Developments in Hydrofoil Assistance for Semi-Displacement Catamarans

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ABSTRACT

The current trend for faster, more efficient, high-speed multi-hulls has led to the development of hydrofoil assisted catamarans. A number of studies and designs concerned with the development of these vessels have been conducted worldwide and are reviewed. The main body of this paper discusses the recent developments at the University of Stellenbosch concerning the design and development of semi-displacement hulls and hydrofoil systems that compliment each other. The hydrodynamics of semi-displacement hulls and suitable foil assist systems for these hulls were investigated. Recent tests of a number of hull forms and foil systems provide design guidelines for semi-displacement type hydrofoil assisted catamarans. These tests show that semi-displacement catamarans can benefit from hydrofoil assistance in terms of both efficiency and speed over a wide range of Froude numbers and displacement.

INTRODUCTION

The use of the modern slender catamaran hull form, combined with lightweight materials allows high speeds to be reached without excessive power requirements, making semi displacement catamarans the leading type of commercial high-speed craft for passenger transport. Development of new vessels is increasingly being governed by a number of major factors including cost, capacity, speed, range, sea keeping, environmental issues, reliability and safety [1]. Hydrofoil assistance is currently being investigated to provide benefits in a number of those areas, particularly in increasing speed, reducing operating cost, improving sea-keeping, reducing wake and increasing range.

Further development is now taking place in a number of countries and regions including, Scandinavia, United States, Russia, Germany, Japan, Korea, South Africa and New Zealand. Figure 1 shows the number of hydrofoil assisted fast ferries ordered and delivered worldwide in recent years.

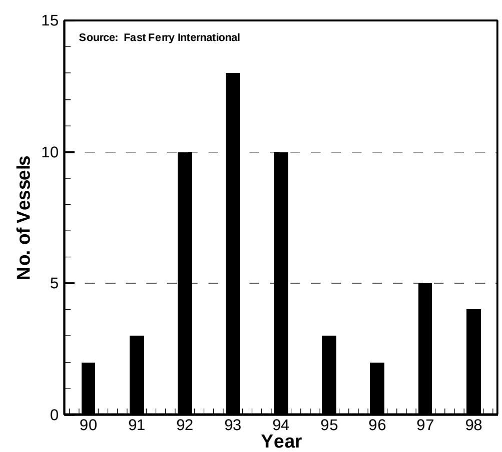

Figure 1: No. of Hydrofoil Assisted Catamaran Ferries Ordered and Delivered recently.

The figure does not include craft such as Navy patrol boats, yachts etc. for which, foils were designed in South

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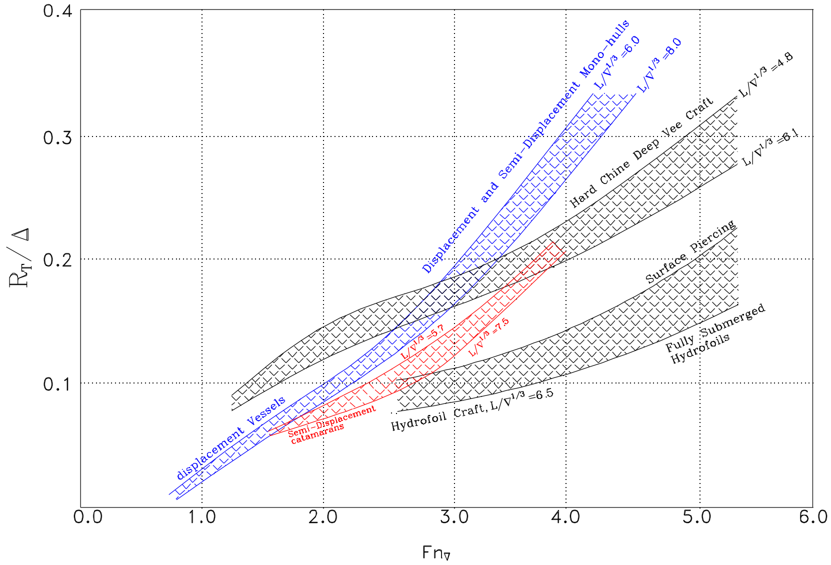

Figure 2: Resistance Coefficients for Sea Craft

Africa and a large number built.

New propulsion systems are allowing higher speeds to be reached with conventional catamarans. At these higher speeds dynamic lift can be utilized, so new designs are more and more incorporating changes to take advantage of dynamic lift provided by the hydrofoils, and to a lesser extent by the hull. It is the opinion of the authors that there will be an increased use of hydrofoil assistance for semi-displacement catamarans in the future. Until recently hydrofoil assistance has not been considered suitable for the low operational Froude numbers of such catamarans, compared with what is considered the efficient operating range of hydrofoils. Figure 2 shows the typical resistance tendencies for high-speed sea craft [2,3]. The tendencies are presented only as a function of Froude displacement number (Fn_∇) and length-displacement ratio ($L/\nabla^{1/3}$), since these are known to be the most important parameters affecting resistance [4]. Conventional semi-displacement catamarans operate in the speed range $1.5>Fn_\nabla>2.5$ and their length displacement ratio is usually in the range $5.7<L/\nabla^{1/3}<7.5$ increasing with the size of the vessel.

Conventional experience indicates that hydrofoil assistance only becomes suitable above $Fn_\nabla=2.5$ [3]. It is therefore logical to doubt the suitability of hydrofoil assistance for semi-displacement type catamarans. It is often the case that hydrofoils cause an increase in resistance [5,6,7,8] at the lower Froude numbers before providing significant improvement at high speeds. Figure 3 indicates the idea. For speeds up to about $Fn_\nabla=2.0\text{-}2.5$, there is an increase in resistance before a significant decrease in resistance for the high Froude numbers above $Fn_\nabla=2.5$.

This tendency seems to be quite general for most hydrofoil-assisted catamarans and only be avoided under certain conditions. This is of course not suitable for the operating range of semi-displacement catamarans. Improvements in the semi-displacement speed range are much more sensitive to parameters such as fraction of the load carried by the foils and the configuration of the foil system. These points require careful consideration when designing hydrofoils for this lower Froude number range. A review of the literature and some of the recently built vessels gives a good idea of what is possible concerning hydrofoil assistance for semi-displacement catamarans.

