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BOTTOM IMPACTS ON SMALL CATS

Design Brief

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Hydrofoil-Supported Catamarans

The first commercial high-speed HYSUCAT (hydrofoil-supported catamaran) was produced in South Africa more than 30 years ago. Since then, acceptance has been slow, but increasingly the sophisticated technology is recognized for improving speed, fuel efficiency, seakeeping, and comfort.

by Gunther Migeotte

The advantages of hydrofoil support are many; so why aren't all high-speed catamarans foil supported? The short answer is that the complexity of the technology doesn't forgive mistakes, and to work properly, a hydrofoil arrangement must be precisely suited to the hull shape, displacement, center of gravity, and propulsion system. A more complete answer demands an account of the design origins and practical development of the type.

Background

In hydrofoil-supported catamarans, a hydrofoil system—located in the tunnel between, and sometimes below, the hulls—carries a significant part of the vessel's weight via dynamic lift. This is generally possible only on high-speed craft, since the hydrofoils depend on speed to generate sufficient lift.

Nonlifting hydrofoils are commonly employed on displacement and semi-displacement catamarans solely for improving seakeeping (and increasing resistance). The *USS Hayes,* built as a hydrographic survey ship for the U.S. Navy in the 1970s, was the first significant catamaran with hydrofoils, albeit not lifting foils. At the same time, pioneering research in the Soviet Union was being done on high-speed hydrofoil-supported catamarans for heavily loaded vessels using the MBK series of hulls, which were split along the symmetry plane to create an asymmetric planing catamaran. (No finished boat was produced.)

Development of asymmetrical hulls with hydrofoils followed a similar path in South Africa. At Stellenbosch University, K.G. Hoppe developed the first South African commercial high-speed hydrofoil-supported catamaran in 1980; it was based on a new hydrofoil configuration patented in various countries (most of the patents have expired). This hydrofoil arrangement plus hull, HYSUCAT (HYdrofoil SUpported CATamaran), is a registered trademark in many countries, and is

Facing page—*The elaborate foil system is clearly visible between the hulls of this 45m (147.6') TriCat model built by FBM Marine (United Kingdom). This HYSUCAT can transport 330 passengers at speeds of 45 knots and is powered by twin gas-turbine engines.* ***Right***—*A smaller model illustrates some basics of the original HYSUCAT patent: a foil system comprising a main hydrofoil and two stern hydrofoils combined with an asymmetric-hull catamaran.*

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applied as a brand name or company name by boatbuilders worldwide that offer hydrofoil-supported catamarans based on the original patent (see photo above). In fact, the majority of hydrofoil-supported catamarans today employ the technology originally developed at Stellenbosch University, although most of these boats are not branded as HYSUCATs.

Since 1980 more than 1,000 hydrofoil-supported catamarans have been built worldwide in sizes ranging from 4.5m to 42m (15′ to 138′) in length, and the fastest vessels achieve upwards of 70 knots.

Main Principles

Hydrofoil-supported catamarans work on the principle that a significant portion of the boat's weight is carried on the foils, lifting the hull partially out of the water. The lift-to-drag ratio of a hydrofoil is typically L/D = 20, while that of a typical planing hull is L/D = 4–6. Therefore, the load fraction on the foils is being carried far more efficiently than that on the hull. From a resistance point of view, it makes sense to carry as much load on the foils as possible and get the hull out of the water.

Of course, it's possible to lift the hull completely out of the water and carry 100% of the load on foils. This is the most hydrodynamically efficient, but keeping the hull partially in the water offers two distinct advantages in stability and propulsion.

First, the hulls provide the necessary stability in pitch and roll. While shallowly submerged hydrofoils are naturally stable under the surface, without the hull adding stability, it is necessary to have either:

- surface-piercing hydrofoils with a span beyond the beam of the hull and positioned below the keel. (The added beam and draft make the hydrofoils prone to damage, and they are not practical in most applications.) or
- deeply submerged hydrofoils using sophisticated flight control (but this adds considerable cost and complexity to the foil system).

