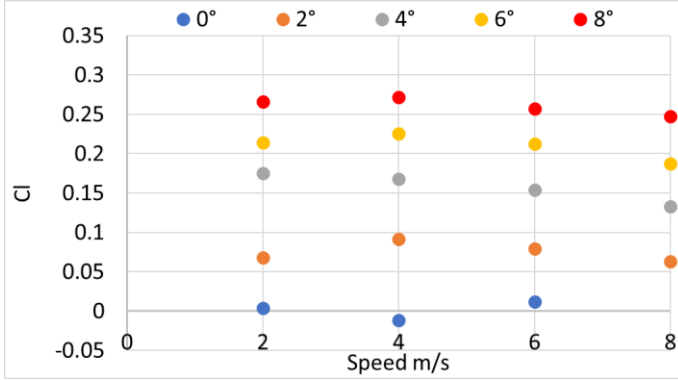


Figure 6: Nominal fin lift coefficient (C_l) variation

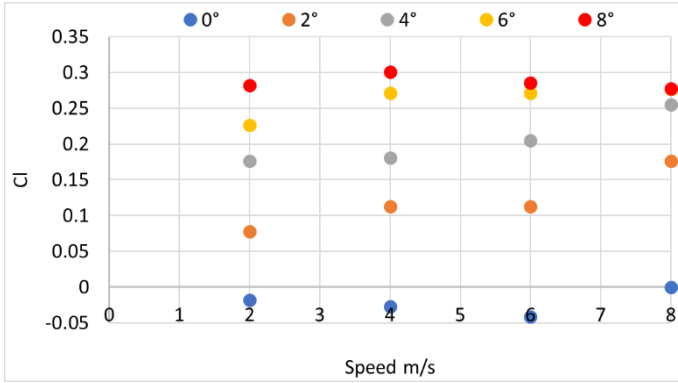


Figure 7: Wash-in fin lift coefficient (C_l) variation

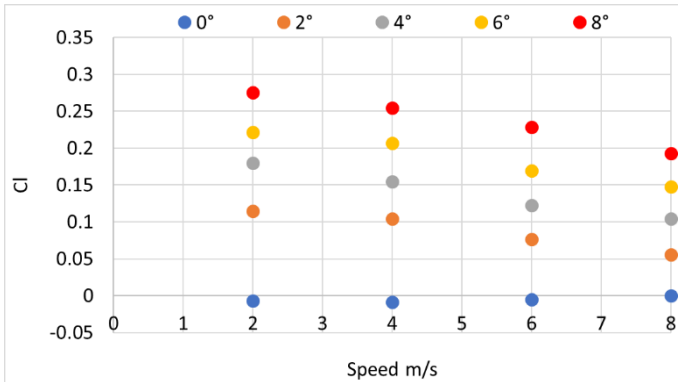


Figure 8: Wash-out fin lift coefficient (C_l) variation

As expected, lift coefficient increases with AoA for all fins.

Considering the Nominal fin of Figure 6, at lower AoA combined with lower speed (when the fin is ‘unloaded’) lift coefficient remains rather constant, considering the inherent variability in the data. However, as the fin is loaded up at speeds of 6 and especially 8 m/s there is strong evidence of a reduction in lift coefficient, which is clear at all non-zero AoA. This is commensurate with the design ethos of the commercially evolved nominal fin (by F-Hot Fins Ltd) to **twist off** slightly at higher loadings, reducing AoA locally, unloading the tip and improving control.

In contrast, for the Wash-in fin of Figure 7, for AoA 2 & 4° as speed is increased and the fin increasingly loaded up, the lift coefficient increases signifi-

cantly, and across the whole range of speeds considered. Again, this is commensurate with our design ethos of the Wash-in fin to **twist in** to a large degree at higher loadings, increasing AoA locally, loading up the fin and increasing lift (this was done in such an extreme way to make any resulting effects easily observable, not to try to optimise the fin, as of yet). The observation that this increase in C_l is only seen at lower speeds for 6 and 8° AoA, and that this increase is steeper for 6 than 8° indicate strongly that the high amounts of bend-twist wash-in built into the laminate of this fin lead to an earlier stall and subsequent loss of lift as the fin is more highly loaded.

