The Design of a Hydrofoil System for Sailing Catamarans

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This paper describes an investigation into the effect of the addition of lifting foils on the total hydrodynamic resistance of a sailing catamaran hull representative of those produced in South Africa. A canard lifting foil configuration with main foil amidships and front foil at the bow was chosen. This configuration was found to be stable across the speed range without a trim and ride-height control. The effect of leeway and heel both with and without the lifting foils was investigated. Experimental testing was conducted using towing tank testing, and results from this were verified numerically. The hull and foils were modelled separately using thin ship theory and vortex lattice methods combined with empirical equations for viscous drag. The canard configuration provided a reduction in resistance above a displacement Froude number of 2. The effects of leeway and heel were shown to depend strongly on hull shape, so no universal trends could be observed, and these effects were shown to be dramatically altered by the addition of the lifting foils.

Nomenclature

AOA	Angle of Attack
BOA	Beam Overall
b	demihull beam
C4	Hull of Insel *et al.*[12]
CE	Centre of Effort (of sails)
COG	Centre of Gravity
DWL	Design Waterline
Fr_∇	Displacement Froude Number
LCG	Longitudinal Centre of Gravity
LWL	Design Waterline Length
RH1	Representative Hull #1
S	separation between demi-hulls
T	Maximum Draft
T_c	Canoe body draft
WSA	Wetted Surface Area
Δ	Displacement (weight)
∇	Displacement (volume)

1. Introduction

1.1 Background

Research into the motorised HYSUCAT or Hydrofoil Supported Catamaran has been conducted at the University of Stellenbosch for over 20 years. Based on the success of the research conducted on the HYSUCAT and other power boat craft, the objective of this research is to investigate the feasibility of using the HYSUCAT configuration, which utilises fixed foils and has

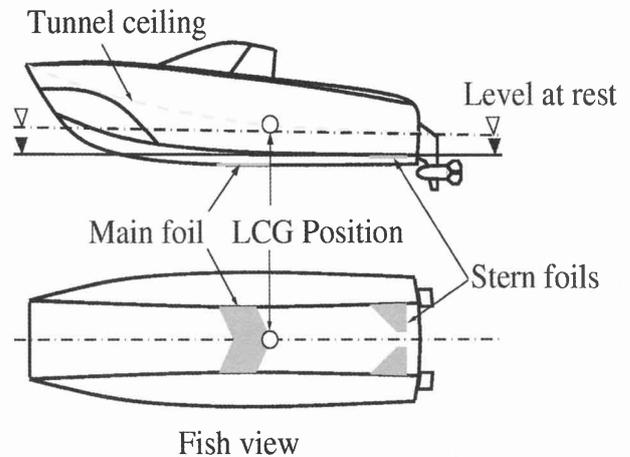no trim and ride height control, on a sailing catamaran that best represents those being produced in South Africa.

Figure 1: Diagram of a HYSUCAT

The concept of using hydrofoils to improve the performance of sailing craft is not new. A patent registered in 1955[1] describes a sailing catamaran dingy modified to operate with hydrofoils. A number of other hydrofoil supported craft, such as the catamarans "Mayfly"[2] and "Icarus"[2], and the hydrofoil supported trimaran "L'Hydroptere"[3] have been developed in order to attain high speeds. Further details on the history of hydrofoil sailing craft are provided by these two references.

1.2 Design approach

Given that a standard sailing catamaran has rudders near the stern and daggerboards amidships, it would make sense to attach foils to these. If lifting foils are placed elsewhere they would require additional struts which in turn would upset the balance of the boat, thus requiring a redesign in terms of balance. Placing foils on the rudders and daggerboards would therefore allow for a simple 'add-on' hydrofoil design. The foils are also placed in relative safety (against impact or entanglement) below the tunnel of the boat and do not extend past the beam of the boat. The main foil will be no deeper than the daggerboards, if impact occurred with a sandbank or any submerged body, it is likely that it would have occurred in any case and the same can be said of the rear foils and their attachment to the rudders. However, the longitudinal centre of gravity (LCG) is intuitively expected to be not far aft of the main foil resulting in an aircraft type configuration with most of the load on the main foil and as a result, poor pitch stability. Since pitch-pole is a problem for sailing catamarans, the stability of this configuration was considered to be marginal without the LCG relatively far aft or a trim control system and a canard-type configuration (figure 2) was used. The aircraft configuration is, however, very similar to the standard HYSUCAT configuration that has proved successful on power catamarans.

