DEVELOPMENT OF MODERN HYDROFOIL-ASSISTED MULTI-HULLS

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Abstract Hydrofoil-assistance has found application over the last 2 decades in a variety of high-speed craft including workboats, military craft, pleasure craft and high-speed ferries. The application of these hybrid high-speed ships is discussed with reference to recent milestones in their development and application. Prospects for their future are discussed with reference to current design capabilities and challenges for future development.

1. Introduction

Development of hydrofoil-assisted catamarans has a long history spanning back to the early 70's and the first displacement catamarans to be built such as the USNS Hayes [1], which used hydrofoil-assistance to rectify its poor seakeeping and wet deck slamming problems. The Soviets also conducted research at this time (by Yermolayev [2]) on hydrofoil systems for high-speed planing vessels and also developed a series of hydrofoil-assisted monohulls. Since these early developments significant progress has been made in the application of hydrofoil systems for both seakeeping and ride control and also for reductions in resistance. This paper focuses on the application of hydrofoils for reductions in resistance rather than for ride control.

The most common hydrofoil-assisted multihulls are:

- So-called *hydrofoil catamarans* that make use of hydrofoil and propulsion systems that allow the hulls to be lifted completely clear of the water. These vessels are not inherently stable and need expensive ride control systems to keep them stable. These vessels are in essence similarly to conventional hydrofoil craft such as the Boeing JetFoil.
- *Hydrofoil-assisted catamarans* that make use of hydrofoils to lift the hulls only partially out of the water. The fact that the hulls remain in water contact mean the vessels are inherently stable and can make use of conventional catamaran propulsion systems such as flush inlet waterjets.
- More recently a number of *hydrofoil-assisted trimarans* have been built. These vessels typically make use of a central hull and two small amahs. Hydrofoils are typically installed in each of tunnels.
- *SWATH type hydrofoil-assisted catamarans* have recently been introduced that make use of very large voluminous hydrofoils that provide significant buoyancy in addition to dynamic lift.

Notable milestones in the development of hydrofoil-assisted multihulls are:

- 1980, launch of the first planing hydrofoil-assisted catamaran in Cape Town, South Africa to the newly patented HYSUCAT design [3]. To date over 300

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vessels ranging from 5m to 36m in size have been built to this design making it the most successful hydrofoil-assisted catamaran design to date.

- 1989, development of the first fast passenger ferries making use of hydrofoil-assistance by Hitachi Zosen in collaboration with the University of Tokyo [4]. This design was groundbreaking in the sense that it combined SES-type slender demi-hulls with hydrofoils and an active ride control system for improving passenger comfort. To date eight 35m vessels of this type have been built as well as one 40m vessel.
- 1989, development of the first planing hydrofoil-assisted catamarans in China. A development similar to Hysucat development for planing boats was undertaken from 1989 to 1997 [21].
- 1991, development of the Norwegian FOILCAT series of hydrofoil catamarans [5] by Kvaerner Fjellstrand and Westamarin. A 35m and a 40m version were developed both of which are no longer in production. Four vessels in total have been built, 3 by Kvaerner and one by Westamarin.
- 1993, development of hydrofoil-assisted catamarans in Korea. KRISO in collaboration with Hyundai Heavy Industries, [7] and Daewoo Shipbuilding and Heavy Machinery [8] both developed different types of hydrofoil-assisted catamarans. Hyundai and Daewoo both built one vessel each (40 and 45 m LOA respectively) for use as fast passenger ferries.

- 1993, development of the Mitsubishi Super shuttle hydrofoil catamaran in Japan [9]. Two of these vessels have to date been built, the first in 1993 and the second in 1998 to the same operator.
- 1994, Design and construction of Hydrofoil-supported ferries in Germany. A development was undertaken by various shipyards including Lürrsens and Henze Shipyard for the development of hydrofoil-assisted catamarans. Two ferries (20m and 30m LOA) were built by Henze shipyard [10] making use of the HYSUCAT foil system.
- 1999, First HYSUWAC type hydrofoil-assisted catamaran launched. The 45m, 170 tonnes vessel built by Halter Marine in the USA achieved 42 knots with 2x2000kW.
- 2001, The first hydrofoil-assisted trimaran launched. The vessel is a 55m ferry operating between Korea and Japan [11] and was built by North West Bay Ships.
- 2002, The launch of the world's fastest passenger ferry, a 40m, 50 knot hydrofoil-assisted catamaran developed in Russia and built by Almaz in St. Petersburg [12].
- 2003, The first lifting body type hydrofoil-assisted catamaran technology demonstrator launched making use of SWATH lifting body technology. [20].