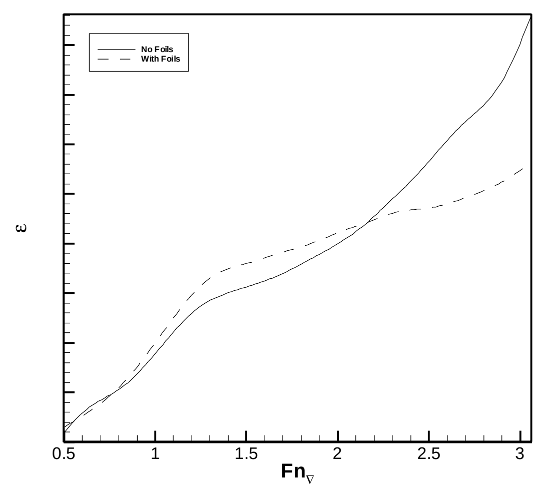

Figure 3: Resistance Comparison for a Semi-Displacement Catamaran

LITERATURE REVIEW

A variety of different ideas for hydrofoil assistance has been tried in the last two decades. Only those vessels and designs known to the authors that have relevance to modern designs for semi-displacement catamarans are reviewed. This literature review is by no means complete.

Nearly all of the earlier research on hydrofoil assistance focused on planing type catamarans operating in the higher Froude number range $Fn_\nabla>2.5$ where the two forms of hydrodynamic lift (planing and hydrofoil lift) can easily be combined. The knowledge gained from these planing hull developments is important because semi-displacement type hydrofoil-assisted catamarans can utilize some planing lift at the higher speeds as is explained later in this paper.

Planing Catamarans with Hydrofoil Assistance

The earliest (1974) useful reference known to the authors, by Yermotayev et al. [4], comes from the developments in Russia. The research done was on planing catamaran hull forms with and without hydrofoil assistance. What is significant, is that resistance improvements can be gained using hydrofoil assistance at $Fn_\nabla=1.2$ and greater. Figure 4 shows the resistance comparisons. This is already far below what is considered the efficient speed range for hydrofoils, unfortunately little information is given on the foil configuration, hulls and displacements used. A resistance improvement of 25% is possible at $Fn_\nabla=1.5$ and of about 40% at $Fn_\nabla=2.5$. The length- displacement ratios ($L/\nabla^{1/3}$) are not given but can be estimated from the given data to be in the range of 3.1 to 5.0.

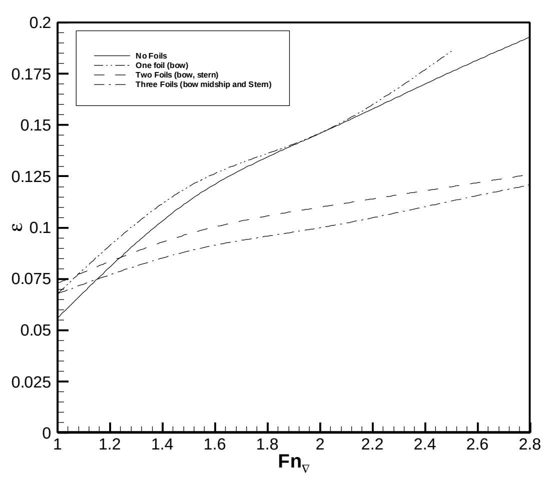

Figure 4: Resistance Comparisons for planing catamarans with tandem foils

The HYCAT development (1981) by Calkins [9,10] is a deep Vee planing catamaran that utilizes two hydrofoils mounted in tandem at keel depth. The foils carry about 90% of the vessel displacement at design speed. The HYCAT design (Figure 5) is significant as it shows an early attempt to optimize the hull-hydrofoil system by utilizing extended keels to provide smoother flow and deeper submergence for the foils. The hull is hard chined to reduce wetted area and utilize some hydrodynamic lift. No vessels were built but a number of design studies were carried out.

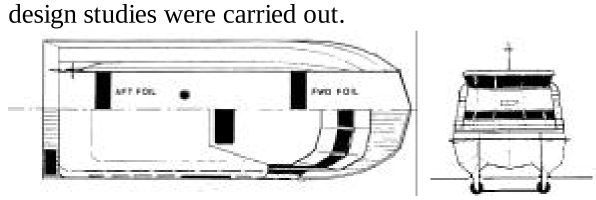

Figure 5: HYCAT concept

The vessel has a low length-displacement ratio ($L/\nabla^{1/3}=4.54$) and consequently its resistance characteristics do not compare well with modern lighter semi-displacement catamarans. No resistance comparisons are given for the vessel without foils so it is unknown how much advantage the foils bring.

The Hysucat Development was started in 1980 by Prof. K.G. Hoppe [6,11,12,13] at the University of Stellenbosch. Figure 6 shows the original principle configuration. The system consists of a main foil just ahead on the LCG and sometimes two stern foils operating close to the free surface to provide trim stability by utilizing the free surface effect on the lift. The main foil carries somewhere between 40% and 75% of the load at design speed depending on the size and displacement of the vessel.

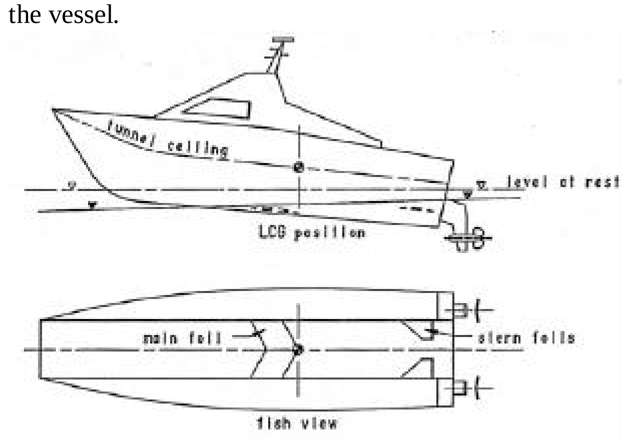

Figure 6: Hysucat Configuration

Results of this development show that resistance improvements of up to 40% are achievable with the foil system for $Fn_\nabla>2.5$. The first launch of a vessel was in 1982 and since then over 200 Hysucats have been built ranging from 6m to 36m (few are ferries so Figure 1 does not indicate these vessels). A large number of model tests have been performed for a wide range of length-displacement ratios and foil loadings. These model tests have allowed a performance prediction model to be developed based on Savitsky's planing theory, thin foil theory and empirical corrections from model test and back-feed prototype data.

Recent Developments for Semi-Displacement Catamarans

The development of hydrofoil assistance for semi-Displacement catamarans is a much more recent activity, and the various developments worldwide have led to a number of vessels being built:

Several publications [*for example*: 6,14,15] concerning Hydrofoil Catamarans (HC Series) utilizing very slender hulls are available. The concept was developed by Hitachi Zosen in conjunction with University of Tokyo, based on Hitachi's experience and technology building Supramar surface piercing hydrofoils. The design is now being applied commercially as 30m (40 knots) and 40m (45 knots) vessels in Fast Ferry Applications.

