Comparative Evaluation of a Hydrofoil-Assisted Trimaran

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Model tests and numerical simulations investigate the application of a hydrofoil supported water craft (Hysuwac) hydrofoil system for trimarans, drawing on experience for foil-assisted catamarans. While foils are demonstrated to effectively decrease the resistance of trimarans, a comparison shows that a catamaran with similar displacement and same speed is still superior to the trimaran, with or without foils.

1. Introduction

Trimaran concepts have recently claimed significant advantages above mono-hulls and catamarans[1-3]. These advantages apply to ship types that require a relative high performance, seaworthiness, maneuverability, larger deck area, stability, while having a low speed loss in waves and minimizing the resistance at high speeds[4]. These advantages are especially beneficial for ferries and some combatants. Hydrofoil assistance, especially for catamarans, can significantly decrease resistance and increase passenger comfort in waves. Ride control systems improve the ride comfort further with a slight reduction in resistance as secondary effect. While there is much experience in the performance characteristics of foil-supported catamarans, there is very little available information or research activity on foil-assisted trimarans. This paper therefore focuses on some of the performance characteristics of these vessels.

A number of recent examples indicated renewed interest in this type of vessel. A 127 m trimaran Benchijigua Express was launched in 2005 built by West Australia Shipyard, Austal. The Benchijigua Express is the world's largest all-aluminum ship. It operates with a ride control system that ensures improved passenger comfort. The 55 m Dolphin Ulsan designed and built by North West Bay Ships (NWBS) also incorporates lifting foil technology with a ride control system to improve comfort, seakeeping and efficiency, Figure 1. VT Maritime Dynamics (VTMDI) designed the ride control system for the Dolphin Ulsan and the foil system produces a lift that is approximately 30% of the full-load displacement increasing the vessel speed by 3 to 4 knots[5].

When designing a trimaran, a large number of different parameters need to be considered. For the main hull, the length and slenderness ratio are of primary concern. The main reason why a trimaran concept was developed was to achieve a relatively high slenderness ratio for the main hull that will decrease the wave resistance and effectively decrease the total resistance[2]. A very slender hull needs outriggers for stability. A longer and more slender vessel requires a lower installed power for constant displacement due to a higher length-displacement ratio and lower Froude number[6]. The displacement and position of the outriggers rather than the width of the main hull are responsible for the initial transverse stability of the vessel[7]. Doctors and Scrace[8],and Migali et al.[9] suggest that an outrigger should support 3% to 8% of the total displacement to ensure a low resistance. The percentage displacement of each outriggers can be as low as 1.25% of the total displacement of the entire vessel[3].

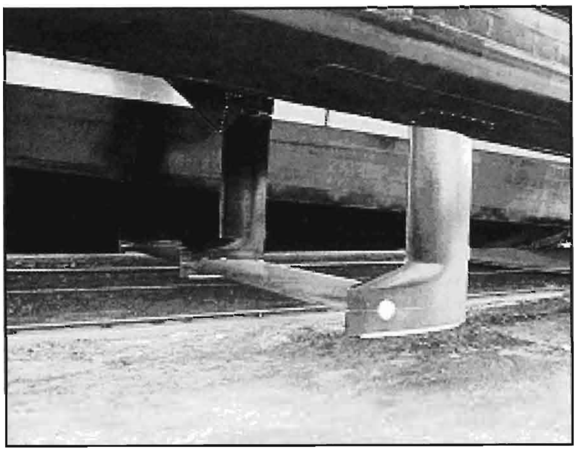

Figure 1: Ride control system of Dolphin Ulsan

Thus design aspects to be considered for the outrigger configuration include their slenderness ratio, position, shape, size and displacement ratio compared to the main hull. The type of vessel application, special requirements regarding foil location and slenderness ratio will influence the length of the outrigger. Doctors and Scrace[8] suggest the outrigger lengths should be 30% to 40% of the length of the main hull. Stagger and clearance are the terms used to describe the position of the outrigger in the longitudinal and transverse directions respectively. There are two favorable stagger locations for the outriggers[10]: one with the transoms of the outriggers aligned with the transom of the main hull and the other with the bow of the three hulls aligned. The shape of the hulls and the intended application of the vessel again influence the clearance location. The outrigger cannot have a hard chine. At relative high speeds a hard chine hull starts to plane. At this speed the outriggers, being fixed to the main hull, cannot lift out of the water and the resultant immersed hull form produces significant spray resistance[11].

The entire configuration is not only influenced by hydrody-

Figure 2: Hysucat ferry Nordblitz

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namic considerations, but also the type of application the vessel will be used for. Addition of foils at optimum locations, loading considerations, deck area requirements and safety consideration also influence the configuration.