The milestones above spanning over two decades represent only the most significant vessels. To date it is estimated that over 600 hydrofoil-assisted vessels have been built worldwide ranging from pleasure craft, workboats, military craft and fast ferries. Reference [13] provides some additional information about recently built hydrofoil-assisted catamarans.

2. Types of hydrofoil systems for multi-hulls

In general a number of different foil systems have found application. These range from simple passive monofoils to complex tandem foil systems that integrate ride control through adjustable foils or flaps into the foils design. Figure 1 and 2 shows examples of fixed and adjustable foil systems. The configurations of the foil systems also vary considerably from vessel to vessel. Figure 3 summarizes the different foil systems currently in use.

The types of hydrofoil configurations shown in Figure 3 consist of two fundamental types:
Those with hydrofoils located *between the demi-hulls* of a catamaran or trimaran such as those illustrated in the left column of Figure 3.
Those that have hydrofoils that *extend below the keel line* of the hull such as those illustrated in the right column of Figure 3.

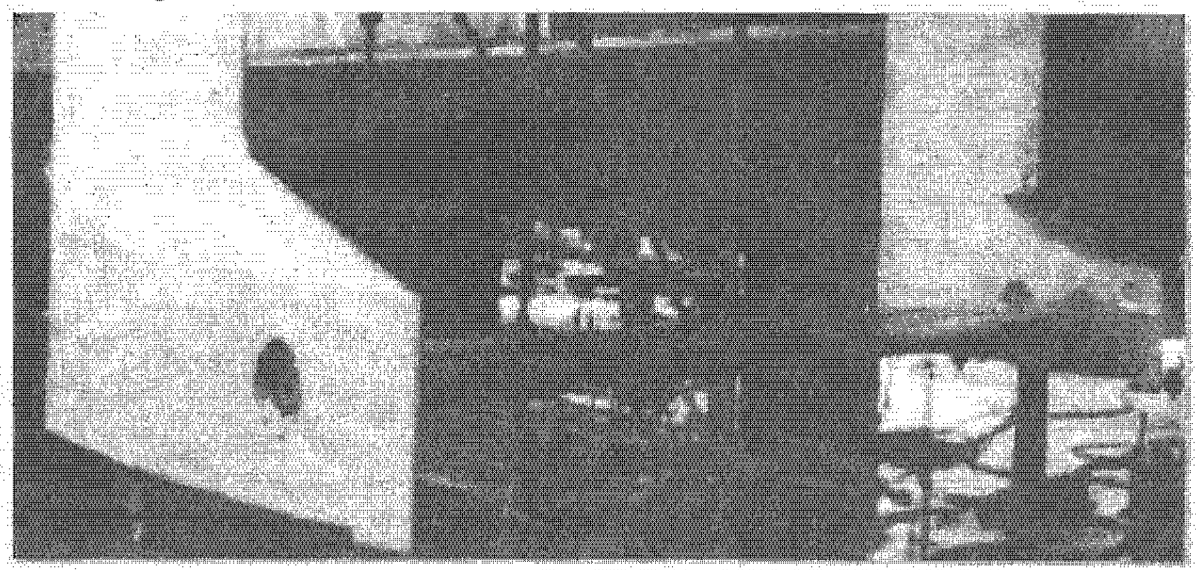


Figure 1: A hydrofoil with adjustable incidence angle

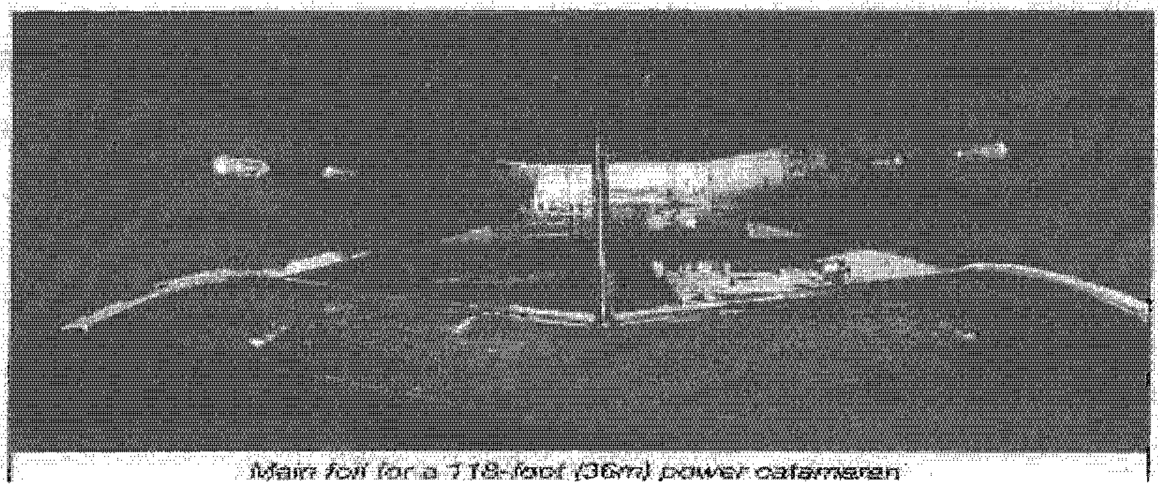


Figure 2: A fixed HYSUCAT hydrofoil mounted between the demi-hulls of a 36m catamaran