Up to four hydrofoils in tandem where tested during the development of the vessel. The final design utilizes two foils that span the hulls at keel level in tandem. Ninety per cent of the vessels weight is carried by the foils at design speed. The vessel uses extremely slender hulls with relatively deep sections as shown in Figure 7. This has the advantage of reducing the wave-making and wetted area of the hulls at speed.

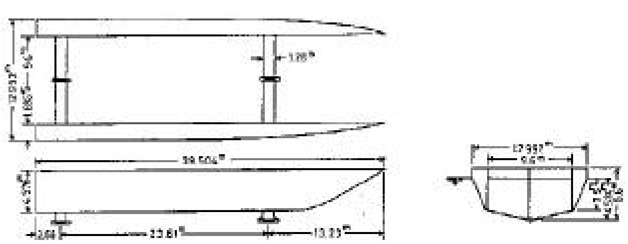

Figure 7: HC Catamaran Model [6]

Hyundai has a development program for super high speed marine transportation [16] and has designed and constructed a 45.5m foil assisted passenger vessel. The vessel has round bilge hulls with hydrofoils spanning the beam of the vessel slightly below keel depth. The foils have controllable flaps, and have been placed in extreme fore and aft positions to maximize motion damping. The vessel is shown in Figure 8.

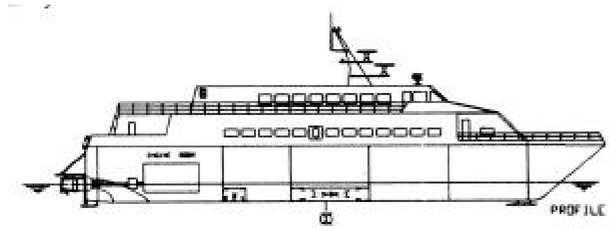

Figure 8: Hyundai 45.5m catamaran Ferry

The foils were intended to carry 40% of the displacement for both drag reduction and sea-keeping improvements. Although the vessel provided Hyundai with valuable feedback for future designs, the original design needed additional foil refinement before it could be put into service [17]. No resistance comparisons are given in the literature.

Daewoo Shipbuilding has developed a hydrofoil-assisted catamaran (F-CAT 40) [17] that uses a single passive hydrofoil (NACA 66 section) just aft of the LCG below keel depth. The foil develops lift equal to 25% of the displacement and decreases the resistance by 15%. This allows an increase in speed of about 2.5 knots for the 42m vessel, bringing its maximum speed to 40 knots. The vessel is shown in Figure 9. Daewoo compared a number of hull designs [7] and found that a hard chined hull gave better resistance characteristics that the round bilge form. Comparisons for the various hulls with and without foils show that the resistance is higher for the vessel with foils over a large portion of the speed range. The foil brings improvements from about 29 knots onward.

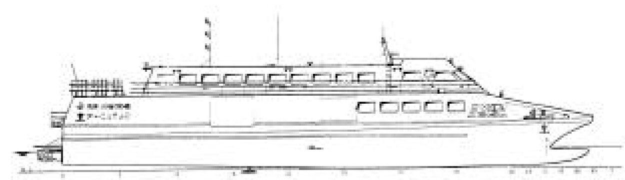

Figure 9: Daewoo F-CAT 40

The most recent addition to the hydrofoil assisted catamaran range is the 32m Marinteknik SuperFast Catamaran shown in Figure 10. The hull and hydrofoils were designed by the St. Petersburg office of Marine Technology Development Ltd. [42].

Figure 10: Marinteknik SuperFast Catamaran

A bow foil under each demi-hull is used to lift the forward part of the hull out of the water so reducing the wetted area. The foil is 1.3m below keel depth on struts. The hull is hard chined and has a shallow draft, allowing it to develop planing lift at high speeds. Marinteknik states the vessel uses 40% less power than other high-speed vessels and reaches 45 knots with 2940 kW. The resistance to weight ratio (R_T/Δ) is stated as being about 0.0833 at Fn_∇=4.0 [42].

A number of developers [18,19,20,21,22] have taken hydrofoil-assisted catamarans one step further and apply the foils to lift the hulls completely clear of the water (the so called 'hydrofoil catamarans'). If extra stability is required, these vessels can operate in the intermediate condition where both hull and hydrofoils are in water contact. The keel height above the water can be set by the helmsman with the aid of the ride control system. The hull shapes are hard chined and the foil configuration is either two tandem foils [20] or two canard foils mounted forward with a main foil aft [19,22]. Figure 11 shows an example by Kvaerner Fjellstrand.

Figure 11: Kvaerner-Fjellstrand FOIL CAT

HYDRODYNAMICS AND RESISTANCE

Before any discussion on design is given, it is appropriate to present an introduction to the hydrodynamics of these vessels. The resistance improvement gained over conventional catamarans is due to a number of effects. The foils function to unload the hull thus allowing the hull to rise out of the water. This has a three-fold effect on the resistance. 1.) The wetted area and waterline length is reduced thereby reducing the friction of the hull. 2.) The wave making of the hull is reduced. 3.) A number of interference effects between hull and foils can reduce the resistance in some cases. These points are discussed in more detail in the following paragraphs.

Resistance Breakdown

The calm water resistance consists of a number of foil-hull interference resistances in addition to the usual resistance components of the foils and the hull. A resistance breakdown is presented in the flow chart of Figure 12. The total resistance can be broken into the usual frictional and residual components. The details of each are discussed in the following sections.

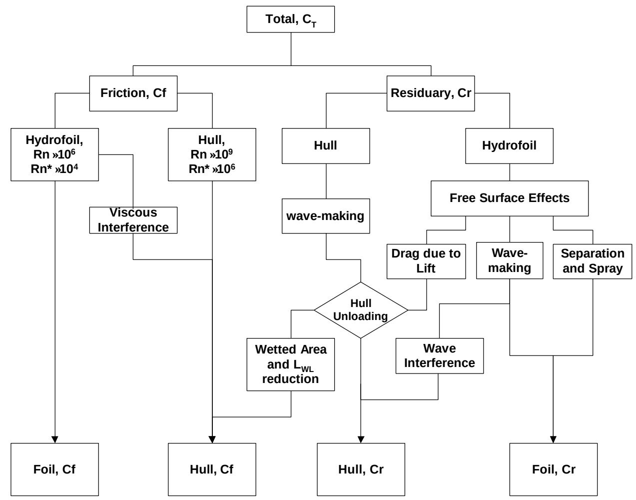

Figure 12: Resistance Breakdown for Hydrofoil Assisted Craft

Residual Resistance

The residual resistance is mainly due to the wave making of the hull, and due to the free surface effects on the foil system (wave resistance, induced drag, separation and spray). A number of references are available and are given in [4] for estimating catamaran hull resistance, but the problem is that the hull lifts out of the water at speed making most of the empirical data that is available inapplicable. Any resistance prediction method would have to include the effects of large changes in trim and sinkage on the resistance of the hull.