Foils can significantly decrease the resistance of a catamaran. Migeotte and Hoppe[12] determined that certain semi-displacement hulls and hydrofoil systems should compliment each other to achieve an optimum performance. In 1979, Hoppe[13] developed the Hysucat (hydrofoil supported catamaran) at the University of Stellenbosch, e.g. http://www.hydrofoildesign.com/. Since 1982, over 350 Hysucats have been built ranging between 5.5 m and 36 m. Figure 2 shows the 22 m high-speed Hysucat ferry Nordblitz developed in collaboration with the German Hense shipyard. The ferry has a top speed of 34 knots and a total weight of 57 tons. The foil-system on semi-displacement and planing catamarans consists of a large main-foil just ahead of the longitudinal center of gravity (LCG) and two stern trim foils operating in close proximity of the free surface. The main foil is designed to carry between 40% and 75% of the weight, depending on the size and displacement of the vessel[14]. The hulls of the Hysucat generally are fully asymmetric with plane internal sides. This allows for more even flow over the foils[14]. Another foil system was developed by Hoppe[15] at the University of Stellenbosch for hydrofoil supported water craft (Hysuwac). Semi-displacement catamarans were designed to minimize hull-foil and fore-aft interference effects with foils carrying high load fractions at non-planing speeds. The efficiency of this design was proved by several model tests and further through industrial applications[14]. The foil-system employs one or two bow foils mounted underneath the keel and a stern foil mounted in the tunnel. If two bow foils are used then the foils are arranged with one underneath each hull. The system is especially advantageous in reducing the hump resistance and achieving an efficient high-speed resistance. This basic Hysuwac configuration has therefore been adopted for the trimaran investigation reported in this paper.

2. Basic Theory

The resistance components of a trimaran are similar to that of a mono-hull with a very slender hull but with additional components for the viscous and wave-making interference resistance of main hull and outriggers. The viscous interference resistance is due to two factors: the change in pressure around a hull affects the form factor (1+k) used to calculate the viscous resistance and the velocity increases in the tunnel between the hulls disturbing the potential flow field of both hulls resulting in an additional resistance. The wave interaction of main hull and outriggers can increase or decrease the total wave resistance, depending on dimensions and mutual positions. If the outriggers are positioned far apart the wave interaction is negligible[16]. The increased slenderness of the main hull of a trimaran decreases the wave-making at the bow and thus the total resistance. The total resistance of a trimaran can be determined using the method of Dubrovsky[7]. The method employs an interaction coefficient due to the dimensions and mutual positions of the outriggers and main hull. The interaction coefficient at certain Froude numbers can be less than 1 indicating a reduction in total resistance[17].

Hydrofoils function in a similar way as airfoils, except for two particularities[7]: the free, wave-forming surface and the possibility of cavitation. Foil thickness, chord length, aspect ratio, chamber line, and angle-of-attack influence the lift-to-drag ratio of a hydrofoil. At low Froude numbers the addition of the foils generally increases the resistance of the vessel. Only at higher Froude numbers will the addition of foils decrease the high-speed resistance. The foil efficiency changes as the foil approaches the free surface. Lift decreases, drag increases. For the Hysucat system, the stern foils will naturally stabilize the vessel due to this effect the foils operate in. The lift and drag of the foils can be determined using numerical or theoretical methods. The most common instability that occurs in the planing phase is when the front foil breaks through the free surface and re-submerges due to no lift being created above the free surface. The cycle is repeated and results in a pitch-heave instability[14].

Foils on a trimaran create additional resistance components. Not only will the hulls and foils create drag due to their shapes and profiles respectively, but there will also be an interference drag between the hulls and the foils. The struts too cause additional drag. The beneficial lifting force generated by the foils creates induced drag. The resistance of the vessel will, however, be decreased lifting the hulls partially out of the water, thus decreasing the wetted surface area, the waterline area and entrance angle, and the viscous interference between the outriggers and the main hull. Foils are only successful if the lift-to-drag ratio of the foil-system is larger than the lift-to-drag ratio of the vessel itself [5]. Migeotte and Hoppe[12] decomposed the resistance for foil-assisted catamarans into frictional and residual resistance. The same resistance components are assumed to be feasible for hydrofoil-assisted trimarans, but the interference and viscous resistance components will differ in magnitude and characteristics.

	Trimaran	Center-Hull	Outrigger			Trimaran	Center-Hull	Outrigger	
Displacement	161000	151342	4830	kg	Max cross sect area	5.91	5.31	0.30	m²
Volume	157.1	147.7	4.7	m³	Waterplane area	139.73	97.09	21.33	m²
Draft to Baseline	2.09	2.09	2.09	m	C_p	0.71	0.75	0.71	
Immersed depth	2.09	2.09	0.4	m	C_b	0.36	0.60	0.41	
L_{wl}	37.29	37.29	22.36	m	C_m	2.59	0.80	0.59	
Beam waterline	11.03	3.17	1.27	m	Clearance			4.88	m
Wetted Surface Area	248.86	193.48	27.69	m²					

Table 1: Principal vessel characteristics

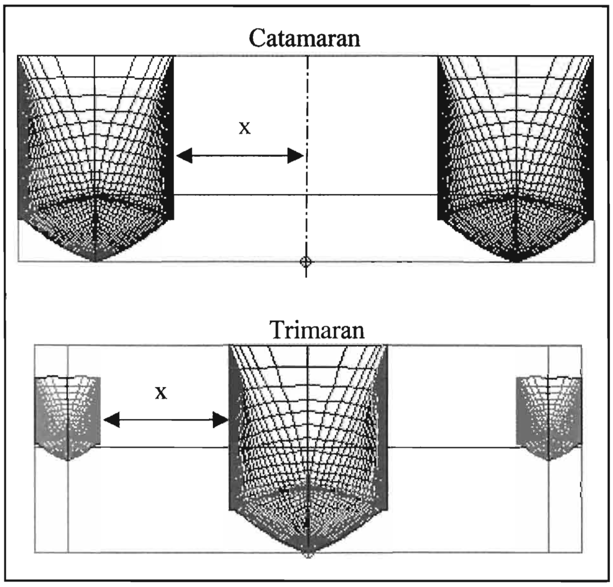

Figure 3: Distance separating hulls

3. Trimaran and foil design

The configuration is considered to be the most important factor in the design. A similar hull that was used for a Hysuwac catamaran[14], was used for the main hull to provide direct comparison with the recently tested catamaran with similar displacement, see Table 1. The outriggers used a scaled down version of the same hull, but the length increased to be 60% of the main hulls length due to the foil-system requirements. To obtain a good direct comparison with the Hysuwac catamaran, the spacing x between the hulls of the trimaran (Figure 3) was taken as the distance from the inner side of the hull to the centerline of the vessel along the waterline of the catamaran. The reason for this is to have a similar aspect ratio for both hydrofoil systems taking into account the interference created underneath and near a hull.

