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The application of canting keel concept in racing windsurfing fins: does it lead to superior performance?

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Abstract

Windsurfing is a young, dynamically evolving sport. As the numbers of windsurfers increase around the world, equipment producers race against each other, using the latest materials and technologies in the never ending pursuit of better performance. The aim of this research is to investigate the latest development idea – the canting fin. The project is based on Formula Windsurfing, a racing discipline, where fins reach 70cm of length and have crucial influence on a competitor's final result.

Primary data was collected in two stages, in both qualitative and quantitative forms. The former involved 4 male, international-level windsurfing competitors who tested two provided sample fins – one of a classic design and the other, with the same geometry and material properties but altered into the canting concept. Subjects' observations were recorded using a semi-structured questionnaire. The second stage of data gathering was based on GPS measurements of fins' performance. Once again the two described sample foils were used to identify the advantages and disadvantages of the novel design. At this point, over 5000 of speed and course measurements were taken providing a significant data set.

The presented results show numerous differences between the tested fins. Overall, combining all of the measured characteristics, the canting fin proved to be superior by 44% in a simulated competition situation. In a competitive situation, research participants would have chosen the new fin in 87% of the tested situations over the classic design.

The project generated an interesting set of results without having to base on multiple assumptions. It was 100% practise-based and was designed as an alternative to laboratory-based modelling. Factors influencing data precision and the measurement error were discussed and several areas for further research were outlined.

Dictionary of Terms

Fin, foil – the underwater part of a windsurfing board responsible for maintaining direction and manoeuvrability.

Fin's stiffness – for the use of this research, only referred to in terms of stiffness along the vertical axis of a fin.

Fin's twist – The stiffness of the very end of the fin withstanding twisting in a plane parallel to the board.

Formula Windsurfing, FW - a class of racing windsurfing that has evolved over the last 15 years in order to facilitate high performance competition in light and moderate winds. Sail reaching 12m^2 , 1m-wide boards and 70cm long fins are its most distinctive features.

Jibe - a sailing manoeuvre where a sailing vessel turns its stern through the wind, such that the wind direction changes from one side of the boat to the other.

Knot – a unit of speed equal to one nautical mile (1852m) per hour. 1 knot = 0,514[4] m/s.

Leeward - the direction downwind from the point of reference.

Mph – miles per hour. Used always in the context of land miles (1609m).

Planing – according to Larsen and Eliasson (1994):

At zero speed this force [buoyancy] balances exactly the weight of a floating body. However, as soon as the body starts moving, the hull puts water particles into motion by exerting a force on each particle. The same force, but in the opposite direction, is exerted on the hull. This force per unit area may be called the hydrodynamic pressure. […] At high speed this vertical pressure force may be considerably larger than the buoyancy, lifting the hull more or less completely out of the water. A hull predominantly supported by the hydrodynamic pressure is considered to be planing.

Reach – a course of sailing perpendicular to the wind's direction.

Spin-out – a situation when water flow get's separated from a fin. The board looses "traction" and starts sliding sideways.

Tack - a manoeuvre by which a sailing boat turns its bow through the wind.

Windward - the direction from which the wind is blowing at the time in question.

Acknowledgements

I would like to acknowledge everyone who has helped at any stage of the production of this research. Firstly my thanks go to Ross Pomeroy, who has been the project advisor and helped with the design and the choice of appropriate methods and tools for this research. I would also like to thank the University technician, Richard Kenyon for his infinite patience and great help with GPS devices and associated software.

Finally I would like to thank Wojtek Brzozowski for the idea for this project and all the athletes of the Leba Professional Windsurfing Centre for their support and participation in this research.

Thank you all.

1. Introduction

From the moment windsurfing gained a racing discipline, fins started being recognised by competitors and equipment designers as a significant part having big influence on the general performance. As described by Broers (1992) – "In general the importance of the performance of fins has been realised by board manufacturers. However, there still is a large amount of mystique as to how they function." Nowadays there are still very few relevant data available even though the modern windsurfing racing fin is 70cm long and has bigger then ever influence on the competitors final result.
This study was designed to provide scientific data on the latest fin-development idea, which is for the purpose of the project called the canting-fin. The new design allows a fin of standard shape, profile and elastic properties to swing towards the windward side of a board, adding to the elastic deformation in the same direction, which happens under the force exerted by a windsurfer and the counteracting pressure of water on the leeward side of the fin.

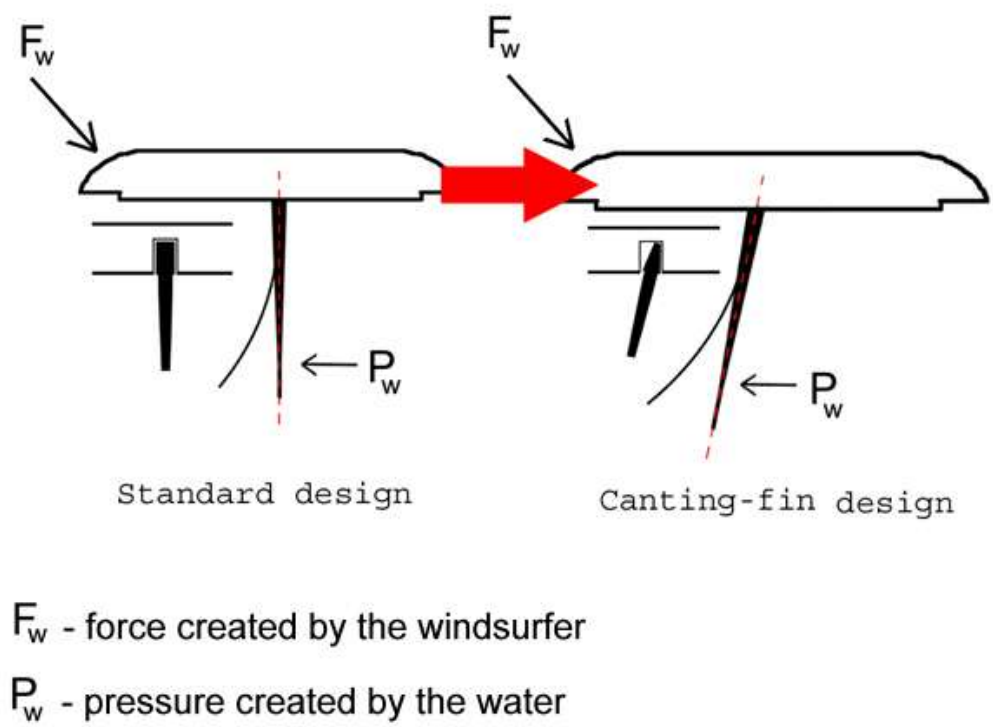

Figure 1. Graphical presentation of the canting fin concept.

The research compares the classic fin with the novel design in terms of effective performance. The following chapters provide an overview of the background science, describe the data collection and analysis methodology, and present the results and the drawn conclusions.

1.1 Aims

The primary aim of this project is to construct and to carry out a scientific research investigating the influence of a canting-fin on the performance in Formula Windsurfing.

1.2 Objectives

Three key objectives were outlined for this project in its earliest stages. Firstly, to maximize the number of subjects participating in the qualitative research and the number of measurements in the quantitative part. Secondly, to minimize the amount of assumptions and scale of measurement errors. Finally, the last goal was to produce a significant piece of work for the windsurfing industry.

2. Background

The idea for this research evolved over the past 3 years of observing the FW class and testing of many different equipment settings and combinations. The two people who influenced the project the most were Jean-Jacques Deboichet, a French fin manufacturer and Wojtek Brzozowski, triple Formula World champion (1999, 2000, 2008) (source: Formula Windsurfing Official Website – champions list). The former has been the leader in terms of fin design and market share for many years. During the FW World Championship in 2006 79% of competitors used Deboichet's fins (source: Formula Windsurfing Official Website – 2006 equipment list). He was interviewed on two occasions in year 2005 and 2007. Brzozowski is personally partly responsible for the general shape of this research as it was him who first tested the canting-fin concept in windsurfing and suggested this area for further study in November 2007. Since then he was interviewed on multiple occasions. All of the mentioned interviews were conducted by the author of this research.

In terms of the theory reviewed as a foundation for this project, insufficient amount of windsurfing-specific researches was identified to base the methodology design on those alone. It was therefore decided to use broader areas of aero- and hydrodynamics. The available windsurfing-related publications were also reviewed and taken into consideration.

