

# CFD MODELLING OF THE EFFECT OF FILLETS ON FIN DRAG

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## ABSTRACT

This paper describes work being done at Swansea University on the design of wave riding surfboards, with preliminary emphasis on the stabilising fins. Two specific CAD (Computer Aided Design) tools are being developed, one for surfboard design and the other for fin design, both of which allow export of NURB (Non-Uniform, Rational, B-spline) surface geometry in the IGES (Initial Graphics Exchange Specification) format. The fin design tool has the capability of allowing different National Advisory Committee for Aeronautics (NACA) foils series to be set at separate cross-sections along the fin.

Fins and surfboard/fin combinations can be imported directly into the CFD (Computational Fluid Dynamics) package FLUENT and with careful consideration of surfing dynamics to obtain values of critical flow variables, estimates have been obtained of the pressure and friction drag forces, which are thought to correspond to those occurring in practice and will be validated experimentally at a later stage. These results, however, have already been used to examine a number of disputes in the manufacturing industry, one of which is whether glass-on fins induce more or less drag than equivalent fins fixed to the board by a box. This component of the research is just a small part of the larger objective which is to bring scientific and engineering advances into the design and manufacture of surfboards. As the project progresses, CFD will be used to resolve more complex drag components, such as wave drag (free surfaces), induced (vortex) drag and cavitation drag, as well as being coupled to a finite element stress analysis to optimize flexural properties of boards and fins.

**ADDITIONAL INDEX WORDS:** *Computer Aided Design (CAD), Computational Fluid Dynamics (CFD), Surfboard Design, Fins, Wave Riding, Drag Coefficients, National Advisory Committee for Aeronautics (NACA) foils*

## INTRODUCTION

Lengths of surfboards typically range from 1.5m (5'0) to 2.7m (9'0), depending on the type of waves for which they are intended to be ridden, with smaller boards generally used in smaller waves. Until the early seventies, surfboards tended to be longer and more rounded at either

end. During the late sixties and early seventies surfboard shapes evolved into the more streamlined shapes used today. A great deal of historical literature can be found describing the evolution of surfboard shapes over the past 50 years, see (FINNEY and HOUSTON, 1996, MCTAVISH, 1973, YOUNG, 1990), and Figure 1 shows the rapid progression over the sixties and seventies towards smaller, more streamlined shapes, with the emphasis being more on manoeuvrability and speed. A generic modern surfboard is shown in Figure 2.

Fins placed on the bottom of the surfboard implement the dual functions of a rudder in sailing (to provide steering direction) and a centreboard (to provide stability). In the seventies most boards would have used a single middle fin, with a few “speciality” boards using two fins. Some of the main advances in surfboards over the eighties can be attributed to fin numbers and placements on the surfboard. The late seventies saw four times world champion Mark Richards use twin fins in many different types of wave conditions irrespective of known inherent stability problems of the twin fin format (in bigger waves, the twin fin has a habit of “spinning out” and sending the surfer flying!). However, a shock win by Simon Anderson at the 1981 Bells Classic in big waves on a new three fin combination that he called “The Thruster”, pushed the twin fin into the history books. Despite a flurry of experimentation in the late eighties using multiple fin combinations in excess of three, the thruster’s combination of the manoeuvrability of a twin fin with the stability of a single fin, has led it to become the standard fin combination, although single fins are still sometimes used in big wave conditions.

As can be seen in Figure 2, the fins in the Thruster combination are arranged at the tail-end of the board with the middle fin lying on the central axis (stringer) of the board behind the two side fins, which lie about 30-50 mm (1-2 inches) from the rails of the board. Single fins and middle fins are almost always double convex foiled, but the outside fins have usually only had a single convex foil on the outer edge and a straight inner edge, see Figure 6. Recently fins are being made which have a small inside concave foil. Typical sizes of a fin would be a height of 120mm (4.8 inches) and a base of 112 mm (4.4 inches), and these would be roughly the same for both the outer fins and the middle fin, although another recent trend is to have the outer fins slightly smaller than the inner one.

### **SURFING HYDRODYNAMICS**

While hydrodynamic studies have been done on watercraft for quite a while, mainly for commercial and military ships, it is only over the last decade and a half that Computational Fluid Dynamics (CFD) software has been extensively applied to the design of recreational watercraft, see (BULGARELLI *et al.*, 2003, ROSEN *et al.*, 2000), such as yachts and speed boats, with initial work dating back to the pioneering efforts of John Bertrand in the design of a winning America’s cup yacht in 1983. Early successes over the last few years combined with dropping costs of both hardware and software has meant that CFD has increasingly contributed to the design of yachts.

The application of CFD to sport, and in particular to improved performance of sports equipment is very topical, with articles in the latest the spring issue of FLUENT news, (BIXLER, 2004) , and the Journal of Sports Science (LYTTLE *et al.*, 2000) to the study of advanced swimming suits (sponsored by Speedo) for the Athens Olympics, demonstrating the large impact it is having on design, but to the author’s knowledge, apart from an original

article by Terry Hendricks in surfer in 1969, (HENDRICKS, 1969A, HENDRICKS, 1969B, HENDRICKS, 1969C, HENDRICKS, 1969D) , and a thesis by Michael Paine, (PAINE, 1974) , little has been published specifically related to the hydrodynamics of wave riding craft. However, even these are out of date as advances over the last twenty years in CFD have placed numerical simulation of flow within the grasp of the home computer, allowing numerical experiments to be performed and aide design by calculating entities such as drag coefficients, viscous and pressure drag forces.

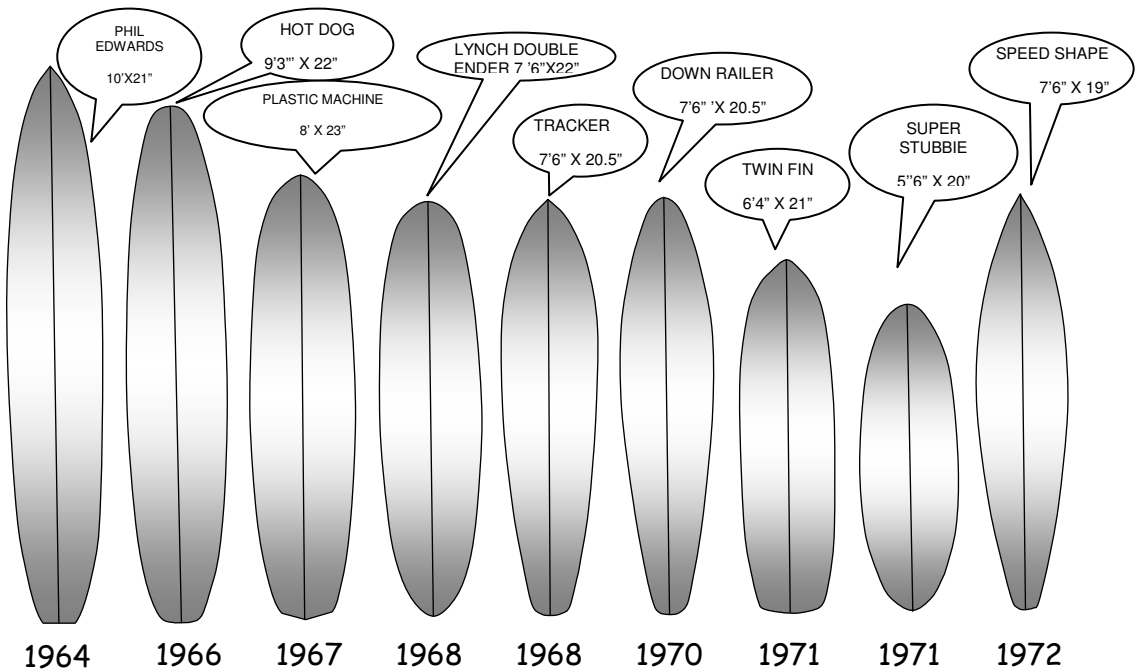


Figure 1 – Evolution of the surfboard shape through the 60s and 70s

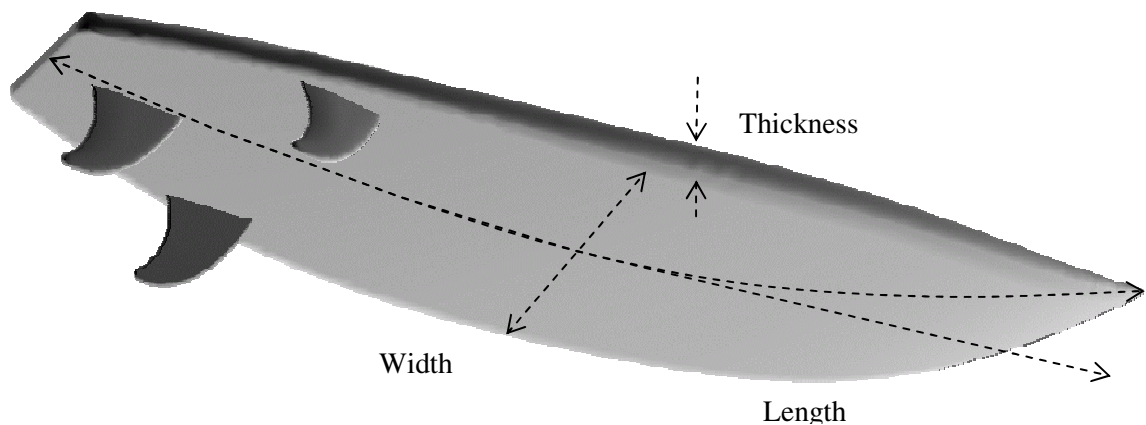


Figure 2 – Geometry of a modern surfboard with “Thruster” fin combination

For reference, much of the current work applies to the full range of wave riding craft, classed as self powered (Surf-skiing, Belly boarding and Surfing) and wind power assisted (Windsurfing and kite-surfing), all having in common the complex interaction between the wave's constantly evolving water surfaces and the surfboard's orientation, making any study of the flow dynamics far from trivial. In surfing, a base speed is determined by the speed of the wave (itself determined by wave height, period and water depth at the breaking point), but a surfer could theoretically reach up to twice this speed by virtue of their own energy input and skilfully maintaining their acceleration by repeatedly manoeuvring up and down the face of the wave.