Since the span of the tunnel of sailing catamarans is usually quite large compared to power craft, a high aspect ratio, high

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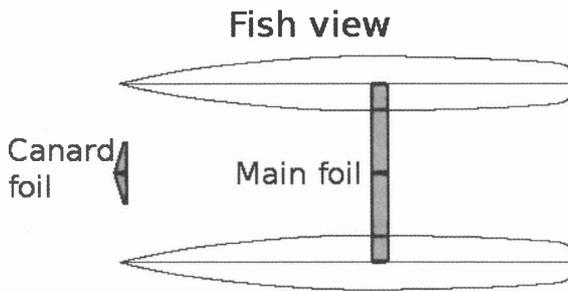   Stellenbosch, 7602 Matieland, South Africa
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Figure 2: Canard Configuration

efficiency, foil could be placed between the daggerboards.

In terms of thrust position and direction, the modelling of a sailing catamaran is more complex than its motorised counterpart. The thrust force acts at the Centre of Effort of the sails (CE) and often has an athwartships (transverse) component. Both the position of the CE and the percentage athwartships component depend on the point of sail of the boat (direction relative to wind direction). The athwartships component results in a leeway angle (which through lateral resistance counters the athwartships component) and heel (which counters the moment created by the vertical misalignment of these two forces by a lateral shift in buoyancy). The alignment of the resistance and thrust forces to ensure yaw stability is achieved by the adjustment of the rudder angle.

As a result of the elevated thrust position, combined with their fine bows that offer little buoyancy, sailing catamarans are particularly susceptible to pitchpole, a condition in which the leeward (downwind) demihull bow sinks, causing the boat to pitch forwards and capsize. By raising the boat, the lifting foils would raise the CE thus increasing the pitching moment. However, the reduced total drag with foils could result in a net reduction in pitching moment and therefore an increase in speed at which pitchpole occurs.

2. Experimental Setup

2.1 Prototype

A hull representing those produced in South Africa (hereafter referred to as 'RH1') was designed and its principle parameters are given in table 1.

LOA (m)	11.2
BOA (m	5.7
LWL (m)	11.0
bDH (m)	1.33
S (m)	3.04
T_c (m)	0.35
T (m)	1.35
Wet-deck clearance (m)	0.85
Δ (tons)	2.6
Boat speed range (knots)	0 – 25
Fr_v range	0 – 3.5

Table 1: Principle parameters of the RH1

2.2 Scaling considerations

Scaling effects on the model tests conducted during this investigation can be divided into those associated with the hull, and those with the foils. In order to ensure similarity for hull resis-
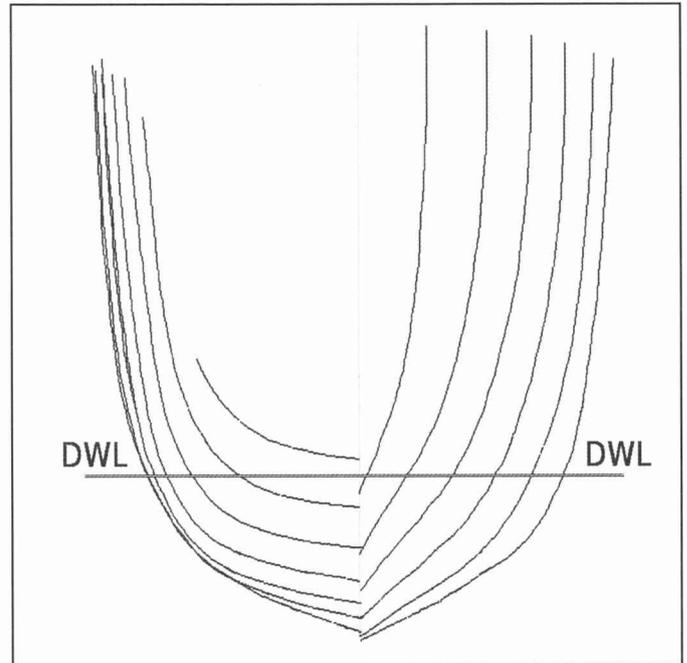

Figure 3: Section Plan of RH1

tance, the method of Froude-similarity scaling outlined at the International Towing Tank Convention of 1957[4] was used. For this method, Froude number similarity is enforced. Drag on the model is decomposed into frictional and residual components. The frictional component is dependent on the Reynolds number, and is obtained for the model, while the residual component is dependent on the Froude number. The frictional component may be determined from Reynolds number based correlations, which allows the calculation of the residual component, which is identical in non-dimensionalised form for the model and prototype due to Froude similarity.

The viscous drag on the foils cannot be scaled using the previous method as the short chord length of the model foils results in laminar flow over these surfaces, which cause drag mechanisms such as laminar separation to have a significant effect on the model. The application of Kirkman and Kloetzl[5] allows the drag for the foils to be scaled. However, the trim, stability and stability in terms of resistance to pitchpole for the model are expected to be conservative for the model in comparison to the prototype.