Contrarily, for the Wash-out fin of Figure 8, for all positive AoA, as speed is increased and the fin increasingly loaded up, the lift coefficient decreases significantly, and across the whole range of speeds considered. Again, this is commensurate with our design ethos of the Wash-out fin to **twist off** to a large degree at higher loadings, decreasing AoA locally, unloading the fin and decreasing lift (again, this was done in such an extreme way to make any resulting effects easily observable, not to try to optimise the fin, as of yet). In this case, this lift decrease is seen for all AoA, including 6 & 8°, and across all speeds as unloading the fin tip via wash-out reduction of the local AoA does not lead to stall.

Overall, at the lowest, 2 m/s speed, there equivalent values of C_l for each AoA are very close for the three fins, which would be expected as at these low speeds the fins are only lightly loaded and bend-twist coupling effects would be small. However, at higher loadings there is a strong correlation of increasing lift from Wash-out to Nominal to Wash-in fins, which is commensurate with the coincident designed increase of bend-twist from Wash-in to wash out.

In fact the Nominal fin lift coefficient values are closer to that of the Wash-in fin than to the Wash-out fin, which may be most simply illustrated by relative closeness of the Nominal fin at the origin and the 2-way FSI Wash-in fin in the design space diagram of Figure 9 adapted from (Sutherland et al., 2022). It is important to note that Figure 9 shows numerical FSI results for the previously studied 37 cm fin, not the current 44 cm fin, but that since the same layup schedule rotations were used here it is valid to consider it in this illustrative light.

3.1.2 Drag Force

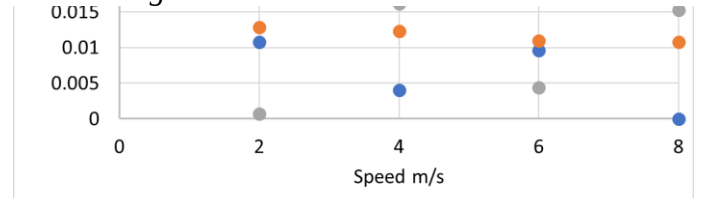


Figure 10, although the expected increase in drag coefficient with AoA is evident.

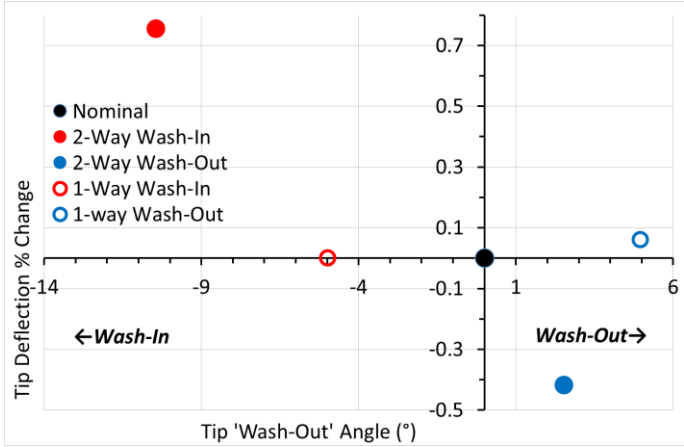


Figure 9: Fin design space positions (37 cm fins FSI results)

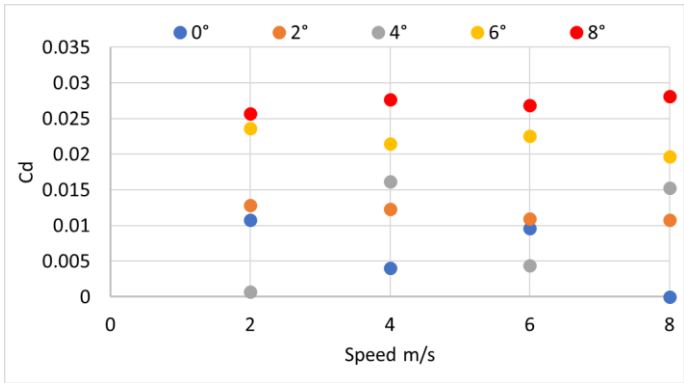


Figure 10: Nominal fin drag coefficient (C_d) variation

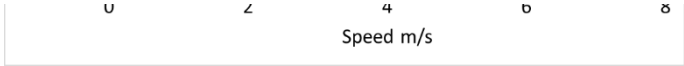


Figure 11 there is a clear increase in drag coefficient with both AoA and speed, which is exactly what would be expected as the local AoA increases towards the tip (as designed) as speed, fin loading and hence bend-twist effects increase.