Drag on the surfboard can mainly be attributed to four effects:

- **Skin friction drag (or viscous drag)**  
This form of drag is mainly influenced by the amount of surface area in contact with the water at any given moment, but also by roughness of the surfboards surface and the viscosity.
- **Form drag (or pressure drag)**  
This is mainly influenced by the projected area of the shape of the object on the main flow direction, but has quadratic dependence on the velocity; turbulence can have unaccountable effects on its value at higher velocities.
- **Wave making drag**  
The water level rises at the front of the board and the back, with a dip along the sides, and a wave-like shape is adopted by the free surface along the side of the board, transferring momentum to the water particles it comes into contact with. This represents a net transfer of energy, which also forms a mechanism of resistance to motion, i.e. drag.
- **Spray making drag**  
This occurs in surfing mainly during sharp turns, but at higher speeds it will become increasingly important in terms of its contribution to drag.

In naval terms, the dynamics of flow for a surfboard are comparable to the characteristics of planning craft of medium to high Froude numbers. The range of speeds involved would suggest that the board will probably be either planning motion (or on the verge of) most of the time when a surfer is successfully riding a wave. Here, planning should be differentiated from the ploughing motion of a board which has not reached the planning speed, and in which the water is carved away from the front of the surfboard. The surface between the air, water and surfboards is referred to as the free surface, and as the speed at which the surfboard travels through the water is varied, it continuously changes in elevation along the length of the board. The flow wraps around the rails and forms a bow wave and a series of wake waves, which are the cause of the wave drag resistance. During the later stages of planning, the board appears to come up onto its own bow wave, and at this stage the wave-drag starts to decrease.

Further borrowing of naval engineering knowledge tells us that for surfboards moving at these speeds, the wave drag dominates other forms of drag, even though its value is at a maximum in the first instances of getting the surfboard planning, and then decreases with subsequent acceleration. Wave drag of planning craft is an area of limited theoretical analysis, and most

data is experimental in nature, thus ongoing discussions are in progress with Southampton Institute to set-up a series of experiments on model surfboards using a 60m Tow-tank, which will establish the free surface and drag data for scaled model surfboards simulated maximum velocities of up to 8-10 m/s.

As a preliminary phase in this project, the capability was examined of the commercial CFD package FLUENT to settle an on-going dispute in the surfboard manufacturing industry, as to whether glass-on fins induce more or less drag than equivalent fins fixed to the board by a box. The work has concentrated mainly on a flow past fins as a way of determining the pressure and viscous drag, however, it is clear that further investigation will be required, to account for wave drag via the free-surface around the surfboard, and its interaction with the fins.

Surfboard design is at a stage in which it would greatly benefit from computational modelling and CFD and stress analysis could play a role in improving surfboard design, by:

- a) Optimising fin/surfboard configurations by understanding the flow past/over fins as a function of drag, lift and fin stiffness;
- b) Optimising overall surfboard hydrodynamics for speed as a function of surfer body weight/surfboard buoyancy and the effects on the free-surface wave drag;
- c) Optimising overall surfboard stiffness determined by structural properties of the board as a whole, mainly focussing on stiffness during critical manoeuvres, but also to improve designs for impact damage.

### **CAD TOOL FOR SURFBOARD DESIGN**

Surfboard making is very much a craft, and design advances have been led by trial-and-error approaches and test-driving by professional riders in both the windsurfing and surfing arenas. There has been a recent move to mass production of surfing boards by companies who use CAD and automation to produce the boards, see (MAYNARD, 2003; TAYLOR, 2003), leading to the reaction by leading traditional surfboard manufacturing companies of patenting specific surfboard designs and actually licensing back their designs for mass-production under their own brand name.

This has created a need for specialist software to produce CAD files specific to surfboards, which is easy enough to use for non-specialist users. A CAD package has been developed by Dr Ian Pearce at Swansea University called Dat98, which creates three dimensional surfboard designs, see Figure 3. The software is much simpler to use than a full-blown CAD package, being based on standard criteria which shapers use to make boards (length, width, tail width, etc), but also allowing more intricate details to be added, such as rocker at specific sections, bottom "V". With direct CNC output capability the software also been linked up to shaping machines.

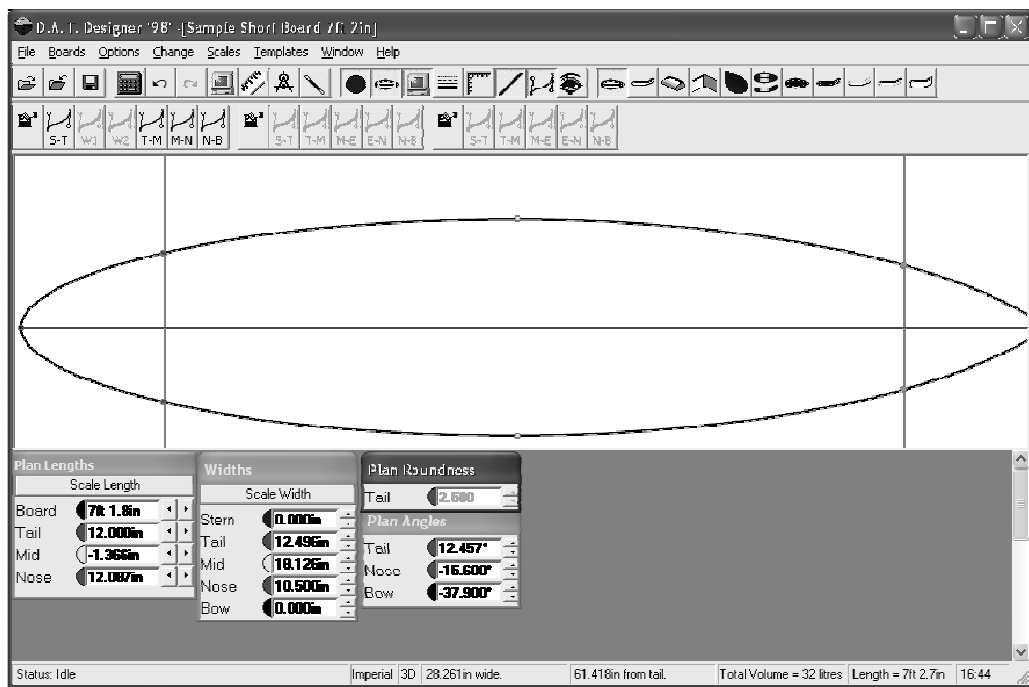


Figure 3 – DAT 98 Surfboard CAD Design Tool (Plan form)