Foil configurations with the foils located between the demi-hulls have the advantage that the foils are well protected by the hull and there is low risk of damage during operation or docking of the vessel. Locating the foils in the tunnel does however limit the amount of load the foils can carry and in general the lift is usually limited to a maximum of about 70% of the displacement weight for small planing catamarans and down to about 25% for larger semi-displacement catamarans. In order to carry more load in an efficient manner on hydrofoils, it is necessary to make use of hydrofoils that are more deeply submerged. This means locating the foils below the keel line on struts that allows the hull to be lifted farther out of the water, reducing wetted area and increasing the load fraction on the foils up to 100% if necessary.

In general, planing type hydrofoil-assisted catamarans make use of hydrofoils that are located in the tunnel between the demi-hulls and do not protrude below keel level. For planing speeds this type of foil system produces sufficient lift to provide very good improvement in planing performance without introducing the complication of having foils protrude below he keel. Such designs are very practical for pleasure and military craft where they can be used in a variety of applications and can for example be beached or trailored without difficulty.

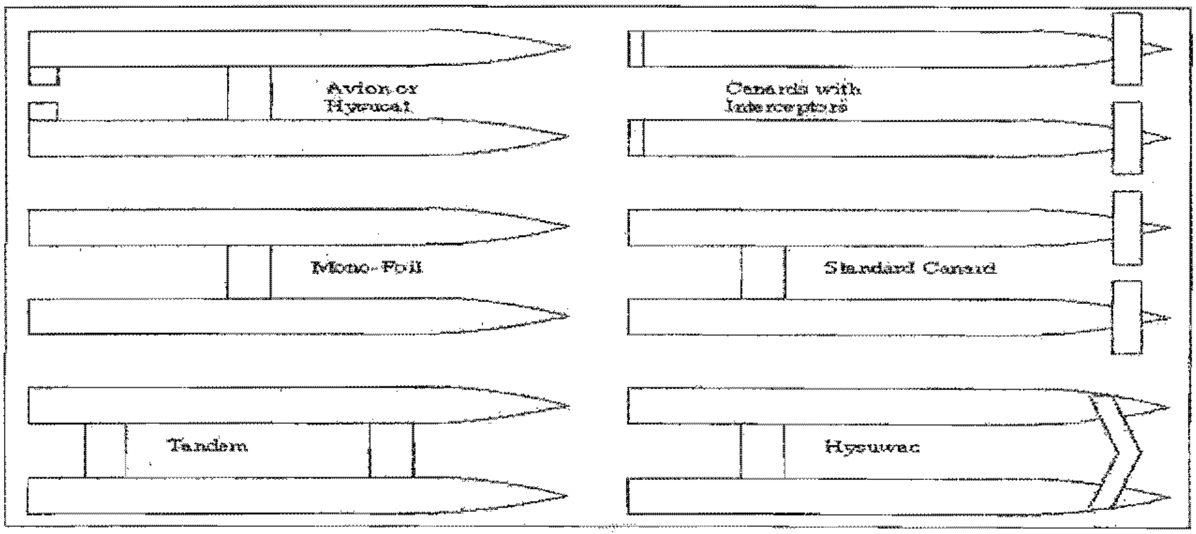


Figure 3: The most common configurations of hydrofoil-assisted craft currently in operation

Semi-displacement and semi-planing multi-hulls usually make use of hydrofoils located below keel level. Hydrofoils located at keel level are only capable of bringing very limited reductions in resistance that often do not justify the extra cost of the foil system. In order to gain more substantial benefit out of a foil system, a higher lift system is required such as those shown in the right hand column of Figure 3. By positioning the foils below the keel, they are deeper submerged and suffer less from the "free surface effect" and thus are capable of generating more lift and better able to reduce resistance at non-planing speeds.