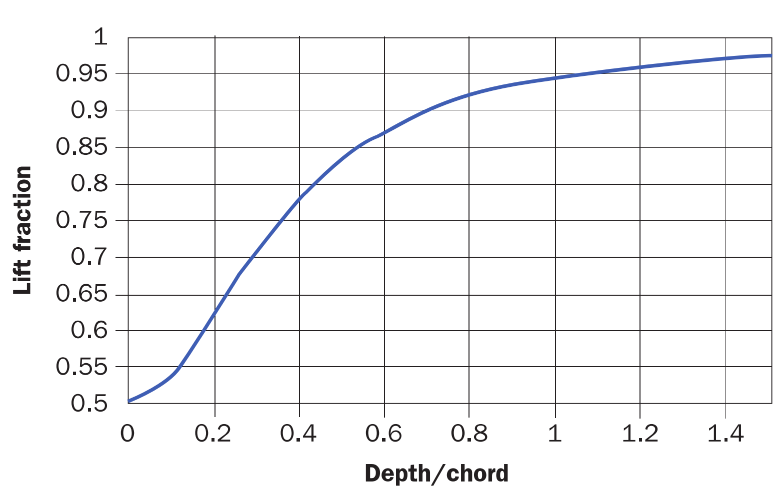
Second, with the hulls still in water contact, conventional propulsion such as propellers, waterjets, surface drives, pods, and outboard engines can all be used in their standard, proven configurations without difficulty.

The most common foil configuration in use today is a main hydrofoil and two stern hydrofoils combined with an asymmetric-hull catamaran, shown at left. Another common variant for applications requiring more lift in the stern is to replace the two rear foils with a single foil spanning the tunnel.

Both configurations apply the same basic idea that the main foil is located at keel depth, and the rear foil is located some distance above the keel near the transom. **Figure 1** shows how the lift of a hydrofoil changes with its depth below the surface of the water. As shown, the forward foil is the main load-carrying foil, so it should be as deeply submerged as possible to have the best possible lift-carrying capability. Also, it makes practical sense to position the foil at keel depth so the keel protects it from grounding.

The rear foil or foils maintain pitch stability. Without them, the hull tends to pitch around the main foil, creating a porpoising-like instability in all but calm water. To work effectively, a

Figure 1. Hydrofoil Lift



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The lift of a hydrofoil reduces quite dramatically as the foil gets closer to the free surface of the water. However, once it is submerged deeper than one chord length, there is little further change in lift.

change in pitch angle should cause a significant change in the rear foil lift to counter the vessel motion. As the hydrofoil-supported catamaran pivots in pitch around the main foil, any change in pitch results in a change in submergence and angle of attack of the rear foil. Figure 1 shows us that such a change in submergence produces a strong change in lift if the foil is shallowly submerged at less than about 0.5 chord length, hence the reason to position the rear foils above the keel.

Here's how the rear foils counter the pitch movement: If the vessel pitches up, pivoting around the main foil, the rear foils will submerge deeper and increase their angle of attack, increasing lift and creating a bow-down moment to counter the vessel motion. If the hull pitches down, the rear foils will come out of the water, losing lift completely, again countering the pitch motion of the boat.

In practice, however, it is not quite that simple. The front foil usually creates a wave trough downstream of it, which alters the submergence of the rear foil. Also, the hulls create waves in the tunnel, further complicating matters. So it can be quite difficult to work out a suitable position for the rear foils. Unless computational fluid dynamics (CFD) and/or model-testing is applied to the problem, it takes experience to get it right—particularly for transitional-speed applications. Shown above is a foil at its design submergence at top speed.

A shallowly submerged rear foil running at its designed depth. The foil is almost planing, and its lift is about 50%–60% of a deeply submerged foil's lift. If the bow pitches up, this foil will submerge deeper with increased angle of attack, creating more lift, which counters the bow's pitch-up motion.

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Design Challenges and Advantages

The complexity of hydrofoil-supported catamarans has resulted in some spectacular failures by inexperienced designers and builders over the years, tarnishing the general perception of the technology's capability.