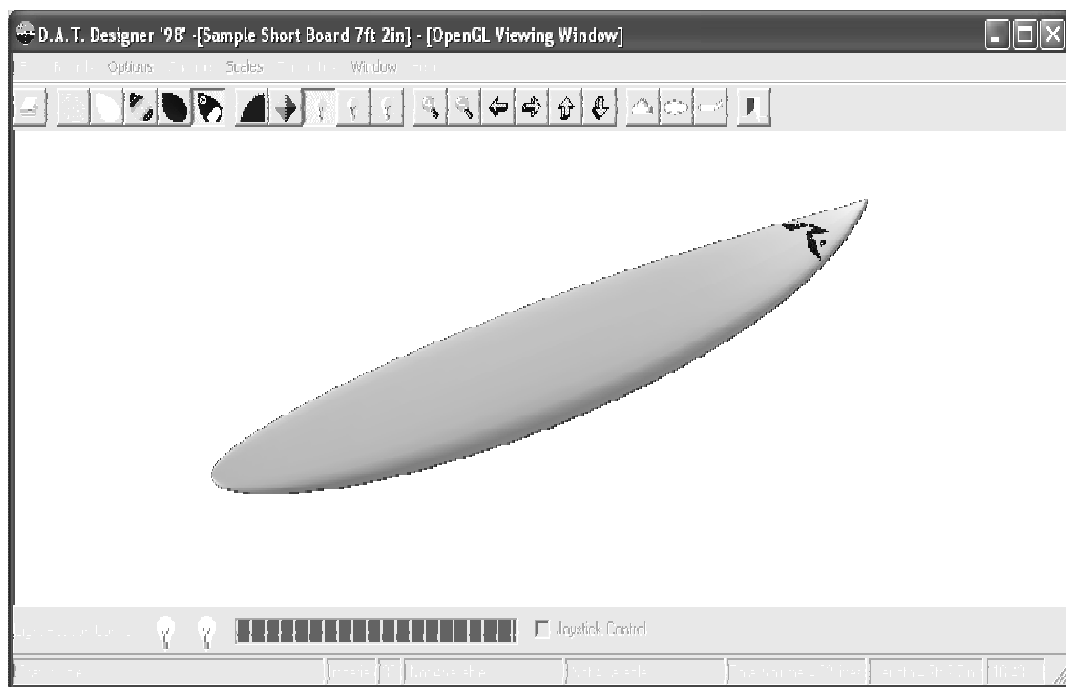


Figure 4 – DAT 98 Surfboard CAD Design Tool

Work is in progress to include a module for fin design in Dat98 (coupling fins to the surfboard) and CAD data export capability which is directly compatible with CFD and stress analysis software. This has been done by exporting surface data in the IGES format. The fin design module has the added capability of using NACA series foils (4-, 5- and 6-series) at the various cross-sections along the fin. The intention of this capability is to allow CFD studies of fins with specific foils at these sections which will optimise drag by coupling laminar and turbulent foils at relevant sections.

## COMPUTATIONAL FLUID DYNAMICS

### Calculation of Drag Forces using CFD

#### *Geometry and Boundary Conditions*

The computational experiments placed the fins in a 4m long water flow tank, with a 1x2m rectangular cross-section, as shown in Figure 4. The inlet speed of the flow was varied from 1 to 7m/s, although these could easily have been run at higher values, these did correspond to the surfing speeds suggested by (HENDRICKS, 1969d) and (EDGE, 2001) for waves in the 0.5m to 2.5m range, as shown in Figure 5. In particular, the estimated speed of 3.8 m/s for a 1.5m (5') wave would give surfer speeds in the 3.8 to 6.8 m/s range. More recent wave speed estimates are given by (PATTIARATCHI, 1997), referencing the original work by (WALKER, 1972), suggests there may be a maximum board speed of 12m/s (40 ft/sec) restricted by the surfer's ability to paddle into and keep-up with waves peeling faster than this. Also shown is the experimental data of (PAINE, 1974), which by his own admission in a personal correspondence, may be marginally on the high side. This restriction does not apply to higher speed tow-in surfing and wind-surfing disciplines for which a wider range of velocities would be need to be modelled.

For all the experiments, generic fins were used with a 112mm base, 120mm height, and a 23° rake (similar to the FCS G3000) with a maximum foil thickness of 6 mm for the side fins, and a maximum foil thickness of 12 mm for the middle fin, as shown in Figure 6 (b). Fillets (representing the layer of glass which attaches fixed fins to the base of the surfboard) were added of radii of 5, 10, 15 and 20 mm as shown in Figure 6 (a) and Figure 7.

## CFD METHODOLOGY

A CFD calculation gives velocities at all points in the flow domain by solving either the Navier-Stokes Equations (for Laminar Flow Modelling) or the Reynolds Averaged Navier-Stokes Equations (RANS, for Turbulence Flow Modelling). Once the model has been solved, which can take up to 3-4 hours depending on the number of elements in the domain on a 3.6GHz Xeon Dual Memory workstation with 4GB RAM. The solution data also gives pressures on solid surfaces within the domain, and these can be integrated to get pressure and viscous drag forces. This is the most sophisticated way of calculating drag forces for an object, arguably better than scaled experimentation. In the work presented in this paper a Laminar flow model was primarily used as it is substantially faster, even though it was known to be under-predicting the forces by up to 50%. However, for the relative comparisons of the pressure drag between fins with and without fillets, Laminar and Turbulence models give different magnitudes but similar trends with changes to angles of attack and velocity scaling.

### COMPUTATIONAL EXPERIMENTS: A SINGLE MIDDLE FIN

The first set of experiments involved placing a single, double-foiled fin (corresponding to a centre fin) in the tank. The orientation angle of the fin to the oncoming flow (angle of attack)

was varied between 5°, 10°, 15°, 20° and 25° for both the filleted and un-filleted fins. However, it is believed that in reality the forces on a fin when surfing would only correspond to maximum angles of attack up to 10° to 12°.