Predicting the forces and residual resistance of the foils is less of a challenge, as hydrofoil theory is well developed, and gives good results for preliminary foil sizing and positioning on the hull.

Hull-Foil Wave Interactions

The wave system of the hydrofoil interacts with the wave system of the hull resulting in wave interference that can be positive or negative. Experiments by Hoppe [7] have shown that a net resistance reduction is possible for planing catamarans with foils and plane internal sides (isometric hulls). These interference reductions are of the same order as the foil drag but are only achieved in some cases. Reductions may not be possible for semi-displacement catamaran hulls, as the flow is more complex for the lower Froude numbers. The exact mechanisms that cause these effects is unclear, but numerical potential flow investigations done by Van Walree [23] on the hull-foil interactions of hydrofoil craft (monohulls) before take off, shed some light on the problem. The trailing vortices from the foils induce suction forces on the hull. These suction forces are in the order of 10% of the vertical forces on the hull and seem to increase with speed. The reduction in pressure is mainly on the aft sections of the hull, meaning that the hull will trim and sink more heavily, most likely increasing the resistance.

In the case of catamarans, if the foils span the tunnel the end plate effect of the hull should reduce the strength of the trailing vortex sheet from the foils. For catamarans with plain internal sides, the assumption that the flow in the tunnel over the foils is two-dimensional gives fair resistance predictions meaning that the trailing vortex sheet is reduced. Van Walree also shows that the lift reduction of the foils due to the hull is less significant. For the foils 2 to 3 chord lengths below the hull, the loss in lift was 3.4% for the low speed case (Fn_∇=1.4) examined and less for the higher speeds. These effects will obviously differ depending on the foil configuration. For catamarans with canards or foils mounted on struts below the keel, the distance of the foil below the keel is usually in order of 1 to 2 chord lengths. The hull-foil interference effect will then be greater than that calculated by van Walree.

Friction Resistance

Friction is the largest component of resistance for all high-speed catamarans. A breakdown of friction resistance and can be divided into foil and hull friction components and the viscous interactions between the two (see Figure 13).

Calculating the foil friction accurately is especially important for accurate correlation of model test data. It is well known that it is difficult to maintain turbulent flow over the foils at model scale as the Reynolds number of the foils is too low ($Rn=10^4$). The Reynolds number also has an effect on the lift of the foils by reducing the lift curve slope and angle of zero lift on the foils. Van Walree [23] gives a good account of this effect. This means that the vessel will behave slightly differently at model scale. A description of these and other problems associated with model testing foil-assisted catamarans is given in [24].

Hull friction is the largest component of resistance for the hull and reducing it depends largely on reducing the wetted area of the hull. Hull friction can be calculated using the ITTC 57 friction line.

Comparisons between model test data and back-feed prototype data from existing Hysucats has allowed a reliable correlation procedure to be developed at the University of Stellenbosch. The method relies on accurately predicting the laminar separation and friction resistance of the model foils using published data [25]. Once the laminar flow has been accounted for, the model test data can be correlated using Froude's hypothesis.

Viscous Interference Effects

Viscous interference effects are due to the boundary layers of the foil and the hull combining at the corners forming the intersection of the hull and hydrofoils. The boundary layer is retarded by the adverse pressure gradient along the rear of the foil creating additional pressure drag. This effect is minimized by maintaining an approximate angle of 90° or more between hull and foils [26].

Resistance Prediction

There are a number of difficulties in predicting the performance of semi displacement hydrofoil assisted catamarans. The empirical methods available to designers are not suitable for a number of reasons: Existing empirical methods are not able to determine the hull resistance, as they generally do not consider the effect of large changes in trim and sinkage. There is also almost no way to predict the interference effects between hull and hydrofoil empirically. This is in contrast to planing catamarans with hydrofoils where the method of Savitsky [27] combined with thin foil theory gives good predictions as interference effects become less important at high speed. This method combined with empirical corrections can provide reliable results. Such a method, developed at the University of Stellenbosch, allows planing type Hysucats to be designed and built without model tests in some cases [28].

For semi-displacement hulls, a more exact hydrodynamic theory needs to be applied to the problem. Numerical computations will no doubt be able to provide a lot of useful information to the designer in future. Such methods are currently being developed [29,30,31], and are being applied to preliminary design studies. The method of Kornev and Taranov [31,32] was developed for, and successfully applied to preliminary design of the vessel pictured in Figure 10.

At present it is still very difficult to design these vessels without model testing. Even for the cases where hydrofoils are fitted to existing hulls, model tests are required for resistance data, optimizing foil positions and establishing stability limits. For the present state of the art, model testing remains the most important tool for design and optimization purposes.

HYDROFOIL DESIGN

In review of the literature presented it becomes clear that there is considerable variation in foil assisted vessels that have been built. There are no hard and fast rules that can be used for foil design, and much research is still necessary before it can be said that any one design is superior over another for the desired application.

There are two potential types of hydrofoil assisted catamarans: new vessels, where the foil system and hull are designed to match, and secondly hydrofoil retrofits to existing vessels. In the latter case, the foil system has to be designed to match an existing hull, and this often results in a foil configuration that is less than optimal but that can nevertheless bring substantial improvements in resistance.

The following points are the most important and have to be considered early in the design process of all vessels:

Foil Loading.

Foil loading of as little as 25% of the displacement weight of the vessel for a single foil, and up to 100% using multiple foils is in use. It is the authors experience that the best resistance improvements can be gained for semi-displacement catamarans by supporting as much of the load on the foils as is practically attainable. A similar conclusion is offered by others [14,33]. The foil load depends on factors such as propulsion, position of the longitudinal center of gravity, cavitation limits, strength and stability considerations. A higher foil loading means the hull is lifted further out of the water. Consideration has to be given to the immersion of waterjet inlets and fences may have to be put up to keep air out of the waterjets. The position and shifts of the LCG become more important as the hull is lifted higher out of the water, as there is now less hull area in water contact to provide stabilization.