Getting the right balance between the various force vectors (hydrofoil lift, hull lift, thrust, resistance, etc.) is critically important to success. Changes to the weight or centers of gravity often have dramatic effects, with difficulties somewhat akin to designing good stepped hulls. To further complicate matters, there are no simple design rules to follow. For example, even choosing the percentage of weight carried by the foils depends on multiple factors, such as speed, wave heights, hull shape, and propulsion (see the **sidebar** on common design mistakes, on page 76). Most vessels are in the region of 30%–60%.

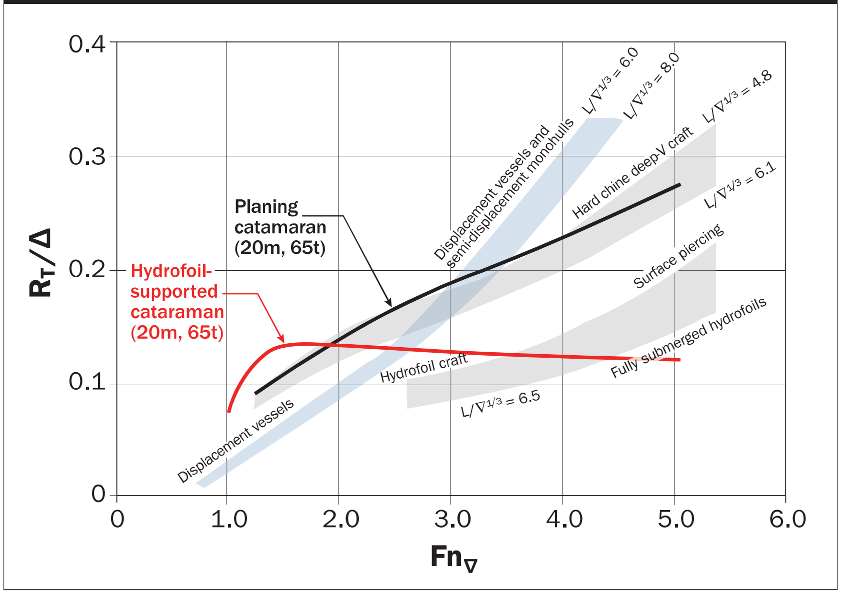
Success requires close cooperation between the builder and the designer, with careful monitoring of weight and centers during the build; and necessary adjustments must be made to the foil arrangement and settings once final weight figures are known. The builder also has to take special care in the foil system setup, ensuring that the tolerances for angles of attack are maintained (normally within 0.1°). The whole process is more akin to aircraft industry procedures than to standard boatbuilding.

With proper implementation, however, the performance advantages are significant and have been proven on hundreds of vessels. It is known from a large body of anecdotal evidence that hydrofoil-supported catamarans have softer riding characteristics than equivalent catamarans or deep-V monohulls. There has been very little proper measurement to quantify the effects, but the available test data indicate that pitch, heave, and vertical accelerations are reduced in the order of 50% at the center of gravity and farther aft. In broad terms, the hydrofoils counter the motion of the hull. Take for example the scenario of the hull striking an oncoming head wave: when the bow strikes the oncoming crest, the hull starts to rise, changing the inflow angle to the hydrofoil and in turn reducing the lift. The hulls then carry more load, allowing them to pierce through the wave rather than following the wave slope exactly, as a lightly loaded hull does. Conversely, if the hulls heave downward into a trough, the foil lift increases, helping the hull not to slam. Pitch is improved in a similar way but mainly due to the effect of the rear foils.

In short, choppy seas the ride tends to be extremely smooth, with the hydrofoils allowing the vessel to run smoothly on the crests. In long waves, hydrofoil-supported catamarans tend to become airborne more easily, but this tends to be with constant trim angle if the hydrofoils are set up correctly, and does not create excessive vertical accelerations. The reentry also tends to be smoother if a swept hydrofoil is used.