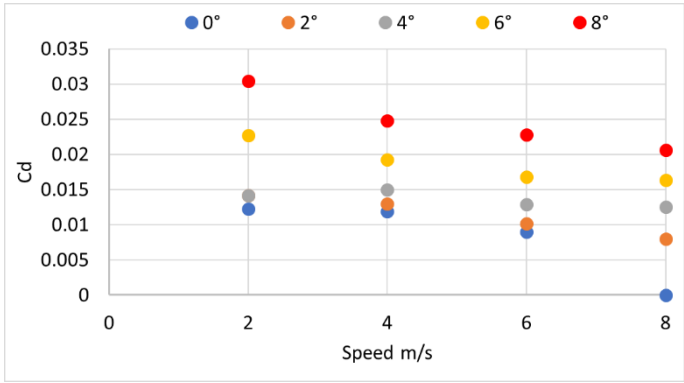


Figure 11: Wash-in fin drag coefficient (C_d) variation

Contrarily, for the Wash-out fin in Figure 12 there is a clear increase in drag coefficient with AoA but a clear decrease in drag coefficient with speed, which is exactly what would be expected as the local AoA decreases towards the tip (as designed) as speed, fin loading and hence bend-twist effects (in the opposite direction to the Wash-in case) increase.

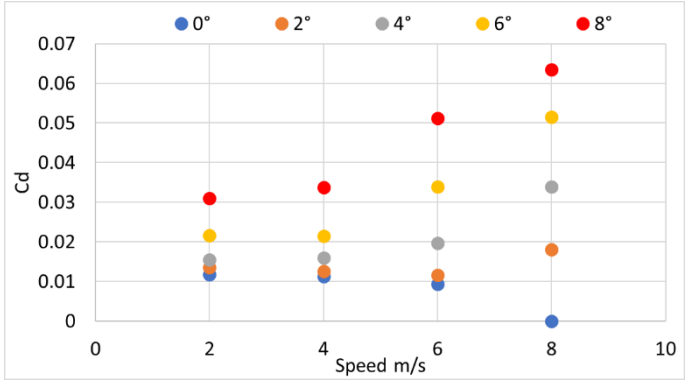


Figure 12: Wash-out fin drag coefficient (C_d) variation

Hence, the tank testing showed that the ply rotations did give the intended wash-in and wash-out behaviour of the respective modified fins, as designed.

4 MECHANICAL DIC TESTS

Digital Image Correlation (DIC) provides full-field displacement fields comparing “reference” – taken before loading - and “deformed” images of the same coupon on which a speckle pattern was previously applied, and using two ‘stereo’ cameras. Here this technique was used to compare the twist of the three fins point-loaded to 100 N at a span of 200 mm and ¼ chord from the leading edge, using an Instron 5569 and with the fin base fully-clamped. Due to practical constraints on the positioning of the cameras, only the lower 165 mm of the fin span was imaged, for further details see (Pierre Amossé, 2023). The DIC equipment and settings and the MatchID software parameters used to process and analyse the results are given in Table 1.

Table 1: DIC equipment and settings

Equipment	Parameter	Value
Camera		2 Manta G504B (5MPx)
	Stereo angle	20°
	Sensor size	8.5 x 7.1 mm
	Pixel size	3.45 µm
	Maximum resolution	2452 x 2056 pixels
Lens	Exposure time	30000 µs
		2 AF Nikon 28 mm f/2.8D
Speckle pattern	Aperture	f-4
		Spray painted
	Speckle size	≈ 12 pixels
Software	Area	230 x 175 mm
		MatchID
	Subset	55 x 55 pixels
	Step size	15 pixels
	Strain window	69 pixels
	Shape function	Quadratic
	Interpolation function	Bicubic
Cross-correlation function		ZNSSD
	Stereo transformation	Quadratic

The out of plane displacement results of the DIC tests of the three fins are compared in Figure 13.