3. Resistance Tendencies

All hydrofoil-assisted vessels have the same general resistance tendencies:

- At speeds below the displacement hump, there is no improvement is resistance compared to the same hull without foils. In many cases the foils are a source of additional appendage drag and the total resistance of the vessel is increased by 5-10%. Only the most efficient foil systems cause no increase in resistance at low speeds. The foils do nevertheless provide significant motion damping and sufficient lift is generated for them to be efficient ride control devices.
- At semi-displacement and semi-planing speeds (e.g. speeds of typical fast ferries) only the most efficient foil systems bring useful resistance reduction of
- up to about 40%. The amount of improvement is high dependent on hull shape, foil-hull interactions, and configuration of the foil system.
- At planing speeds it is relatively easy to obtain improvement in performance. At these speeds the lift produced by the foil system can be in excess of 60% of the boat displacement and reductions in resistance can be up to 50%.

4. Foil systems mounted at keel level

Figure 4 shows the typical resistance tendencies for a foil system mounted at keel level.

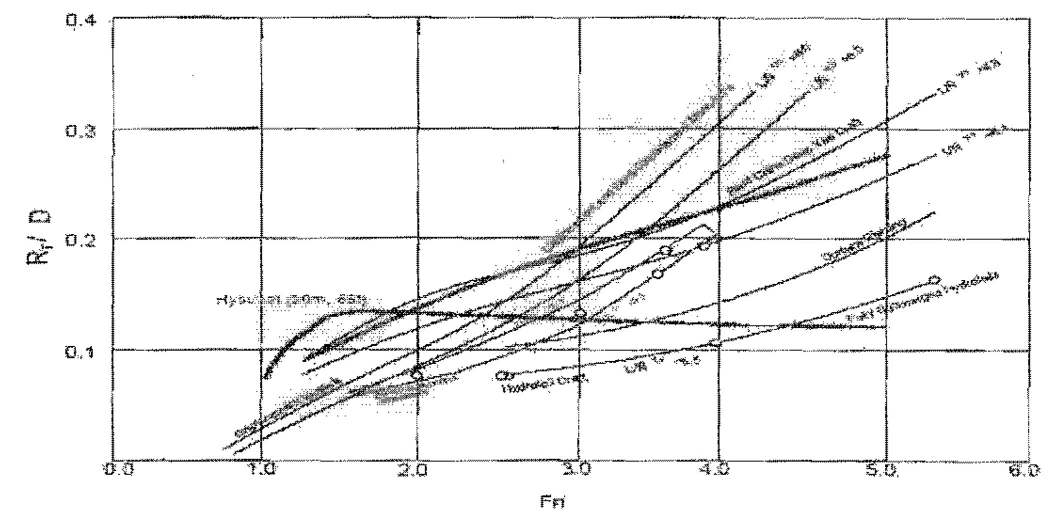


Figure 4: Resistance displacement ratio of a Hysucat for different volumetric Froude numbers in comparison with different types of craft

The figure clearly shows the increase in resistance due to the hydrofoil system around hump speed and the strong decrease in resistance above $Fn_{\nabla}= 20.2$. Hydrofoil systems such as the Hysucat have a relatively flat and sometimes downward sloping resistance curve as shown in the figure.

5. Foil systems with foils mounted below the keel

Figure 3 illustrates the wide variety of foil systems that are in use making use of foils under the keel. The resistance tendencies of these vessels is quite varied and is highly dependent on the configuration of the foil system. Figure 5 illustrates these resistance tendencies. Three distinctive phases of operation are present, displacement, transition and planing. These are shown in Figure 6. Of particular interest is the *transition speed range* as this is the range in which the majority of fast ferries operate. In the transition phase the resistance is highly variable and a transition resistance hump is common. The extent of the hump is largely dependent on the hull shape and the foil system layout. Vessels with canard foils forward (see Figure 3) typically have the highest hump as the small foils do not have the lifting capacity to lift the hull sufficiently out of the water at transition speeds. The Hysuwac foil system offers the best transition hump resistance characteristics. Due to the high aspect ratio front foil, it can provide good lift at transition speeds. The optimum resistance curve in Figure 5 is representative of that achievable with the Hysuwac foil system.

Figure 5 also shows the general relationship between waterjet thrust and resistance. If the transition hump is under predicted, the vessel may not have any thrust margin to overcome the hump even though, if this hump could be miraculously overcome a much higher speed could be maintained in the planing phase. A number of vessels have had difficulty overcoming the transition hump due to poor design and this has resulted in some hydrofoil-assisted catamarans being complete failures.