Another advantage is that at planing speeds a drop in resistance of up to 50% is possible, which equates to significantly higher speeds or lower powering requirements. Lower power normally results in a 10%–30%

Figure 2. Resistance Comparison of Conventional and Foil-Supported Cats



One primary advantage of HYSUCAT technology is a drop in resistance at planing speeds, which converts to lower power requirements and better fuel economy. The solid red line represents a typical resistance curve for a HYSUCAT, the black that of a conventional planing cat. Both are overlaid on resistance curves for other hull types.

reduction in fuel consumption at planing speeds. **Figure 2** shows the typical resistance trends for various hulls, and also the typical hydrofoil-supported catamaran resistance curve, which is commonly flat or even downward sloping. As examples, in **Figure 3** various hydrofoil-supported catamarans are compared to similar non-foil-supported vessels by employing Michael Peters/Eduardo Reyes K value (see *Professional BoatBuilder* No. 126, page 40, Figure 7) as well as the transport factor, TF.

$$TF = \frac{gV\Delta}{P_B}$$

where:

g = 9.81 m/s^2
V = speed in m/s
Δ = displacement in metric tons
P_B = installed power in kW

The benefits extend to maneuvering: As the hull is partially lifted out of the water, its lateral area is reduced, allowing tighter turning circles than conventional catamarans and monohulls can execute. Unlike regular catamarans, hydrofoil-supported catamarans can be designed to lean into a turn much like monohulls. The foils do not impair handling or create directional-instability/broaching problems. Tight turns can be performed in waves without any form of instability.

Finally, measurements done on a variety of vessels with and without hydrofoils have shown that by adding a hydrofoil system, wake wash (wave height and wave energy) is reduced by almost 30%, because of the wave-cancellation effects between the hull and hydrofoils. Hydrofoil-supported catamarans are thus well suited to pristine natural areas.

Figure 3. Comparisons of Three Hullforms

	Stingray hydrofoil-supported catamaran	Chantier Delavergne monohull	HAWC 11 hydrofoil-supported catamaran	SEASWIRL 3301 monohull	SAR14 hydrofoil-supported catamaran	Freeman 40 catamaran
Length overall	44′/13.42m	39′4″/12m	35′/10.67m	33′5″/10.05m	42′8″/13m	40′/12.2m
Beam	14′5″/4.4m	11′9″/3.59m	12.5′/3.65m	11′/3.35m	13′9″/4.2m	13′/3.96m
Deadrise	22°	—	24°	20°	24°	—
Test weight	23,237 lbs/13.5 t	21,515 lbs/12.5 t	12,120 lbs/5.5 t	12,190 lbs /5.53 t	22,928 lbs/10.4 t	16,087 lbs/7.3 t
Speed (as tested)	42 knots	42 knots	46 knots	40.4 knots	49.6 knots	52.6 knots
Installed power	2 x 429 hp	2 x 600 hp	2 x Suzuki 250 hp	2 x Yamaha 250 hp	4 x Yamaha 300 hp	4 x Yamaha 300 hp
Propulsion	Arneson surface drive	France Helices surface drive				
Fn_∇	4.49	4.55	5.58	5.01	5.54	6.23
K value	2.14	2.25	2.20	2.26	2.20	2.26
Transport factor	4.47	2.96	3.35	2.30	2.91	2.17

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A comparison of three different HYSUCAT models, a conventional high-speed catamaran, and two planing monohulls. Note the Stingray catamaran with 40% less power and 8% more weight than the Delavergne monohull for similar speed. The HAWC 11 has 5.6 knots higher speed for the same weight and propulsion as the significantly lower-deadrise Seaswirl 3301. Compared to the Freeman 40 conventional catamaran, the SAR14 shows almost the same speed with about 5,000 lbs (2,268 kg) of additional weight and a much larger superstructure creating wind resistance.

Calm-Water Performance

Figure 4 illustrates the resistance characteristics of a hard-chine hydrofoil-supported catamaran. (This is shown in more general terms in Figure 2 compared to different types of hulls.) Three speed ranges are identified by volumetric Froude number: displacement, transition, and planing.