2.1 About Formula Windsurfing

Modern windsurfing has three internationally recognised racing disciplines: Speed, Slalom and Formula. Formula Windsurfing is the youngest of all windsurfing classes (created in 1999) and has technological progress embedded in its core (source: Formula Windsurfing Official Website – equipment rules). It quickly became the main engine pushing the whole sport forward in terms of equipment design and the use of latest technologies and materials. Evolution of the class over the years resulted in the current shape of the FW equipment. Its most distinctive features are: a metre wide board and 70 centimetres long fin. Increasing the size of the fin and the board's width from the original windsurf board enabled the windsurfer to plane in 7 knots (official limit for FW racing – source: Formula Windsurfing Official Website – championship rules) and achieve greater efficiency on upwind and downwind courses then ever before (superior to most sailing classes). As shown later on, it is the combination of the relatively stable upwind courses with the very fast unsteady downwinds that is the greatest challenge for equipment designers.

2.2 Aircraft-related Theory

The first related area in which applicable theory was searched for was aerodynamics and the design of aeroplane wings. This path has been chosen by some of the previous researchers and provided a broad base to relate some of the windsurfing fin design issues to. When looking at a wing in movement, as one takes any given point on the wing's surface, the force acting on this point can be described by a vector. This vector depicts a resultant force being a sum of 3 key constituents: aerodynamic lift, drag and moment.

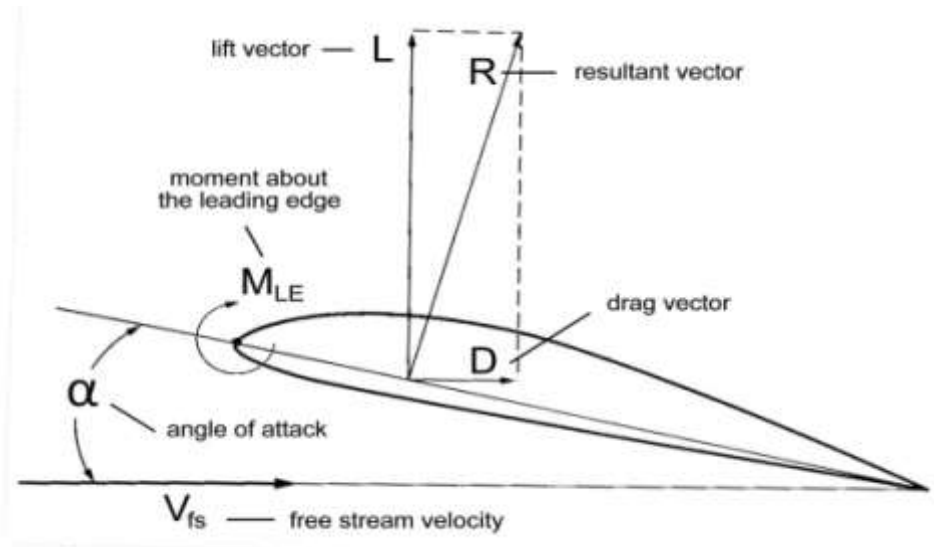

Figure 2. Forces acting on a wing section, adapted from Anderson (1999)

The first two are described by Anderson (1999) in the following words: "[...] the component of the resultant force perpendicular to the free-stream velocity is the lift, and the component of the resulting force parallel to the free-stream direction is the drag." Now let's take the wing's cross section. If one placed an axis perpendicular to the cross section in any given point, the moment would be the tendency for the axis to spin in one way or the other. It is a result of pressure and shear stress distributed all over the wing and exists everywhere except a specific point called the centre of pressure. If one placed an axis through the centre of pressure, there would be no moment in any direction.

2.3 Aircraft-related Theory - Similarities and Differences

The important question in terms of this project is how these basics of aerodynamics transfer to hydrodynamics. If one tried to model the forces acting on a windsurfing fin the three key components would definitely be noticeable. The fins lift in practice allows a windsurfing board to move in any given direction other then directly with the wind. The drag is obviously present and can be described as a combination of form drag, depending on the shape of the fin, and the skin friction which depends on the fin's texture. The moment is less intuitive but nevertheless definitely present. It could be proven with a simple experiment. If one grabbed a fin by its rear edge and attempted to push it through water it would try to turn. This effect would be the moment about the

point at which one was holding the fin. So the forces acting on a wing do act on a fin as well. However the similarities end here due to the factors influencing the character of lift, drag and moment. Those factors, as described by Kroes and Rardon (1993) are: ambient density, wing/fin area, angle of attack, ambient viscosity and ambient compressibility. The differences are visible instantly. Water is a totally different environment then air. It is denser, which not only means that it causes more drag and is less compressible, but also generates buoyancy which adds a new factor to the equation. Water is also more viscous which influences the skin friction but also means that the flow separation (turbulence) will occur at a different point — more on this issue later on. Another difference is that a windsurfing fin is required to work on both tacks so only symmetrical foil sections are of interest for this use. It is as if an aeroplane was expected to fly upside down.

Despite the listed dissimilarities there is one task that the designers of both aeroplane wings and FW fins must face. The wing, just like a fin, needs to be efficient in two different situations. First of all, at high speeds, where the free-stream velocity creates significant amounts of lift even with a relatively small angle of attack or a narrower profile. For a plane this is the state when it has reached the cruising altitude and speed, in windsurfing it is the downwind course. The opposite end of the range means lower velocities and the need to create lift in some other way. In aviation this occurs at take-off and landing, in windsurfing - on upwind courses. Aeroplane designers except for using cambered (non-symmetrical) foil sections also add flaps on the trailing edge and slots on the leading edge.

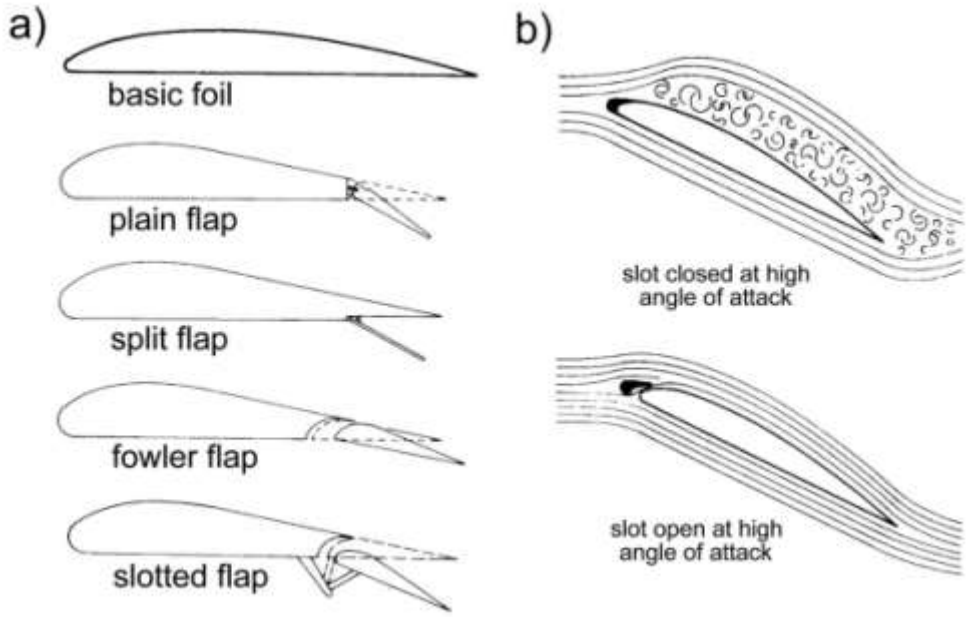

Figure 3. Aircrafts' flaps and slots, adapted from Kroes and Rardon (1993)

The former element allows the generation of additional lift at slow speeds during landing. The latter allows a wing to maintain laminar flow at higher angles of attack.