Figure 4 shows the configuration of the foil system. The hydrofoil design is complex due to conflicting design requirements in each of the different operating phases (displacement, transition, planing). A hydrofoil design cannot be contemplated in isolation. The addition of a foil-system can significantly reduce the performance of a vessel due to the interactions between the hulls and foils, but also the interference between front and rear foils. Hydrofoil sections may consist of a circular arc for the upper surface with a flat lower surface or circular arcs for both surfaces. Concave lower surfaces give higher efficiency in close surface proximities[15]. Generally the foil section must be as thin as possible to avoid cavitation. Long slender vessels that are heavily loaded will benefit from a Hysuwac configuration due to the large portion of the load that is carried by both foils and the large potential spacing between the foils. A sufficient tandem configuration not only reduces the interference effect between the foils, but also enhances the pitch stability of the vessel due to the large lifting forces created near the bow and the stern.

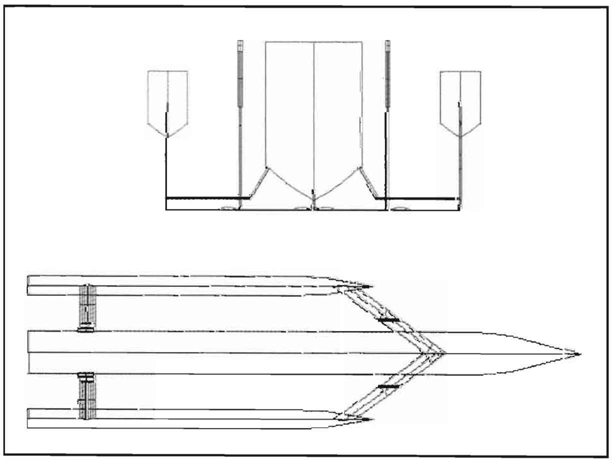

Figure 4: Hysuwac foil-system for trimaran

4. Experimental and numerical procedures

Accurate ship resistance predictions are still difficult[18]. Model tests are so far the best option, providing resistance, guidance for foil position, foil angle-of-attack and establishing the stability limits of a vessel. Model tests also have their limitations, namely scaling, blockage and shallow water effects. A problem arises when conducting towing tank testing due to the lack of turbulent flow over the foils. This highlights the importance of accurately calculating and scaling foil friction. Different laminar-turbulent transition due to different Reynolds number in model and full scale, surface tension (spray) and cavitation pose fundamental scaling problems. Still, the total resistance, trim, sinkage and the overall behavior of the model usually can be determined with sufficient practical accuracy through model tests. The model basin of the University of Stellenbosch has the following dimensions: Length 90 m, breadth 4.5 m and depth 2.7 m. Maximum trolley speeds used were approximately 6 m/s. Higher speeds are possible but are associated with larger stopping distances and hence reduced effective test lengths.

The testing procedure without the addition of foils included three different longitudinal center of gravity (LGC) positions with three different outrigger clearance positions[17]. Intervals of 1 m/s were tested over the speed range of 1 m/s to 6 m/s. The main aim of the project was to determine if the addition of foils are advantageous to the trimaran, therefore no further detail and results will be discussed regarding the trimaran without foils and different outrigger positions. A single, constant outrigger position was therefore used in the common test procedure for both models, i.e. for the case with the addition of foils and for the case of the model without foils. The angles-of-attack of the foils were optimised to ensure that the vessel behaved reasonably stable. Only for the case of the 34% LCG position a pitch-heave instability occurred.

The scaling procedures for the trimaran with and without foils differ. Ship resistance without foils can be tested and measured according to Froude's law. Froude's law states that the ship (without foils) resistance can be divided into frictional and residual resistance components, with the residual resistance following his 'law of comparison' (Froude similarity)[18]. The residual resistance takes changes into account due to interference, transom resistance and other resistance components excluding the hull frictional resistance. Tests are performed keeping Froude similarity. The scale effect is compensated by empirical corrections like the ITTC'57 correlation line. The scaling for a hydrofoil-assisted trimaran uses Hoppe's scaling procedure[14]. The method used to obtain testing data is reasonably accurate. The error involved with the results determined regarding the measurement and scaling method can vary between 5% and 10%.