According to Bertram[4], the hull length based Reynolds number should exceed 5×10^5 for fully turbulent flow for the scale model. In addition, White[6] recommends that the surface roughness-based Renolds number for the model exceed a value of 120. It was determined that a scaling factor of 8.6, yielding a 1.3 m long model, with length and surface roughness based Reynolds numbers of 1.5×10^6 and 600 respectively, which are larger than the minimum values specified for these quantities, with negligible blockage and shallow water effects.

2.3 Towing tank

The Stellenbosch University towing tank was used in this study. The principle dimensions are given in table 2.

There are two standard methods of experimentally testing a scale model of a sailing boat. The first is called free-sailing where the model is towed from its exact CE. This will require a variation in the CE to represent several points of sail and an active rudder system which provides yaw stability for each speed is needed. The second is called semi-captive and is a

Length	90m
Breadth	4.5m
Water Depth	2.7m
Max Carriage speed	8.2m/s

Table 2: Principle parameters of towing tank

more systematic approach where the model is tested at various speeds, leeway angles and heel angles, but is allowed to trim and rise freely. This requires a complex mechanism called a dynamometer which is not available at the towing tank.

In order to reduce the number of experiments, a compromise between the two methods of testing a sailing boat was used. The heights of the CE for three common points of sail (running, beating and reaching) were calculated from the methodology laid out by Larsson et al.[7]

"Running" is the condition when the boat is travelling in approximately the same direction as the wind. Heeling moment is minimal in this case.

"Beating" occurs when the boat is travelling at 45° away from directly into the wind. The heeling moment is very high as most of the thrust generated on the sail is in the transverse direction.

"Reaching" is when the boat is travelling in any direction between "beating" and "running". Heeling moment varies depending on direction but can be very high. Top boat speeds are achieved within this regime of sailing.

It was noted that there was little change in the height of the CE between the different points of sail. It was therefore decided that the model would be towed from the correct height so as to provide the correct effect on trim of the elevated thrust force and the leeway and heel angles were set independently, so that their effect could be determined individually. This provided a simple setup that would require a minimum number of tests without requiring adjustment of the rudder angle for each speed.
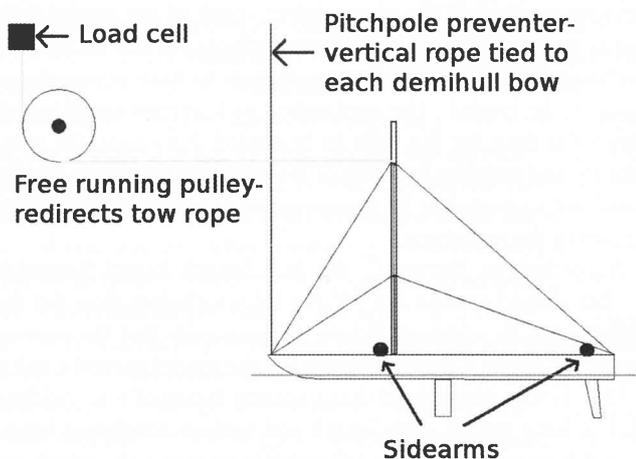

Figure 4: Side view of experimental setup

The leeway angle was set using sidearms with turnbuckles allowing for angle adjustment. These sidearms were counterbalanced and mounted with ball joints so that the displacement of the hull was not affected. The heel was set by fixing the mast angle. Figure 4 shows the side view of the experimental setup and figure 5 is a photo showing the sidearms from the front.

This resulted in an inaccuracy as the rudder angle is not set correctly. Since the induced drag on the rudders was calculated to be small for reasonable rudder angles and only a small per-
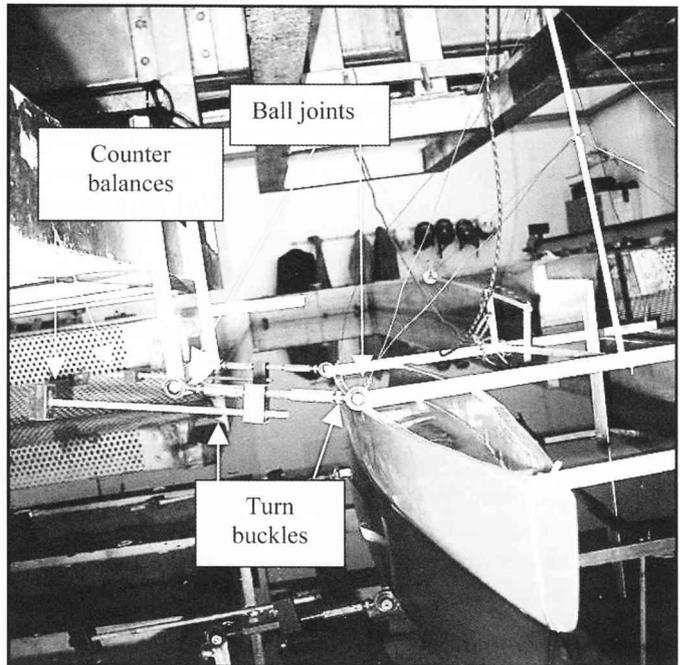

