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Hydrofoils Applied to Canting-keel Yachts

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ABSTRACT

Hydrofoils have been applied to many different types of marine craft, including yachts. However, most of these have been for attempts at speed records or by inventors and, notably, the international Moth class, but so far not to modern racing yachts. They provide a number of advantages, and this project has investigated the feasibility of application to a modern canting-keel maxi yacht.

The investigation began with drawing up a set of lines for a modern canting-keel maxi yacht. A resistance was then predicted, both with and without foils, using the Delft Systematic Yacht Series and a three-dimensional analysis of the foil-borne resistance. A towing rig was designed and constructed, and several models built and tested on open water and in a swimming pool to compare the resistance and performance, both with and without foils. Finally, a radio-controlled sailing model was constructed and tested, both with and without foils.

The results showed a clear speed advantage for the foil-assisted maxi yacht. Just as with canting keels, fitting foils to an ocean-racing maxi will not be without its problems. However, the evidence is compelling, and it is considered only a matter of time before someone sets a precedent with a full-scale yacht, which others will follow.

1. INTRODUCTION

The use of hydrofoils on sail-powered vessels is not new. Hydrofoils are used in the quest for speed, and the hydrofoil helps vessels achieve this with its high lift/drag ratio. The first sailing vessel to use a hydrofoil was *Monitor*, built in 1955 (International Hydrofoil Society 2006) and shown in Figure 1.

Since then, hydrofoils have been applied to many different types of craft, including monohulls, proas, catamarans and trimarans.

Due to the complexity and fragility of previous foil systems, their use has been confined mainly to the realms of sailing speed record attempts and inventors. However, with the use of composites and high-tensile fibres, modern foils are much more robust and simpler in design.

In recent years the introduction of canting keels to racing yachts has brought a marked increase in speed. The concept, like many innovations, attracted criticism and resistance from the establishment but has been embraced by those with more liberal views in the pursuit of speed.

The authors consider that hydrofoils are waiting in the wings for their turn to push monohull sailing speed limits higher. They therefore embarked on a testing program to investigate the feasibility of fitting foils to a modern canting-keel yacht.

2. SAILING HYDROFOILS

2.1 Previous Hydrofoils

Some of the notable sailing hydrofoils have included the following:

- *Monitor*

  Built at the then huge cost of $20 000, *Monitor* was essentially a monohull with a set of ladder-type main foils on outriggers to port and starboard and a small ladder foil aft which acted as a rudder. She reached 25 knots when launched, and 30 knots a year later (IHS 2006).

Figure 1 *Monitor* sailing on Lake Mendota, USA (Photo Edwin Stein)

- *Williwaw*

  This vessel was built in 1968 and made many ocean voyages (Keiper 1996). She was essentially a sloop-rigged 10 m trimaran, with ladder foils on the side hulls and stern, and a large V-foil at the bow of the main hull.The foil take-off speed was 10–12 kn, and she regularly sailed at 15–22 kn.

- *The Ugly Duckling*

  This vessel was built as a proa in 1982 for a serious attempt on the world sailing speed record, then 34 kn (Smit 1982). The vesel was built for a low budget, using a Tornado catamaran rig and plywood hulls. She achieved 24 kn when fully foilborne, but never broke the world record. However, she showed what could be achieved, and subsequent proas have held the world sailing speed record over the years.

- International Moth Class

  The Moth is an international class of dinghy and is a development class with liberal views on design. In the quest for speed, the class has adopted the use of hydrofoils, as shown in Figure 2. The results are dramatic, with speed increases of between thirty and one hundred percent having been achieved over their non-foilborne predecessors (International Moth Class Association 2006).

Figure 2 Hydrofoil Moth (Veal 2006)

- *L'Hydroptere*
This French-designed trimaran (the name is Greek for water-wing) has convincingly demonstrated just what a hydrofoil vessel can do. She has broken many speed records, including an open-water speed record of 47.2 kn and crossed the English Channel in less time than the first aircraft to do so! (*L'Hydroptere* 2006)

Figure 3 *L'Hydroptere* at speed (www.hydroptere.com)

There have been many others, but the sample of vessels described has shown that increases in speed are achievable with the application of hydrofoils.