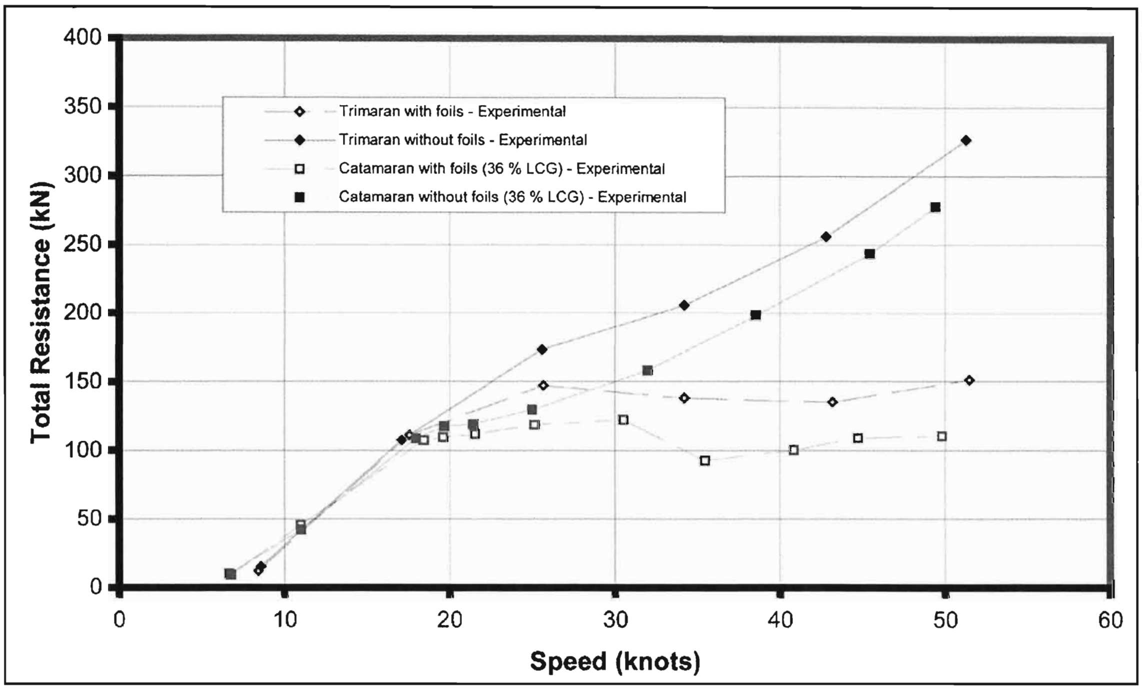

Figure 5: Total resistance vs speed for 32% LCG

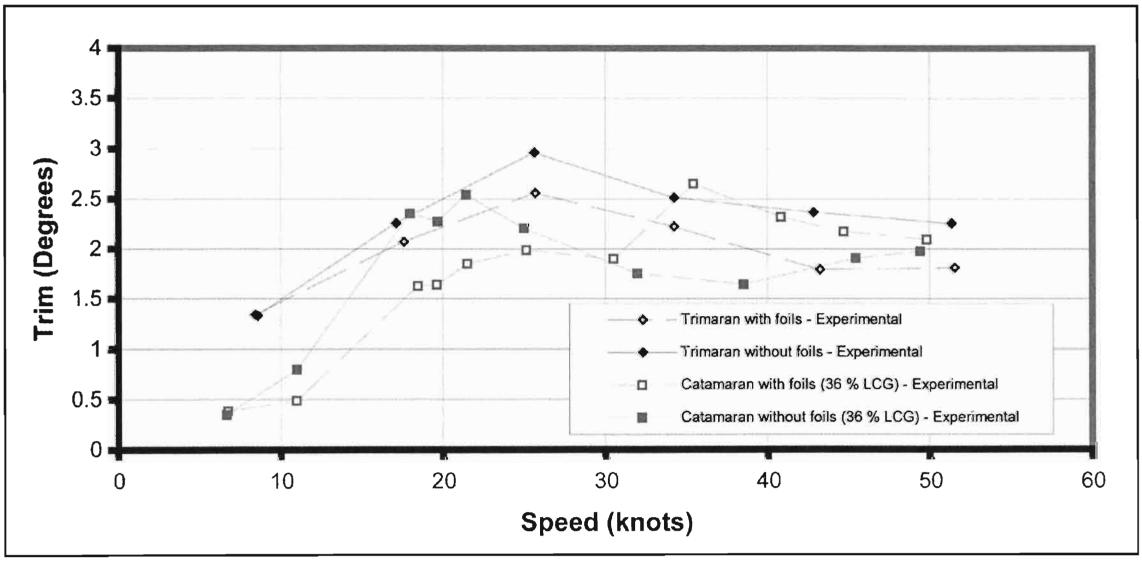

Figure 6: Trim vs speed for 32% LCG with foils compared to the catamaran

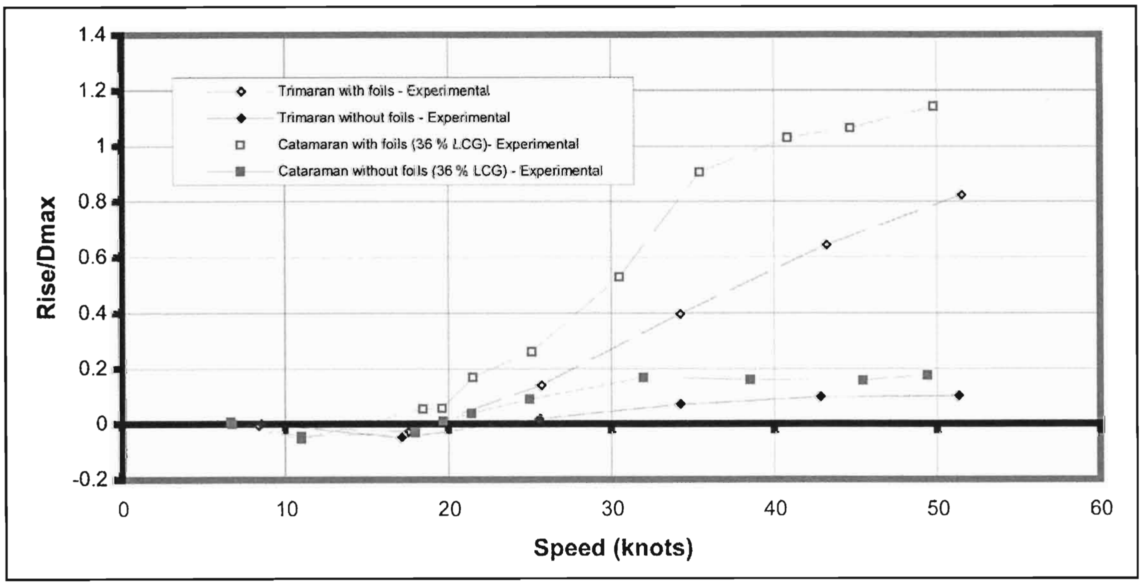