Figure 5: Photo showing sidearms from front

centage of the flow over the hull would be affect by the rudder, the effect on resistance was considered negligible.
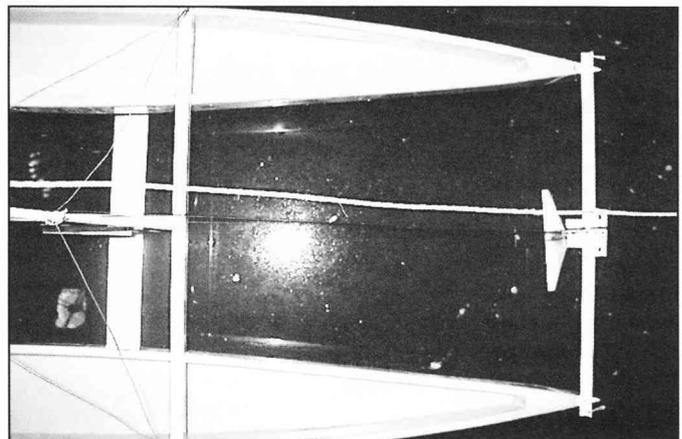
3. Experimental Results

Figure 6: Canard configuration

Firstly, a suitable LCG was established. After that the model was tested without leeway and heel angle, both with and without the lifting foils. A lifting foil configuration which provided reasonable stability was established (see figure 6) and the resistance curve of this was compared with that of without lifting foils. As shown in figure 7, a reduction in total hydrodynamic resistance is only achieved above a displacement Froude number of 2. This is in agreement with several other similar studies of hydrofoil assisted catamarans with semi-displacement demihulls.[8,9,10,11]

Normally the model ran at positive trim angles (bow up) but it was noted that if a forward pitching moment was applied (the trolley accelerated) the model would reach a new equilibrium with a low trim angle (bow down). This not only yielded an undesirable increase in resistance but would also not be stable in terms of yaw stability) due to the forward movement of the CLR) and in waves would be susceptible to pitchpole. Figure 8 shows the two running conditions.

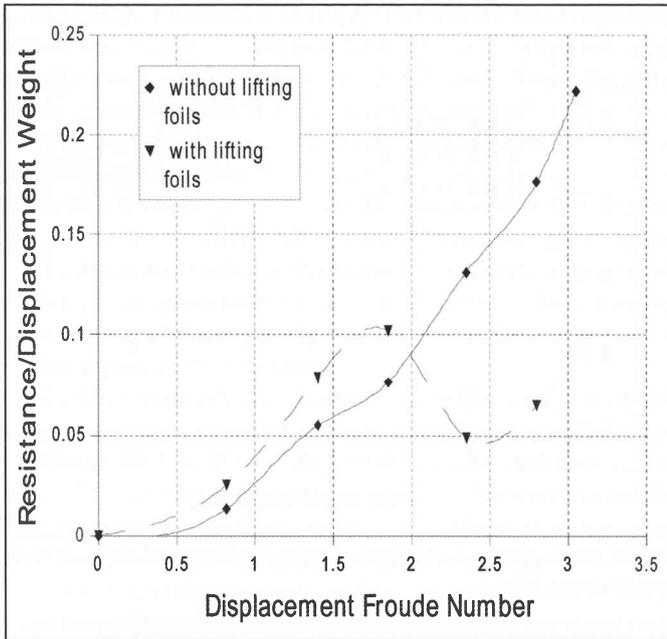The experimental results of RH1 were validated by comparing

Figure 7: Comparing total hydrodynamic resistance of with lifting foils to without.
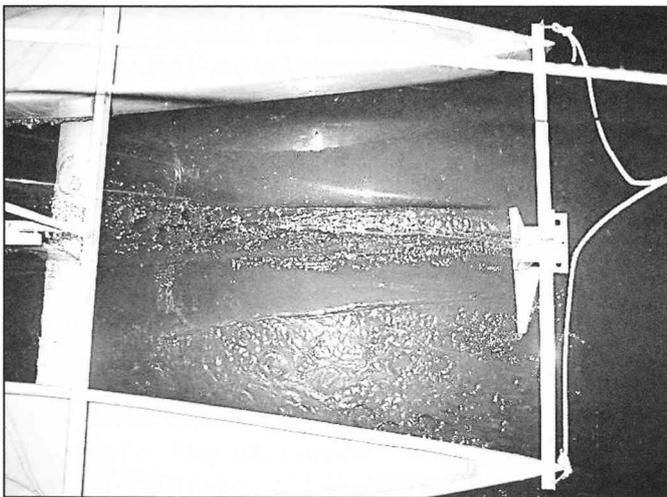

