Optimisation of NS14 Sail Design

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Foreword

For this paper, I have tried to condense 180 pages worth of thesis into a relatively concise piece of work, which is much more easily said than done! I have tried to tailor the content to a sailor with reasonable knowledge of the physics behind sailing and a sound engineering mind, without discussing the real basics or the high-end scientific theory.

Abstract

Recent developments in mast and sail materials have led to the rise of the square-head mainsail across a range of designs from the 12 ft Skiff, right up to the largest state-of-the-art super-maxis. These sails have drastically improved the performance of these vessels by increasing the developed area at the head of the sail, as well as improving the aerodynamic efficiency as it approaches a shape more like a wing than a traditional sail.

The benefits of the square-head mainsail have been widely publicised but are yet to be proven on the NS14 dinghy, a class which I currently sail and have sailed for a number of years. Through investigation using wind tunnel testing, computational fluid dynamics and full-scale testing, I aim to try and find an optimal square-head development which will provide the greatest lift-to-drag ratio from a number of prototypes which have several physical and mould shape variances.

Introduction

The square-head mainsail has proven to be more efficient, particularly (but not limited to) in light airs and in downwind conditions by a large number of sources in recent times. Square-head mainsails can be seen on a variety of sailing craft from sailboards, small skiffs, larger skiff classes, sports boats, mid-sized racing yachts and the largest and fastest multihull and monohull super-maxis.

The NS14 dinghy, although renowned for its narrow, high-aspect ratio mainsails, are yet to dive head-first into the realm of square-head mainsails like many other skiff classes have done of late. Recent events have seen owners and sail makers toying with the idea, but no definitive results have come about, meaning the type of testing and analysis I have conducted for this Thesis should illustrate what is possible, and what is not for the NS14 class.

I have investigated an optimisation process on three major areas:

- The width of the head;
- The amount of leech shape; and
- The mould shape, or ‘depth’ of the sail.

With all of these components put together, I have found an optimised square-head mainsail that gives the highest possible performance in the upwind condition for a range of wind strengths. The upwind condition was chosen as it has the least number of variables. When reaching or running, performance often depends primarily on crew weight and hull shape, as well as the usual factors such as fleet position and crew ability.

The upwind sailing angle of the NS14 is basically constant across the fleet, and does not depend so much on crew weight or hull shape (although they still are a contributing factor). This simplified many calculations, as well as reducing the monotony of not only testing several sails, but testing varying wind angles as well.

It must be said from the outset that this Thesis is not about trying to prove the advantages of the square-head mainsail over more conventional types of sail. There is enough literature and proven results around these days that clearly show the advantages of the square-head mainsail. This piece of research has tested several square-head mainsails to see which combination of leech shape, head width and mould shape provides the largest lift-to-drag ratio.

For most sailing craft, the primary benefit of the square-head mainsail is to drastically increase mainsail area for a given rig size, which may be up to 75% in extreme cases. This is not the case though for the NS14 dinghy, as the sail area is limited and already of quite a high-aspect ratio. This means we aim to optimise efficiency rather than the sheer horsepower of the sail. From a more scientific point of view, an increased area at the head of a mainsail tends to create a more stable flow of air across the sail section by reducing the tip vortices, and therefore drag component, allowing the sail to develop a greater efficiency and drive force than its triangular and high-aspect counterparts. These tip vortices are clearly illustrated below, which are derived from computer modeling I undertook during this Thesis. It is also proven that a straight leech profile from head to clew (rather than a curved or angled profile) produces much less drag as the air is exiting the sail at the same time along the length of the foil surface resulting in less turbulence off the trailing edge.

While the advantages of this mainsail configuration as a means to create a more powerful, efficient sail have been well publicised, it also has its advantages as the wind speed increases and it is desirable to de-power the sail to keep the boat sailing flat and fast at all times. A square top mainsail will ‘twist off’ or de-power evenly from the head down to the clew, and is able to be flattened relatively easily with the use of onboard controls such as the boom vang and cunningham.