An important point governing foil loading is the cavitation limitation and structural requirements of the foils. Cavitation can usually be avoided with the aid of the correct foil profiles, sweep, and span wise variation of camber and angle of attack [34,35,36]. On Hysucats delayed cavitation circular arc type profiles with the maximum thickness approximately at mid chord are used, similar to those suggested in [34,35] and shown in Figure 13.

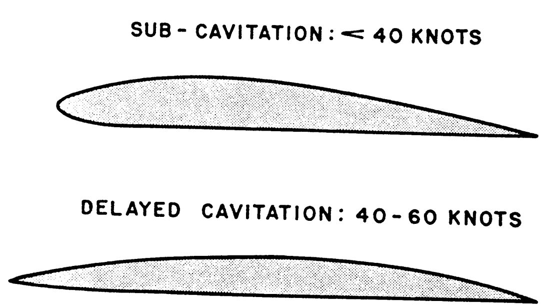

Figure 13: Sub-Cavitation section compared with Delayed Cavitation section

The foil camber and thickness has to be carefully matched with structural limitations of the material being used, as the thin foils have to bear high loads. Often a number of vertical struts will have to be used to support the foil. Predicting foil loads (dynamic and fatigue loads in particular) is difficult as no international consensus or guidelines are available. A number of references [37,38] are available that describe the structural design of hydrofoils for catamarans in more detail.

Foil Positioning

If foils are being retrofitted to existing vessels, a primary concern becomes the position of hard points on the hull that can support the load of the foils. The hull usually has to be strengthened at the foil attachment points. Otherwise, for new designs the position of the LCG and LCP of the hull at speed is of primary concern. Model tests at the University of Stellenbosch have shown that incorrect foil positions in relation to the LCG can result in the vessel becoming unstable in pitch and yaw or simply do not bring the desired resistance improvements. The best foil positions for resistance improvements are often close to the stability limits of the vessel. Care has to be taken to make sure the vessel is stable at speed, within the normal range of displacement and LCG variation for the vessel. A concept design will often require much refinement and several modifications may have to be made to the foil positions and angles of attack before the design is perfected and free of instabilities. The towing tank remains the most valuable tool for this.

Foil Configuration

Figure 14 summarizes the basic configurations that are in use. The literature review has shown examples of each.

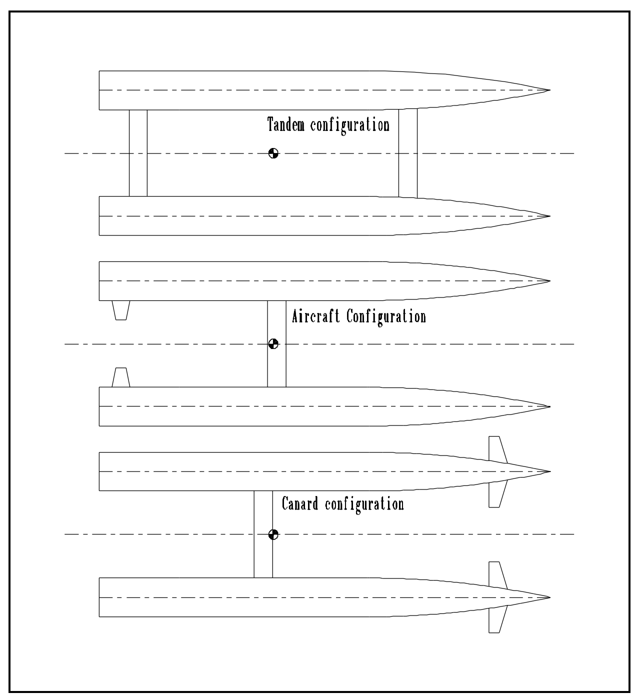

Figure 14: Hydrofoil Configurations

The tandem configuration seems to be the most popular, being applied on a number of hydrofoil-assisted catamarans (e.g. Figure 7 and Figure 8) and hydrofoil catamarans [20]. This is most likely for simplicity, and the fact that it allows a large proportion of the vessel load (up to 100%) to be carried efficiently on the high aspect ratio foils.

The avion (or aircraft) configuration or its simpler version, the mono-foil, have found much application in planing vessels with resistance improvements of up to 40% being achieved on Hysucats. The F-CAT (Figure 9) has shown that this system is also applicable to large semi-displacement type catamarans bringing resistance improvements of about 15% at design speed.

The canard configuration, used on a number of vessels, allows a large percentage (up to 100%) of the vessel weight to be carried on the foils. Bow foil vertical struts can also double as steerable surfaces if necessary. Tests done at the University of Stellenbosch [1,39] have indicated that the canard system brings resistance improvements from Froude numbers as low as 1.0 in some cases without any increase in resistance for speeds below that. Figure 15 shows the foil configuration.

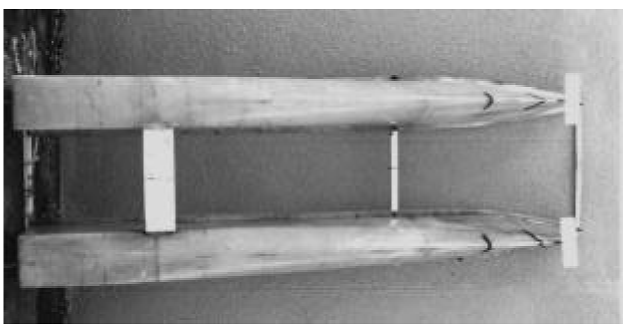

Figure 15: Model with Canard Hydrofoil Configuration

This seems to be unique to this configuration. This system is being further developed at the University of Stellenbosch and is discussed in more detail later in this paper.

The choice of a suitable configuration is a complex task and depends mainly on the hull geometry (demi-hull shape and tunnel width) and the amount of load to be carried by the foils. In designs for the lower Froude numbers the foil configuration plays a much more critical role as the resistance problem illustrated in Figure 3 becomes of importance.

The resistance improvements for the low speeds are also significantly influenced by the shape of the hull. This becomes of particular importance for retrofit projects to existing hulls. The influences of hull geometry are described in more detail in the next section.