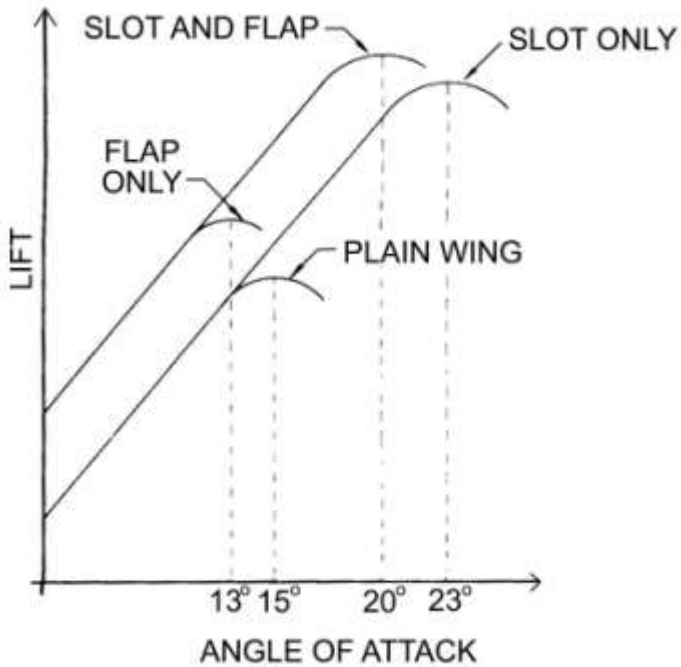

Figure 4. Effect of flaps and slots on wing's performance, adapted from Kroes and Rardon (1993)

As shown on figure 4 both of these appliances address the problem of different lift requirements at different stages of flight. Such structures are not possible to mount on a windsurfing fin; however the canting fin, according to Brzozowski's tests undertaken prior to this research, should improve the balance of lift generated by a fin on upwind and downwind courses.

2.4 Yachting-related Theory - Foil Profiles

The second area chosen to search for relating theory was yacht racing. This time the ambient coefficients match those of windsurfing. Some very interesting studies were reviewed investigating different profiles of keels and radars and the flow around them at a variety of speeds. Due to whole range of measurements that were taken in this research, each of the profiles in question could be described with mathematical functions relating the flow speed to the performance of the section. Such a set of functions enables a designer to choose the best shape to compromise for different conditions which would be very useful in Formula Windsurfing. Those studies were helpful in terms of visualisation of more of the factors influencing a windsurfing fin's performance however it is not the optimal profile of the fin that is the subject of this study therefore further analysis in this particular area was not conducted.

2.5 Yachting-related Theory - Types of Flow

An important factor for both aviation and marine applications is the type of flow over a surface — already briefly mentioned. There are two basic types of flow: laminar and turbulent. Laminar flow occurs when the free-stream flowing around an object "sticks" to the object's surface and passes around smoothly. On the other hand turbulent flow separates from the object it is passing around, causing spins and backwashes. It may be a result of surface roughness or a significant angle of attack. The uncontrolled flow separation due to increasing velocity or angle of attack is a phenomenon known in aviation as "stalling" and as "spinning-out" in windsurfing. In both situations the foil keeps on loosing lift until the laminar flow is regained after a drastic decrease of velocity.

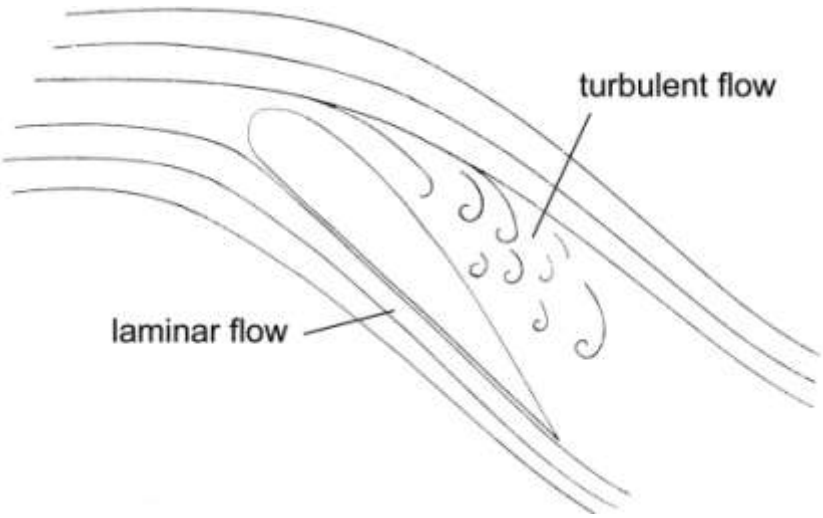

Figure 5. Laminar and turbulent flow, adapted from Kroes and Rardon (1993)

So laminar flow or turbulent flow — these are the two extremes. But what is in between? Somewhere between these two a different particularly interesting phenomenon was discovered. It is a somewhat controlled micro-turbulent flow occurring in a very thin layer just by the objects surface with laminar flow surrounding it from the outside. This effect occurs naturally on the skin of sharks and dolphins hence a surface creating this effect is commonly known as shark-skin. Since the first well-known successful use of shark-skin layers in swimming costumes it attracts a lot of attention and is currently available in the form of spray-on paints that could be possibly used in windsurfing. The question is — how much does it influence the skin friction? According to Jean Jacques Deboichet (interview from year 2005) he has produced several fins finished with shark-skin paint and handed them to his test team. The testers did not know which fins were finished in the classic way and which had the innovative layer on. After several hours of tests the windsurfers did not manage to deduce which fins were altered. Not all the details of this experiment are known and perhaps it could be rerun in a more scientific manner, however it suggests that one should not expect any major breakthroughs as a result of shark-skin finish.

When it comes to high performance yachting and the choice between laminar and turbulent flow, Bethwaite (1996) says that research shows very little difference between skin friction of perfectly smooth surface and slightly roughened in air. However, he suggests that in water the difference becomes significant and that the higher the polish the better. In favour of this statement Berthwaite also claims that laminar flow proves to be effective in reducing form drag.

The theory of stream flow types could become essential if any of the research participants would notice a clear tendency for spin-outs of the canting fin. Otherwise this theory would not be directly applicable to the results of this research.

2.6 Yachting-related Theory - Canting Keels

What was of more interest to this particular project was the fact that top-level yacht racing uses an application called the canting keel. According to Hobbs and Manganelli (2007) it was first used in year 1991 by Michael Desjoyaux on a Mini Transat yacht. Since then the concept was being developed especially thinking about solo sailors in long distance races. It has been a major improvement which finds a proof in the fact that since Christophe Augain won a solo round the world race in 1996/97, all around the world races were won by yachts equipped in a canting keel. Canting keels made yachts much narrower (less form drag) as there is no need for human or water ballast – say Hobbs and Manganelli (2007).

Figure 6. Canting keel concept visualisation, adapted from Canting Ballast Twin Foil Technology

Unfortunately for this research, the canting keels only seem to work similar to the canting fin proposed for the windsurfing board. The crucial detail is the dead weight mounted on the end of a yacht's keel. The ability to move this weight outwards on the windward side means a greater righting moment and as a result better stability of the boat. A windsurfing fin, on the other hand, does not have any weight on its tip which means that the whole principal behind the idea is different.

2.7 Formula Windsurfing Fins

As mentioned by Berthwaite (1996), the twist of a keel on a yacht (corresponding to a moment on a plane's wing) is eliminated due to the use of stiff materials. In FW fins on the contrary, certain amount of twist is left on purpose. There is no scientific research on the topic of the influence of fin's twist but Jean Jacques Deboichet in an interview from year 2007 described a prototype fin he produced with totally blocked twist of the fin's tip. This time the test team was confident that the blocked fin did not perform as well as the classic ones. It is a good moment to describe the structure of a standard Formula Windsurfing foil. Not everything is known when it comes to how the fins are constructed.