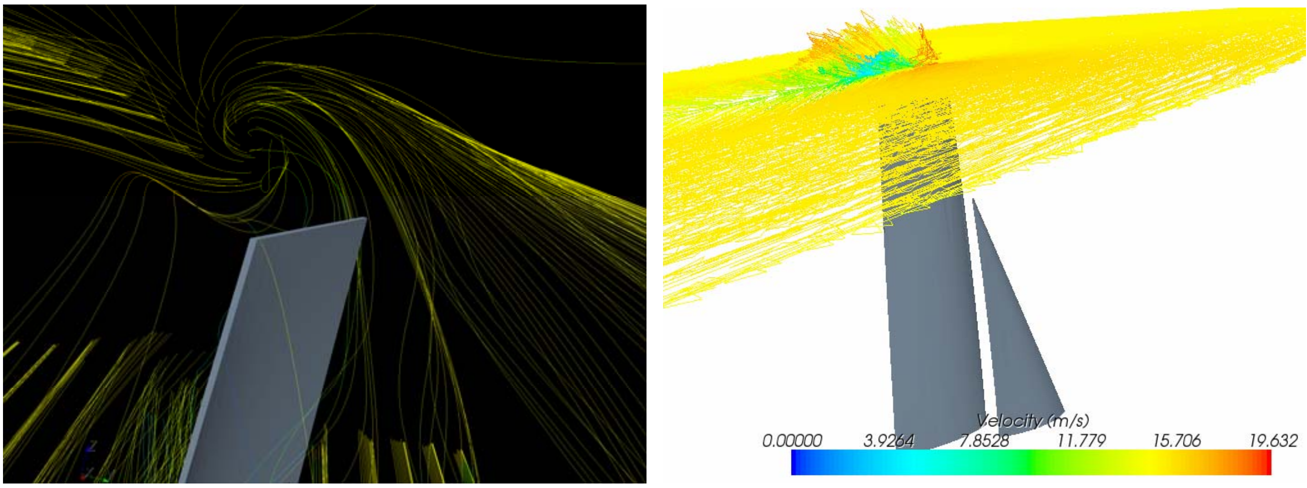
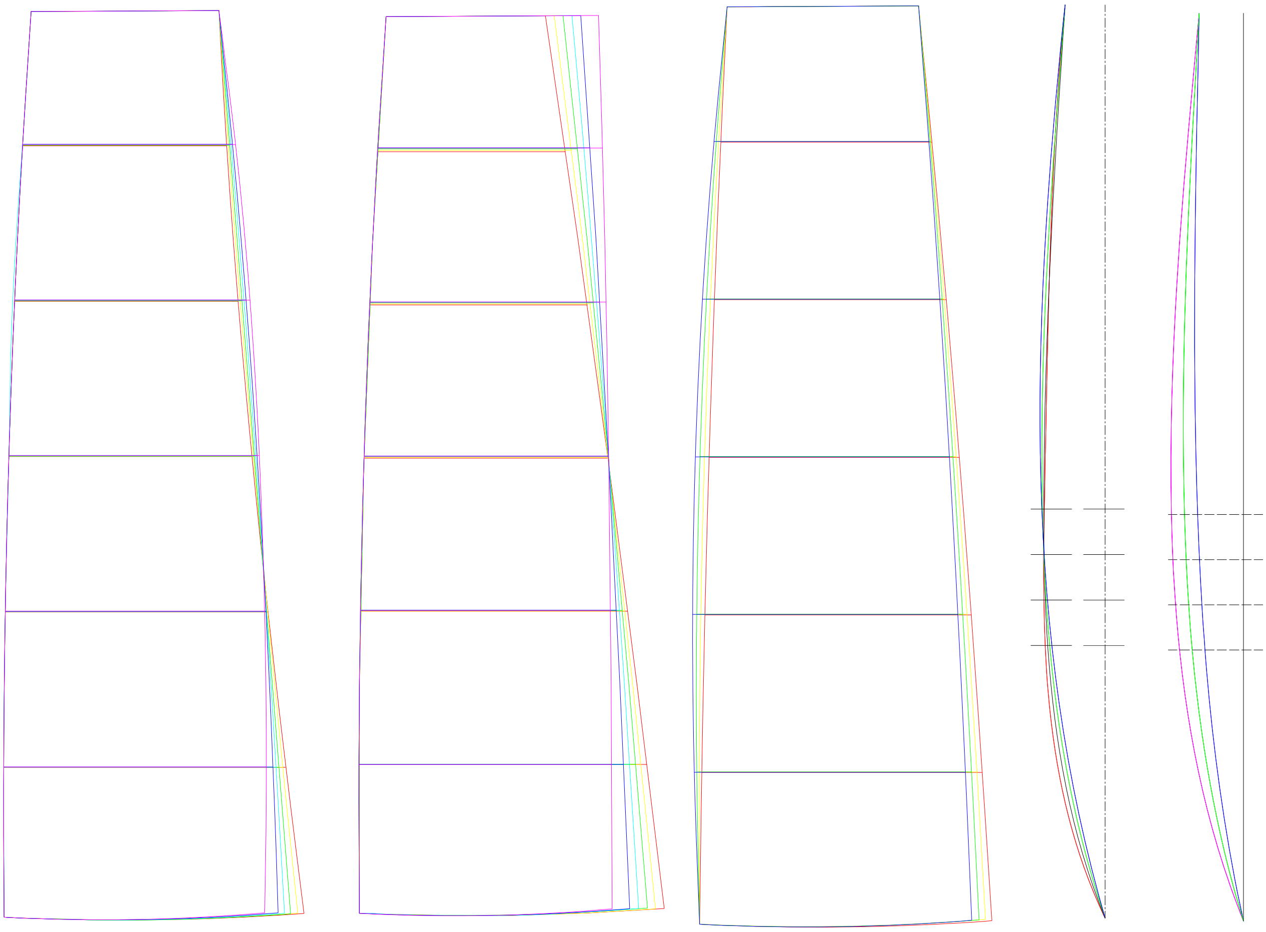


Figure 1: Tip Vortices Generated and Tip Velocity-shed Generated
(derived from Computer Simulations run over the course of this Thesis)

Sail Shape Generation

Using a CAD-based sail design package, a large database of sail designs has been created by modifying the primary sail shape components: head width, leech shape, luff round, and mould shape. Models have been generated by varying head widths between 900 mm and 1200 mm, varying leech shape between -50 mm and +100 mm, varying luff round between 25 mm and 100 mm, varying draft location between 30% and 45% chord length, and varying depths at the various control locations between 1% and 10% of the chord length.
The Figure below shows graphical representations of the variations described above, showing how each parameter contributes to each varying sail shape.



Graphical Representations of Sail-shape Variations

Sail Analysis

Sails are soft, flexible, and naturally unstable anisotropic membranes which deform according to the prevailing wind speed and direction, sea state, boat speed, angle of heel and the trim according to the point of sail the boat is traveling on. This makes accurate modeling complex, as the conditions that a sail experiences over the duration of a race may vary enormously as separated flow regions and unsteady phenomena reap havoc with the modeling process. Current methodologies used in the aerodynamic analysis of sails in (or close to) the close hauled condition are carried out using a combination of wind tunnel experiments and three-dimensional computer simulations. This employs a powerful combination which gives results based upon not only the theory side of analysis, but real life scenarios as well.

The goal of the optimisation process conducted in this Thesis is to generate a sail shape which will improve the speed of the boat through the water. It must be considered that increasing the driving force of the sail will also increase the side force and therefore the heeling moment. As the NS14's transverse stability is gained purely (with the help of the underwater appendages of course) by the crew leaning out over the side of the boat, the greater the side force, the harder the crew needs to hike out, or alternatively sail adjustments need to be made to de-power the sails. This may be detrimental to the performance of lighter crews in heavier conditions who tend to be overpowered more easily due to less righting moment provided by the crew weight. It may be assumed though, for the purposes of this analysis, that a higher boat speed will be reached if the sails generate more driving force and hence a higher lift-to-drag ratio. Experienced crews are able to adjust their boat according to the conditions even if they are on the lighter side of crew weight.