HULL DESIGN

A review of the literature presented indicates that a number of different hull design approaches have been tried and are applied on existing foil-assisted catamarans. The hull design is usually linked to the foil configuration being used. The following has become clear from model tests and examination of the hull designs of existing vessels. For those vessels where the foils carry a smaller proportion of the displacement load, the hull lines seem to agree with conventional semi-displacement hull design principles. (The vessels shown in Figure 8 and Figure 9 are examples). This makes good sense, as the hull is responsible for most of the lift and resistance of the vessel. In the cases where a large proportion of the load is carried on foils, two unconventional approaches have been adopted for the hulls. The hulls are either made very slender, as is the case with the Superjet Catamarans (Figure 7), or alternatively the hulls have been designed to utilize some hydrodynamic or planing lift, for example the SuperFast Catamaran (Figure 10). The hydrofoil catamarans (e.g. Figure 11) show similar designs for utilizing planing lift when the hulls are in water contact. Both ideas try to take full advantage of the hulls being lifted partially out of the water to minimize the resistance of the hull. The details of the three types of hull forms (conventional, slender and those utilizing dynamic lift) are discussed separately in the following sections:

Conventional Semi-Displacement hulls

Conventional semi-displacement hulls are characterized by the following points:

1.) Sharp Vee sections in the bow with a small angle of entrance.

2.) Round bilge along the entire length of the hull, sometimes with decreasing bilge radius sternwards, forming a hard chine at the transom.

3.) $B/D_{demi\text{-}hull} \leq 2.0$ at amidships.

4.) A reduction in transom depth compared with amidships. This is often associated with a reduction of the cross-sectional area towards the transom.

5.) The LCG is usually located between 40% and 45% of the length between perpendiculars, measured from the transom.

Tests done at the University of Stellenbosch on hydrofoil assistance for these hulls show that they are not optimal for hydrofoil assistance but that their resistance can be reduced with a suitable hydrofoil system. Round bilge hulls suffer from a transverse flow component around the hull that causes negative or suction forces [40] that counteracts the foil lift and reduce the benefit of the foil system. The suction forces are further exaggerated by reduction of the transom depth or rocker.

These hulls are designed to operate at low trim angles between 0° and 1° and so do not generate any dynamic lift. Model tests done at the University of Stellenbosch show that these vessels tend to sink slightly at high speed due to the suction forces. To gain improvements using hydrofoil assistance relies on increasing the running trim to somewhere between 1.5° to 2.5°. The amount depends on the extent of the hull's rocker. If low running trim angles are maintained, resistance improvements are often insignificant or non-existent as the hull cannot be lifted sufficiently out of the water to get the necessary resistance reductions.

Another problem that arises due to the suction forces on the hull is that there are large and sudden changes in trim and sinkage associated with the unloading of the hull. This kind of instability occurs with foil systems designed to carry a large percentage (70%+) of the load on the foils. Figure 16 shows the typical example of what is often found. Over a very small change of speed, the flow over the hull will change dramatically, causing a sudden step like change in the trim, sinkage and resistance of the vessel.

The cause of the step is due to the unwetting of the hull and a sudden disappearance of the suction forces acting on it. The Froude numbers where this change occurs depends on the position and configuration of the foils and on the hull shape. The severity of the change is also dependent on the hull shape.

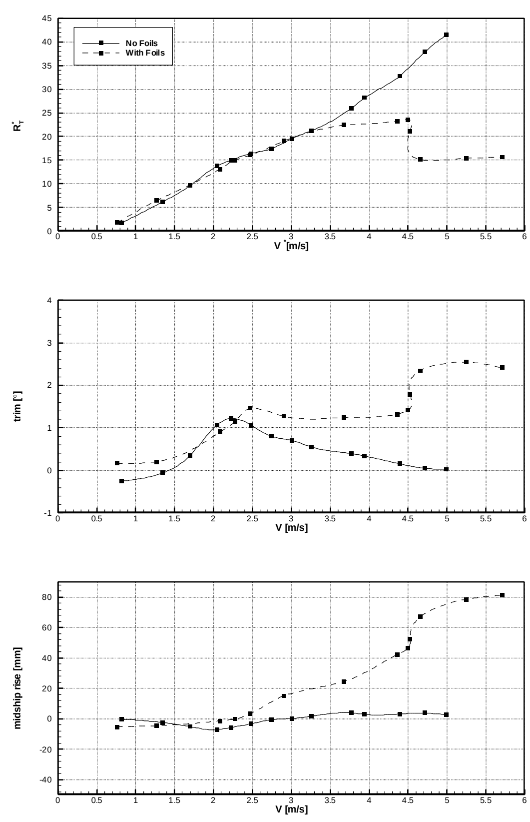

Figure 16: Changes in Resistance, trim and sinkage due to unloading of hull

This problem can be avoided for new ship designs, but in the case of foil retrofits to existing hulls; methods are needed to eliminate the problem. Continuing research is being done to find ways to reduce or eliminate this problem. The aim is to try to reduce the resistance over the whole speed range to the same low values achieved after the step.

Very Slender Hulls

Using very slender hulls as utilized on the HC catamaran shown in Figure 7 seems to eliminate the problems of conventional semi-displacement hulls. The high slenderness of the hulls reduces the wave making to a minimum and the very deep-Vee section shape ensures that the wetted area is significantly reduced as the hull rises. The 10% to 20% buoyancy the hulls still provide is adequate to stabilize the vessel longitudinally and transversely [34].

Care has to be taken with the design, as experience at the University of Stellenbosch shows that making the hulls too slender in the bows strongly affects the directional stability of the vessel. This situation is further aggravated if there are vertical struts in the bows to support the foils.

Model test results by Miyata [5] indicate that the slender hulls still show sudden changes in trim similar to conventional semi-displacement hulls but to a lesser extent. With the aid of the ride control system, this can be eliminated.

Hulls utilizing some hydrodynamic lift

As higher and higher speeds are being reached more and more catamarans are being designed with hard-chined deep-Vee type semi-displacement/semi-planing hulls to take advantage of the hydrodynamic lift. These hulls generally have the following characteristics:

1.) Sharp Vee sections in the bows with shallower hard chined Vee sections aft.

2.) The hulls generally have less rocker or transom area reduction than conventional semi-displacement catamaran hulls.

3.) Addition of spray rails can reduce resistance further (5%) for high speeds.

4.) The hulls tend to be slightly beamier and have a shallower draft than the round bilge counterparts with $B/D_{demi\text{-}hull} \geq 2.0$ at amidships.

5.) The position of the LCG is further aft between 35% and 40% of the length between perpendiculars, measured from the transom.

With the assistance of hydrofoils, the hull can be lifted "on to the plane", and can benefit from dynamic lift from much lower speeds than would otherwise be possible. This makes these kinds of hulls ideal candidates for hydrofoil assistance.

The hard chined hulls can still suffer from the same suction forces explained earlier but to a reduced extent.