Figure 7: Rise-draft (maximum) ratio vs speed for 32% LCG with foils compared to the catamaran

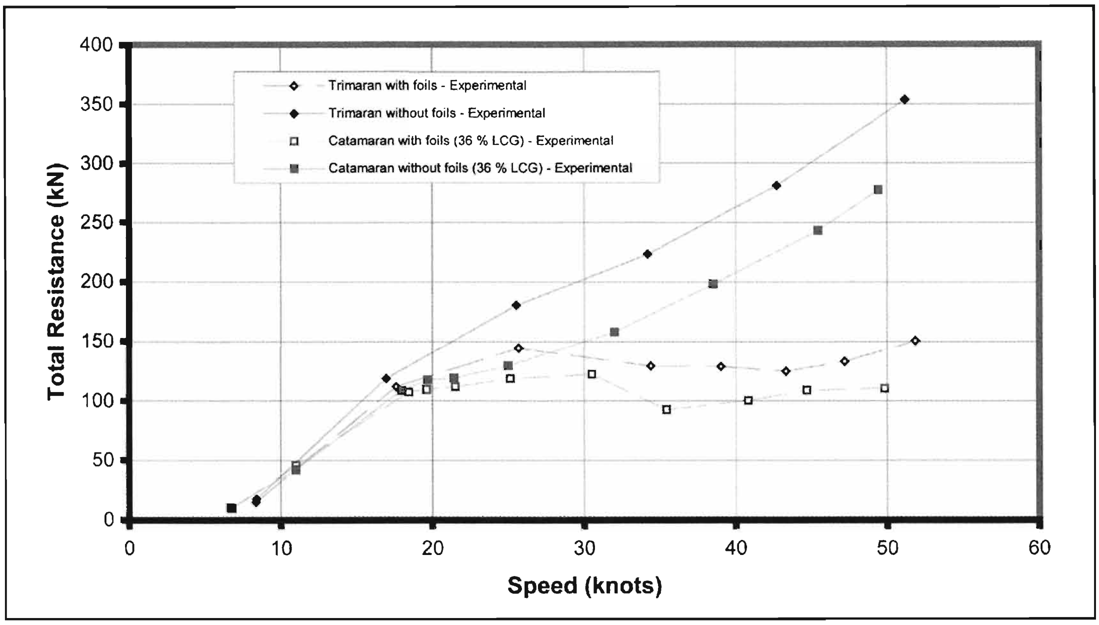

Figure 8: Total resistance vs speed for 30% LCG with foils compared to the catamaran