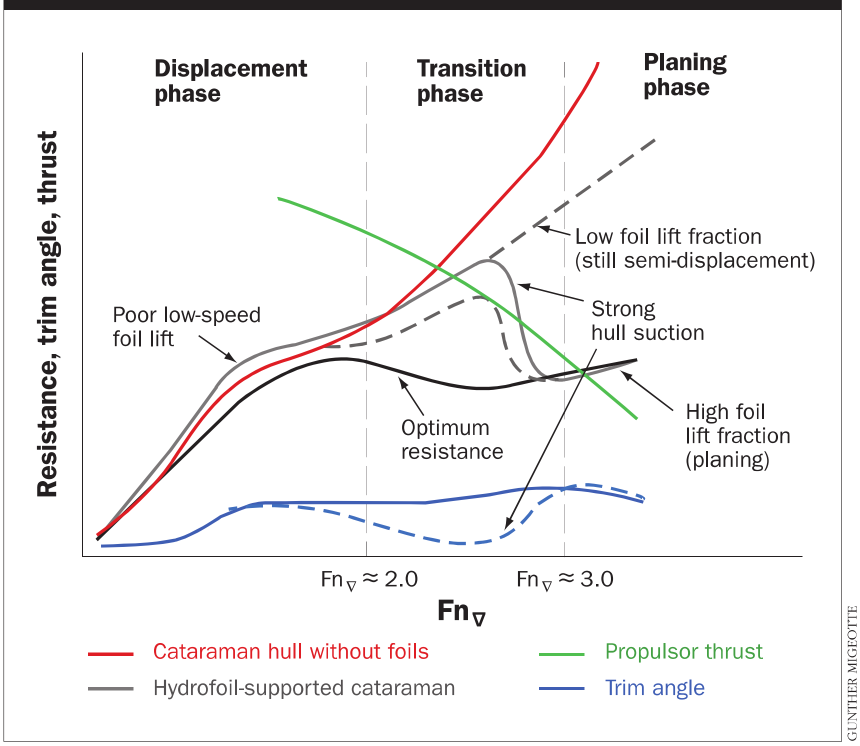
In the **displacement** mode, $Fn_\nabla<2.0$, the hydrofoils' lift is a small fraction of the boat weight, so the foils can't affect hull resistance much. Resistance reduction, if any, is usually less than 10% and is due to strong stern foils trimming the vessel optimally around hump speed—similar to the effect of a trim tab.

At **transition** speeds $2.0<Fn_\nabla<3.0$, things are complicated by strong interactions between the hull and the foils. For hydrofoils designed to carry only a small fraction (<40%) of the vessel weight at design speed, they transition from increasing resistance to a situation where they now reduce resistance, compared with the same hull without foils. A good rule of thumb is that for resistance considerations it makes sense to use hydrofoils only if the design speed is $Fn_\nabla>2.2$. Below this Froude number, there are usually cheaper ways to achieve the same results: for example, by using trim tabs or interceptors (but these devices will not have the same motion-damping effect).

A transition hump resistance can be present depending on the hull shape (particularly the buttocks) and the hull–foil interactions that result. If the transition hump is too high, the boat can get stuck on it and never achieve planing speeds. If the foils eventually overcome the hull suction, the end of the transition hump causes a sharp drop in resistance, and the hull literally "pops-up" out of the water with a sudden increase in trim.

True **planing** hulls designed to operate at $Fn_\nabla>3.0$ achieve the best performance, with resistance reductions of more than 50% possible. As mentioned earlier, the resistance curve of hydrofoil-supported catamarans is flat or even down-sloping at planing speeds. A word of caution here: a flat resistance curve means the thrust curve and the resistance curve intersect each other at a finer angle. Small changes in resistance due to trim adjustment, added weight, LCG shift, etc., have a more pronounced effect on the speed than they would in a conventional catamaran or monohull, so achieving contract speeds can be tricky.

Figure 4. Performance Tendencies for Hydrofoil-Supported Catamarans



Overlaying thrust, resistance, and trim angle data illustrates: at which Froude number the added lift from foils tends to overcome their added resistance; the importance of correctly sizing the lift fraction to the hull; and the effect of strong hull suction on resistance and trim angle.

Hydrofoil Fabrication and Structural Design

Hydrofoils are very thin structures that carry a lot of load in a highly dynamic environment. High stresses and fatigue are common problems, along with impacts with floating debris or groundings.