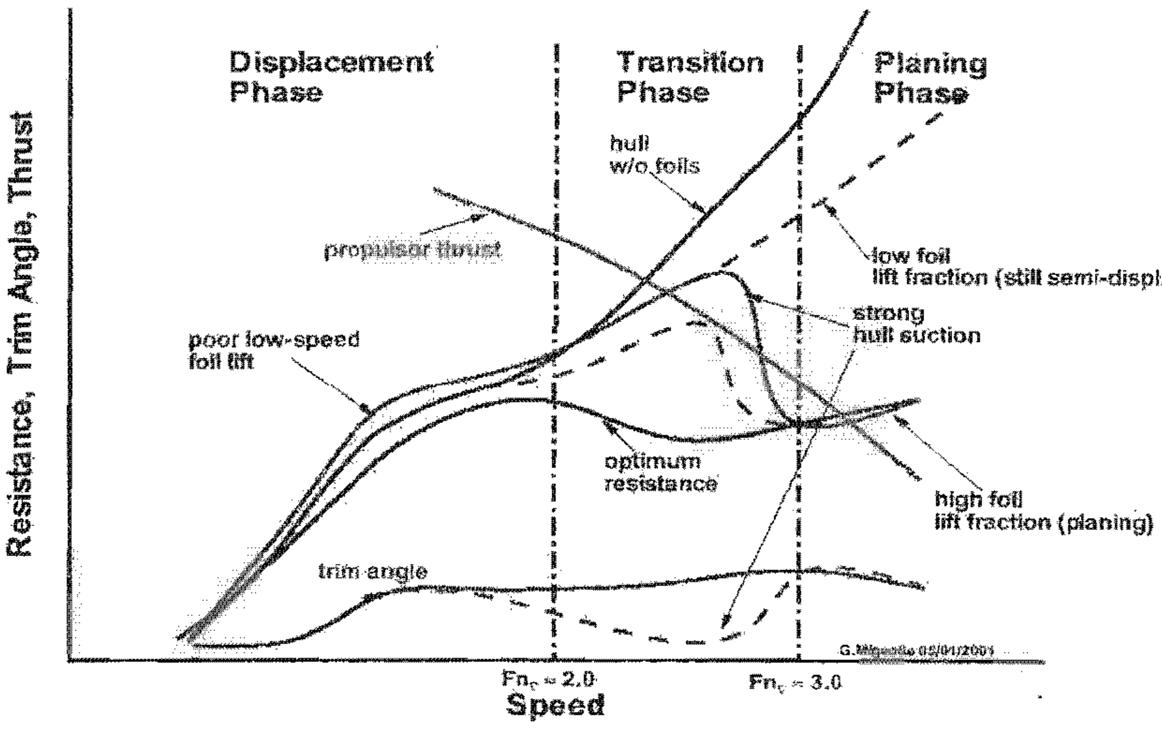
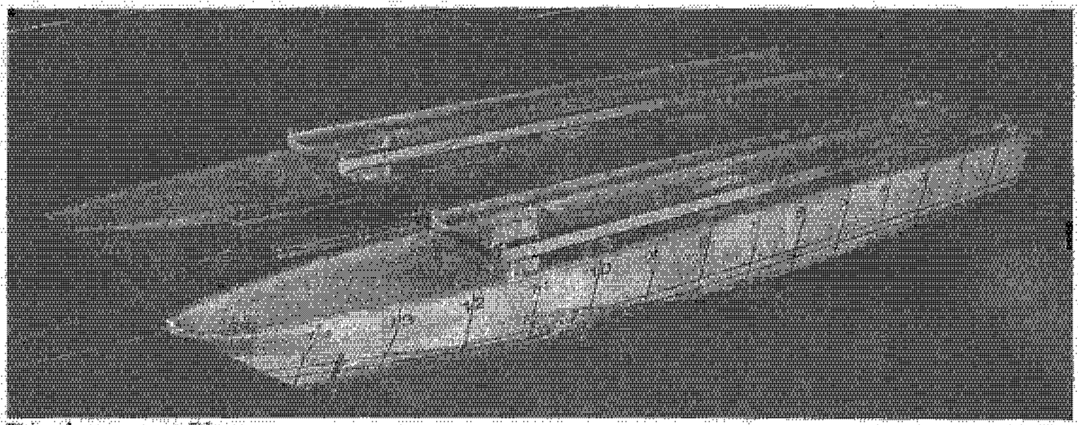


Figure 5: Resistance tendencies for hydrofoil-assisted catamarans which have foisl located below keel level