Figure 8a: Picture of bow-up running condition

its resistance curve to that of a similar hull, the "C4" described by Insel et al[12]. The results are shown in figure 9 and table 3

As the C4 model is more heavily loaded, as can be seen from the $L/\nabla^{1/3}$ given in table 3, we expect a higher gradient
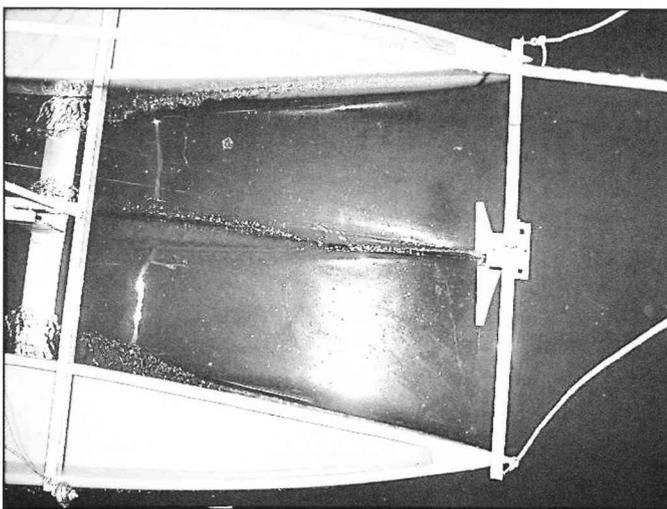

Figure 8b: Picture of bow-down running condition

Model	C4 (NPL series)[12]	RH1
L	1.6	1.3
L/B	9	8.24
B/T	2	3.7
$L/\nabla^{1/3}$	7.417	10.3
C_B	0.397	0.39
C_P	0.693	0.559
C_M	0.565	0.718
A(m²)	0.338	0.24 (Hydrostatics results)
LCB (%L aft amidships)	-6.4	-6
S/L	0.4 (chosen to match)	0.3875
S/B (resulting)	3.6	3.19

Table 3: Comparing parameters of C4[12] to RH1

on the curve for RH1, since hulls are less efficient when lightly loaded as they have high surface area to displacement ratio therefore relatively high viscous drag. The results correspond to the expectation of the author where similar characteristics are displayed.
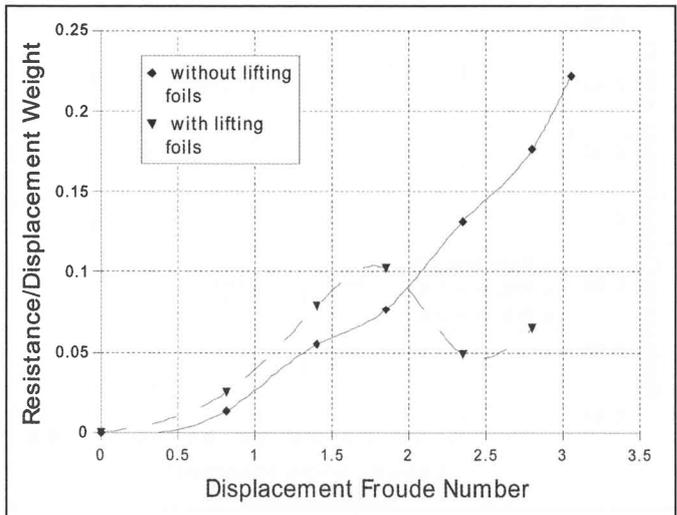

Figure 9: Comparing resistance curves of RH1 to that of the "C4" hull[12]

The leeway and heel angles were then varied to determine their effects. During experimentation it was found that the wave interaction between the demihulls was significantly altered by changes in leeway or heel angle. Since this wave interaction is heavily dependent on hull shape and speed, no universal trends could be formulated with regard to the effects of heel and leeway on the resistance of a sailing catamaran. The effects on RH1 are given below.

3.1 Effect of leeway

Figure 10 shows the effects of leeway on the resistance of RH1 without lifting foils. The change in wave interference resulted in a slight increase in resistance with leeway angle for low and moderate speeds. For high speed ($Fr_\nabla \approx 2.8$) a reduction in resistance is observed at moderate leeway angles.