As with any simulation process, many idealisations must be made for the environment in which testing takes place. Solving the problem of the actual sail shape in a specific set of conditions involves solving a highly non-linear problem of fluid-structure interaction which is extremely computationally expensive, and outside the scope of a Bachelor's Thesis. In the computational environment, this may mean idealising the situation using rigid, non-deformable sails, zero angle of heel, constant wind velocity, constant wind gradient, zero twist-angle, zero sea-state and modeling the sails only to reduce computational cost. In the wind tunnel, this may mean idealising the situation using constant wind velocity, constant wind gradient, zero twist-angle, zero sea-state, zero angle of heel and inaccurate representation of the mast and rigging (for structural purposes - probably negligible).

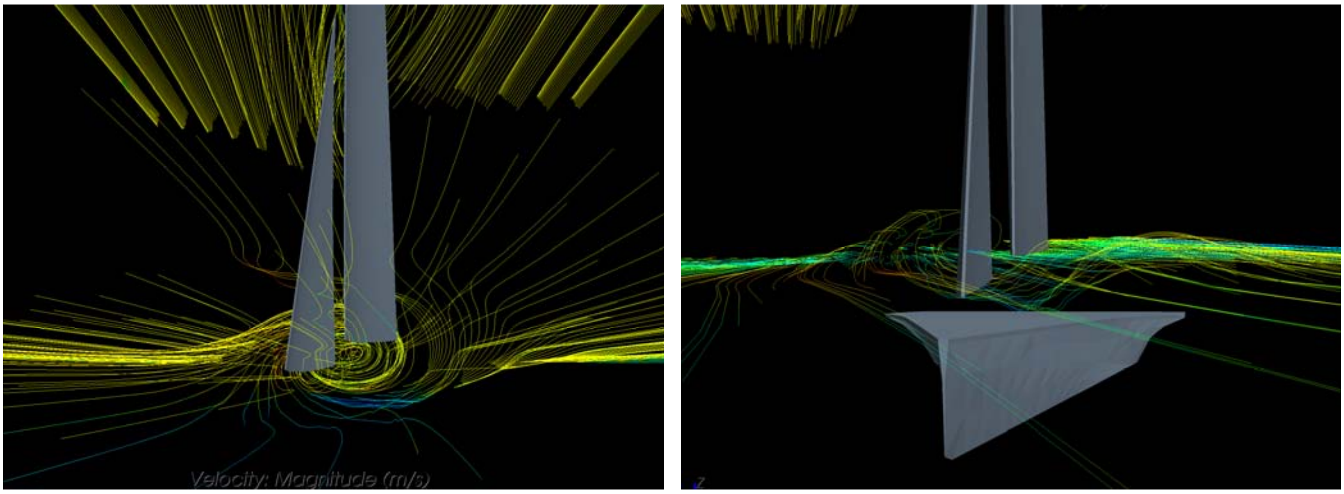
A single sail rigged in isolation where there would usually be two-or-more sails will produce considerably different forces compared to the forces generated by each sail when they exist together, as they are in constant interaction with each other. This means that although this is a mainsail design optimisation process, for both computer and wind tunnel analysis, it is important to have the jib present in order to give accurate results. Across all of the models, the jib will be the same to give consistency. The combination of the mainsail and the jib in experimentations will produce a resultant lift force larger than the sum produced independently by each sail. The mainsail will generate a much greater drive force in isolation, and the jib a slightly lesser drive force in isolation, compared with the two sails in interaction.

Wind Tunnel Background

From earlier discussion regarding idealisations in the wind tunnel environment, it must be noted that for apparent wind angles forward of the beam (as I intend to test), the expected twist in the oncoming flow over the span of the sail are very small; less than 5 degrees. As such, experimentation is not conducted under twisted-flow conditions, as the advantages gained by these small twist angles are far outweighed by the disadvantages the uneven turbulent wake behind the vanes introduce into the flow at the low scaled flow velocities being tested. It may be concluded from this that at apparent wind angles higher than 90 degrees, wind tunnel testing in un-twisted flow should provide accurate results, as the twist of the onset flow is negligible. Consideration for the wind shear gradient is also idealised at these low Reynold's Numbers, which would tend to over complicate the wind tunnel testing procedure.

There are two fundamental ways to approach model testing inside the wind tunnel; test a series of design shapes and their corresponding flying shapes, or test a series of flying shapes, and design sails based upon these shapes. Taking computational power into account, and keeping 'design shape vs. flying shape' in mind, I have tested a variety of design shapes. The actual flying shape of the sails fluctuate enormously in varying wind conditions as previously discussed, but this is a scenario every sail designer faces. It is up to the knowledge and skills of the sail maker to design a sail which will perform well under its designated wind-range.

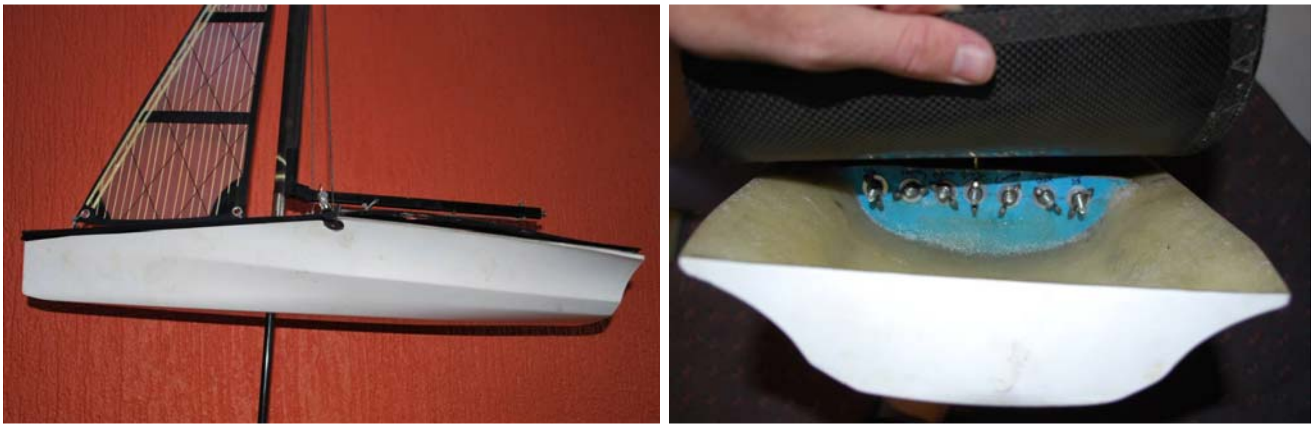
The presence of the hull as well as the mast and sails significantly improves the prediction as it makes the flow more realistic, and includes the end plate effects of the hull on the generated sail foot vortices. It is also important that the mast be included, as failure to do so will give unrealistic leading edge separation characteristics, as described previously. It is therefore of significant importance to have the hull, mast and jib present for wind tunnel experiments, as flow modifications and interaction forces due to the presence of these bodies all contribute towards the performance of the sail. Examples of the flow on the isolated sails and in interaction with the hull can be seen below.