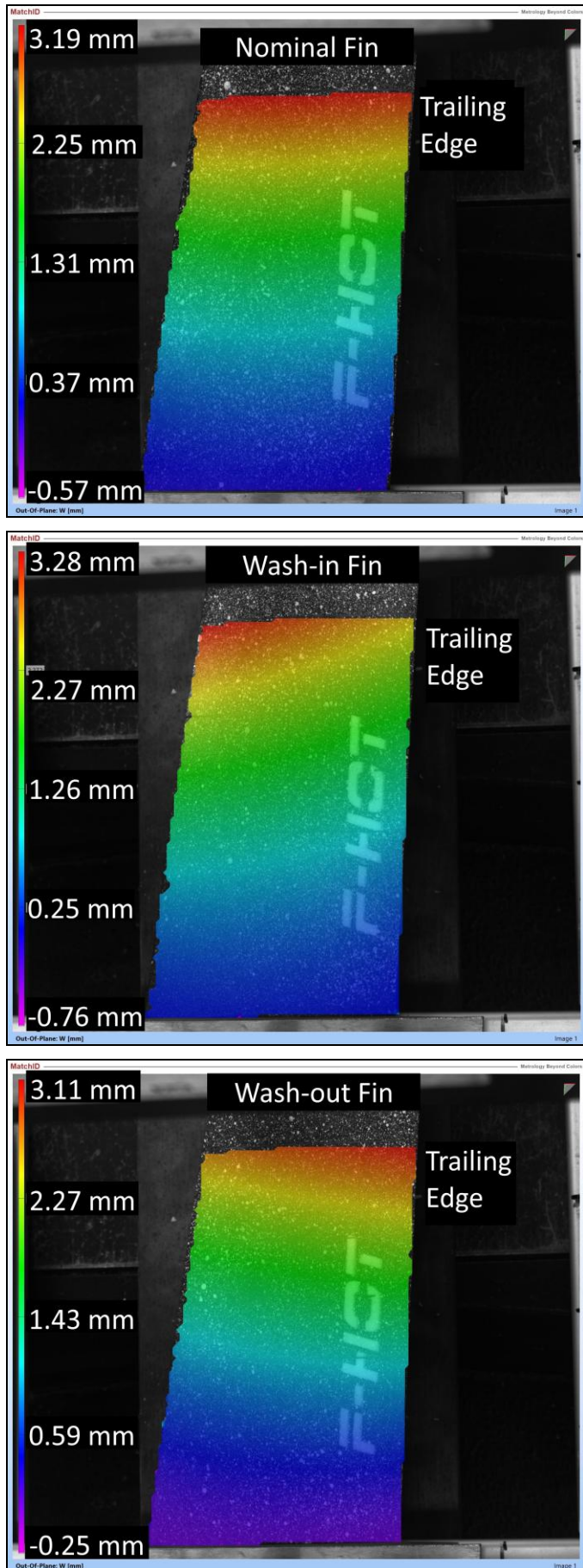


Figure 13: DIC out of plane displacement results

Even as these fin spans closer to the base, Figure 13 clearly shows that at a given span the trailing edge of the Wash-in fin deflects less than the leading edge (resulting in bands of colour rotated clockwise compared with those of the Nominal fin), i.e. the fin is indeed ‘washing-in’.

Conversely, at a given span the trailing edge of the Wash-out fin deflects more than the leading edge (resulting in bands of colour rotated anti-clockwise compared with those of the Nominal fin), i.e. the fin is indeed ‘washing-out’.

The nominal fin, under this simplified point loaded cantilever simplified loading, exhibits a neutral bend-twist behaviour with neither wash-in nor wash-out (resulting in horizontal bands of colour).

The wash-in and wash-out of the respective fins is seen, as expected, to increase in magnitude as the span considered increases. At these lower spans, the smaller displacements make it difficult to identify any differences in the magnitude of the overall displacements between fins.

5 1-WAY FSI ANALYSES

There is only space here to very briefly summarise the numerical analyses, for further information see (Cardoso de Brito et al., 2022; Howard, 2023; Pierre Amossé, 2023).

5.1 FEA

The same approach as used to construct an ABAQUS FEA model by (Cardoso de Brito et al., 2022), also using the same validated material properties, was followed, with updated geometry for the 44 cm fin using the IGES files used by F-Hot Ltd to CNC the moulds (Pierre Amossé, 2023) (Figure 14).