The fin manufacturers guard their secrets very well. Despite two occasions, on both of which questions about the fin's layers were asked, Deboichet did not give his secrets away. What is known is that every fin consists of a core made of dense foam covered with numerous layers of uni-directional and bi-axial carbon fibre. It is certain that some of the carbon fibre is aligned longitudinal parallel to the leading edge of the fin (uni-directional). Other layers have been seen in a -45°+45° alignment. The composite is cured with the use of a tough resin - possibly epoxy. When a fin is ordered, besides a choice of one of a few shapes, the customer has the choice of fin stiffness. Those parameters are controlled by adding or subtracting a layer of carbon cloth from the composite or by changing the alignment of some of the layers. Depending on the density and thickness (g/m^2) of a fibre cloth and whether it is unidirectional, multidirectional or a mat, the properties of the whole composite change significantly. Those characteristics are described by the composites rule of mixtures:

$$\boldsymbol{E = \left(E_f \,.\, Vol_f \,.\, \alpha \,.\, \beta \,.\, l\right) + \left(E_m \,.\, Vol_m\right)}$$

where:
$E_f - \ fibre\ Young's\ modulus$
$Vol_f - \ fibre\ volume\ fraction$
$E_m - \ Young's\ modulus\ of\ the\ matrix\ (resin)$
$Vol_m - \ matrix\ volume\ friction = 1 - Vol_f$
$\alpha - fibre\ cloth\ factor$
$\beta - crimp\ factor$
$l - fibre\ critical\ length$
α fibre cloth factors:
1 - unidirectional cloth aligned along the axis of bending
±0 - unidirectional cloth aligned perpendicular to the axis of bending
0,5 - 0°, 90° cloth
0,25 - +45°, -45° cloth
0,375 - an unorganized mat
source: Valery (2001)

The latest trends, according to Deboichet show that the majority of orders nowadays consist of the softest (most elastic) fins. This trend was confirmed in numerous interviews with many world class competitors who admit to using softer fins which, as

they say, produce more lift. This is not only another important difference between yachting and windsurfing, but also an interesting insight into how FW fins work and which characteristics are regarded as positive. How will the canting effect influence the behaviour of a fin? It is expected that none of the elastic properties in any of the dimensions (neither flex nor twist) will be altered. The new element will be the initial position of the fin before it starts to deflect elastically. The initial position will be canted towards the direction of bending causing the final position of the fin to be several centimetres further outside – as shown in figure 7. On-shore measurements show that the canting concept deflects the initial fin's position around 2,5cm from the original axis.

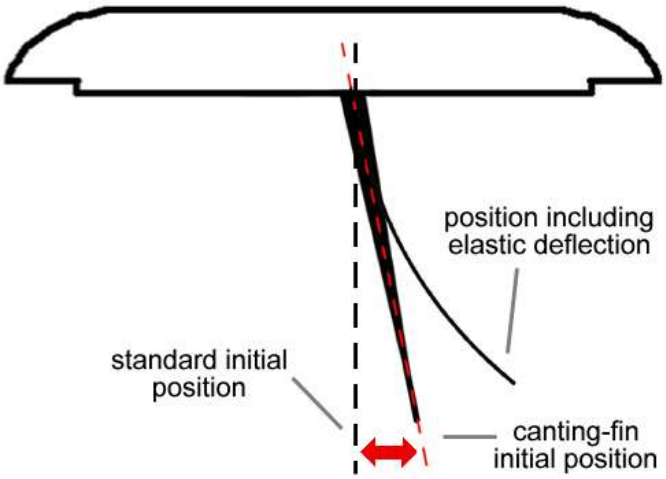

Figure 7. Canting fin's deflection

2.8 Windsurfing-specific Research

Three scientific papers researching the fins' general stiffness, tip flexibility, geometry and surface finish were found. All of these were published in 1992 by: Chiu et al., Broers et al. and Baller. All of these researches base on similar assumptions and refer to each other extensively. An important drawback of the windsurfing-specific literature found is that all the researchers have used the same laboratory method and based their experiments on closed circuit wind tunnels, which effects in almost no critical discussion between the authors. Moreover, because the observed environment was air rather than water, all the results depend on calculations based on the Reynolds Number which were not fully reliable for a dynamic, deflecting windsurfing fin. Another significant limitation is the problem of insufficient wind speeds generated within the used tunnel. It was described to a certain extent by Chiu *et al.*(1992) – "A speed of 50 ms^{-1} was used, which corresponds to a Reynolds Number […] or an equivalent speed of 3.47ms^{-1} [in water]". No evidence of research more recent than 1992 or using a different data collection method was found.

3. Methodology

In order to investigate the influence of the canting fin on the performance of a Formula Windsurfing board, two phases of primary data collection were designed. The first stage consisted of qualitative data gathering based on a questionnaire given out to professional windsurfers. The subjects would have tested two provided fins against each other and state their subjective opinions on the performance through the survey. The second phase of sampling was based on GPS quantitative measurements of performance of a windsurfer with the two tested fins.
Since human participants were involved in the initial data collection stage, an ethical approval was required from the University of Plymouth Human Ethics Committee (appendix 1).

3.1 Qualitative Data Collection

The first phase of data collection was carried out in Leba, Poland, at a professional racing windsurfing training centre. It was decided to respect the idea's creator, Wojtek Brzozowski, request and narrow the potential subject search to his sparring partners in order not to introduce the canting fin concept to a wider group of competitors. The concept of an "expert interview" was applied at this stage – described by Flick (1998). It is a method of qualitative research used in narrow, specialised areas or when high level of knowledge is required from the subjects. In this case, the expert interview allows the conducting of an experiment based on a small number of subjects for the sake of high accuracy of the results.

Four, male, adult competitors with international competition experience took part in the experiment. Each subject went on the water with the standard fin mounted and compared the performance with a partnering competitor. The fin was then changed to the canting design and the subject went out for a short race once more with the same partner, who hadn't altered any of his equipment settings. The participant was then asked to fill in a questionnaire reporting on his subjective feelings and the choice he would make in a competition situation between the two given fins. This procedure was carried out twice for each participant – in light wind (6-10 knots) and intermediate wind (14-20). Subjects were initially unaware of which fin was mounted in their board at the time of testing. They were only informed about the sequence of tests, when filling in the survey.

All subjects were given research information sheets (appendix 2) and consent forms (appendix 3) prior to the experiment. Participants were weighed on the day of performing the experiment.

The questionnaire (appendix 4) was designed according to recommendations made by Hague (1993) and Oppenheim (1992). It was decided to construct a semi-structured (both open and closed questions) set of attitudinal questions. All questions were formed in an unbiased way and did not suggest any particular answers. The whole experiment was conducted by the project leader providing better motivation and response from the participants – as suggested by Flick (1998).

3.2 Quantitative Data Collection

The second stage of data collection took place on the Plymouth Sound. The research author (an experienced windsurfing competitor) went out for a 2 hour-long session, during which short simulations of a race consisting of 2 upwind legs of 30 seconds, 2 downwind legs of 30 seconds and a reach of 60 second, were performed repeatedly.

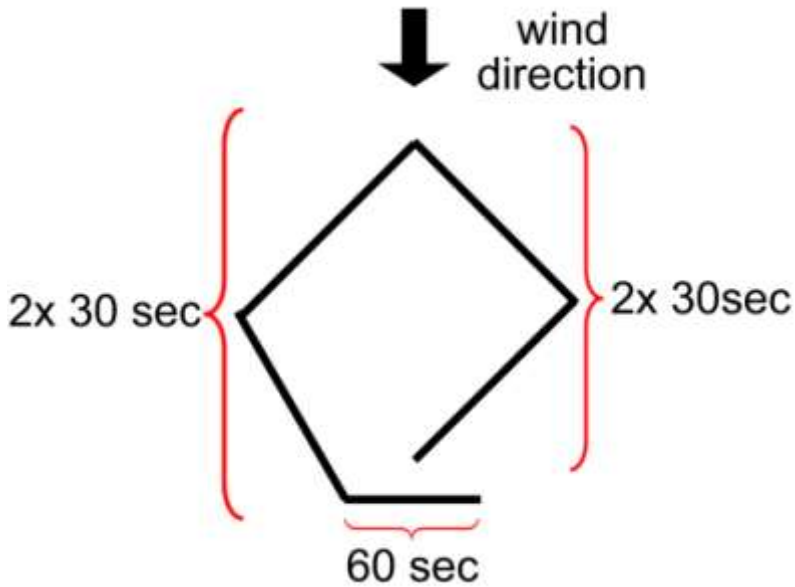

Figure 8. Quantitative data measurement course

The standard fin was used first, and the session was then repeated with the canting fin. During the whole time, the subject was equipped with a GPS device taking a measurement of the exact position, speed, direction of movement and lateral elevation every second. The experiment was carried out during a day of consistent wind of 12-15 knots, no significant swell and a small tidal range, which did not generate any significant currents in the Plymouth Sound.

A GPS device was chosen for this experiment, which not only had the very high sampling frequency of 1Hz (1 measurement per second), but was also capable of saving the tracks from the whole day of measurements, allowing a graphical representation of the distances, courses and angles between consecutive legs. A total of 5714 records was logged in from this data collection session.

3.3 Data Analysis

The data collected through the questionnaires, was organised in several ways, showing the mean results for each of the asked questions, as well as in respect to the subject's body mass and wind strength looking for any occurring trends and relationships. No advanced statistical tests were run on this set of data due to the small sample size.