CFD Modeling Showing Foot Vortices with Sails in Isolation, and Showing Reduced Foot Vortices with Hull Present
(derived from Computer Simulations run over the course of this Thesis)

Wind Tunnel Model

The wind tunnel model was created using a range of different techniques. The size of the model has been determined by the 540 mm, 1/8 scale model of Stuart Freizer's 2008 '*Moondance*' design of which Ian Dixon has a mould for. I made modifications to the inside shell of the model by including a mast step for the mast to sit in, and a composite panel towards the stern of the model to house my various control lines.



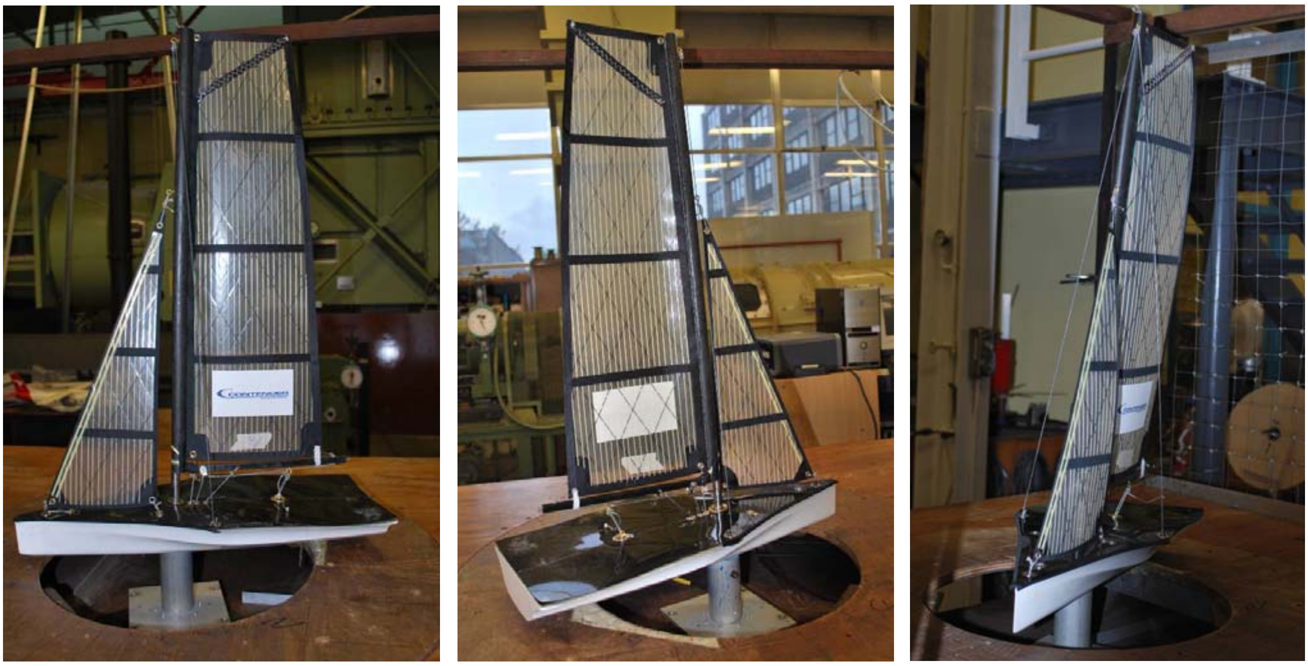
Profile View of the Wind Tunnel Model, and Control Lines below the deck

The mast is an old piece of caravan awning track supplied by Minter Rigging which I have transformed into a crude wing mast by 'bogging' up the region between the two pieces of track, and wrapping it in a layer of carbon fibre mat to hold it all together, and make it look aesthetically pleasing. The backbone of the mast is a composite carbon fibre un-tapered windsurfer batten. The rigging is 1.5 mm Vectran rope, which has very low stretch characteristics and high strength without causing too much disruption to the flow due to its small diameter. This rope was also used for the mainsheet, vang, outhaul and cunningham control lines on the model. The deck is a flat piece of off-cut carbon/epoxy mat, and was ideal as it provided the necessary end plate to the mainsail, whilst still being flexible enough to gain access to the controls to swap over sails during testing. Eyelets were put into the locations where the control lines cut the deck to make the model tidy and aesthetically pleasing.

Details of the Mast Section and Deck/Control Ropes

Wind Tunnel Testing

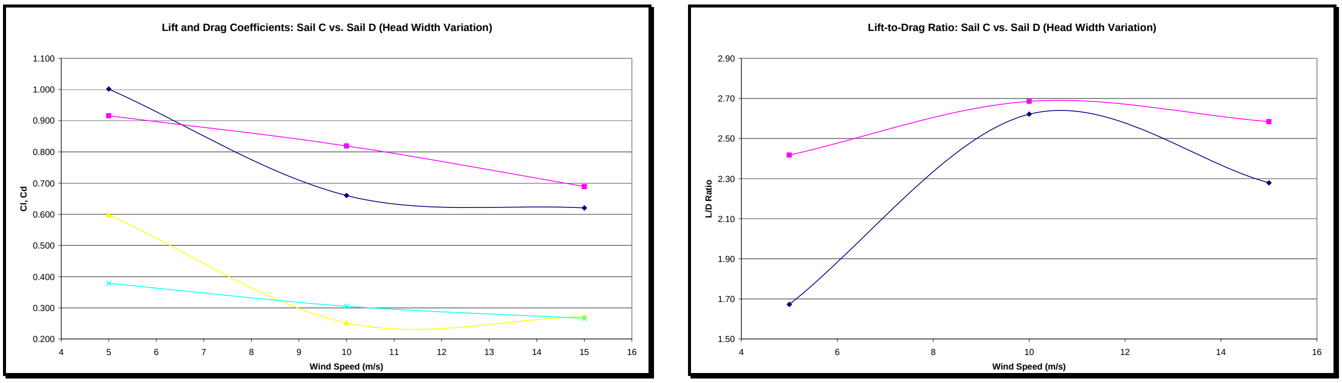
Testing was carried out on the 29 March 2010 in the 760 mm (30”) Open Test Section, Open Circuit Wind Tunnel at the University of New South Wales. The model was mounted into a housing which accommodated the mast protruding through the hull, which could be locked in using a simple screw. This housing was then mounted onto the ATI SI-130-10 Multi-axis Force/Torque Sensor to calculate the relevant forces on the model