In recent years the introduction of the canting keel into the world of racing yachts has brought with it a marked increase in speed for those vessels. A modern maxi-yacht with a canting keel regularly travels at speeds of 15–25 kn (International Sailing Federation 2006). It is in this speed range that a hydrofoil should be beneficial in reducing the total resistance of the yacht. Through the inherent efficiency of a foil, a speed increase can be achieved due to a higher lift/drag ratio in comparison with that of a planing hull.

The authors embarked on a project to investigate the feasibility of fitting hydorfoils to a modern maxi-yacht with a canting keel. The key to a successful foil-borne vessel is the power/weight ratio, which is directly related to the righting moment/weight ratio when using a conventional sail configuration. The righting moment, in turn, is directly related to the span of the foils.

The arrangement for the current concept of a foil-assisted monohull was commenced with research of the foil configurations of previous foil-assisted sailing vessels. *L'Hydroptere* gave much inspiration, with her use of angled outer foils and a T-type foil on the rudder. The angled outer foil gives lateral resistance and provides passive ride-height control due to the affects of dihedral. A T-foil attached to the rudder is an efficient way of stabilising the pitch of the craft.

3. DESIGN

3.1 Modelling

The basis for the design project was chosen to be the 30 m maxi-yachts *Alfa Romeo* and *Wild Oats*, designed by Reichel-Pugh. The basic dimensions of these vessels are available on the web (Reichel-Pugh 2006) but, understandably, no lines plan was available from the designer. However, a hull shape was drawn up, using the Rhino CAD package, having the correct dimensions, displacement and general hull shape. We are confident that this shape, while not being an exact replica, is sufficiently close to be able to test the concept, and to show what happens when the vessel becomes foilborne.

3.2 Scaling

For the manufacture of a model of the 30 m maxi-yacht, a scale ratio of 1:25 was selected, giving a model length of 1.2 m.

Making model to the correct scale displacement proved the most challenging task of all. The racing displacement of the 30 m maxi-yacht is 26 000 kg, which translates to $26\,000/25^3 = 1.664$ kg at 1:25 scale. The challenge lay in keeping the model this light, yet strong enough to handle the sailing forces.

Initial estimates of masses which would be required were as follows:

Item	**Mass (kg)**
Keel	0.915
Fin and rudder	0.130
Sails and rig	0.110
Deck and support structure	0.110
Radio-control unit	0.140
Hull	0.259
Total	**1.664**

With a 1.2 m hull, a mass of only 259 g is a very hard task. Strength scales as the square of size, while mass scales as the cube (the square-cube law), so the material for our 1:25 scale model should be relatively twenty five times stronger than that of the maxi-yacht! If it were not for the non-scaling of materials, then the model would be almost impossible to make.

3.3 Resistance Prediction

Having determined the size of the model, preliminary estimates of the resistance were made using the Delft Systematic Yacht Series for the hull and Design Foil for the foil. The Delft Series II resistance prediction is available in Gerritsma et al. (1991) and was programmed. Although not catering for modern vessels travelling at over 20 kn, the Delft Series predicted resistance up to the speed at which the foil system would take over.

At more than 20 kn the yacht would become foilborne, and the Design Foil program (Dreese 2006) was used to calculate the resistance of the foils. Design Foil is a two dimensional CFD program that is simple to use and proved a useful tool in selecting the foil geometry. A NACA4412 foil was chosen for its characteristics at different angles of attack (other than at optimum). Results of the resistance calculations are shown in Figure 4.