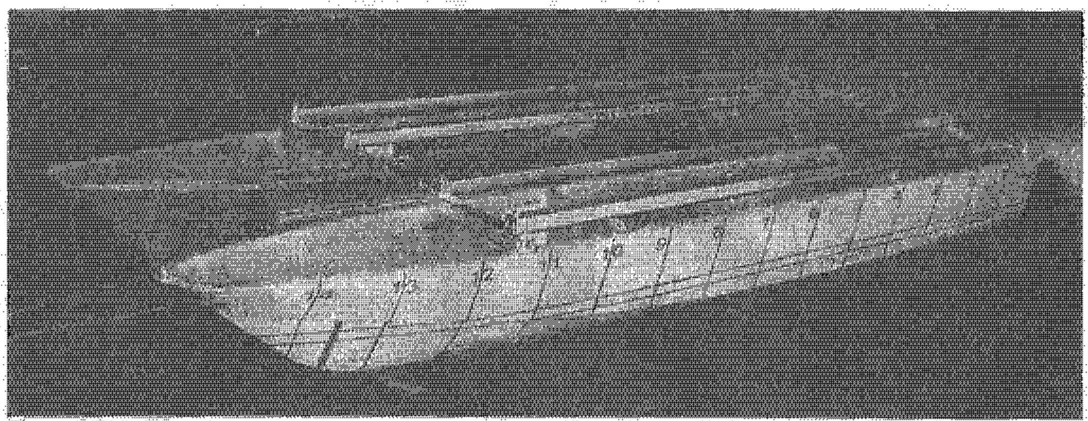
6. Propulsion systems for Hydrofoil-Assisted Catamarans

In general carrying 70% of the displacement weight on foils implies that the hull has been lifted almost all the way out of the water and in such cases the propulsion systems often need careful consideration to ensure that no ventilation occurs. Flush inlet waterjets are the most susceptible to this problem. Figure 7 shows Kvaerner's solution to this problem for the FoilCat: integrating the water inlet with the strut of the rear hydrofoil. This is not dissimilar to the intakes used by conventional waterjet propelled hydrofoil craft such as the Boeing Jetfoil. While this solution does ensure that no waterjet ventilation takes place, the overall propulsion efficiency is significantly reduced.

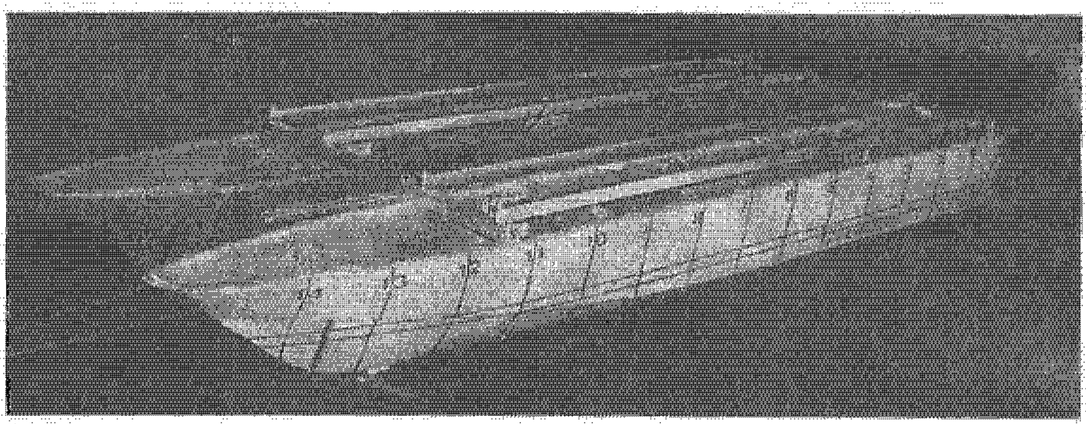
Many of the hydrofoil-assisted catamarans currently in operation today are vessels that have been retrofitted with hydrofoils. For such vessels it is not possible to easily modify the waterjet intakes and the hydrofoils need to be carefully designed so that the best reduction in resistance is obtained without lifting the hull out of the water to the extent that the waterjets ventilate.



Displacement Phase



Transition Phase



Planing Phase

Figure 6: Model test illustrating displacement, transition and planing phases for hybrid hydrofoils