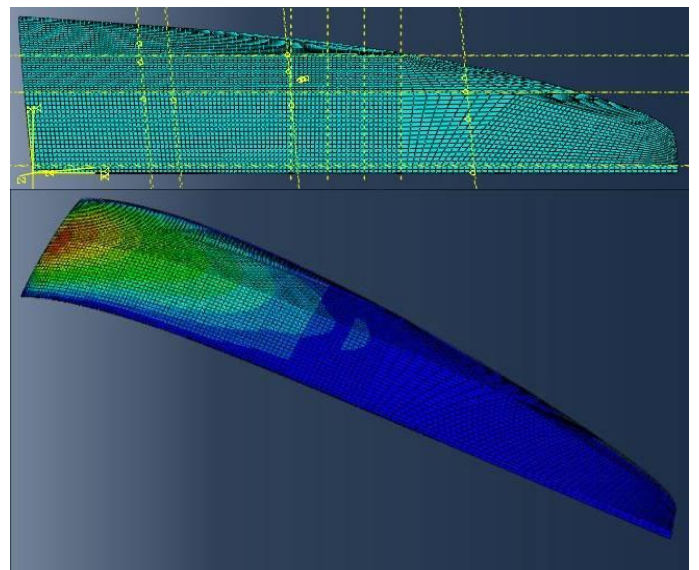


Figure 14: ABAQUS FEA model

As for the physical fins, all aspects of the three FEA models were identical, except for the ply direction rotations of the outer plies.

5.2 CFD

Similarly, the same approach as used to construct a STAR CCM+ CFD model by (Cardoso de Brito et al., 2022) was followed, with updated geometry for the 44 cm fin using the IGES files supplied by F-Hot Ltd (Howard, 2023) (Figure 14).

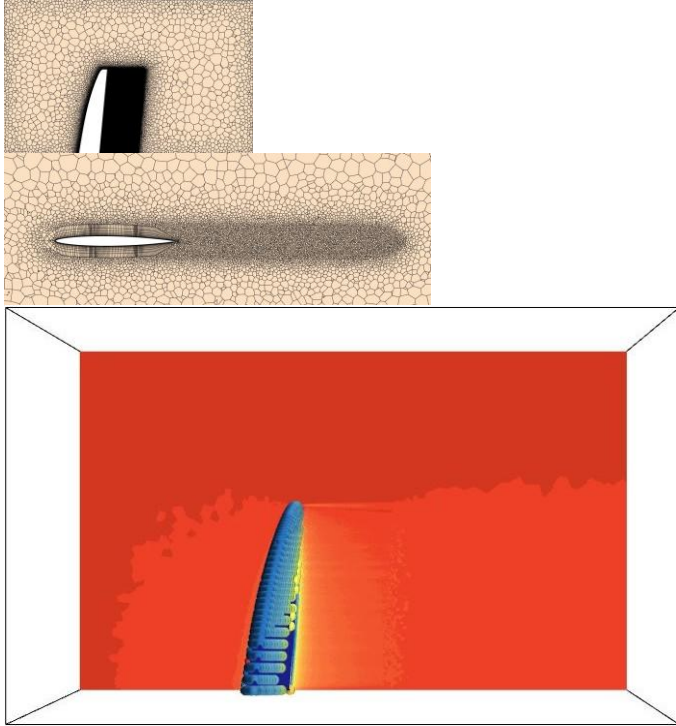


Figure 15: STAR CCM+ CFD model

5.3 1-Way FSI

As of now, only 1-way FSI analyses have been completed, which will not give the actual deflection and twist values that would be seen under sailing conditions (full, iterative 2-way analyses are required for this for these flexible fins (Cardoso de Brito et al., 2022)). However, 1-way analyses did allow valid comparisons to be made of the bend-twist characteristics of the three fins (Pierre Amossé, 2023).

Here, the CFD model of Section 5.2 was used to obtain pressure fields for a moderate AoA of 4° and speeds of 8, 12 and 16 m/s (Figure 16), which were then applied to the three FEA models of Section 5.1 to give the 1-way FSI twists at three spans (140, 280 and 420 mm) (Figure 17) and tip displacements (Figure 18).