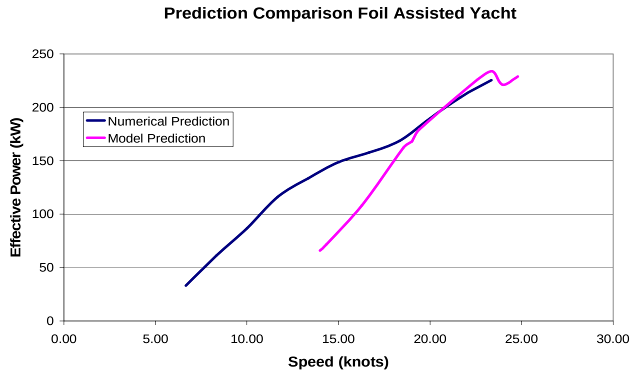

Figure 4 Resistance calculations from Delft Series and Design Foil

It is not possible to include all of the forces which will act on a hydrofoil-assisted yacht. However, the results of this resistance prediction have been useful in the design of this concept. The resistance predictions have added weight to the viability of this concept.

3.4 Arrangement

The arrangement used for the design of this concept is shown in Figure 5. It is envisaged that implementatin of this concept would incorporate active main foils to give a constant ride height; much in the same way as the foil of a modern Moth dinghy works. This results in a foil depth which greatly diminishes the free-surface effect, thus reducing wavemaking resistance. An active foil will also deliver good seakeeping characteristics (a smooth ride), by eliminating wave impact loads.

The incorporation of retractable foils would solve the problem of foil resistance at speeds below foilborne, and solve most berthing problems.

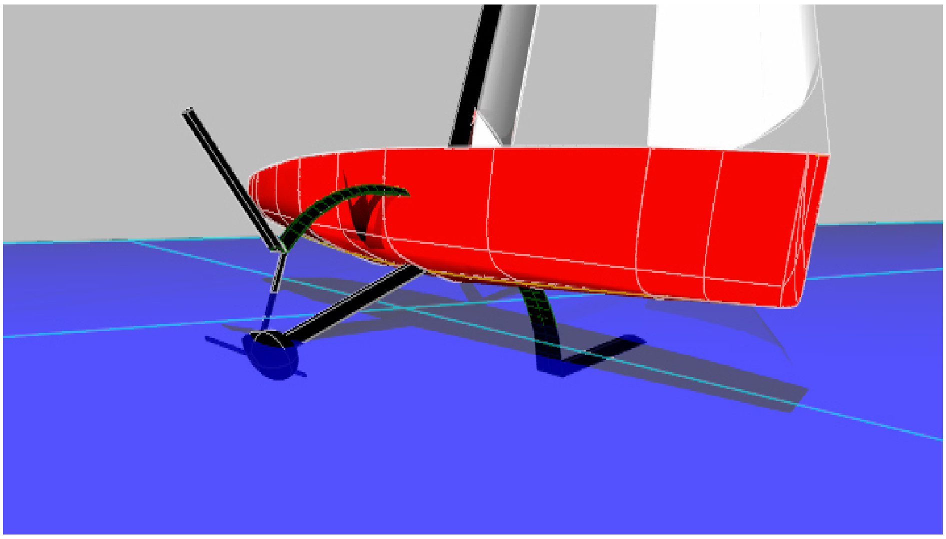

Figure 5 Concept of the hydrofoil-assisted maxi-yacht

4. CONSTRUCTION OF MODELS

The building of the prototype male plug and female mould gave a good insight into the effort required to create a full-size mould for production. Building of a male plug is a task which requires the utmost precision and quality of finish. Any imperfection, mark, or blemish in the male plug will be carried over to the mould and, most likely, to every production hull to come from that mould. Spending the time to get it right from the start saved a large amount of time later. Much of the time was spent checking dimensional precision and fairness of the surface. Any variation required filling and sanding until a level of perfection was reached.

The prototype was built using a foam sandwich structure. Strips of Divinycell foam were attached to a plywood mould with double-sided tape and covered with a layer of fibreglass and resin as shown in Figure 6. The prototype was lifted off the mould and glassed on the inside.

Many weeks were then spent filling and sanding the outside until perfect finish and shape was acquired, as shown in Figure 7.