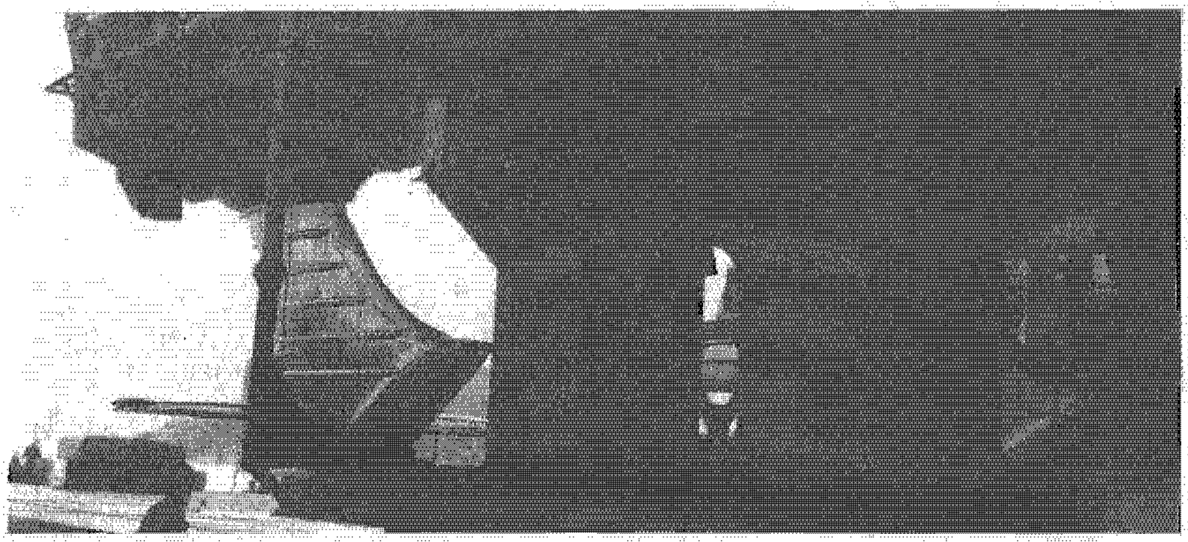


Figure 7: Waterjet Intake of the Kvaerner FoilCat

7. Planing Hydrofoil-assisted catamarans

At planing speeds it is well known that multihull interactions are generally small and if present are usually beneficial [14] as each planing hull can be modelled by the lifting analogy of Wagner [15]. Similarly the presence of hydrofoils also creates positive interference effects. Investigations by Hoppe [16] have shown that the positive interference amounts to about 20% of the drag reduction achieved with the foil system. During the design of a planing hydrofoil-assisted multi-hulls it is therefore not necessary to pay detailed attention to the complex hull-foil interactions. Conventional methods for designing planing hulls such as Savitsky's method [17] combined with classical hydrofoil theory usually gives satisfactory results to design a hydrofoil-assisted multihull. The results of such methods in experienced hands provide reliable results eliminating the need to model test the vessel [18].

8. Non-planing hydrofoil-assisted catamarans

Designing foils for non-planing speeds is hydrodynamically much more complex as at these speeds there are a number of detrimental interactions between the multiple hulls and also between the hulls and the foils.

These interactions include:

- Suction or lift on hull due to the hydrofoils
- Influence of hydrofoil trailing tip vortices on hull and propulsion system
- Wave interference between hull and hydrofoils
- Interaction between fore and aft hydrofoils A thorough understanding of these interactions is required in order to design a foil system that can provide useful resistance reduction and importantly be free of any kind of dynamic instability.

Designing a suitable foil system for non-planing hydrofoil-assisted multihulls requires a computational method that can capture the complex interactions between the hull and foils. A computational code that has the capability to model free surface effects, lifting surfaces and also calculate the exact path of the hydrofoil trailing tip vortices is required. Methods such a classical hydrofoil theory have no way of accounting for such complexities and one is forced to make us of CFD. Our experience has shown that methods solving potential flow equations provide the correct level of complexity for design purposes. The authors make use of the non-linear vortex lattice method (NVLM) as implemented in the AUTOWING software by Kornev [19]. A potential flow method such as AUTOWING allows for reasonable computational times needed for design.

AUTOWING has the capability to model the wave interactions, the vortex roll-up process and the interactions between multiple hydrofoils satisfactorily for design purposes. Figure 8 shows a typical AUTOWING result showing the free surface of a HYSUWAC type hydrofoil-assisted catamaran. Note the downwash in the tunnel between the demi-hulls created by the hydrofoils, which is not present on conventional catamarans.