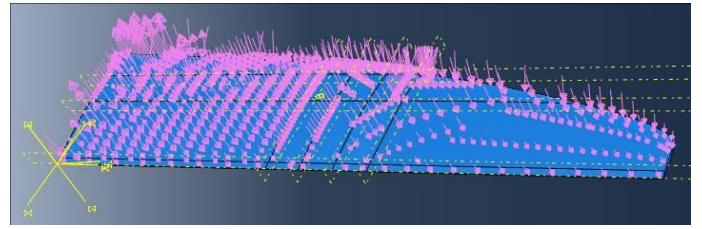


Figure 16: Example CFD pressure field used for 1-way FSI

Once again, Figure 17 clearly shows that the fins behave as they should do, with the Wash-out fin twisting off progressively along the span, and more severely as speed increases. Conversely, the Wash-in fin trailing edge actually twists into the flow, increasing the local AoA off progressively along the span, and more severely as speed increases. The twist of the nominal fin lies between the other two, exhibiting moderate twist-off. It should be noted here that, although the twist angles seen appear small, compared with the expected range of sailing AoA of 0 to 4° , they are highly significant.

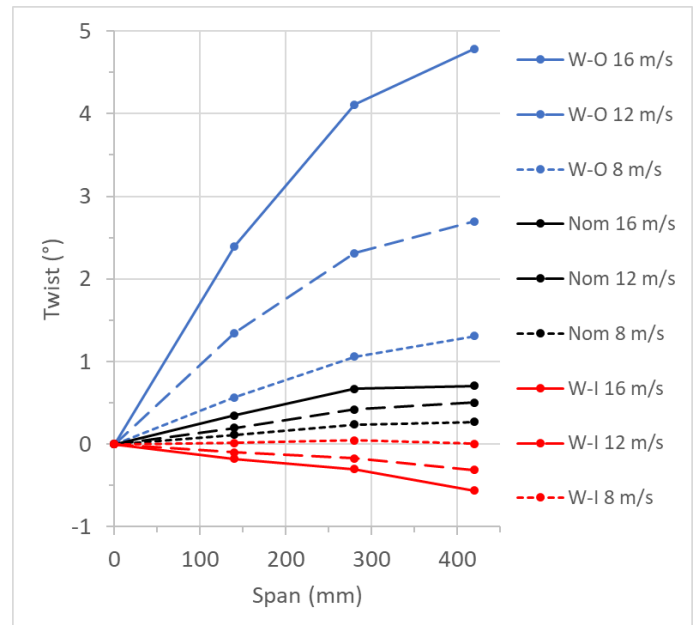


Figure 17: 1-way FSI twist results

The almost identical 1-way FSI tip deflections (Figure 18) of the Nominal and Wash-in fins exhibit a stiffer response than do those of the Wash-out fin.

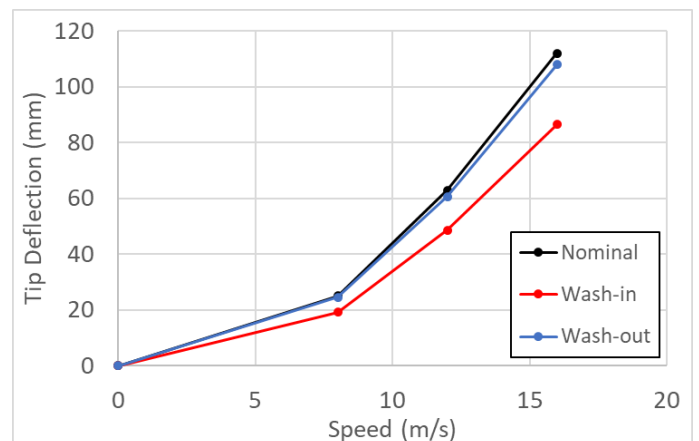


Figure 18: 1-Way FSI tip deflection results

6 CONCLUSIONS AND FURTHER WORK

Extensive experimental and numerical comparisons of three otherwise identical FRP windsurfing fins with different hydro-dynamically tailored laminate orientations to give different bend-twist responses have been completed and reported here.

Towing tank and mechanical DIC tests, as well as numerical 1-way FSI results all show that the simple rotation of a small number of plies in the laminate can reliably give the intended fin twist (wash-out / ‘twist off’ and wash-in) and deflection characteristics.

With this successful verification of the method, various further studies are currently underway, including: Mechanical DIC testing concentrating on the fins’ upper spans; FEA / CFD / FSI lay-up schedule parametric studies to further quantify the effects of the number, position and rotation angle of plies on the twist behaviour; Combination of experimental and numerical methods with feedback obtained from ‘on the water’ sea trials carried out by professional and expert sailors.