The 5714 records of quantitative data had to be filtered several times in order to cut out all the irrelevant pieces of information. At first, using the graphical representation of the tracks from the measurement day, each of the legs (total of 71) was described with a starting and finishing points. Each of the points was identifiable in the table of all measurements via a unique point-id number. This allowed the division of the records into 71 ranges, each of which represented one leg on the tracks visualisation.

All the speed measurements were then organised in a descending order and presented as a graph.

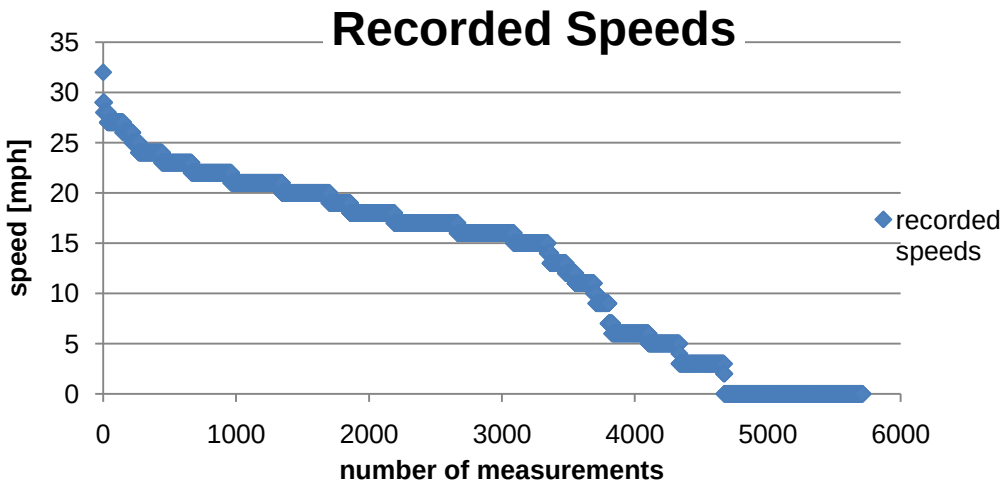

Figure 9. Recorded speeds organised

This allowed the velocity to be identified at which the windsurfer achieves planing. This was visible on the graph as a barrier between small amounts of measurements at low speeds (a vertical trend) and much bigger amounts of records from higher speeds (horizontal trend). This correlation was also related to the minimum speeds logged in the middle of long upwind (slowest) legs, where the subject never stopped planning. The planning transition point was identified at the speed of around 10 knots.

All the records containing a speed lower then 10 knots were then deleted. From within the 71 identified ranges, only continues sets of records above the planing barrier were left. This guaranteed that all measurements taken while tacking, jibing or stopping for another reason were avoided. This sequence of data filtering left 3595 records in an organised table.

Table 1. Organised quantitative data

leg	start point	finish point	average speed	average course	number of measurements & seconds	course
12	685	739	17,85	293,51	54	upwind
13	749	796	18,81	160,73	47	upwind
14	806	857	18,71	300,08	51	upwind
15	868	981	21,57	127,32	113	reach
16	982	1030	20,45	97,59	48	downwind
17	1042	1091	21,36	327,32	49	downwind
18	1092	1124	22,21	312,24	32	reach
19	1125	1172	17,90	287,29	47	upwind
20	1183	1235	18,96	143,45	52	upwind
21	1246	1296	17,80	300,45	50	upwind
22	1303	1352	17,60	147,64	49	upwind
23	1353	1403	22,41	130,69	50	reach

Based on the significant data only, a series of statistical tests and results arrangements were undertaken in order to present the data from all important angles depicting the findings. Except average speeds and mean angles on all courses, the effective performance upwind and downwind was calculated. In order to present this characteristic formula from appendix 5 was used.

3.5 Accuracy and Precision Considerations

The accuracy and precision of this research could be influenced by several factors, especially at the quantitative data collection stage. One of the possible sources of error is the measurement error of the GPS device. When describing the insights of the Global Positioning System, Hofmann-Wellenhof et al. (1997) suggested that 95% of time, the GPS works within a 10m measurement error range.

Other factors possibly influencing the collected data are: wind variability, waves and currents. In order to minimise those, a day of consistent wind conditions averaging 13-14 knots, no swell and limited tides was chosen. The maximum variation in wind direction within any given period shorter than 30 minutes on the measurement day was estimated at ±10 degrees. The wind speed variations throughout the whole time of data collection were assessed as ±2 knots. The relation between wind speed and the velocity of the windsurfer is not directly proportional, however for the needs of this research an error of ±2 knots (2,3mph) was applied to all speed measurements. Other factors such as waves or tides were omitted due to consistent conditions during the whole session as well as a large number of collected data.

4. Results

4.1 Qualitative Results

The qualitative data obtained from questionnaires was put together showing average responses to each of the questions in figure 10. The Y axis shows a range of 1 to 5, 1 meaning that the standard fin was significantly better, 3 showing no difference and 5 indicating superiority of the canting design. The error bars present the full range between the two most extreme answers.

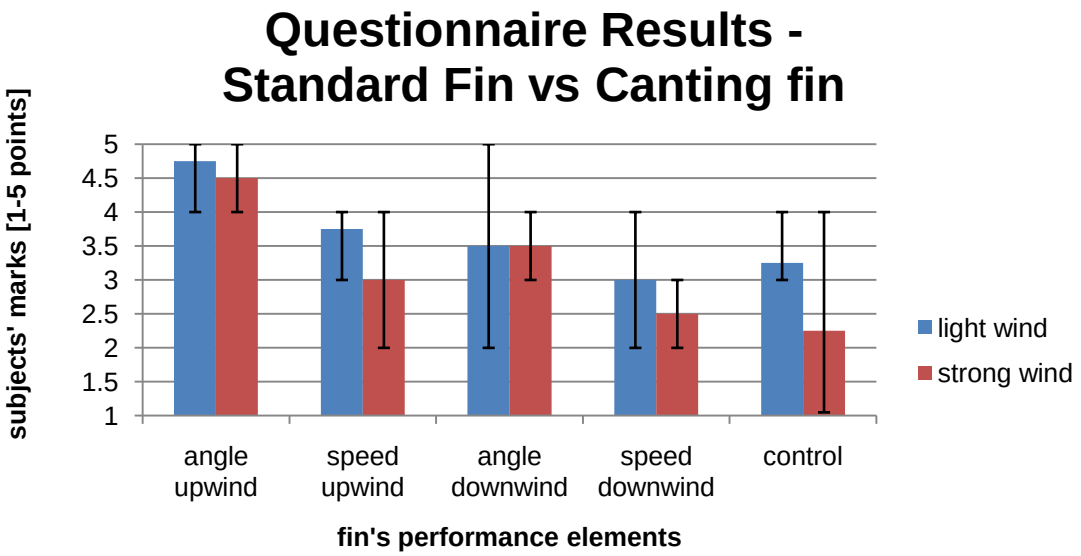

Figure 10. Questionnaire results

Figure 11 depicts the subjective performance assessment of the tested fins depending on subjects' body mass. An average result from all of the questions presented in figure 10 was used as an indicator of the overall performance. Two data series were plotted for light and strong wind respectively. The graph was fitted with trend lines for the two analysed conditions and R^2 values, being the coefficients of trend line correlation. The Y axis is constructed as described in the previous graph.