From figure 11 it was determined that for RH1, with the addition of this lifting foil configuration, the effect of leeway on resistance is small for low speed, a slight decrease at moderate speed and at high speed, the resistance is less at leeway angles of 1.5° and 4.5°, but is increased at 3°.
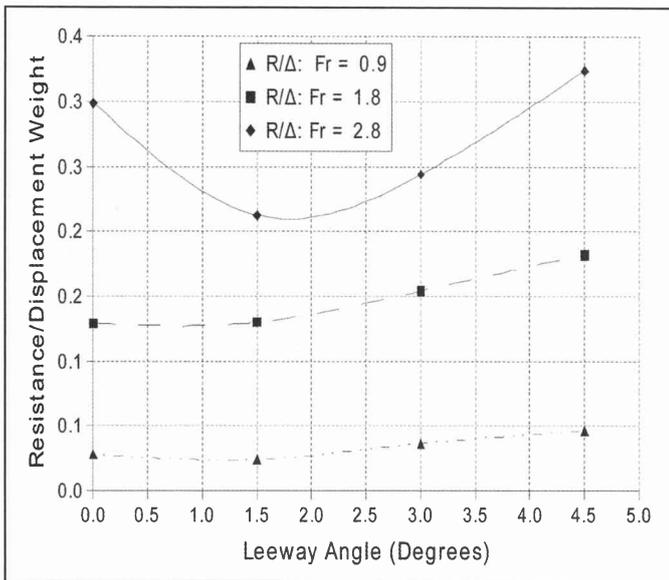
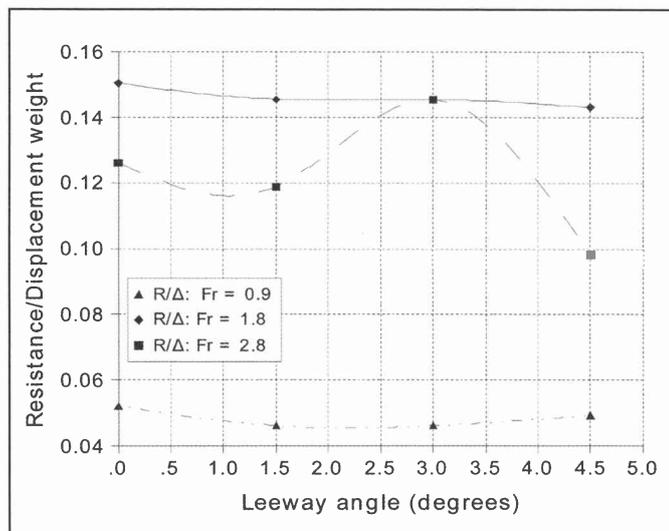Figure 10: Experimental resistance plotted against leeway angle of RH1 without lifting foils

Figure 11: Experimental resistance plotted against leeway angle of RH1 with lifting foils

3.2 Effect of heel

The WSA of a catamaran is reduced with an increasing heel angle until the windward hull emerges fully from the water. This is expected to reduce the viscous drag. From figure 12 it can be seen that the effects on wave interference seem to cancel the reduction in viscous resistance at low and moderate speed but at high speed, the reduction in viscous resistance dominates.

The addition of the hydrofoils resulted in a slightly more complicated relationship as there is a loss in lift due to heel angle (therefore increasing WSA). For example in conditions of almost complete hydrofoil support, the heel angle would lower the leeward hull, thus increasing the WSA (reversing the effect of heel demonstrated without hydrofoils at high speed). The heel angle also brings the main foil to the surface on the windward side, reducing lift and encouraging ventilation, thus reducing performance. The use of a slight dihedral angle on the main foil would provide a better righting moment and foil support at heel angles and the central strut prevents spread of ventilation to the leeward side. However, this was left for a more complete design in future research.

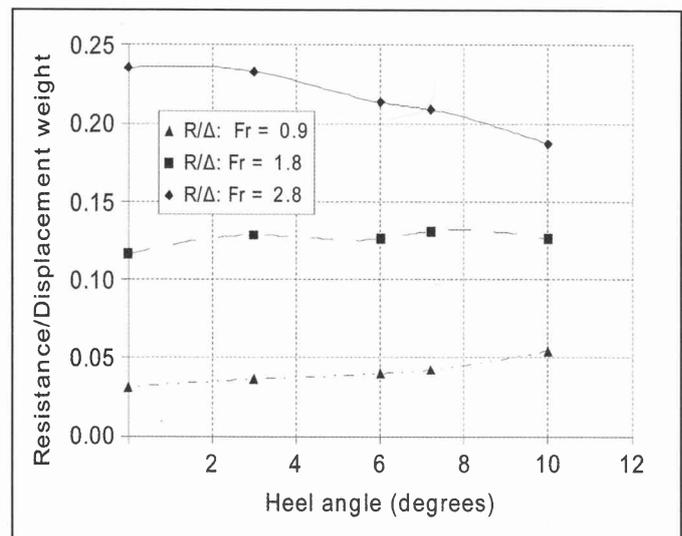At low speed, there is little lift generated on the lifting foils so