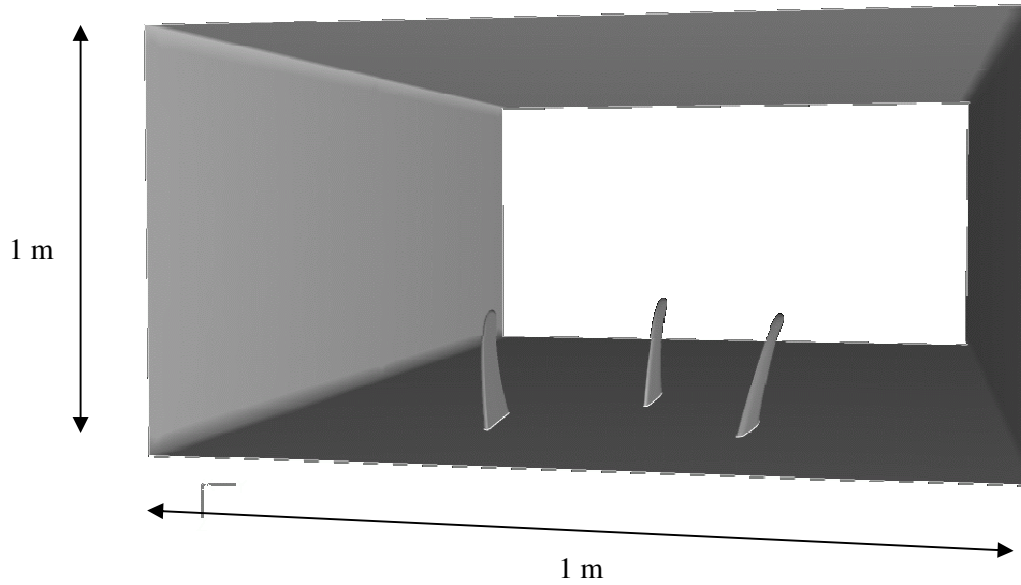


Figure 5 – Numerical Experimentation to calculate fin drag

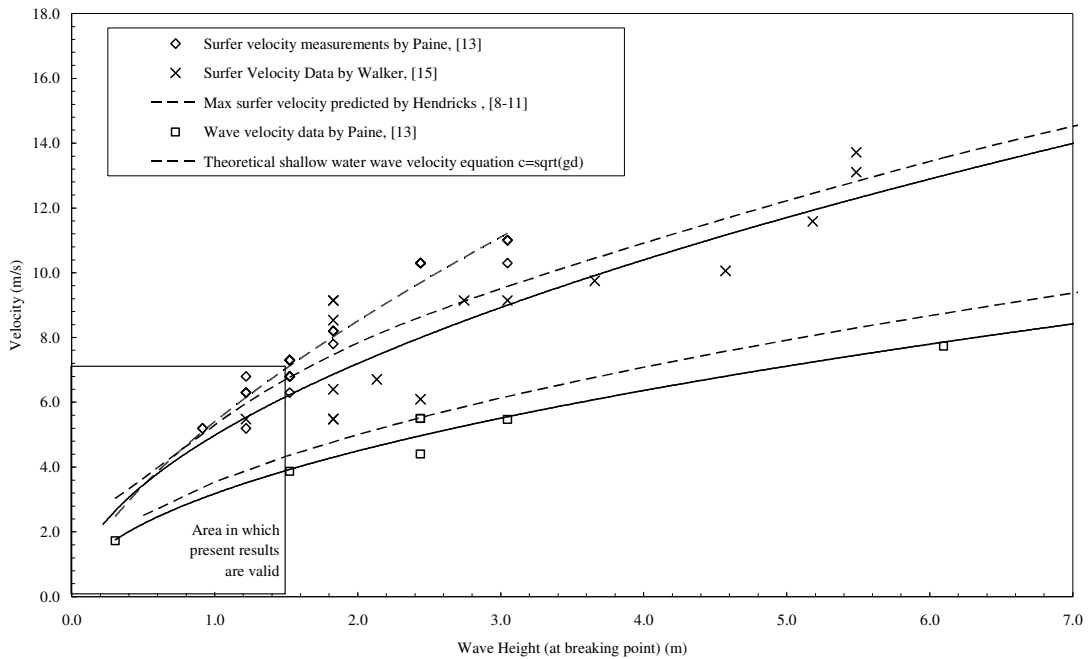


Figure 6 – Wave height versus wave and surfer velocity

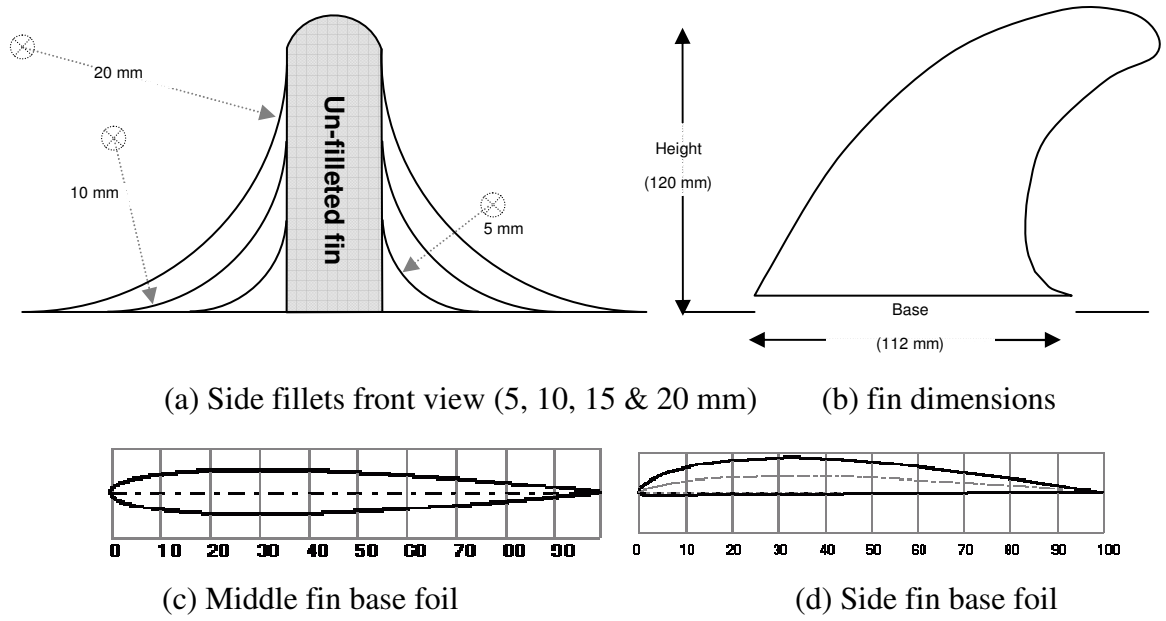


Figure 7 – The fin

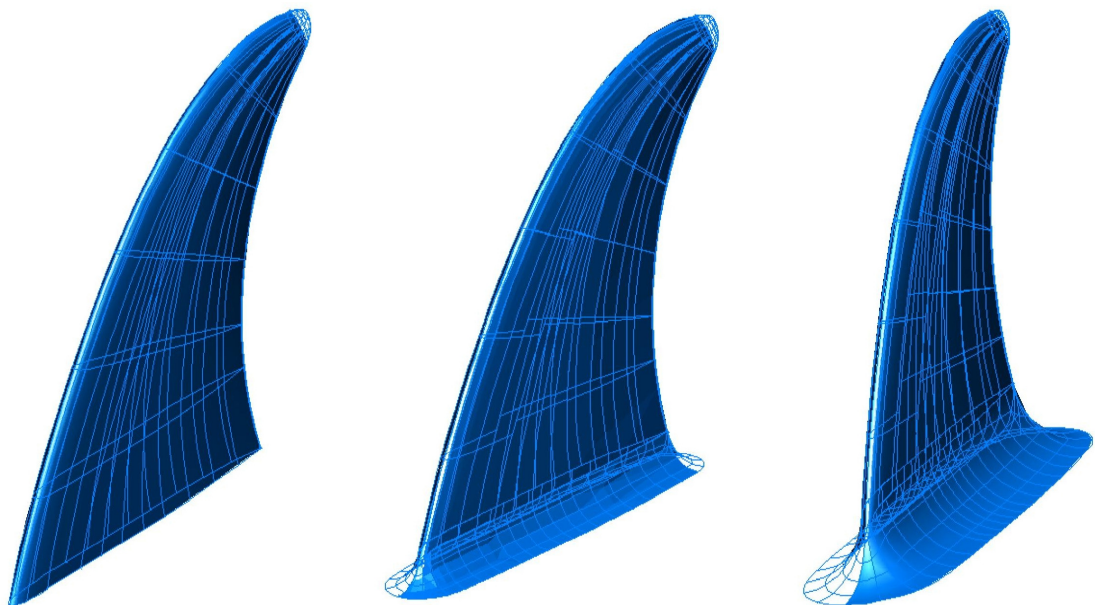


Figure 8 – (a) Un-filleted fin, (b) 10 mm fillet, (c) 20 mm fillet

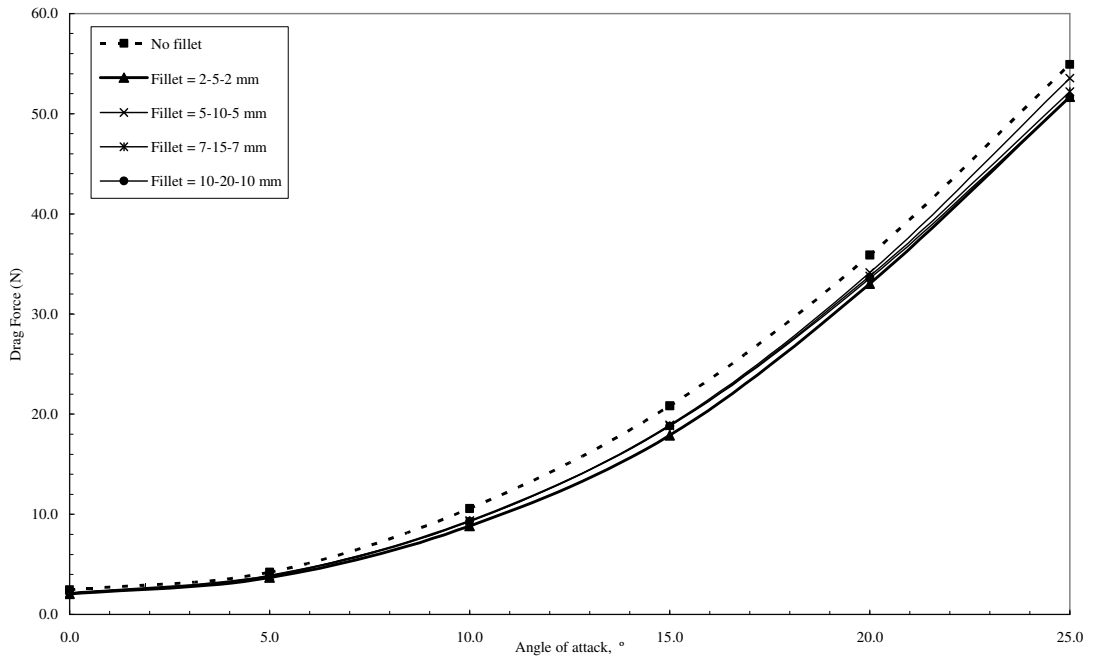


Figure 9 – Drag force for fillets of various sizes

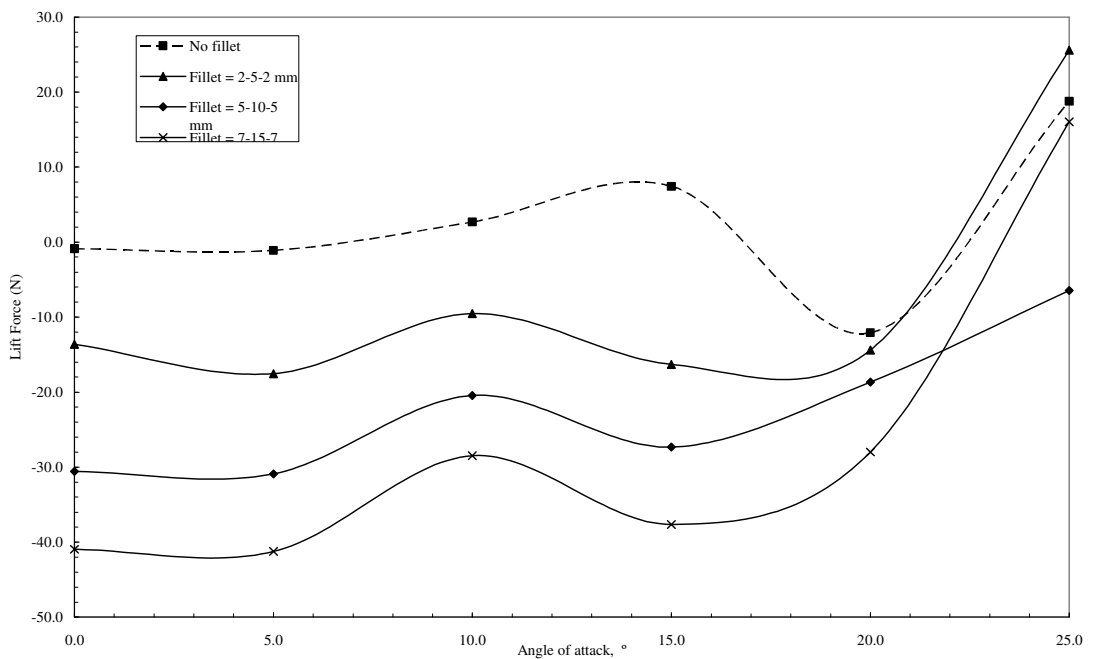


Figure 10 – Lift force for fillets of various sizes

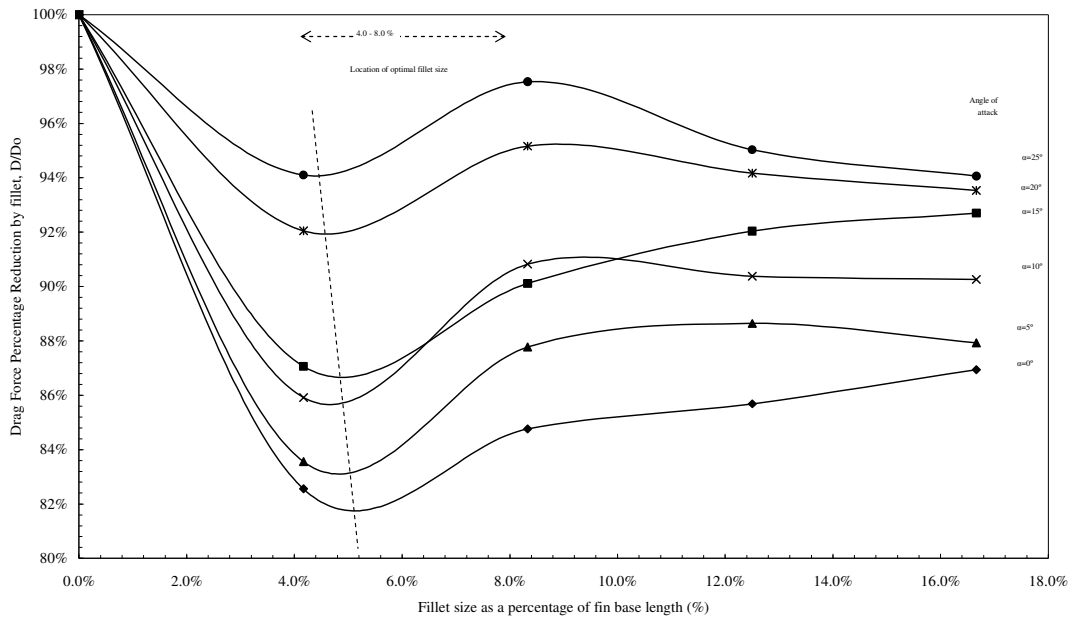


Figure 11 – Drag force of a filleted fin as a percentage of the un-filleted fin

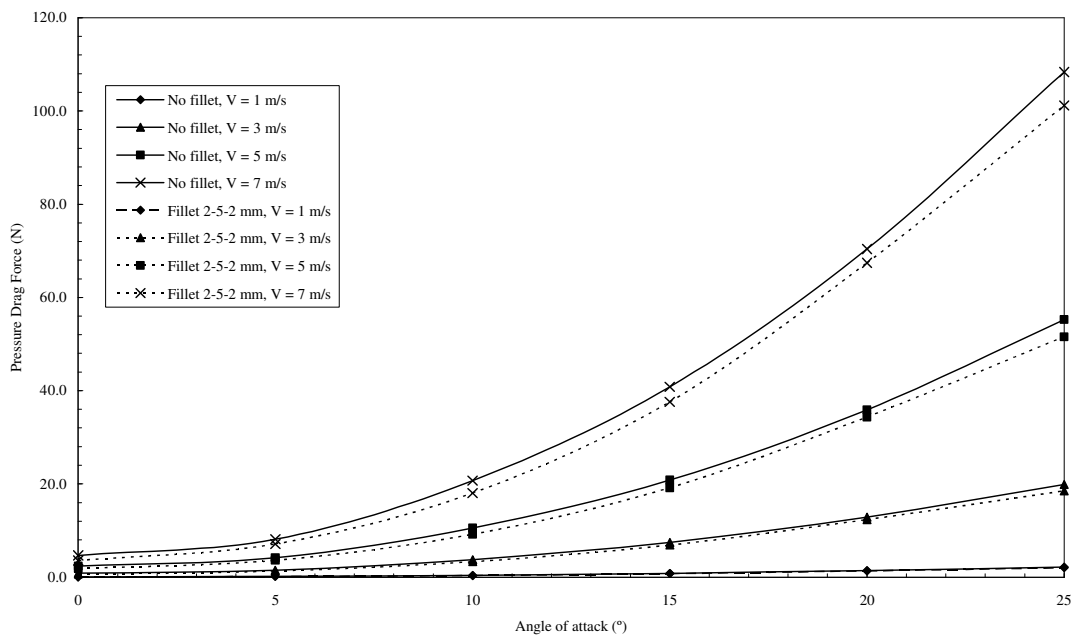


Figure 12 – Drag force for filleted and un-filleted fins for various velocities

Drag forces and coefficients were calculated with FLUENT for various angles of attack using a laminar flow model for both the filleted and un-filleted fins, and the results are shown in Figure 8, which shows the pressure drag coefficient. According to (HOENER, 1965), “Interference drag [also] originates at points where wings, struts or tail surfaces join or penetrate the fuselage, or where different parts of the tail assembly join each other.” He carries on saying, “interference drag can appreciably be reduced by fairings properly installed in the corners”. In fact, the interference drag can be reduced by up to 10% (or more) over an un-faired junction, depending on the fairing radius, which has been found to be at an optimum when it is small, at between 4-8% of the chord length.

The situations that (HOENER, 1965) is referring to could equally well be applied to the intersection between the surfboard and fin, where fairing is equivalent to the fillet which occurs when the fin is glassed onto the surfboard and the chord length would be the length of the fins’ base. As can be seen from Figure 9, drag can be reduced by up to 10-12% with a fillet radius of 4% of the fin base length, which would seem to agree with the findings of (HOENER, 1965), thus, for the middle fin fillets we can indeed reduce the drag. Figure 10 shows what happens to the drag force as both the angle of attack and the velocity are varied.