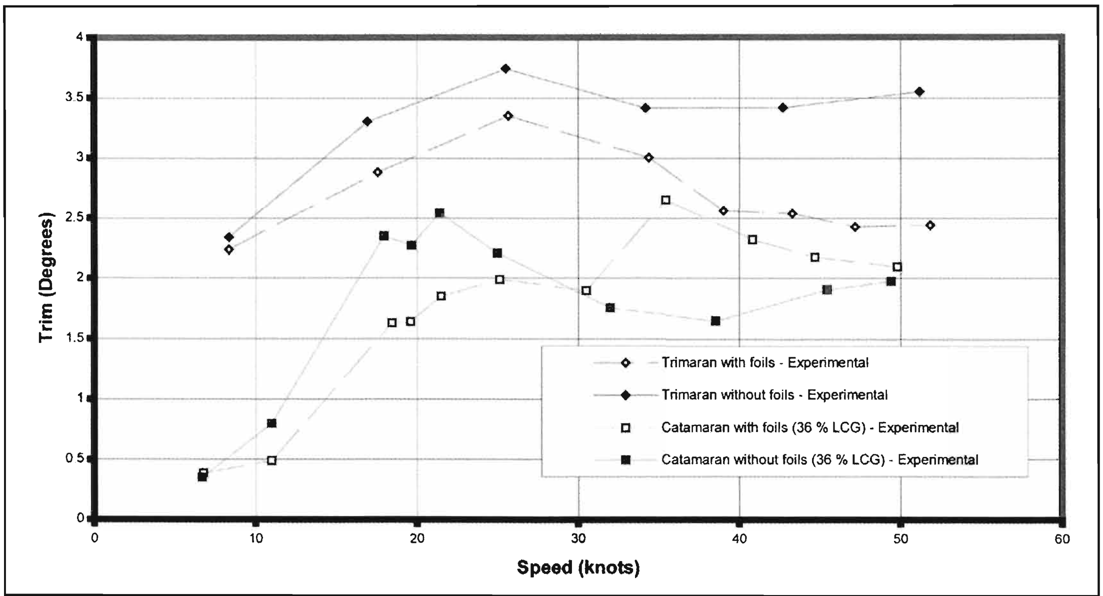

Figure 9: Trim vs speed for 30% LCG with foils compared to the catamaran

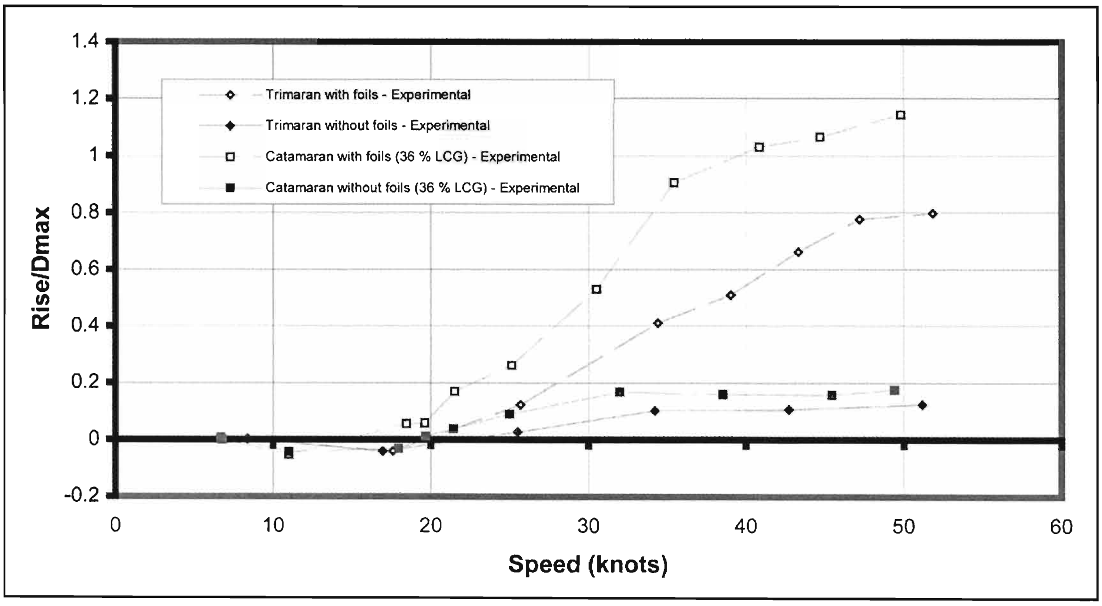

Figure 10: Rise-draft (maximum) ratio vs speed for 30% LCG with foils compared to the catamaran