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REFERENCES

- Ahmed, A. & Wei, L., 2012. Theoretical and experimental methods on bend-twist coupling and damping properties with the relationship to lay-up of the composite propeller marine: A review. *Int. J. Eng. Sci. Technol.* 1: 2907–2917.
- Bandeira, G., Sutherland & L.S., Miller, P.H., 2024. Structural behaviour of a windsurfer fin, in: *Advances in Maritime Technology and Engineering*. Guedes Soares, C. & Santos, T.A. (Eds.), CRC Press, London, pp. 349–357.
- Barbero, E.J., 2011. Introduction to Composite Materials Design, 2nd ed. CRC Press, Boca Raton, FL.
- Blasques, J.P., Berggreen, C. & Andersen, P., 2008. Hydro-Elastic Tailoring and Optimization of a Composite Marine Propeller, in: *Proceedings of the 13. European Conference on Composite Materials: Composites for Sustainable Progress*. British Welding Research Association, Stockholm, Sweden, p. 10.
- Capellaro, M., 2012. Design Challenges for bend twist coupled blades for wind turbines: and application to standard blades. *Wind Turbine Workshop 2012*, May 30 - June 1, Stuttgart.
- Caprino, G. & Visconti, I.C., 1982. A Note on Specially Orthotropic Laminates. *J. Compos. Mater.* 16: 395–399.
- Cardoso de Brito, M., Sutherland, L.S., Pereira J.M.C. & Arruda, M.R., 2022. Fluid-Structure Interaction Analyses for Hydro-Elastic Tailoring of a Windsurfer Fin. *J. Mar. Sci. Eng.* 10: 1371.
- de Goeij, W.C., 1999. Implementation of bending-torsion coupling in the design of a wind-turbine rotor-blade. *Appl. Energy* 17.
- Fedorov, V., 2012. Bend-Twist Coupling Effects in Wind Turbine Blades (PhD Thesis). Technical University of Denmark, Lyngby, Denmark.
- Fedorov, V.A., Dimitrov, N., Berggreen, C., Krenk, S., Branner, K. & Berring, P., 2010. Investigation of Structural Behavior due to Bend-Twist Couplings in Wind Turbine Blades. *Presented at the NAFEMS NORDIC Seminar: 1 „Simulating Composite Materials and Structures “*, Esbjerg, Denmark, p. 9.
- Giovannetti, L.M., 2017. Fluid structure interaction testing, modelling and development of passive adaptive composite foils (PhD Thesis). University of Southampton.
- Giovannetti, L.M., Banks, J., Boyd, S. & Turnock, S., 2016. Developing tools for assessing the fluid structure interaction of passive adaptive composite foils. *6th International Conference on Structural Engineering Mechanics and Computation*, Cape Town.
- Giovannetti, L.M., Banks, J., Ledri, M., Boyd S. & Turnock, S., 2017. Fluid structure interaction design development of passive adaptive composite international moth foil, in: *International Conference on Innovation in High Performance Sailing Yachts 4th Edition*.
- Giovannetti, L.M., Banks, J., Ledri, M., Turnock, S.R. & Boyd, S.W., 2018. Toward the development of a hydrofoil tailored to passively reduce its lift response to fluid load. *Ocean Eng.* 167: 1–10.
- Howard, T.H., 2023. Bend-Twist Hydro Elastic Tailoring of Windsurfer Fins - Hydrodynamic Testing (MSc Thesis). University of Southampton, Southampton, UK.
- Johnsen, F.A., 2013. Sweeping forward: developing & flight testing the Grumman X-29A Forward Swept Wing Research Aircraft, NASA aeronautics book series. National Aeronautics and Space Administration, Aeronautics Research Mission Directorate, Washington, DC.
- Jones, R., 1999. Mechanics of Composite Materials, 2nd ed. Taylor & Francis, Philadelphia, PA.
- Kooijman, H.J.T., 1996. Bending-torsion coupling of a wind turbine rotor blade (No. ECN-I--96-060). ECN.
- Krone, Jr., N., 1975. Divergence elimination with advanced composites, in: *Aircraft Systems and Technology Meeting. Presented at the Aircraft Systems and Technology Meeting, American Institute of Aeronautics and Astronautics*, Los Angeles, CA, U.S.A.
- Lin, H.J., Lai, W.M. & Kuo, Y.M., 2010. Effects of Stacking Sequence on Nonlinear Hydroelastic Behavior of Composite Propeller Blade. *J. Mech.* 26: 293–298.
- Liu, Z. & Young, Y.L., 2009. Utilization of bend-twist coupling for performance enhancement of composite marine propellers. *J. Fluids Struct.* 25: 1102–1116.
- Lobitz, D.W., Veers, P., Eisler, G.R., Laino, D.J., Miglior, P.G. & Bir, G., 2001. The Use of Twist-Coupled Blades to Enhance the Performance of Horizontal Axis Wind Turbines (No. SAND2001-1303). Sandia National Labs.
- Lobitz, D.W. & Veers, P.S., 2003. Load Mitigation with Bending/Twist-coupled Blades on Rotors using Modern Control Strategies. *Wind Energy* 6: 105–117.
- Mulcahy, N.L., Prusty, B.G. & Gardiner, C.P., 2010. Hydroelastic tailoring of flexible composite propellers. *Ships Offshore Struct.* 5: 359–370.
- Nicholls-Lee, R.F., Boyd, S.W. & Turnock, S.R., 2009. Development of high performance composite bend-twist coupled blades for a horizontal axis tidal turbine, in: *ICCM17: 17th International Conference on Composite Materials*. Edinburgh, UK.
- Nicholls-Lee, R.F., Turnock, S.R. & Boyd, S.W., 2013. Application of bend-twist coupled blades for horizontal axis tidal turbines. *Renew. Energy* 50: 541–550.
- Ong, C.-H. & Tsai, S.W., 1999. Design, Manufacture and Testing of A Bend-Twist D-spar (No. SAND 99-1324). Sandia National Laboratories.