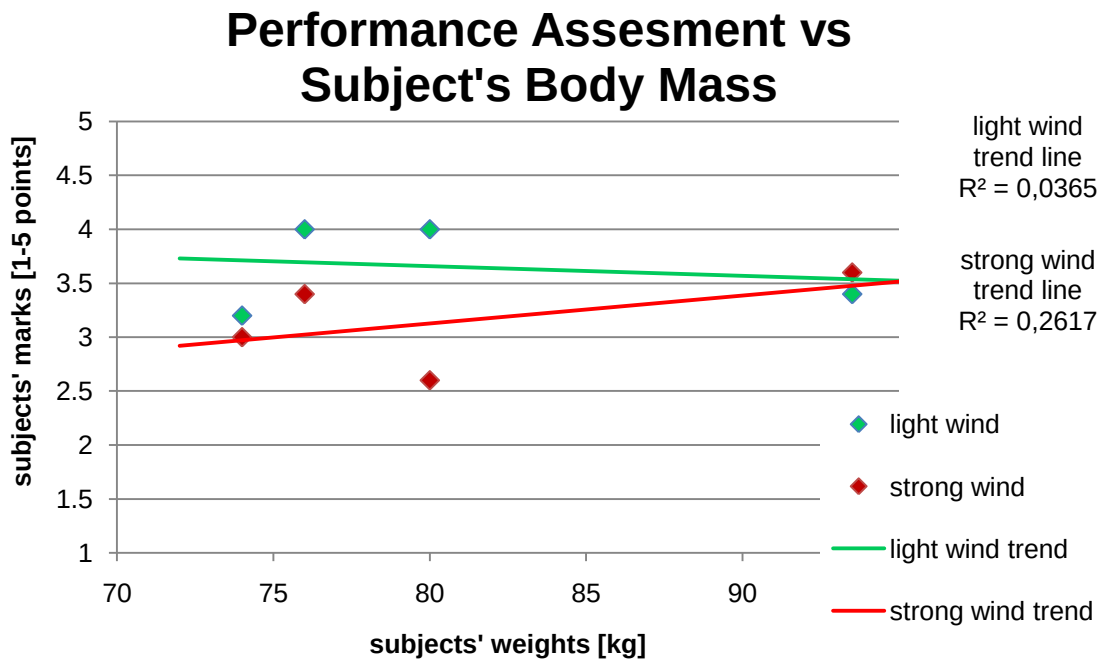

Figure 11. Relationship between windsurfer's weight and performance

Table 2 presents the results from two questions from the questionnaire, where subjects marked one of two possible answers. The questions concerned the existence of a significant difference in the tested fins' performance and the choice a participant would make in a competitive situation with the wind conditions of the testing day. The results were differentiated into overall, light wind and strong wind categories.

Table 2. Results for questions number 1 and 7

	Overall		Light Wind		Strong Wind	
Is there significant overall difference between the tested fins?	Yes 100%	No 0%	Yes 100%	No 0%	Yes 100%	No 0%
Which of the tested fins would you choose for theese particular conditions?	Standard 13%	Canting 88%	Standard 100%	Canting 0%	Standard 25%	Canting 75%

The last question of the survey, asked the participants about any additional thoughts concerning the canting fin that were not included in the previous points. Only one response was recorded – "Canting concept is perfect for marginal conditions. The idea helps a lot with maintaining planing. Above 15 knots it sometimes generates too much lift." (anonymous participant, 2008).

4.2 Quantitative Results

Figure 12 is a depiction of speeds on upwind courses organised in a descending order. Two series of data are compared representing the results for a standard fin and the canting concept fin. Values of the Y axis presented speed in land miles per hour. The

former discussed measurement error resulting in 10 metres of GPS accuracy was disregarded as an inaccuracy of 10 metres at a speed of 20mph means a difference of 0.03%. The earlier indicated error of 2,3 mph for speed measurement was not marked on the graph due to causing problems with the figure's clarity, however it was taken into consideration during the results discussion.

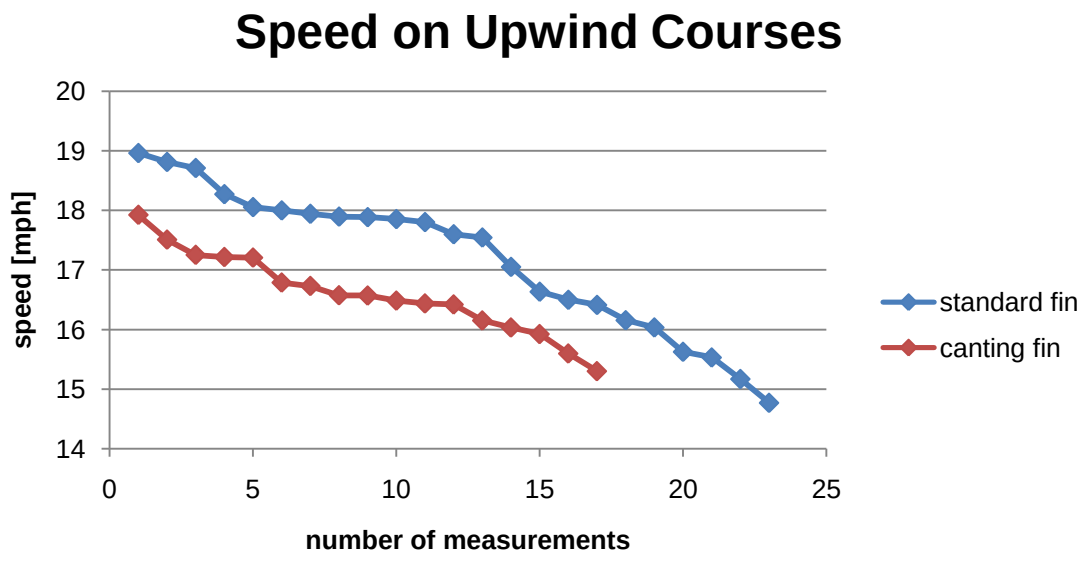

Figure 12. Comparison of speeds on upwind courses

The next figure shows a comparison of speeds on reach courses in the same setup as used in figure 12.

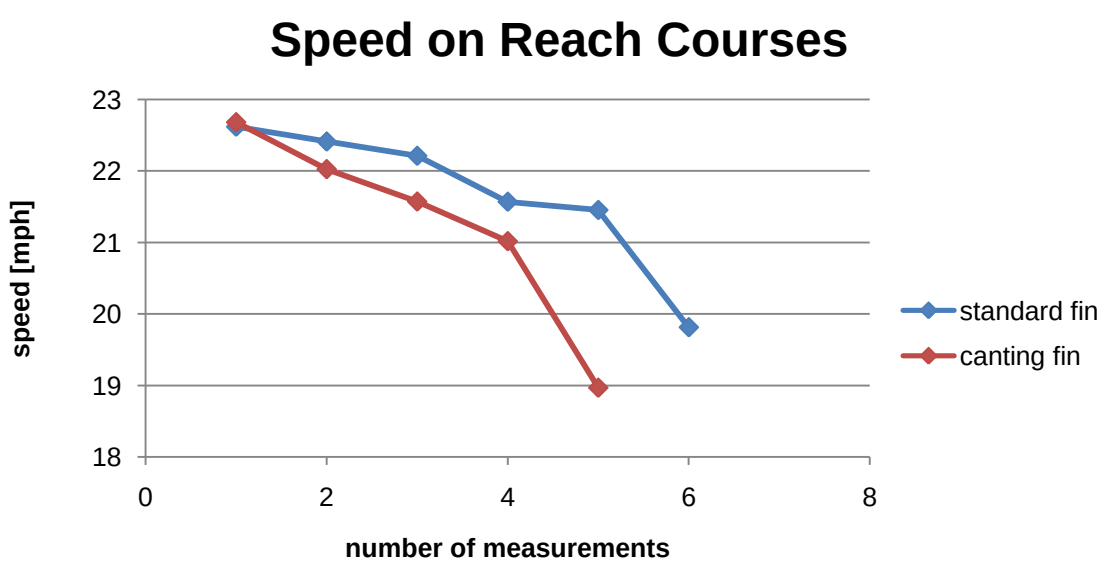

Figure 13. Comparison of speeds on reach courses

Figure 14 represents the recorded speeds during downwind courses. Once again two data series were plotted showing standard fin's and canting fin's performance respectively. Axes presented in land miles per hour and quantity of measurements done. The difference between the plotted series is within the 2,3mph speed measurement error discussed before.