Figure 6 Plug under construction, still attached to building frame

Figure 7 The finished plug

To form the female mould, a thick gelcoat followed by many layers of chopped-strand fibreglass and a set of frames produced a good mould, as shown in Figure 8. From this mould exact copies could be made.

Figure 8 The female mould

As previously mentioned, making the model to the correct scale mass proved the most challenging task of all The challenge lay in keeping the model light yet strong enough to handle the sailing forces. In all, seven hulls were made and only one was light and strong enough to be used as a sailing model; another was slightly heavier and was able to be used as a towing model.

Hull No. 4, shown in Figure 9, ended up being the lightest hull. The first layer was 200 gsm, with a vacuum bag being used to hold the core down after just wetting the contact surface of the core before installing. The final layer of 25 gsm glass was applied with care, trying not to use too much resin as it would fill the cavities of the Nomex. The light weight glass was difficult to work with, as it was easily snagged and pulled out of shape. Even with a lot of care, a little extra resin was used. This hull on release from the mould had a mass of 260 g, but was quite stiff and strong. After fitting out, fin, rudder and radio control added, it came to a total weight of 780 g and was used for the live sailing model. This meant with the rig and keel weight added, the model was 1.770 kg, thus being slightly overweight for the model scale, but close enough to use for sailing.

Figure 9 Hull No. 4 showing Nomex honeycomb core
foils later moved to lower position

In the three subsequent models, fine silk was used as a reinforcement for the inner skin and a lighter 90 gsm fibreglass was sourced for the outer skin. The outer skin and the Nomex laying went very well, but there was some spillage of resin onto the Nomex during the laying of the inner silk skin. Out of the mould, Hull No. 6 had a mass of 340 g, and this hull was fitted with a canting keel to allow the model to run at the desired angle of heel in the towing tests, as shown in Figure 10.

Figure 10 Towing model with canting keel, note foil on centreline

5. TOWING TEST RIG

We had no towing-tank facility available for low cost, and so designed and built a test rig to measure the resistance of the model for a range of speeds while providing the motive force to bring the vessel to the foil-borne condition. The resulting machine turned out to be easy to use, portable and reliable.

The concept was that the model would be pulled through the water by a light nylon fishing line which was wound in by the machine. The machine, in turn, gave a tension reading on a linear spring scale from this nylon line and thus gave the force required to tow the model. Although the nylon line in the water added a small component of resistance, this was disregarded.

The towing apparatus needed various speed settings in order to obtain the different speeds through the water. Speed control was achieved by the use of an electronic controller with negative feedback of the voltage output. This speed controller was built with parts readily available from an electronics store. With a constant voltage, regardless of the load, the model could be towed at a constant velocity.

A simple voltage regulator was incorporated to stabilise the towing speed. Regulated power delivery is very useful when selecting a desired speed especially if the speed is in the early stages of the planing or foilborne regions. As a model approaches foilborne speed, it encounters a resistance hump and the speed controller applies extra power to pass through this hump and into the foilborne mode. Once the model is foilborne, the resistance is decreased, resulting in reduced power requirements. This allowed us to obtain results near the resistance hump.

However, a simple controller would keep on supplying the power required to pass through the hump, even when foilborne, and would cause the model to accelerate to much higher speeds. Also, if the simple controller were to be set at the power requirement of just being foilborne, then the model would never pass through the resistance hump. A simple controller would miss out on some of the most important data needed for this project.

Trial-and-error was used in selecting the correct electrical variable resistor setting which would give a desired power output range needed for the models.

The completed towing apparatus is shown in Figure 11.

Figure 11 Towing apparatus

The crux of the towing apparatus is its ability to give a reading without the influence of internal frictio. Elimination of internal the friction component is achieved with a vertical mast which is perpendicular to the incoming nylon line. On top of the mast is a lightweight pulley, over which the line travels, and then down parallel to the mast and onto the winding spool. Any friction due to the pulley on the top of the mast is transmitted vertically through the mast and not in the direction of the incoming line, so the friction causes no moment on the mast structure. The mast is able to rotate about its base and move in the direction of the incoming line. A spring gauge is attached to one side of the mast to give readings of varying incoming line tensions.