Figure 12: Experimental resistance plotted against heel angle of RH1 without lifting foils

the change in resistance is not expected to be very different from without lifting foils. A slight change in resistance is shown in figure 12 due to the change in foil efficiency, wave interference and WSA. At moderate speed more lift is generated and both demihulls are partially supported. The change in WSA is much like without lifting foils as the main foil is still fully submerged. At high speed, the hull is well supported and heel angle results in an increase in WSA and the main foil piercing the surface. Here the resistance is expected to increase with heel angle due to extensive loss in lift on the main foil due to heel. Figure 13 is in agreement with expected trends.
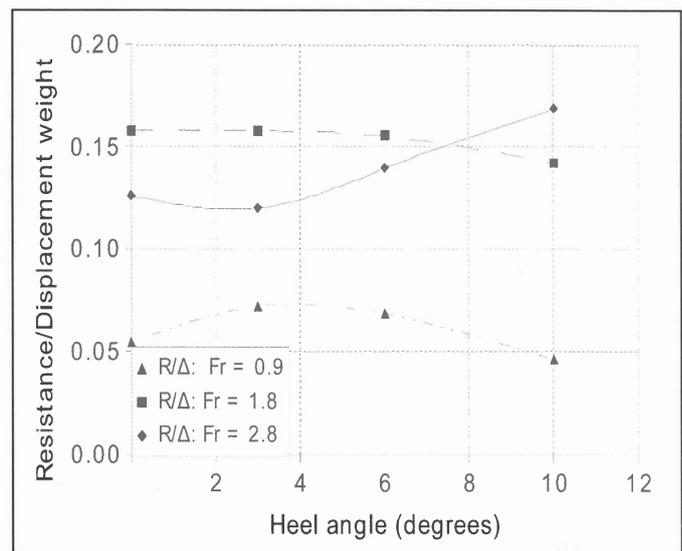

Figure 13: Experimental resistance plotted against heel angle of RH1 with lifting foils

Large heel angles are associated with large transverse aerodynamic forces, which in turn result in large leeway angles. In order to maintain a straight motion with large heel angles, a large rudder angle is usually required which will add additional induce drag. Since this is not modelled, it is expected that the total resistance in reality would be much higher for both large heel and leeway angles.

4. Computational Analysis

In order to verify the experimental results, a computational analysis was conducted. The interference between hull and foils

was considered negligible as the majority of the lifting foils were placed sufficiently far from the hull (mostly within the tunnel). This allowed the hull and foils to be analysed separately. Since the demihulls are slender, thin ship theory was considered suitable and a program utilising this (MICHLET[13]) was used. The foils were analysed using AUTOWING[14], a program designed specifically for the analysis of hydrofoils. The spray drag on the surface piercing struts was not calculated by AUTOWING and was thus calculated empirically[15].
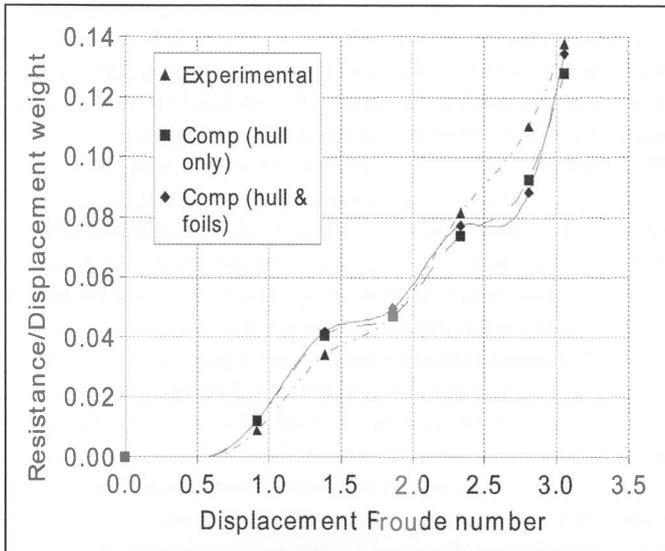

Figure 14: Comparing computational and experimental results for RH1 without lifting foils

Figures 14 and 15 shown the comparison between computational and experimentally determined results for the resistance curve without and with lifting foils attached, respectively. From figure 13 it can be seen that the computational results for the case of without lifting foils agrees very well with the experimental results.
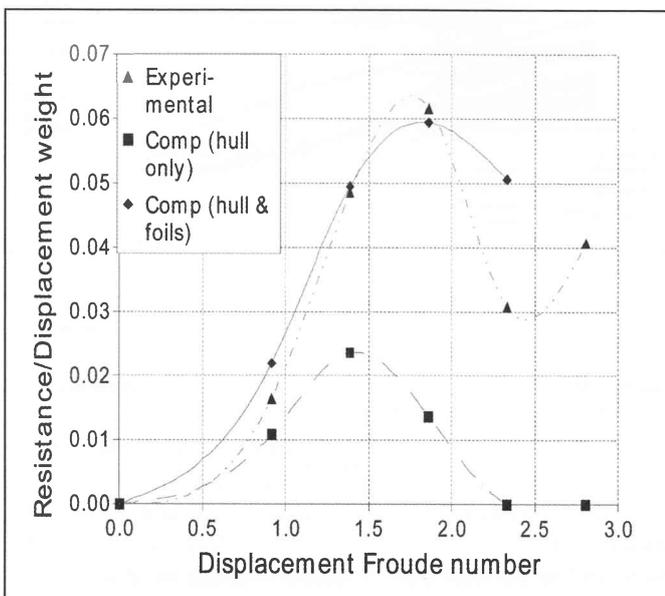