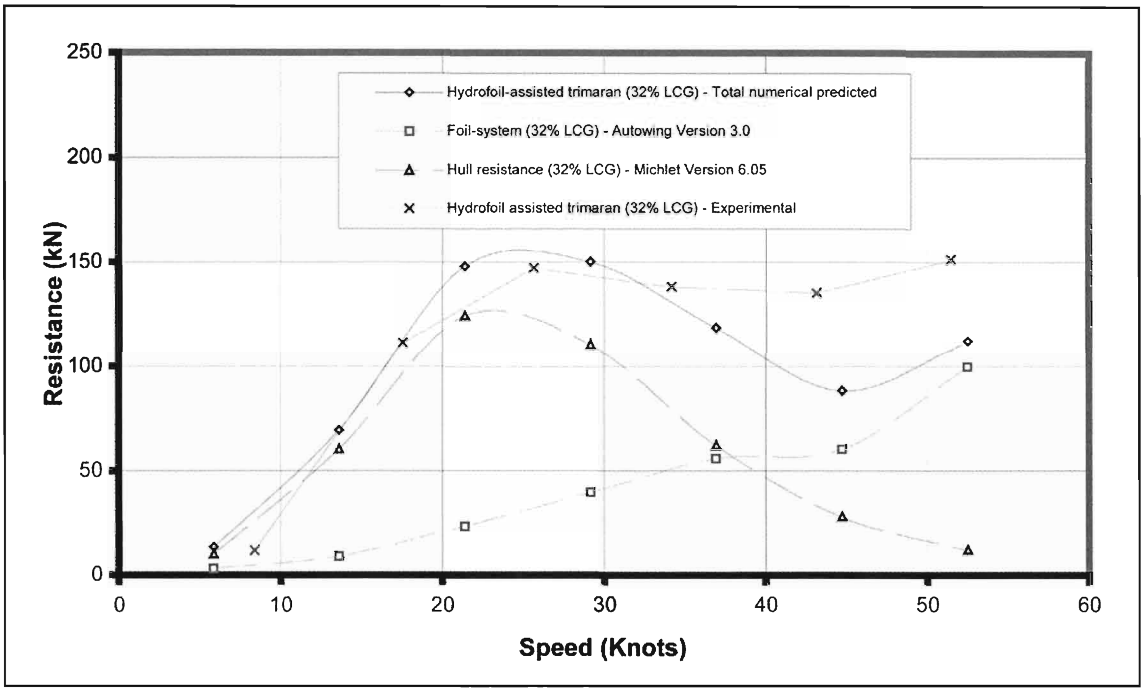

Figure 11: Resistance breakdown for 32% LCG position

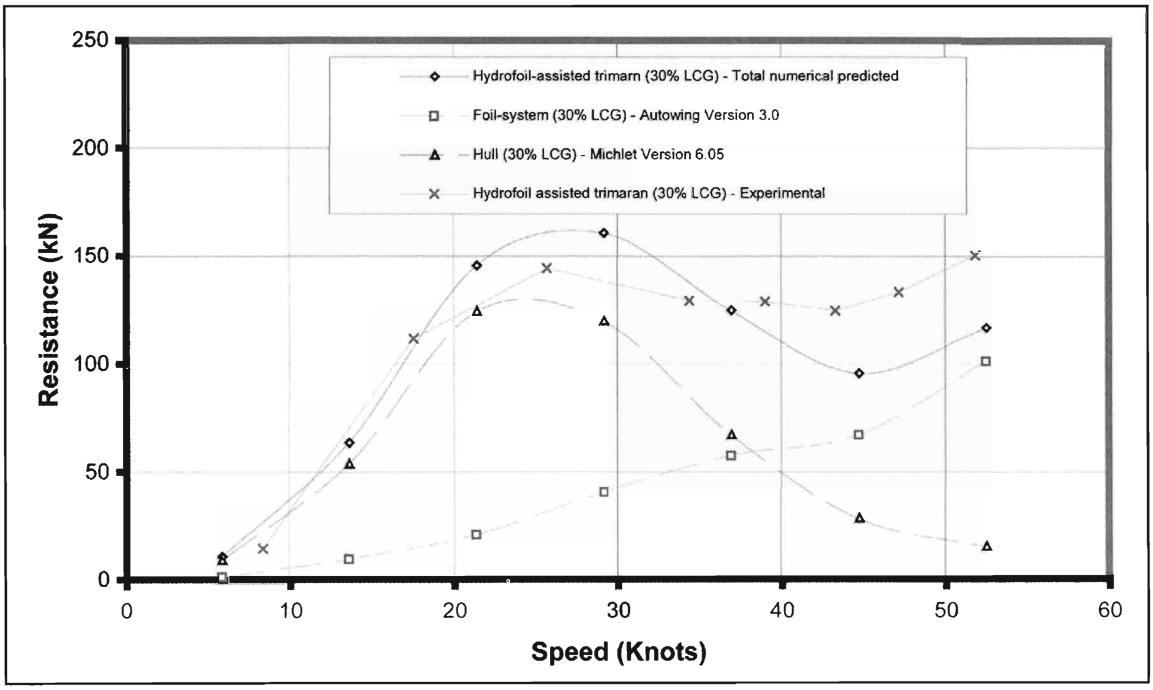

Figure 12: Resistance breakdown for 30% LCG position

Michlet Version 6.05 and Autowing Version 3.0 were used to determine the hydrodynamics of the vessel and hydrofoil system, respectively. The separate resistance data of both the vessel and the hydrofoil-system was added together to obtain a reasonable approximation for the total resistance of a hydrofoil-assisted craft. Interference effects between the hulls and the foils are not accounted for in the numerical prediction method. The trim and sinkage of the vessel and the hydrofoils were taken into account using model test data. A breakdown of the resistance of the vessel and the hydrofoil-system and the amount of lift the foils produce are given in the following section.

5. Results

The results, without foils, of the outrigger location show that the furthest outrigger clearance with the 34% LCG has the least amount of resistance, due to lower interference between the hulls associated with their higher rise.

The addition of foils reduces the resistance significantly of a trimaran and a catamaran as shown in Figure 5. The reduction in resistance for the trimaran and catamaran is approximately 55% and 60%, respectively, at design speed of 50 knots. The resistance of the catamaran is lower compared to the trimaran, both with and without foils; this is mainly due to the lower wetted surface area of the catamaran and a more efficient and well-developed hydrofoil-system on the catamaran. The catamaran, however, was tested having a LCG position of 36%[14]. Unfortunately, no data could be determined for the 34% LCG position of the trimaran with the addition of foils due to an instability that

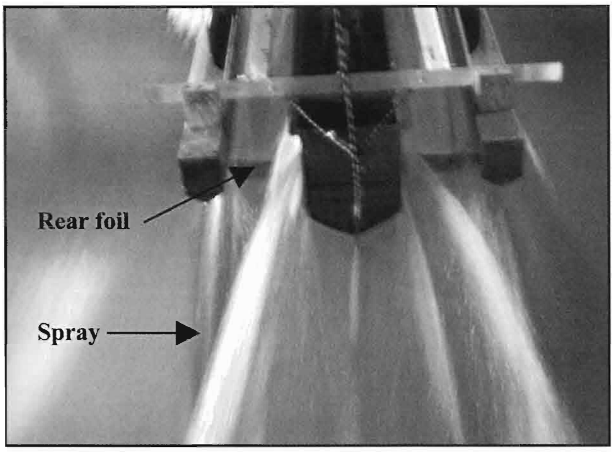

Figure 13: Significant spray caused by the rear foils at high speeds

occurred at high speeds[17]. The center of pressure of the foil system of the trimaran moved in close proximity of the LCG position at high speeds. The center of pressure should be ahead of the LCG for the vessel to operate safely.

Figure 6 illustrates the trim angle of the various configurations as a function of model speed. The local maxima (hump) in the curves reveal that the vessels achieve planing, i.e. the hulls generate enough lift to significantly lower the draft required to support the hull weight and hence a reduction of drag forces (trim angle) results. It can be noted in the figure, which is to be expected from the slender hull design allowed by the trimaran configuration, that the hydrofoil-assisted trimaran has a more gradual transition to planing compared to the hydrofoil-assisted catamaran. The latter displays a steep rise in trim angle between 30 knots and 35 knots, leading into a more abrupt transition to the planing phase.