Various Views of the Model in the Wind Tunnel

I won’t bore you with the many calculations using Reynold’s flow and basic principles to derive the wind tunnel wind speeds, nor Flay’s equations to calculate apparent wind speeds and angles, but good flow similitude was gained using a combination of all these factors to represent true wind speeds (at full scale) between 4 and 12 knots, corresponding to between 5 and 15 m/s in the wind tunnel (calculated using a Pitot-static tube/Micromanometer). The model was set at a constant angle of attack of 20 degrees, which was an average apparent wind angle based on the equations described by Flay.

Nine sails were constructed with variances in leech shape, head width, draft position and depth were tested, and without giving too much away, some insightful results were gained as to the effects of these different variables on the performance of the sail.



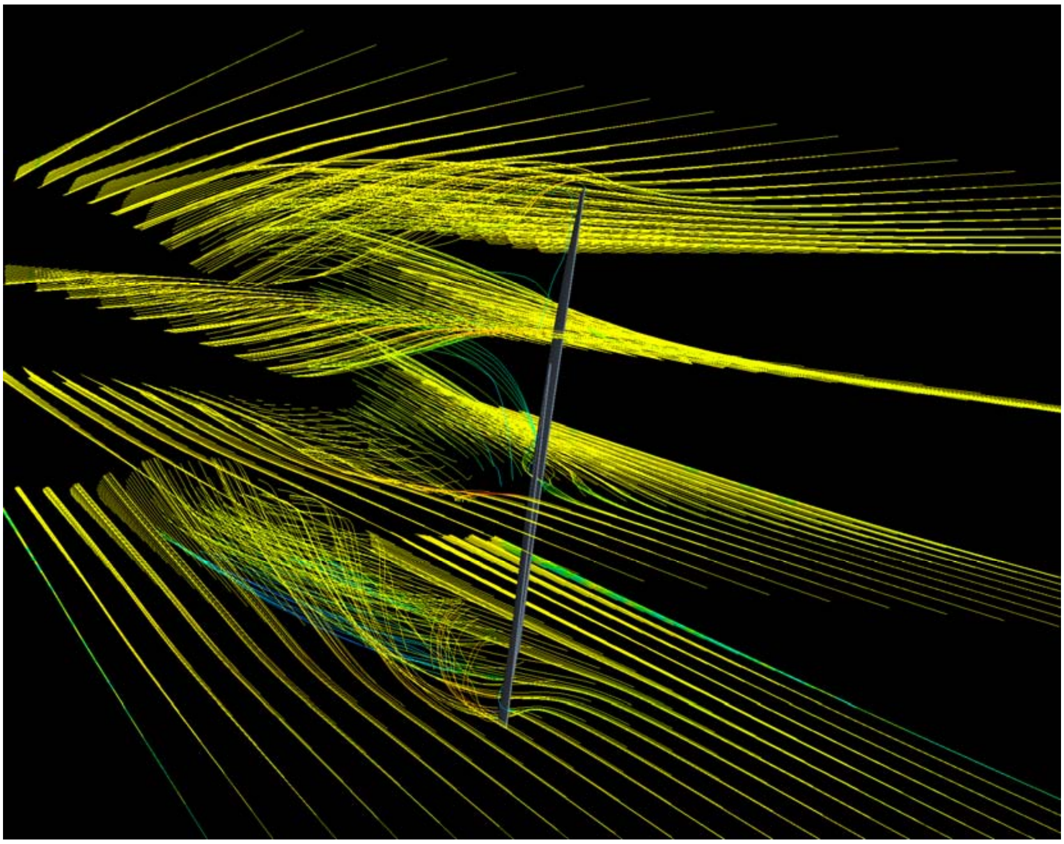
Example Lift and Drag comparisons coming from the head width variation test

Computational Fluid Dynamics Background

Computational Fluid Dynamics (CFD) analysis employing the Reynolds Averaged Navier-Stokes (RANS) flow equations has become routine in the design of hulls and foils for the investigation of hydrodynamic forces, but its use in the prediction of aerodynamic forces has only come to the fore in more recent years. In comparison to the shape of a fair hull or appendage, the sheer complexity above the waterline of a sailing vessel is enormous. This is made even more difficult due to the variations in angles of attack of the oncoming flow, and often inevitable regions of separated flow. In the field of sail design, CFD analysis is performed primarily to compare the gains and losses made on small changes in existing geometries. CFD analysis techniques are a valuable partner to wind tunnel testing, both as a means of verification, and as a means of testing many models in a simulated environment without the need to physically create wind tunnel models.

CFD analysis resolves all of the appropriate physics of an actual flow scenario, and as such, can predict even the slightest viscous trends with amazing accuracy. If required, this form of analysis can also incorporate environmental phenomena such as the wind gradient caused by Earth’s boundary layer, and twist in the apparent wind angle (as described in the Wind Tunnel Background earlier on). We can also carry out full-scale analysis to verify scale model testing, and accurately capture the often subtle relationship between the generation of lift and drag as the physical dimensions of the sail are altered.