A radio-controlled rudder on the model enabled it to be steered in a straight line towards the towing machine. A slight deviation off course (five degrees or less) would not significantly influence the results. An advantage of using the nylon line is that there is a small amount of elasticity in it whereby any small waves or any slight deviation of the model does not instantly translate into a change in the tension at the towing apparatus. Thus a constant tension can be measured while the model is still some distance from the towing apparatus.

6. EXPERIMENTS

6.1 Towing Tests

A preliminary set of trials with the towing rig was conducted in the open harbour in order to refine the process and iron out any bugs in the towing and resistance-measuring apparatus. After a period of trial and error, the towing tests proved successful, and it was time to test the model in a more controlled environment.

The Swimming Pool at the University of New South Wales was selected for the trials, one of the advantages being that distance and time could be accurately measured. Many towing runs were conducted without foils to simulate the conventional hull, with speed and resistance being recorded. Runs were then made with the foils fitted and, again, speeds and resistances were measured. An example is shown in Figure 12.

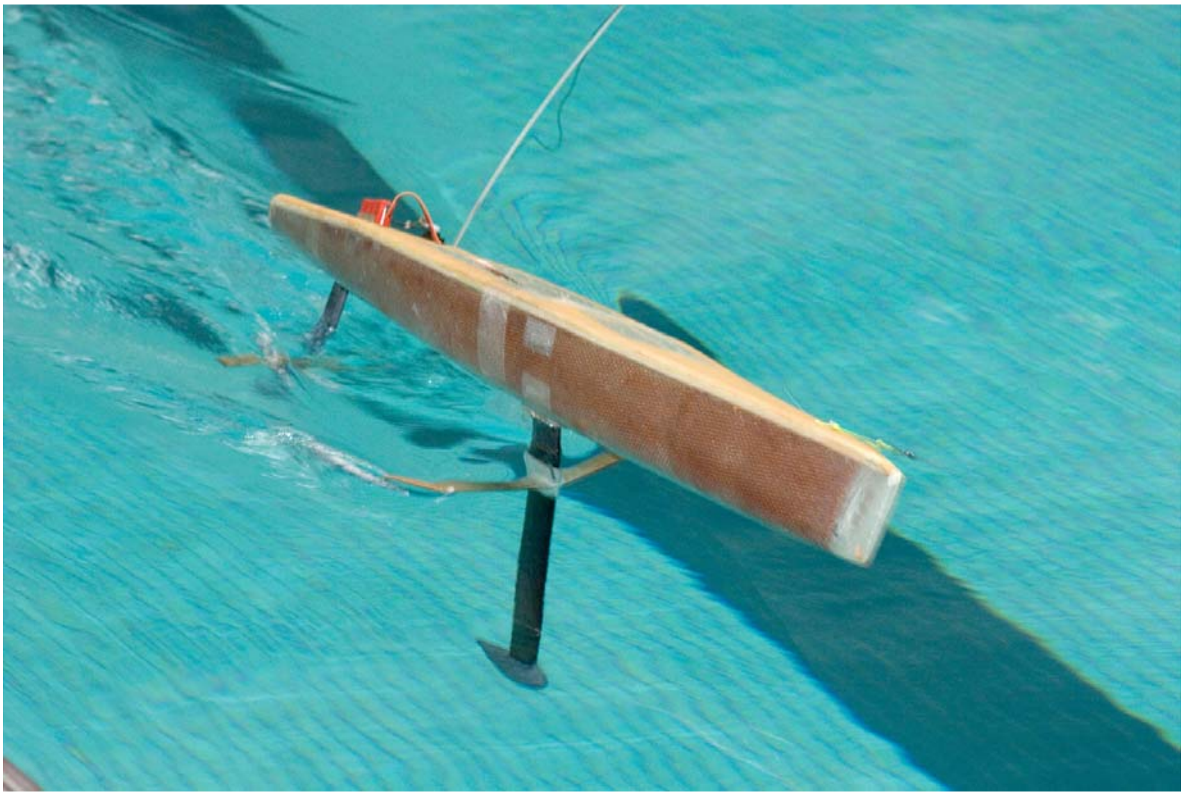

Figure 12 Model foilborne with tips just breaking the surface at 1.74 m/s

Once the vessel was foilborne, any small waves which were present seemed to have very little impact on the way the vessel behaved. Thus small wave conditions might be a more ideal testing scenario for the model in both foilborne and conventional-yacht configurations, as it simulates the true operating environment of an ocean-going yacht.