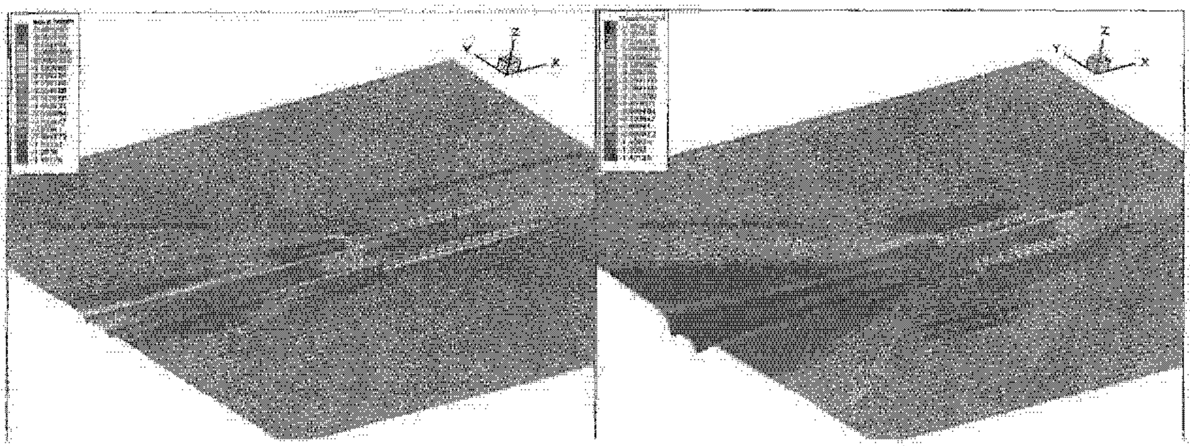


Figure 8: Comparison of free surface of a semi-displacement catamaran with and without foils using AUTOWING

Results of the NVLM as implemented in AUTOWING has been found to agree well with experiment. Figure 9 shows a comparison between measured and calculated resistance for a hydrofoil-assisted catamaran. As can be seen even sudden changes in the resistance, which due to complex non-linear hull-foil interactions are captured by the method.

As with all significant ships that have been built, model testing remains the most valuable design tool for any new development. The accuracy of model testing hydrofoil-assisted catamarans is usually somewhat less accurate than that achieved with conventional ships due to laminar flow effects over the hydrofoils. Often laminar separation of the flow over the foils is a problem. The hydrofoils are usually small in relation to the waterline length of the hull and it is therefore impossible to secure turbulent flow over the foils. Special corrections need to be made for this.

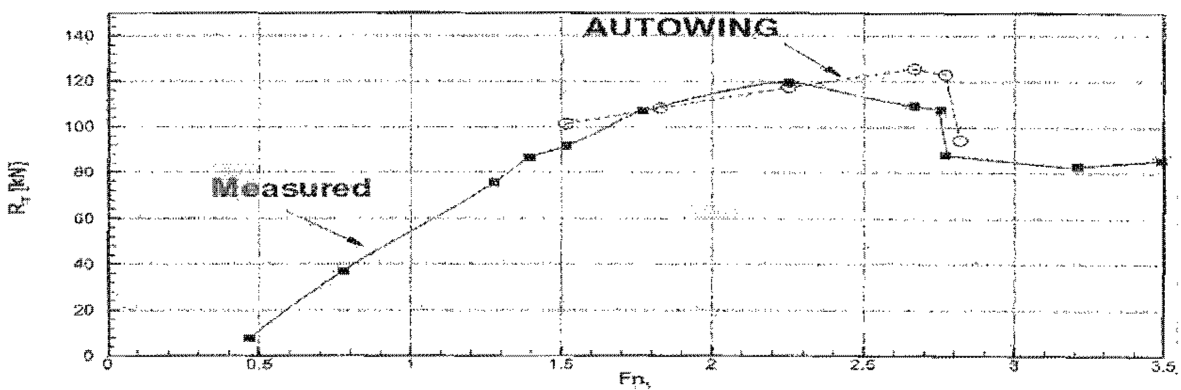


Figure 9: Resistance comparison of AUTOWING in relation to experiment

9. Future prospects and Conclusions

Hydrofoil-assisted multihulls have been in use for over two decades. Early developments in the 80's were mainly on small planing type and initial developments took place worldwide including South Africa, Russia and China. Vessels for use as pleasure craft and military craft predominated developments at this time. In the late 80's and early 90's the first catamaran fast ferries making use of hydrofoil-assistance were developed.

The sizes of hydrofoil-assisted craft have also steadily increased and the largest hydrofoil-assisted multi-hull built to date is the 50m trimaran built by North West Bay ships. It is likely that hydrofoil-assistance will incrementally be applied to larger and larger vessels as these vessels are designed to attain speeds in the order of 60 knots+.

To date the fastest hydrofoil-assisted vessel – built by Almaz – has achieved speeds of over 50 knots and it is expected that future hydrofoil-assisted craft will exceed these speeds as ways and means are found to overcome cavitation limitations at high speeds.

New developments are likely to take place – and already taking place – in the design of trimarans and monohulls making use of hydrofoil-assistance. Also hydrofoils are being integrated with SWATH technology, which will introduce a new range of SWATH/hydrofoil hybrids. Navatek Ships is spearheading this development [20].

Hydrofoil-assisted vessels over the past two decades have been shown to posses various favourable characteristics in comparison to conventional monohulls and multihulls which include, lower resistance, better seakeeping, better manoeuvrability, and lower wake wash. All these are contributing to renewed interest in these vessels in the new millennium and likely result in increasing numbers of hydrofoil-assisted vessels being utilized in all applications of high-speed ships.

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