- Pierre Amossé, 2023. Hydro-elastic tailoring of a windsurfing fin Numerical and experimental investigations of bend-twist coupling (MSc Thesis). University of Southampton, Southampton, UK.
- Sompong, N., 2017. Effects of bend-twist coupling deformation on the aerodynamic performance of a wind turbine blade. *Int. J. GEOMATE* 12.
- Strong, A.B., 2008. Fundamentals of composites manufacturing: materials, methods and applications, 2nd ed. ed. Society of Manufacturing Engineers, Dearborn, Mich.
- Sutherland, L.S., 1993. Windsurfer Fin Hydrodynamics (MSc Thesis) (MSc). University of Southampton, Southampton.
- Sutherland, L.S., de Brito, M.C., Pereira, J.C., Arruda, M.R. & Benson, S., 2022. Fluid-structure interaction analyses of a composite windsurf fin, in: *Trends in Maritime Technology and Engineering Volume 1*. CRC Press, Taylor and Francis Group, UK, London, UK, p. 9.
- Sutherland, L.S. & Wilson, P.A., 1994. Windsurfer Fin Hydrodynamics, in: *Marine, Offshore and Ice Technology*. Computational Mechanics Publications, pp. 51–58.
- Temtching, V. & Augier, B., 2019. Bend-Twist Coupling Analysis of Composite Hydrofoils with FSI, in: *24me Congres Francais de Mecanique*, Brest, France, p. 15.
- Temtching, V., Augier, B., Dalmas, T., Fagherazzi, O. & Dumergue, N., 2018. Analysis of Composite Layup Impact on Hydrodynamic Performances of Sail Yacht Flexible Hydrofoils, in: *JH2018 - 16e Journées de l'Hydrodynamique*, Marseille, France, p. 15.
- Temtching, V., Benoit, A. & Benoit, P., 2021. Hydro-elastic response of composite hydrofoil with FSI. *Ocean Eng.* 221.
- Temtching, V., Navale, E., Augier, B., Dalmas, T., Dumergue, N. & Paillard, B., 2019. Impact of Composite Layup on Hydrodynamic Performances of a Surface Piercing Hydrofoil, in: *The 23rd Chesapeake Sailing Yacht Symposium*, Annapolis, Maryland, USA, p. 15.
- Wansack, J.K., 1983. X-29 Advanced Technology Demonstrator Technical Activity Report. USAF Flight Dynamics Laboratory, Ohio, USA.
- Young, Y.L., 2008. Fluid–structure interaction analysis of flexible composite marine propellers. *J. Fluids Struct.* 24: 799–818.
- Young, Y.L., Garg, N., Brandner, P.A., Pearce, B.W., Butler, D., Clarke, D. & Phillips, A.W., 2018. Load-dependent bend-twist coupling effects on the steady-state hydroelastic response of composite hydrofoils. *Compos. Struct.* 189: 398–418.