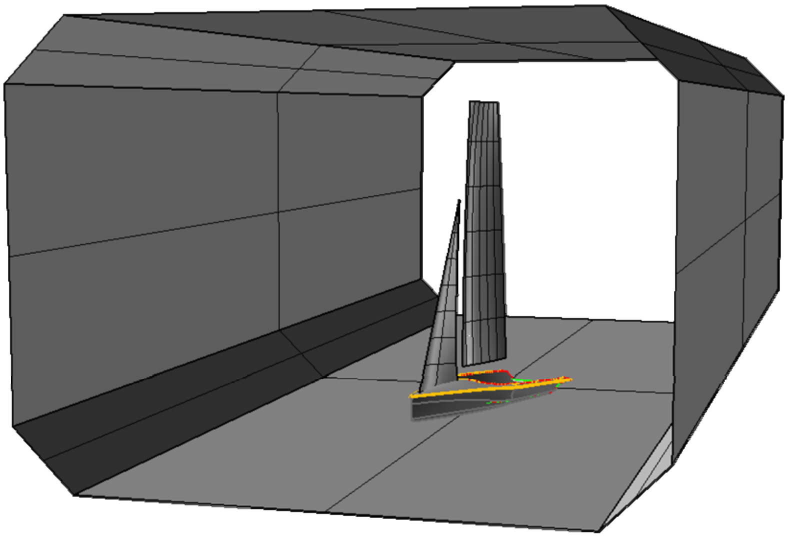
CFD analysis also proves to be a valuable tool when analysing the interaction between the sail and the mast, allowing for high quality flow visualisations from complex scenarios occurring in reality, such as flow separation and the generation of the large tip vortices which tend to govern the flow on square-head sails.



Non-ideal Flow around Sails showing flow rotation, vortex wakes and detached flows. Taken from Thesis CFD modeling.

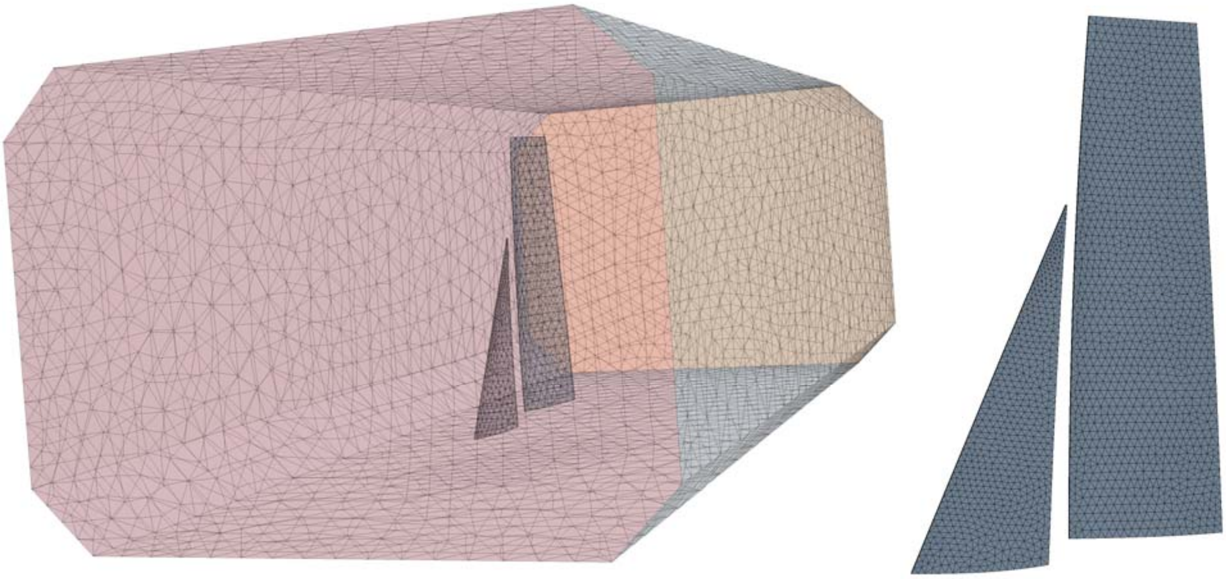
Computational Fluid Dynamics Model

The CFD model was created using a three-dimensional CAD software package. The sail surfaces were generated from the output files from the sail design software, aligned to a base co-ordinate system to ensure the sails were in the same location for every test run, and exported in a file format which the CFD software can understand. The jib remained constant for all of the test runs. The model was based on specifications of the closed-circuit wind tunnel (not the open circuit tunnel in order to abide by energy, mass and momentum conservation laws) provided by UNSW.



CFD Model in the Rhinoceros Environment

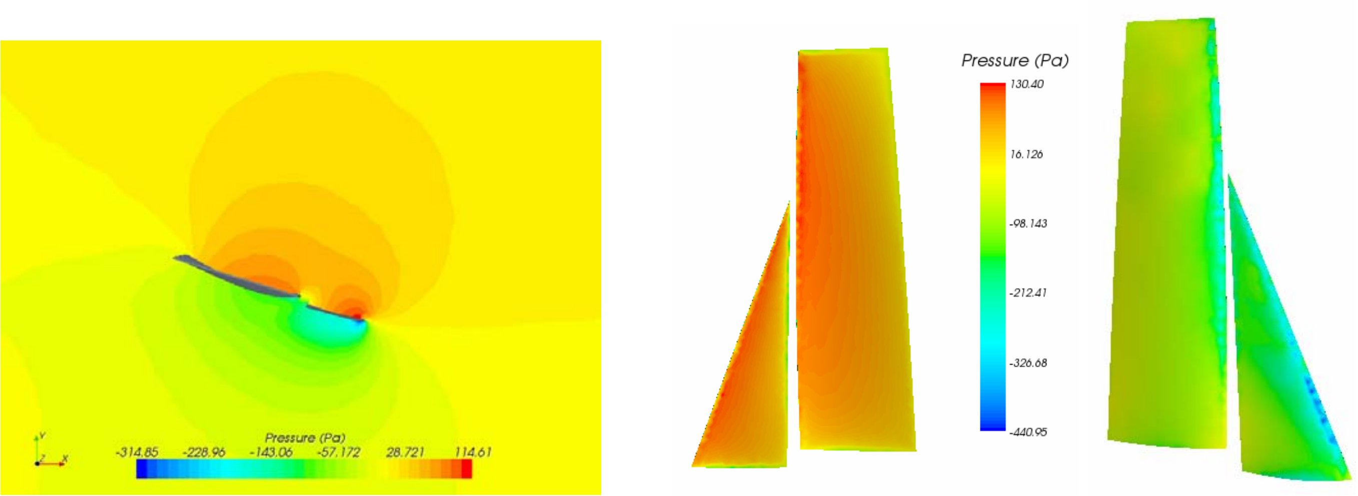
After much experimentation, trial and error, the mesh was generated and sized appropriately according to the relevance of the surface in question. Each component of the model was given a weighting according to their size and relevance to results. The sails were given a 400% weighting, the inlet and outlet were given a 200% weighting, and the tunnel was given the reference weighting of 100%. This ensured the mesh size was reduced to values a modest computer can handle quite easily to ensure results can be gained quickly. This mesh featured around 250,000 elements, and took around five minutes to run through 200 iterations on a home computer.