Figure 15: Comparing computational and experimental results for RH1 with lifting foils. Hull resistance is also plotted to show its relative contribution.

From figure 15 it can be seen that the computational and experimental results for the case of with lifting foils agrees mod-

erately except at high speed. The stability of the AUTOWING calculation was found to break down at higher speed where the foils came near to the surface, yielding unrealistic wave patterns. Since the interference between lifting foils and hull was ignored and AUTOWING could not provide accurate high speed results, this agreement was considered sufficient.

5. Conclusions and Recommendations

It was shown that a reduction in total hydrodynamic resistance due to the addition of the hydrofoil system chosen can only be expected above a displacement Froude number of 2. However, this prediction may be somewhat conservative due to scaling effects resulting from the lack of Reynolds number similarity, particularly for the foils.

For this configuration, a maximum increase in resistance was achieved at $Fr_\nabla \approx 1.9$ of 44% and a maximum reduction in resistance was achieved at $Fr_\nabla \approx 2.3$ of 63%. The hump resistance (maximum increase) could be reduced by varying the main foil AOA but high main foil AOA yielded instabilities at higher speeds.

Although the canard configuration remained stable throughout the speed range, it was found during experimentation that the pitch stability was not robust and sudden accelerations (or perturbations in trim) would result in the boat moving to the bow down running condition. Practically this meant that a trim control system would be required to provide adequate performance and stability. It is therefore recommended that the HYSUCAT type configuration is investigated but the main foil is moved forward resulting in a more even load distribution between the foils, thus increasing pitch stability. Since a stable configuration was not achieved without upsetting the position of the CLR by the addition of lifting foil supporting struts, the main foil may be made independent of the dagger-boards and supported by two struts mounted on either side of the tunnel.

Since a reduction in resistance with the addition of lifting foils is only expected above a displacement Froude number of 2, a retractable foil system is recommended, to be engaged only in suitable conditions.

6. Acknowledgements

References

1. *Gilruth R*, Hydrofoil Craft, 1955, Patent number 2,706,063, United States Patent Office.
2. *Molloy C*, Greed for Speed, 2002, *Yachting World Magazine*.
3. *Thebault A*, Channel Crossing Record, *Broken in* 1995, 1995. Published on the internet: http://www.hydroptere.com/index.php4?lang=EN
4. *Bertram V*, Practical Ship Hydrodynamics, 2000, Butterworth Heinnemann.
5. *Kirkman KL and Kloetzli JW*, Scaling Problem of Model Appendages, 1980, ATTC, University of Michigan, Ann Arbor.
6. *White FM*, Viscous Fluid Flow, International Edition, 1991, McGraw-Hill.

7. *Larsson L and Eliasson RE*, Principles of Yacht Design, 2nd Edition, 2002, Adlard Coles Nautical, A & C Black Publishers Ltd.

8. *Höppe KG*, The Hydrofoil Supported Catamaran, Progress Research Report 1980-2, University of Stellenbosch, Mechanical Engineering Dept., University of Stellenbosch, South Africa.

9. *Höppe KG*, Performance evaluation of high speed surface craft with reference to the HYSUCAT development (part 2). *Fast Ferry International*, 1991, 30(3), 33 – 38.

10. *Miyata H*, Development of a new type hydrofoil catamaran, *Journal of ship research*, 1989, 33(2), 135 – 144.

11. *Migeotte G*, Design and Optimisation of Hydrofoil-Assisted Catamarans, PhD Thesis, Department of Mechanical Engineering, University of Stellenbosch, Nov. 2001

12. *Insel M and Molland AF*, An investigation into the resistance components of high speed displacement catamarans. *Trans. Royal Institute of Naval Architects*. 1992, 134(A), 1-20.

13. *Lazouskas L*, MICHLET 8.07, Available on the internet at: http://www.cyberiad.net/michlet.htm 2005.

14. *Kornev NV and Taranov AE*, AUTOWING 3.0. http://www.se-technology.com/2004.

15. *Loveday HN*, The Design of a Hydrofoil System for Sailing Catamarans, Masters thesis, Department of Mechanical Engineering, the University of Stellenbosch, South Africa. 2006.