The lift of the trimaran is less than that of the catamaran as seen in Figures 6 and 7, due to the lower trim values of the trimaran and due to the different LCG positions. The lower rise the trimaran experiences will effectively result in a larger wetted surface are and therefore a higher frictional resistance that would increase the total resistance significantly. The lift is measured at the LCG position.

The reduction in resistance of the trimaran is approximately 57% at the design speed of 50 knots, as shown in Figure 8. This is better than for 32% LCG. 30% LCG is therefore optimum for this type of foil configuration.

Adding foils results in a visible difference regarding the trim of the trimaran and catamaran, see Figure 9. The strong rear foil created a significant amount of lift, and this is responsible for the difference of the trimaran with and without foils at high speeds. The more pronounced hump (larger second derivative) transition to planing is again visible for the hydrofoil-assisted catamaran. The lift of the trimaran is less than for the catamaran, see Figure 10. This is due to the trim values of the trimaran as well as the different LCG positions. The lower rise of the trimaran results in a larger wetted surface area.

Figure 11 shows the breakdown of the resistance component of the trimaran and that of the foil system. The summation of both these resistance components gives the total numerical resistance prediction for the hydrofoil-assisted trimaran. Figures 11 and 12 also show the experimental values. The total numerically predicted values correspond reasonably well with the experimental values at the "hump" region in Figures 11 and 12. At high speeds, effects like spray and interference cannot be accounted for in the numerical prediction. According to the numerical prediction, at 40 knots approximately 60% of the resistance is due to the drag the foils create.

Figure13 shows the significant spray at the rear foils that is partially responsible for the resistance difference at high speeds. Another reason for the difference in resistance is due to the numerical method that cannot account for the deformation of the free surface that generally occurs at relatively high speeds. There is no simple theory to account for these complex additional components. A future refinement of this foil system should address this problem. Figure14 shows the load that the foil system and the hulls are carrying as the speed is increased. At 40 knots and 50 knots the foil system carries approximately 69% and 81% of the vessels displacement load, respectively.

6. Conclusion

The main focus of the research was to determine if the addition of foils could successfully decrease the resistance of a trimaran. This was accomplished successfully, but the hydrofoil system of the trimaran and the trimaran configuration must be further optimised to achieve better resistance results (e.g. by elimination of the spray shown in Figure 13).

The catamaran with a similar displacement still proves to be superior compared to the trimaran with and without foils according to the study conducted. This is stated keeping in mind that the draft of the trimaran main hull exceeds that of the two catamaran hulls significantly for near equal displacement.

The addition of foils can result in the outrigger length being as long as the main hulls length resulting in a larger deck area and improved dynamic stability in roll. The foils should be able to lift the vessel until the outriggers are only partially touching the water surface, therefore maintaining the dynamic stability compared to when the outriggers are lifted completely above the water surface.

The foil-assisted catamaran is more stable than the trimaran. This is due to the counter balancing moment the hulls of the catamaran configuration create. The

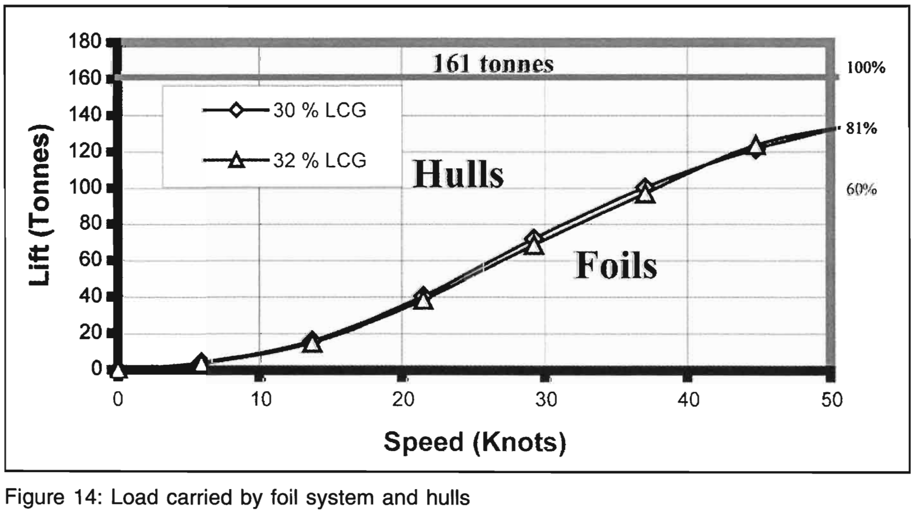

Figure 14: Load carried by foil system and hulls

trimaran cannot create this moment when the outriggers are lifted above the water surface in roll. Outriggers that run clear of the water surface at high-speeds results in the trimaran behaving like a hydrofoil-assisted mono-hull.

Ongoing work focuses on the optimization of the foil system of the trimaran to eliminate the occurring instability as mentioned in the previous section. Shifting the center of pressure of the hydrofoil system further forward by increasing the slenderness ratio of the main hull and outriggers could eliminate the instability. An appropriate foil design that minimizes spray will improve the efficiency of the foil-supported vessel. Acknowledgements This research was supported by the University of Stellenbosch and CAE-Marine within a 2004-2005 research project. Additional funding received from the National Research Foundation is also gratefully acknowledged.

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