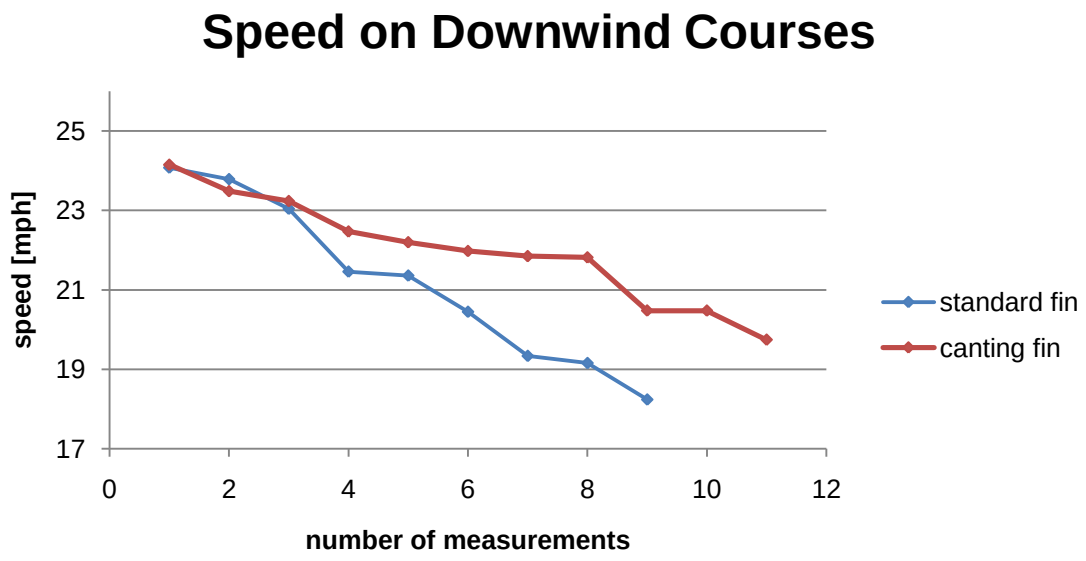

Figure 14. Comparison of speeds on downwind courses

The next graph indicates the differences in upwind performances of the tested fins in terms of the capability of going "more upwind". In order to avoid errors associated with possible small shifts in the direction of the wind throughout the day, the angles between two consecutive upwind legs were measured. The discussed measurement error of ±10 degrees was marked using the error bars.

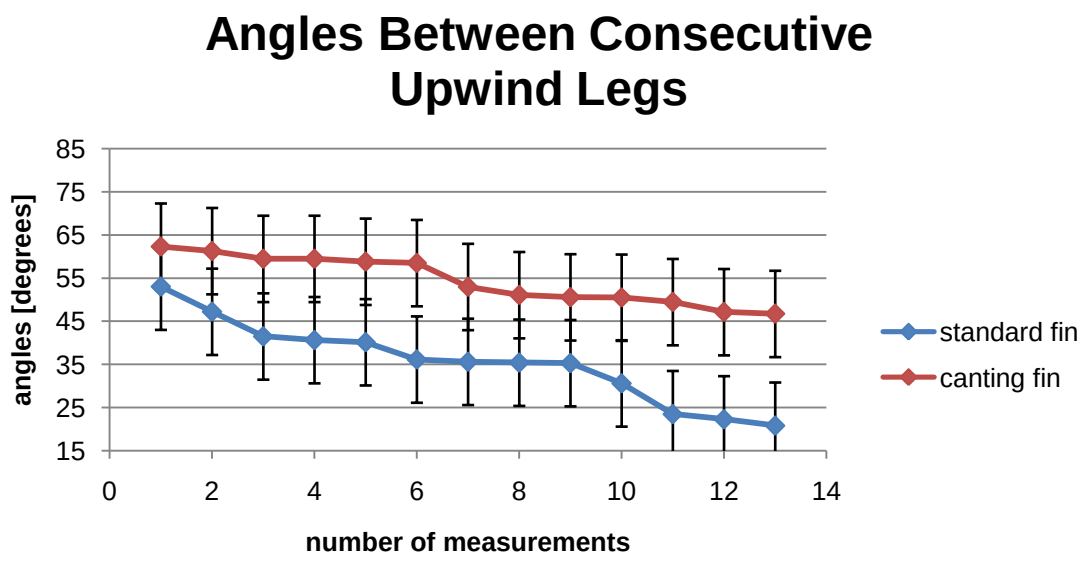

Figure 15. Comparison of sailing angles on upwind courses

Figure 16 is a representation of downwind courses' angles in the manner introduced on the previous graph.

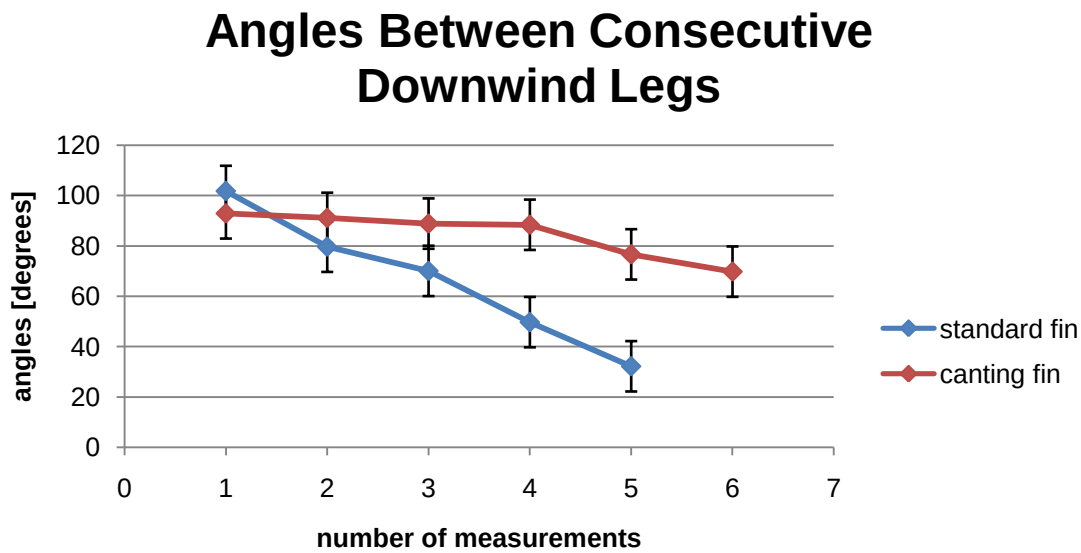

Figure 16. Comparison of sailing angles on downwind courses

Table 3 combines average values for the tested fins in regard of speeds achieved on upwind, reach and downwind courses. It also encompasses the mean angle values, earlier presented in figures 15 and 16. In the angles' section of the table reach courses are not included, as the angle between two consecutive reach courses should always be equal to zero and will differ from this value noticeably only in case of a significant wind direction change during the measurement. Standard deviation for the averages is also shown.

Table 3. Average speed and angle values

Average Speeds and Angles				
	speed [mph]		angle [degrees]	
	standard	canting	standard	canting
upwind	17,18	16,60	32,59	54,48
reach	21,68	21,25	xxxxx	xxxxx
downwind	21,21	21,99	66,69	84,61
	corresponding standard deviation values			
	1,21	0,69	8,54	4,25
	1,02	1,42	xxxxx	xxxxx
	2,10	1,36	14,42	9,97

Table 4 represents the results of combining speed and angle on both upwind and downwind courses. The presented values were calculated using the equation from appendix 5 (presented in the methodology) and base on the average values from table

3. The measurement errors for the presented figures were derived using equations from appendix 6.

Table 4. Effective speed in relation to the wind

Effective Speed in Relation to the Wind			
upwind [mph]		downwind [mph]	
standard	canting	standard	canting
4,82	7,60	11,66	14,80
Corresponding measurement errors - Δ			
± 0,97	± 1,23	± 1,48	± 1,70

Table 5 shows predicted results if a race around a standard Formula Windsurfing course was held. The length of upwind and downwind courses (measured in relation to the wind direction, not the actual distance covered by a windsurfer) was assumed at 1,5 miles and the reach to the finish at 0,5 mile.

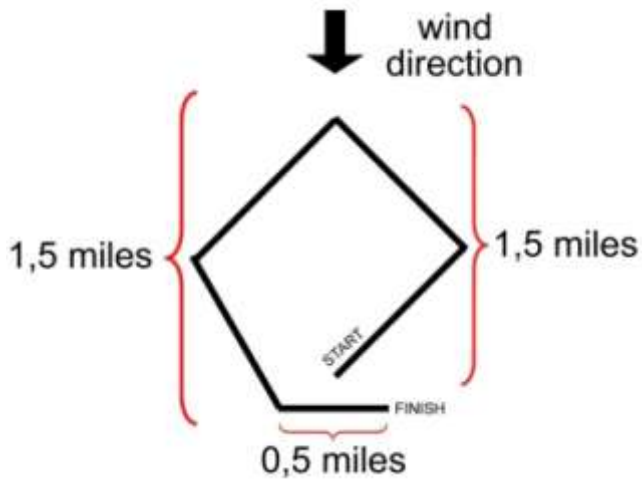

Figure 17. A standard Formula Windsurfing race course

Assuming identical wind conditions for both subjects the results would be as presented in the following table.