### **Empirical Correlation using Boundary Layer Calculations**

A couple of computational runs were done using turbulence models, namely the Spalart-Allmaras model and standard k-e model, neither of which, according to (CONSTANTINESCU and SQUIRES, 2004) are necessarily the most appropriate model for flow in the current regime, with other models giving better results. In both instances, the total drag was up to twice that predicted by the laminar modal, namely due to an increase in the viscous drag contribution. Empirical boundary layer calculations for a flat plate of equivalent dimensions using both laminar (Blasius) and turbulent velocity profiles, gave boundary layer thickness between 30-40% of the height of the fin at the point of impingement with the fin, with the boundary layer becoming turbulent within 4.5 cm (2”) of the initial contact point between the surfboard and the water, similar to the estimates by Hendricks, (HENDRICKS, 1969C). The empirical boundary layer calculations for drag friction as a function of velocity in figure 11 are compared with those predicted by FLUENT, highlighting the invalidity of using laminar flow models, as the fins lie in both laminar and turbulent flow regimes.

### **COMPUTATIONAL EXPERIMENTS: A SINGLE SIDE FIN**

The second sets of experiments were run with a single side fin, with and without fillets, and with the same number of angles of attack and velocity used in the previous section, and the drag data is compared to the single middle fin results in Figure 12. For the side fin, it was found that the presence of the fillet did not cause any appreciable reduction in the drag, and actually marginally increased drag at high angles of attack and velocities.

### **COMPUTATIONAL EXPERIMENTS: THRUSTER THREE FIN COMBINATION**

Finally, the experiments were done with three fins in the channel, using the laminar flow model. Figure 13 shows the contributions to the pressure drag from each of the fins in the thruster configuration at various angles of attack. As can be seen, the left fin (left when looking down onto the board) which leads the turn is giving the greatest amount of drag, mainly due to its projected area being greatest onto the incoming flow. Velocity vectors demonstrate flow features such as re-circulation along the inner edge of the outside fin, Figure

14. The complex vortices emanating from the side fins can be captured by pathlines, see in Figure 15, and the swirling flow downstream from the fins can be seen in Figure 16.