The model required a speed of around 1.74 m/s (16.9 kn at full scale) to become foilborne. However, once foilborne the speed could be slowed to 1.55 m/s (15.0 kn at full scale) and still remain foilborne.

The resistance results are shown in Figure 13, and bear a marked similarity to the numerical predictions which were made in the early design stage (Figure 4), thus verifying the predictions.

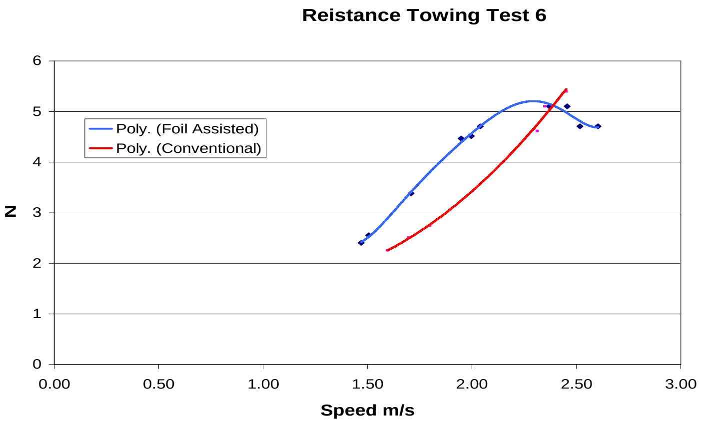

Figure 13 Resistance results for conventional and hydrofoil hulls

6.2 Sailing Tests

A set of sails (main and genoa) and rig was designed, built and fitted to the vessel, as well as radio-control gear. The overall mass ended up approximately 130 g (8%) above the scaled displacement.

Scaling of the wind strength also plays a part in modeling sailing trials. A maxi-yacht sails in winds of up to 40 or 50 kn, so the model could be expected to sail in 10 kn, with average wind speeds of 5–6 kn. This is a light breeze, and there are often periods of associated calm. The mast on the model is 1.5 m tall, and the wind gradient can be extreme at this level.

In all, five sailing trials were conducted, each one an improvement on the previous trials and with many lessons being learned along the way. The first trail was a near-disaster, with the model almost sinking! However, the proof of the pudding is in the eating, and the fifth trial was the most successful. The model became foilborne at about the same speed as the towed model (estimated rather than measured). Figure 14 shows the model up on the foils.

Figure 15 Model reaching on foils

7. CONCLUSIONS

The concept of a hydrofoil racing yacht has been investigated in this project. A 30 m Reichel-Pugh design has been used as a basis, and resistance calculations done to show that speed advantages by way of lower resistance) can be achieved in the range of 15–25 kn. Two models were then built at 1:25 scale, and towing and sailing trials conducted. The results show that this concept works — at least in model form.

Implementation at full scale may not be easy; there will be problems with structure, control and berthing arrangements. Some of the problems can be solved relatively easily, such as by using retractable foils to reduce resistance below foilborne speeds and obviate berthing difficulties; some problems are more difficult to solve. However, canting keels are not without their problems either (and not all have yet been solved), but canting keels are now firmly entrenched for the go-fast enthusiasts. Many factors give a full-sized yacht advantages over the model where hydrofoils are concerned: the ability to trim sails, have an active main foil, and an adjustable rear foil.

It is the author’s belief that when one enthusiast takes the plunge and fits hydrofoils to a full-sized yacht, then the speeds achieved will convince more to follow.

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