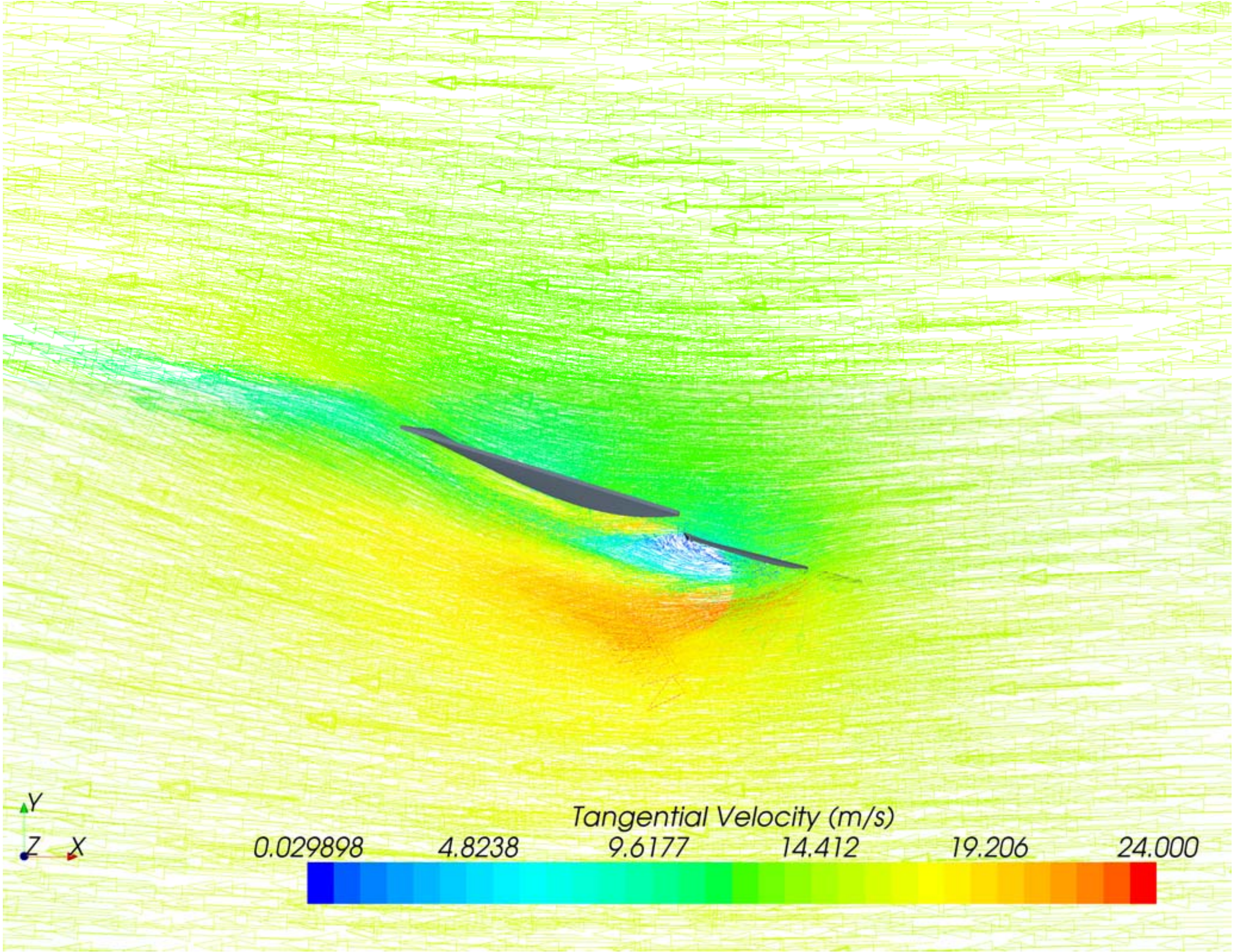
Typical Mesh Representations

Computational Fluid Dynamics Flow Visualisation

It is important before gaining any meaningful results to ensure both numerically and visibly that the modeling carried out makes sense, and the flow around the sails is abiding by intuitive flow patterns, and flow patterns seen in previous experiments. A number of flow plots were carried out to verify my results.