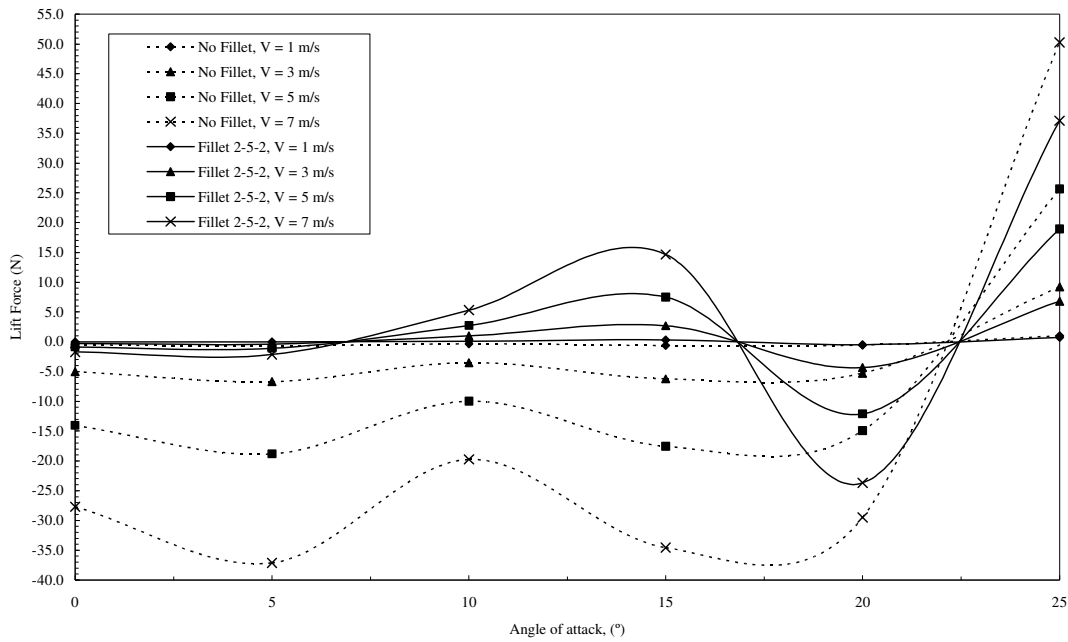


Figure 13 – Lift force for filleted and un-filleted fins for various velocities

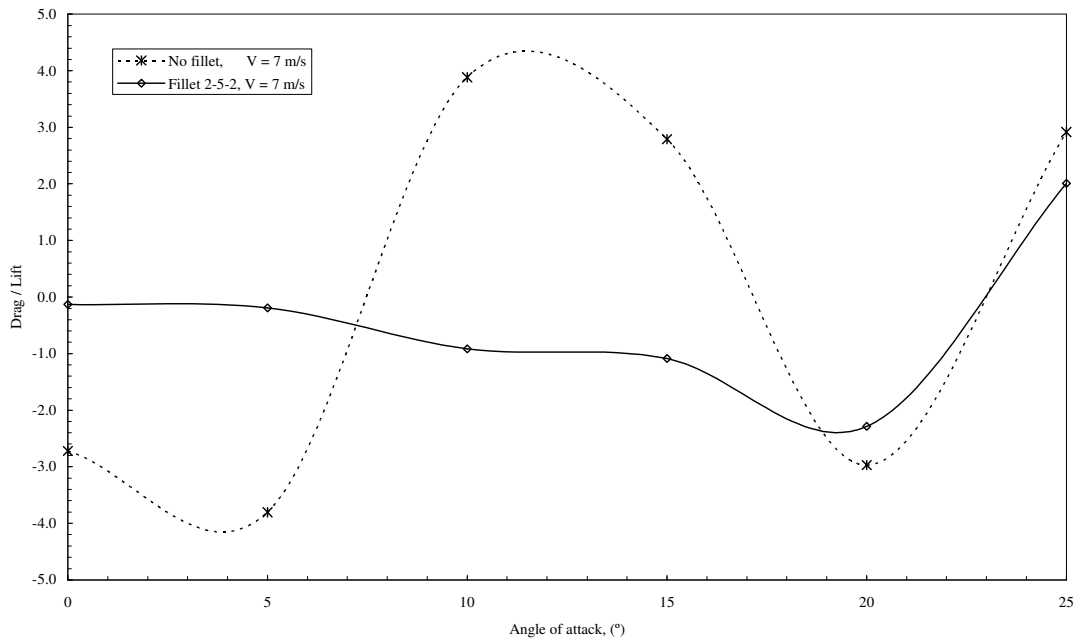


Figure 14 – Ratio of Drag over Lift forces for filleted and un-filleted fins

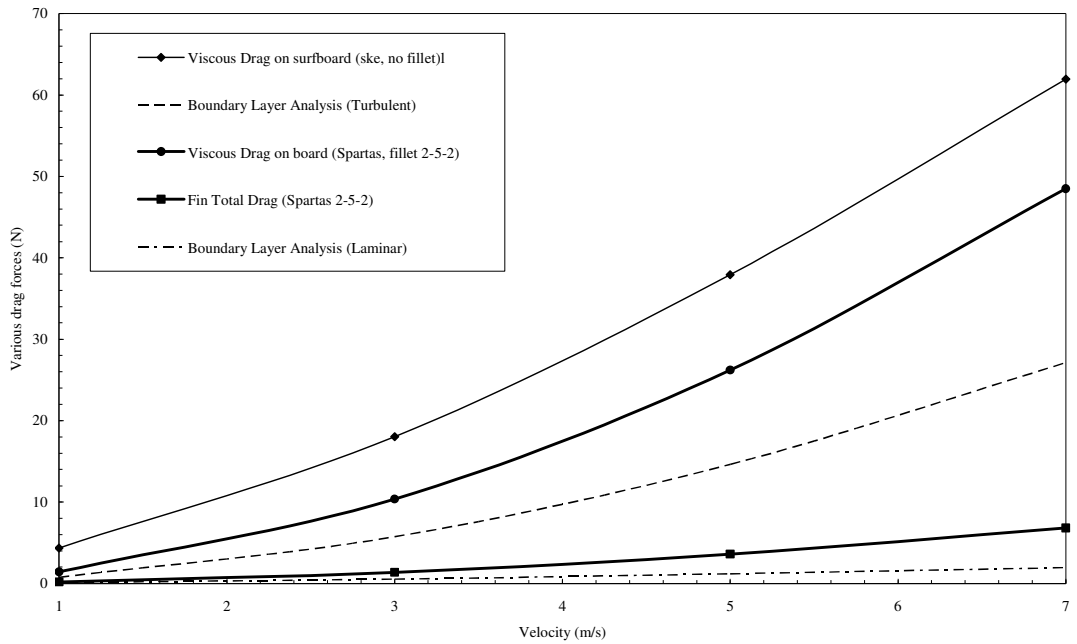


Figure 15 – Viscous drag of the bottom of the surfboard using various models

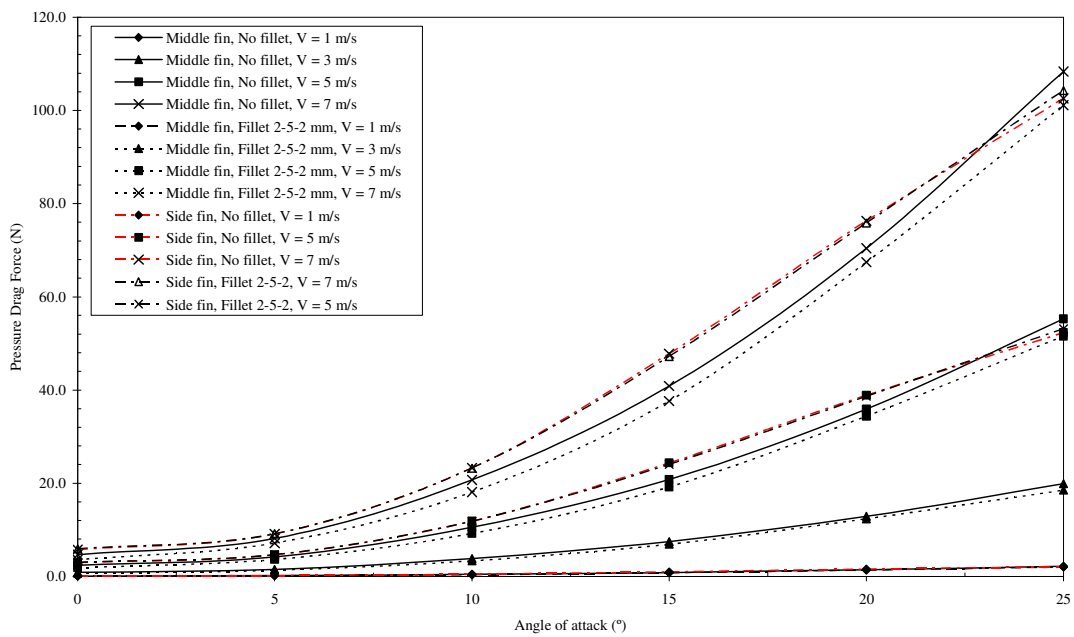


Figure 16 – Side fin drag forces at various angles of attack and velocities

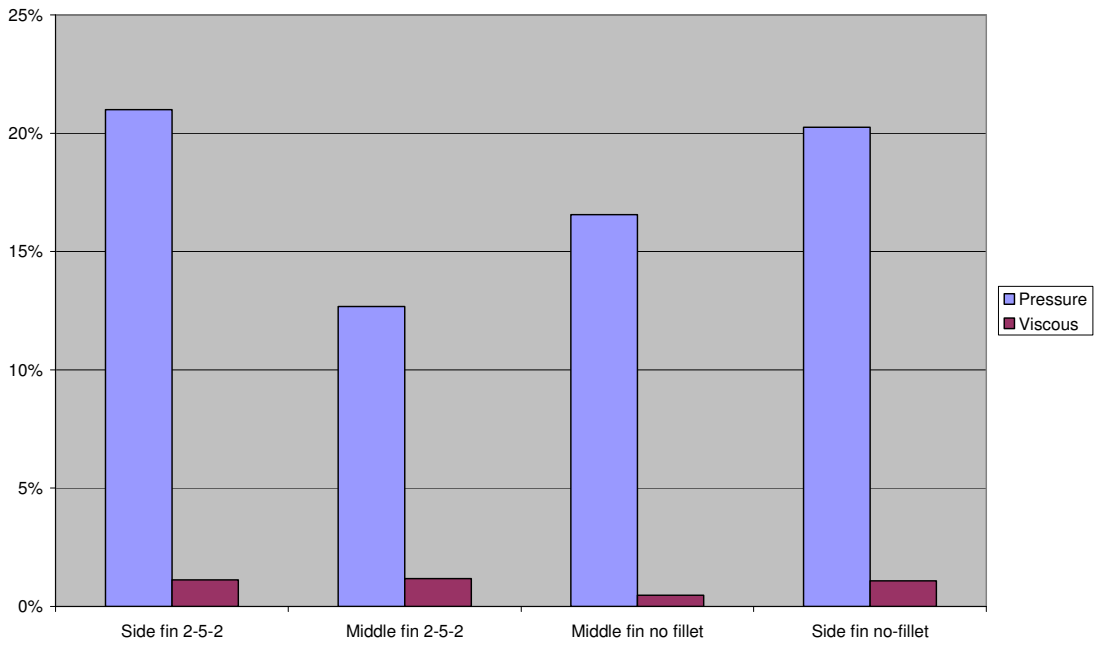