At low speeds, the chine helps retard the transverse flow component around the hull reducing the suction forces [41]. At high speed, the chines separate the flow from the hull reducing the wetted area. Inspection of the hard chined hull forms of the hydrofoil assisted semi-displacement catamarans described in this paper shows that most of them have a straight keel line with little or no reduction in the transom depth compared with the maximum.

The fuller transom will result in a higher hump resistance, but with the proper design of the foils, the hump resistance can be reduced in some cases. Improvement of the hump resistance as well as high-speed resistance forms part of some of the latest research conducted at the University of Stellenbosch and is explained further in the next section.

RECENT DEVELOPMENTS

Developments at the University of Stellenbosch are focused on further refinement of semi-displacement hull forms and the hydrofoil systems for the hulls.

Test results of a canard hydrofoil configuration (Figure 15) have been published previously in [5,39], showing that resistance improvements are possible for $Fn_\nabla=1.0$ and above. Further reduction of the high-speed resistance without increasing the low speed resistance is possible by replacing the canards with a larger aspect ratio foil spanning the beam of the vessel slightly below keel depth and positioned quite far forward. Figure 17 shows a model test of the improved design at speed. The system is similar to that used by the vessel in Figure 10. The difference is that a stern foil is relied on to provide more of the lift than the rear planing forces of the hull. This provides a better solution, as the hydrofoils are more efficient than the low aspect ratio planing surfaces of the hull.

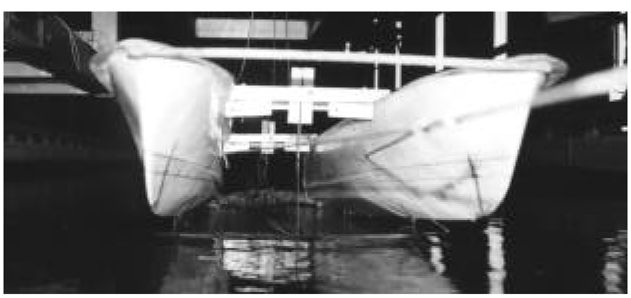

Figure 17: A model at speed with the improved Foil Design

The high aspect ratio bow foil can carry more load in an efficient manner than the smaller canards. This results in the foil generating efficient lift from lower speeds resulting in little or no increase in the low speed resistance. The hump resistance may also be improved in some cases. Improvements to the hump resistance vary depending on the hull shape and the length displacement ratio of the hull. Those hulls with fuller transoms (i.e. larger hump resistances) are easier to improve than lightly loaded vessels with reduced transom areas and a small hump resistance.

Figure 18 shows a typical resistance comparison for an avion configuration and the new foil system (in this case for a conventional semi-displacement catamaran hull form).

The figure shows that there is no resistance increase for the low speed range and improvement is gained from $Fn_\nabla<2.0$ making it possible to increase the efficiency and top speed of the vessel significantly.

This new foil design is currently being investigated for a number of existing vessels ranging from 20m to 72m and for a variety of hull designs including conventional semi-displacement designs and planing hulls.

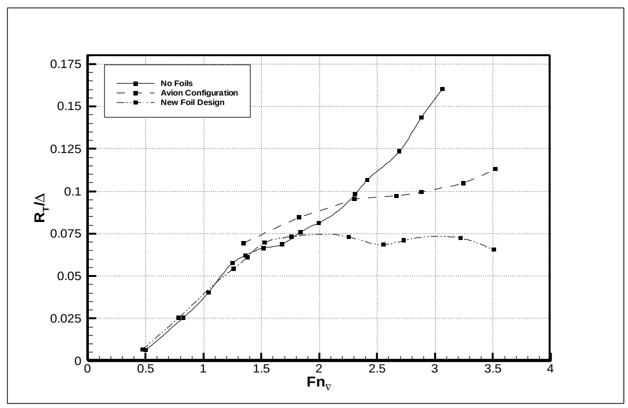

Figure 18: Resistance tendencies for a 40m semi-displacement vessel with a new foil Arrangement

Concurrently research is continuing on the development and improvement of current hull designs to eliminate instabilities and improve resistance using hydrofoil assistance. The aim is to match the hull efficiently with the foil system so that the vessel operates efficiently for a wide range of Froude numbers, with no increase in resistance due to the foils.

CONCLUSIONS

A variety of designs and vessels have been developed and built that take advantage of hydrofoil assistance. These vessels range in size from 6m planing catamarans to 45m semi-displacement type vessels. Larger vessels are also currently being designed. These vessels utilize different hull forms and foil configurations to improve resistance and sea keeping.

A number of different foil configurations are in use, and all can be shown applicable in certain applications. For the best resistance improvements foils that carry a large fraction of the load should be used in a suitable configuration. Such a configuration should also provide adequate stability for the vessel. To avoid an increase in resistance in the region of hump speed the efficiency of the foil system is important.

From the literature and model tests, it is clear that conventional semi-displacement catamaran hulls can benefit from hydrofoil assistance for high Froude numbers ($Fn_{\nabla}>2.0$). A limitation on their use is that their hull shape is not optimal for the high speeds where dynamic forces become significant.

Better resistance improvements and behavior for the high Froude numbers can be gained using very slender hulls or hard chine deep-Vee type semi-displacement hulls.

Developments at the University of Stellenbosch are focusing on development of new semi-displacement hulls that are suitable for hydrofoil assistance for low and high Froude numbers.

From model tests done to date, the best resistance improvements using hydrofoil assistance are gained by designing the foils to provide a large fraction (80%+) of the lift. This is done by using a high aspect ratio bow foil mounted on struts below keel level in addition to a stern foil located aft. In this way most of the hull is lifted out of the water reducing wetted area and wave making to a minimum.

REFERENCES

1 Saks, E. ed. 1997 "The World Fast Ferry Market," Baird Publications Limited, Hong Kong.

2 Schertel, H., Baron von 1973 "The Design and Application of Hydrofoils and their future Prospects," IME.

3 Werenskiold, P. 1990 "Design Tool for High Speed Slender Catamarans," High Speed Marine Craft.

5 Yermotayev, S.G., Aframeyev, E.A., Teder, L.A. and Rabinowich, Ya.S. 1977 "Hydrodynamic Features of High Speed Catamarans," Hovercraft and Hydrofoil, **16**.