Two and three-dimensional Pressure Contour Plots

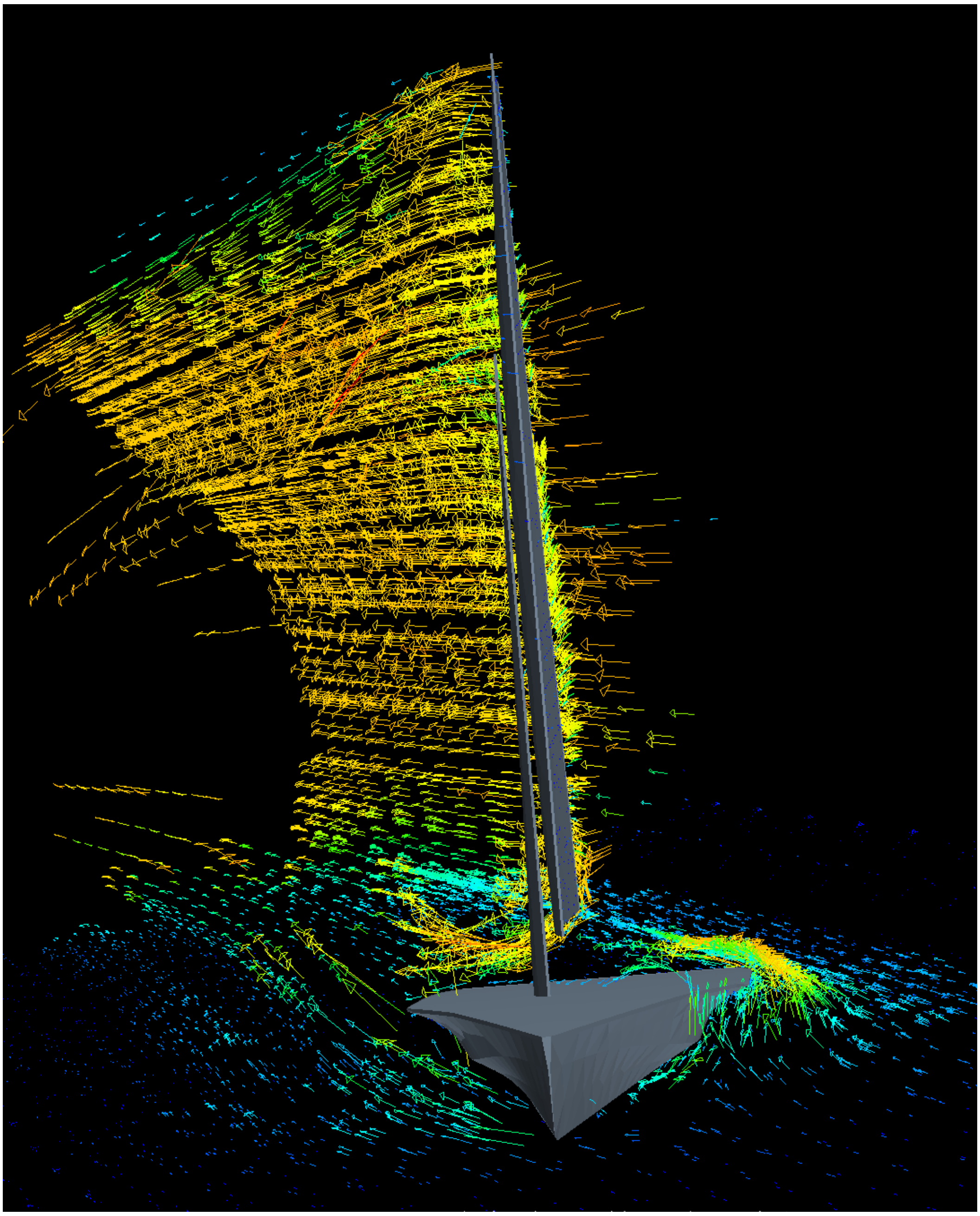


Two-dimensional Velocity Contour Plot

Computational Fluid Dynamics Results

The same nine sails were tested in the computational environment, and the CFD analysis results verify the wind tunnel data particularly well. The CFD analysis results also manage to remove the ambiguity for some of the wind tunnel results, particularly the depth variance models, for which no distinct conclusions could be made from wind tunnel testing.

The combination of several environmental factors such as air flow dissipation in the open-circuit tunnel, positioning of the Pitot-static tube, and the use of deformable wind tunnel sails and non-deformable CFD sails explains why small variations existed between the loads predicted by computer simulation, and those experienced in the wind tunnel. The fact that the conclusions remained the same though verifies that they are both valid methods of testing, and were both carried out in an experimentally viable manner.



Three-dimensional velocity contour plot

Full-scale Model Testing

The last component of this thesis, to ensure all bases were covered, was to construct a full-scale square-head mainsail to test weekly at Cronulla during normal Sunday racing, as well as at the State Titles over Easter. This particular base design was once again a brain-child of Stuart Freizer, although several modifications have been made to date.

It must firstly be stated that quantifying results for full-scale tests are near impossible. Sailing involves so many variables including wind speed and direction, the effects of landforms on wind conditions, the effect of other boats, not to mention tactical decisions, boat handling, crew weight, hull design and mistakes by myself and others around me which all may affect the outcome of a race. All of these factors combined would deem finding numerical data pointless, even though it may look pretty in a Thesis.

The idea of constructing a full scale model was more an exercise in testing feasibility rather than size and shape, and many issues were found along the way.

All of the pretty computational diagrams and wind tunnel data in the world is no good if the sail is not feasible to construct in the real world, and having worked as a sail maker and taken part in the simulation side of things as well, it is a constant battle between the 'whiz-bangs' and the poor buggers who have to build the sail to find a happy medium that works.

Development on this sail is still going on to this day, some 10 months after the sail was first made, but we are now working towards a design that is very promising.

Upwind in Moderate Conditions at the 2010 State Titles.

Conclusions

There were times throughout this thesis I thought I may have bitten off more than I could chew, undertaking all three modes of testing. With a lot of help though, I have gained some excellent results which may not have been obtained by only one or two methods. This has been a very interesting and worthwhile experiment, which has cleared the waters and offered some excellent insights into designing an optimised square-head mainsail for the NS14 dinghy; an area where little research of this kind has ever been done before. It has combined a number of skills learnt at University, and I have had to learn a whole lot more on top of this. Having a vested interest in this project made this an exciting piece of research, and one which can be further built upon in years to come.

Being such a complex topic to research, I have sought considerable help along the way. So many people had a positive influence on the outcome of this Thesis, but I would like to especially mention some for the time and effort they contributed to make this possible:

- My Thesis Adviser and Head Teacher Mr Phillip Helmore
- Neil & Nicole Tasker, and all the boys at Barracouta Sails
- Andrew Baglin for his constant enthusiasm and computer skills
- Stuart Freizer for his sail and hull models
- David & Jan from Contender Sailcloth for the cutting and materials for my model sails
- Paul & Adam Minter from Minter Rigging for supplying me my model mast materials
- Ian Dixon from Dixon Boats for building my 1/8 scale NS14 hull model
- My parents Pete & Deb for all the love and support

If anyone has more questions, comments, or wants further information, feel free to contact me:
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