Figure 17 – Relative contributions of fins to total drag at V=7 m/s and a=0°

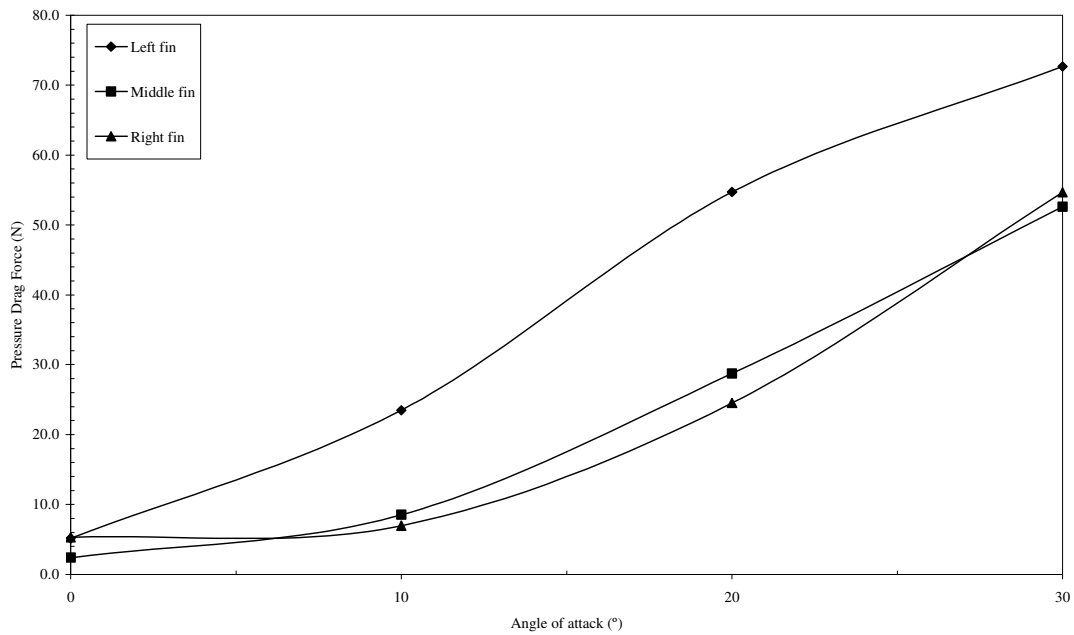


Figure 18 – Pressure drag for three fins in the tank, at V=5 m/s and various angles of attack

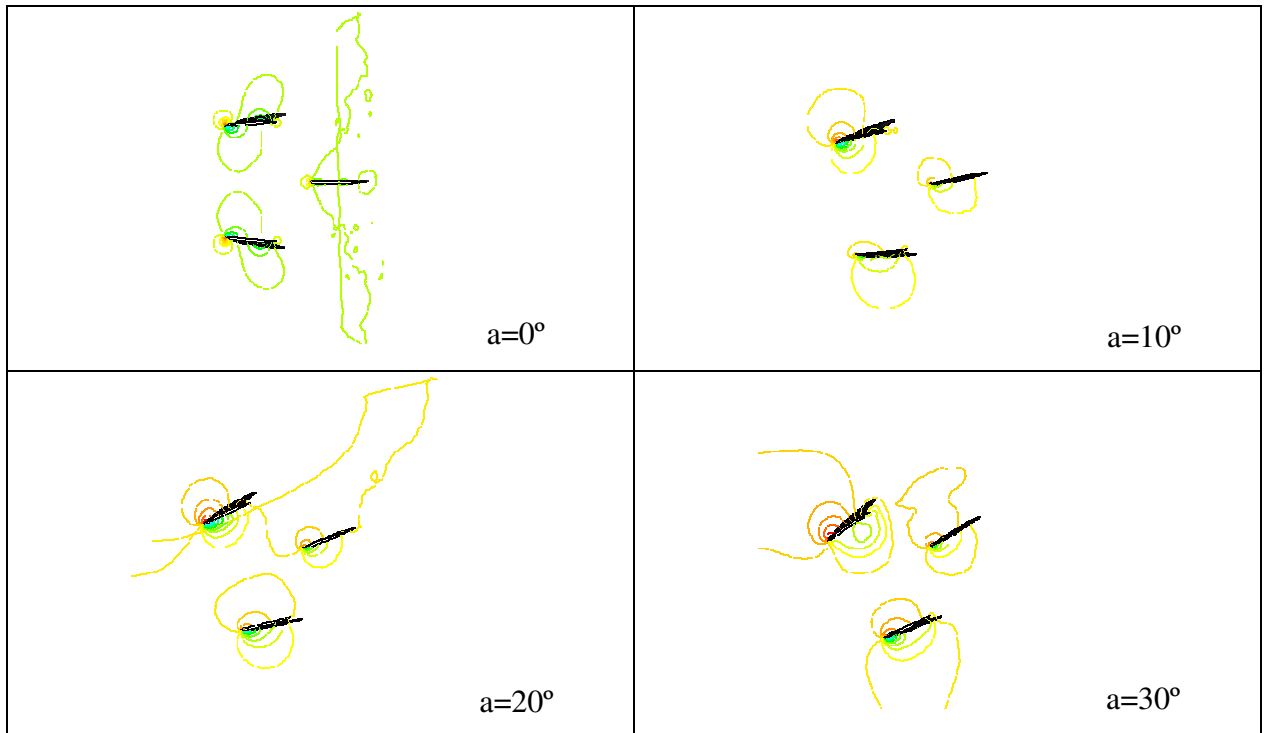


Figure 19 – Pressure contours around base of tank for three fins at various angles of attack

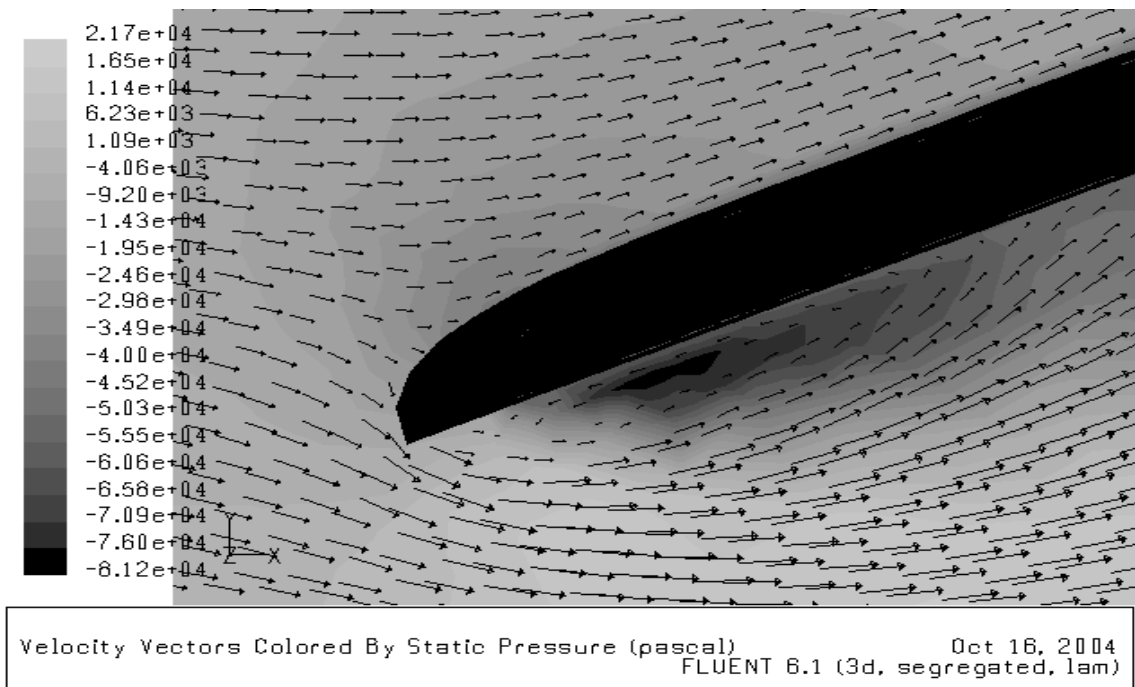


Figure 20 – Velocity vectors superimposed on contours to show re-circulation on inside edge of an outside