Table 5. Race simulation results

A Simulation of Race Results		
	Standard time [min]	Canting time [min]
upwind - 1,5 miles	18,7	11,8
down - 1,5 miles	7,7	6,1
reach - 0,5 miles	1,4	1,4
total time [min]	27,8	19,3

5. Discussion

5.1 Discussion of Qualitative Data

The data gathered from the main section of the survey questionnaire (appendix 4) were presented in figure 10. Due to the construction of the questionnaire, the averaged results appear on a scale of 1 to 5, where values below 3 indicate that in the given characteristic the standard fin was marked higher. Values in the top half, on the other hand, represent that the research participants have subjectively marked the canting fin higher. The error bars show the full range of answers given for every question.

The first interesting features of the presented graphs are the very highly marked upwind angles for both of the tested types of conditions. In addition, the narrow error bars not falling below 4, show that all subjects were confident about the supreme upwind angle abilities of the canting fin. The following bars for upwind speed, downwind angle and downwind speed seem to oscillate around the middle value suggesting no significant differences between the tested fins. However it is worth noticing the unusually big error bar for light wind downwind angle. It represents answers varying from 2 to 5, which possibly means that depending on personal windsurfing style, type of sail or physical parameters of an athlete, the canting fin might be in this respect both beneficial and disadvantageous. Lastly, the evaluation of control is interesting. In light wind, subjects leaned towards the canting fin being the easier one, however when tested in stronger wind, the marks favoured the standard fin. Once more a big spread of answers can be observed here showing no uniform judgement.

As presented in figure 1, it is clear that the force exerted on the board by a windsurfer is related to the amount of elastic deformation of the fin. Based on this observation it was decided to investigate the existence of a trend relating the fin's general performance to the windsurfers' body mass. In order to do so, figure 11 was produced. The collected data was once more divided into two series of light wind and strong wind measurements. Judging by the trend line correlation factors (R^2) no apparent trend was identified. One must note however that 4 points of reference are not enough to discuss any general trends and it would be beneficial to repeat this part of the experiment with more participants to be able to definitely state the absence or existence of any trends.
Table 2 sums up the first and next to last questions from the questionnaire. All of the participants said they felt a significant difference between the tested fins in both types of conditions. This statement is, to a certain extent, contradictory to the results presented in figure 10, where most of the averaged characteristics fall close to the value of 3, representing no noticed differences. Also 100% of the subject suggested that they would choose the canting fin over the standard one in light wind conditions. In stronger winds, 1 out of 4 would stay with his standard design.

All of the collected qualitative data is treated with respect due to the very high experience of all of the participants, however it is obvious that 4 subjects is not enough to form general theories. This data is therefore a point of reference to the following quantitative measurements rather then an individual set of results.

5.2 Discussion of Quantitative Data

Figure 12 depicts the speeds logged in during upwind courses. The range between the maximum and minimum speeds matches the estimated ±2 knots (2,3mph) wind strength variance. The standard fin achieved a higher maximum speed and throughout the 2 hour measurement period, maintained superior speeds overall. The analysed figure suggests approximately a 1mph speed difference between the two tested fins. The difference in the number of data for the compared series is most likely a result of the strict data filtering process, when only consecutive data sets were left. This means that if the GPS device lost signal for 5 seconds, the whole 40 second leg would be deleted from the results.

The next graph (figure 13) visualises the differences between measured speeds on reach courses. As described in the methodology (figure 8) the course diagram designed for the data collection session, included only one longer reach leg. Hence the number of averaged speed values on this graph is approximately 50% of the data for upwind or downwind legs. The compared fins achieved a very similar maximum speed of around 22.6 miles per hour. Throughout the whole data logging period, the standard fin has performed better, but the difference was smaller then during the upwind courses.

Figure 14 depicts the tested fin's performance on downwind courses. It must be noted that the Y axis represents a wider range of speeds this time and so do the measured values. The maximum average speed reached during the downwind courses differed by 0.1mph only between the two fins. It was also the highest value of all the collected data, 24.15mph. This relates to the statement from the introduction of this research, where the downwind course was described as the course where little lift is needed and significantly less drag is formed then on the upwinds. Over the whole measuring period the canting fin maintained higher speeds, however especially at the top end the differences are minimal.

Figure 15 shows the comparison of the tested fins in terms of the ability to sail upwind, which is closely related to the amount of lift generated by a foil. The measured parameters are the angles between pairs of consecutive upwind legs. In this parameter the canting fin shows clear significant superiority over the classic design. It provided a more stable performance over the period of testing with the canting fin's minimal angle only 3 degrees smaller then the standard fin's maximum.

The following graph (figure 16) is not as one-sided. On the downwind courses the angle difference between the two fins was smaller and not visible throughout the whole measurement period. The standard fin's maximum value is greater; however it is within the measurement error range. The other values for the classic design are below the corresponding canting fin's angles.

Summing up the presented figures, there is no clear evidence of superiority of any of the fins at this point. The canting fin proves to provide better angles in relation to the wind direction both upwind and downwind however the average speeds on upwind and reach courses favour the classic design. Predicting a possible ambiguous set of results

it was decided in the research design stage, that the quantitative data discussion should be summed up by the calculation of the effective performance of each of the fins on both the upwind and downwind courses. But in order to be able to calculate those values overall averages had to be calculated. Table 3 presents the average speed and angle values from all of the data collected during the measurement session. In terms of speed one can notice that the differences are minor, favouring the standard fin on upwind and reach courses and the canting fin on downwinds. Supporting the observations from previously presented graphs, the differences in angles are significantly bigger and suggest noticeable superiority of the canting concept fin. Standard deviation was also calculated for the presented values showing the consistency of results – or performance in this case. Except for the speed on reach courses, all of the numbers show much more stable result sets for the canting fin, which indicates that its performance is more predictable and reliable when compared to the classic design.

Table 4 presents the comparison of effective performance on upwind and downwind courses of the two tested fin types. A simple equation based on trigonometry (appendix 5) allowed the combination of the measured values for speed and angle answering the question stated in the research title. The canting fin proved to perform significantly better on both upwind and downwind courses. The differences in both categories are outside the measurement errors and are equal to 58% and 27% of performance increase when the canting fin was used.

Table 5 merges all of the so far discussed quantitative data in a prediction of performance in a race including all types of courses. It is clear that based on the collected GPS measurements one can observe significant superiority of the canting fin. The difference in the simulation race results is 8,5 minutes which means that the windsurfer using the standard fin would need 44% more time to complete the race.

5.3 Collation of Qualitative and Quantitative Data

When comparing the questionnaire results to the GPS data, it must be noted that due to weather difficulties only one measurement day was successful for the quantitative data collection. It provided a set of results for conditions of 12-15 knots, which is in between the two typed of conditions used in qualitative stage (6-10 and 14-20). Despite this difference some conclusions can be derived. The most distinctive of the questionnaire results was the very high mark for the canting fin's upwind angle (ranging from 4 to 5). This feature found full support in the quantitative data, where the canting fin showed, on average, 17.9 degrees of better upwind angle. The two types of gathered data also collate for the reach performance, described in the questionnaire as "control". The survey participants' marks in this category averaged around the neutral 3 value with a slight negative tendency. The GPS measurements in this area indicate very similar performance from the two tested fins with a small advantage in favour of the classic design.

Overall, 88% of participants said, that they would choose the canting fin in a competitive situation. This figure is strongly backed up by the simulation race results where the

canting fin finishes the course within 19.3 minutes and the standard fin needs another 8.5 minutes to cross the finish line.

6. Conclusions

Overall the research proceeded according to its original design and proved to be successful in terms of the methods of data collection and the amount of taken measurements. The planned time frame proved not to be feasible as weather variability was not taken into account to the appropriate extent. Significant problems with the organisation of a safety boat also contributed to the delay in the quantitative data gathering. Despite those problems, the aim and the title question were answered and the objectives were addressed. The canting fin proved to be superior to the standard design fin in most of the tested features and proved to produce an overall performance noticeably better then its classic version.

During the research, several problems occurred, which should be addressed in the future. A precise indication of the point when a windsurfing board (or any other craft) begins to plane was one of the issues. Precise measurement of wind direction and its deviations is also problematic without the use of bulky equipment. Finally, more research into the effects of fin geometry and stiffness on the generated lift and the lift-drag coefficient is required. Windsurfing is one of very few wind powered vessels, which is able to plane upwind, therefore subject-specific research will be needed in order to fully understand and describe the ongoing processes around a windsurfing fin.

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Appendices for this work can be retrieved within the Supplementary Files folder which is located in the Reading Tools menu adjacent to this PDF window.