5 Migeotte, G. 1999 "Development of Hydrofoil Assisted Catamarans with Semi-Displacement Hulls," HIPER'99, 1st International Conference on High Performance Marine Vehicles, Sevenwacht, South Africa, *Proceedings.*

6 Miyata, H. 1989 "Development of a New-Type Hydrofoil Catamaran," Journal of Ship Research, **33**, 135-144.

7 Hoppe K.G. 1989 "The Hysucat Development," University of Stellenbosch, Dept. of Mechanical Engineering, *Report.*

8 Kim B-S. et al. 1993 "Improvement of hydrodynamic characteristics of Catamaran with Hydrofoil," FAST'93 Second International Conference on Fast Sea Transportation, *Proceedings.*

9 Calkins D.E. 1981 "HYCAT: Hybrid Hydrofoil Catamaran Concept," AIAA Paper81-2079, American Institute for Astronautics and Aeronautics, Washington D.C.

10 Calkins D.E. 1984 "HYCAT: Hybrid Hydrofoil Catamaran Concept," Ocean Engineering, **11,** 1-21.

11 Hoppe K.G. 1991 "Performance Evaluation of High Speed Surface Craft with Reference to the Hysucat Development," Fast Ferry International.

12 Hoppe K.G. 1980 "The Hydrofoil Support Catamaran," University of Stellenbosch, Dept. of Mechanical Engineering, *Progress Research Report.*

13 Hoppe K.G. 1991 "The Hysucat Development," Schiffstechnik, Ship Technology Research, **38.**

14 Toshihiko A., Miyata, H., Kawaguchi, H. and Hatta,H 1993, "Development of a Foil Assisted Catamaran 'SuperJet-30'," FAST'93 Second International Conference on Fast Sea Transportation, *Proceedings.*

15 Ohtsubo, H. and Kubota, A. 1991 "Vertical Motions and Wave Loads of High-Speed Ships with Hydrofoils," FAST'91 First International Conference on Fast Sea Transportation, *Proceedings.*

16 Min K-S. 1995 "Design and Construction of the Long Range High-Speed Foil-Catamaran Passenger Ship," 19th Symposium on Naval Hydrodynamics, Seoul, Korea.

17 Peterson F. 1995 "Recent Hydrofoil Developments in East Asia," International Hydrofoil Society, 25th Anniversary Celebration and Conference, *Proceedings.*

18 Maritime Applied Physics Corporation Internet Home Page, http://www.mapcorp.com.

19 Jorde G.H. 1991 "The Development of a 50m, 40 knot FoilCat," IMAS 91, High Speed Marine Transportation.

20 Kihara, K. et al., 1993 "Diesel Driven Submerged Hydrofoil Catamaran Mitsubishi Super-Shuttle 400, the Rainbow," FAST'93, Yokohama, Japan.

21 Kihara, K., Toki, N. and Kitamaura, T. 1995 "Development of Fully Submerged Hydrofoil Catamaran," International Hydrofoil Society, 25th Anniversary Celebration and Conference, *Proceedings.*

22 Berntsen, S. 1995, "FOILCAT 2900 Design and Performance," International Hydrofoil Society, 25th Anniversary Celebration and Conference, *Proceedings.*

23 Walree van, F. 1999 "Computational Methods for Hydrofoil Craft in Steady and Unsteady Flow," Technische Universiteit Delft, Ph.D. Thesis.

24 Jensen G. and Fritsch, M. 1994 "Foil-Assisted Katamaran," HSVA, Hamburgische SchiffBau-Versuchsanstalt GmbH., (in German).

25 Kirkman K.L. and Kloetzli, J.W. 1980 "Scaling problem of Model Appendages," ATTC, University of Michigan, Ann Arbor.

26 Hoerner, S.F. 1965 "Fluid Dynamic Drag," Hoerner Fluid Dynamics, Bricktown, New Jersey.

27 Savitsky D. 1976 "Hydrodynamic Design of Planing Hulls," Marine Technology, **1**.

28 Hoppe K.G. 1999 "Hydrofoil Catamaran Developments in South Africa," HIPER'99, 1st International Conference on High Performance Marine Vehicles, Sevenwacht South Africa, *Proceedings.*

29 Thiart, G. 1999 "Predictions of Hydrofoil Characteristics by a Vortex Lattice Method," HIPER'99, 1st International Conference on High Performance Marine Vehicles, Sevenwacht South Africa, *Proceedings.*

30 Min, K-S. and Streckwall, H. 1998 "Numerical and Experimental Studies for the Prediction of Hydrodynamic Characteristics of Two Dimensional Hydrofoils Operating Under the Free Surface" 22nd Symposium on Naval Hydrodynamics, Washington D.C.

31 Kornev, N and Taranov, A. 1999 "Investigation of the Vortex-Wave Wake behind a Hydrofoil," Ship Technology Research Vol. 46. No.1.

32 Kornev, N. and Taranov, A. 1998 "AutoWing 2.3," http://www.cl.spb.ru/taranov/Index.htm.

33 Hatton R., McKesson C., Scher, R. and Toby, S. 1999 "When the whole is less than the sum of its part," HIPER'99, 1st International Conference on High Performance Marine Vehicles, Sevenwacht South Africa, *Proceedings.*

34 Shen, Y.T. and Wermter, R. 1976 "Recent Studies of Struts and Hydrofoils for High Speed Application," AIAA paper 76-851, American Institute for Astronautics and Aeronautics, Washington D.C.

35. Eames, M.C. and Jones E.A. 1971 "HMCS BRAS D'OR-An Open Ocean Hydrofoil Ship," RINA Journal, **1**.

36 Shen, Y.T. and Eppler R. 1981 "Wing Sections for Hydrofoils-Part 2: Nonsymmetrical Profiles," Journal of Ship Research, **25**, 191-200.

37 Sueoka, H. et al. 1993 "Design and Manufacturing of the Foil Structure for Mitsubishi Super-Shuttle 400 'RainBow'," FAST'93 Second International Conference on Fast Sea Transportation, *Proceedings.*

38 Min K-S., Kim, O-H. and Park, J-S. 1993 "A Study of the Structural Design of the Hydrofoil System for High-Speed Foil Catamaran Ships," FAST'93 Second International Conference on Fast Sea Transportation, *Proceedings.*

39 Migeotte G. 1997 "Development of Hydrofoil Supported Catamarans with Semi-Displacement Hulls," University of Stellenbosch, Dept. of Mechanical Engineering, M.Eng thesis.

40 "Derecktor Shipyard delivers first NGA 45m catamaran," Fast Ferry International, January-Febuary 1999.

41 Blount D.L. 1995 "Factors influencing the Selection of a Hard Chine or Round-Bilge Hull for High Froude Numbers," FAST'95 *Proceedings,* Lübeck-Travemunde, Germany.

42 Pavlov, S. 1999 "Russian Hydrofoils," The Newsletter, International Hydrofoil Society, summer 1999.