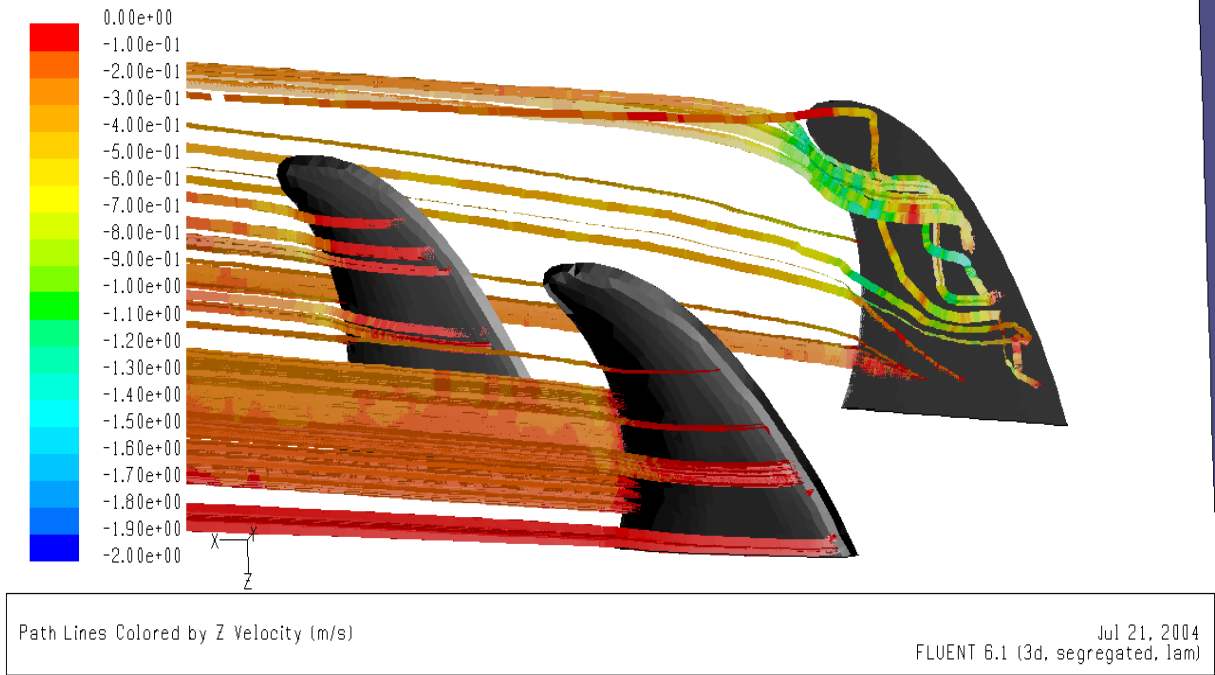


Figure 21 – Path lines at 20° angle of attack, showing the complex vortex generation of the leading edge

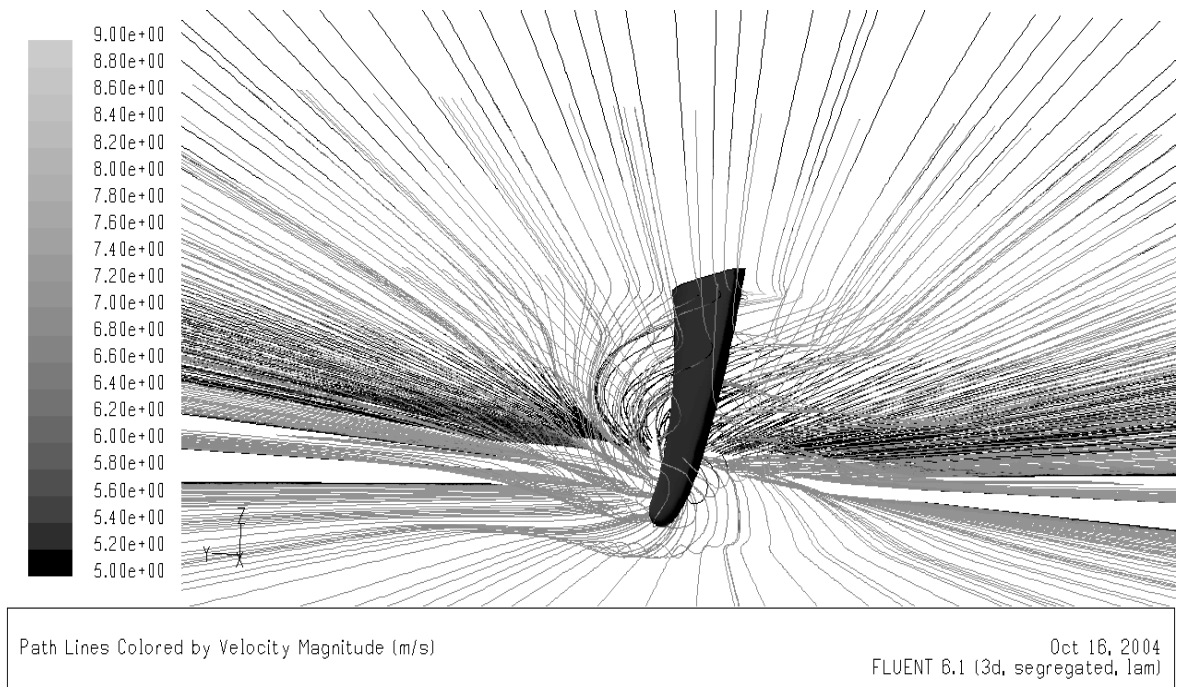


Figure 22 – Path lines around a single fin

## CONCLUSIONS

In some ways, this work has been disappointing, as it has failed to provide a clear cut winner between glass-on fins and boxed fins. On the other hand, it has shown that we can now use CFD to look at very subtle differences in the drag forces and hydrodynamic improvement of fins. The total drag for fins with and without fillets is compared in Figure 17, and shows that the presence of fillets can decrease the overall drag of the fin, even though the viscous drag is slightly increased due to the added surface area, the smoothing of the sharp edges between the fin and the board causes pressure distributions to be spread over a larger area. This decrease in drag is restricted to double-foiled fins (middle fins), and there is very little noticeable difference when fillets are added to the side fins, possibly due to the fact that the inside edge of the fins examined in this work were flat anyway, so the effect on drag of filleting the is less pronounced than for the double foiled fins (middle fin).

However, even for the middle fin the drag decrease is small (10-12%) and even smaller (6-7%) when compared to the total combined drag of the board and fin system that it is unlikely to be noticed in practise, even by expert surfers. However, the presence of fillets was accompanied by an increase in a vertical lift force, which may partially explain the more buoyant, lighter feel to glassed-on fins, and their preference in use by surfers on the professional circuit. Although this may seem to be a score on the side of glass-on fins over boxed fins, it should be pointed out that actual reduction only represents 3% of the total viscous drag of the surfboard (28N as calculated from boundary layer analysis), and is, thus, relatively insignificant even without taking into account the effects of wave drag

This work should be extended by using turbulence models, as it is incorrect in absolute terms to use laminar models for the range of speeds looked at. Preliminary results with turbulence models indicate a substantial increase in the magnitude of the overall drag forces, mainly due to increased viscous drag contributions, but not the trends with velocity and angles of attack. However, uncertainties in turbulence boundary conditions at the inlet of the tank (e.g. intensity and length scales) need to be resolved before these models can be used conclusively, and experiments are currently underway from which data will be used to validate the modelling.

The work also needs to be extended to other fin designs and design parameters, such as the effect of fin “toe-in” (angle at which fins are aligned to the central stringer), effect of foils and effect of fin aspect ratios. From a scientific perspective, it is envisioned that the most challenging work in the future will be in attempting to model the free surface flow over the board using the Volume of Fraction (VOF) model also available in FLUENT, as a way to obtaining estimates of the wave drag.

## ACKNOWLEDGEMENTS

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