Operation usually determines the choice of foil material. Aluminum can work for leisure boats, which operate a limited number of hours in generally calm conditions. However, as the operating conditions get harsher, aluminum foils may crack well within the lifetime of the boat, unless the foil is beefed up beyond the optimum thickness-to-chord ratio. Also, aluminum does not withstand damage well and usually requires repairs after impact with logs or other hard objects.

My material of choice is duplex stainless steel (LDX2101, SAF2205, or in special cases, SAF2504). These steels have extremely good impact and fatigue strength characteristics as well as corrosion resistance. They allow a hydrofoil with optimum hydrodynamic dimensions, good fatigue life, and excellent impact resistance. The main disadvantages are cost and fabrication challenges. Duplex steels tend to distort a lot during welding. It takes an experienced fabricator to put such a foil together within tolerance.

For high-end applications, titanium is a possibility. It offers all the advantages of duplex steel coupled with much lighter weight, but the materials cost more and make fabrication significantly more difficult. Regarding weight, note that the complete hydrofoil system generally weighs less than 4% of the total vessel weight. If you save, say, 50% on the hydrofoil weight using titanium, you still end up with

COURTESY MARTYN CASTELEIN

GUNTHER MIGEOTTE

Left—*This titanium foil was built by Ocean Stainless in Taiwan to mount between the hulls of a 15m (49.2') HYSUCAT yacht.* **Right**—*A crew fabricates the 12m (39.3') stainless steel foil for the 45m TriCat model pictured on page 68. Foils are thin, highly loaded structures operating in a dynamic environment, making it essential to select materials appropriate to the vessel's intended operations. Aluminum foils are suitable only for light use in relatively calm conditions.*

only a 2% lighter boat. The added cost of titanium could most likely be better spent on effectively reducing weight in other parts of the boat.

For commercial and military vessels, classification society approval is a common requirement. Most classification societies do not have detailed rules on design and construction requirements for hydrofoils. The exception is the Russian Maritime Register of Shipping's High-Speed Craft rules. Other classification societies will require the design to be handled based on first principles following their basic guidelines. For example, the international classification society DNV-GL's Classification Note No. 30.8 Section 5, High Speed Light Craft Supported by Foils, requires the following:

- a failure mode and effect analysis (FMEA)
- detail design loads on the foil system with no empirical or simplified expressions
- finite element analysis of the complete foil. In the case of simple hydrofoils, a simplified analysis such as beam theory is possible, but in the case of complex foils that have sweep, dihedral, and multiple struts, such simplifications are not possible.
- buckling analysis
- detailed analysis of bolted connections
- local strength in way of hull support for the foil system.

The design requirements for class are therefore quite arduous. Fortunately, many classification societies consider

Common Design Mistakes in Hydrofoil-Supported Catamarans

• *Too much lift on the hydrofoils* lifts the hull very high out of the water. This has advantages in terms of calm-water resistance but reduces the dynamic stability. The boat becomes more prone to pitch stability problems such as porpoising and bow diving. It also increases the risk of propulsion system aeration. With waterjets it is particularly important, as even 10% air ingestion causes a significant drop in the jet's efficiency.

• *Incorrect foil positions and arrangement.* Many different foil configurations can work for a given application, all with pros and cons. The successful ones have some way of retaining balance and stability in all sea conditions envisaged for the vessel.

• *Poor hull lines.* Hydrofoil-supported catamaran behavior and performance are very sensitive to the hull shape. Nonprismatic hulls and round-bilge hulls often result in complex hull–hydrofoil interactions at transitional speeds (Figure 4) that are difficult to predict without model-testing.

• *No proper account for propulsion lift forces.* Nearly all propulsion systems, including waterjets, inclined-shaft props, and surface drives generate lift in addition to thrust. For conventional high-speed vessels these lift forces are often ignored or taken into account only through crude approximations, as their effect on speed is relatively small. On hydrofoil-supported vessels they can create significant trimming moments affecting performance and stability.

• *Employing aerodynamic principles in designing the hydrofoil.* Airfoils and aircraft wings follow the same broad fluid-dynamic principles, but aircraft do not need to deal with waves, cavitation, marine growth, impacts with floating debris, galvanic corrosion, welding distortion, etc.—all the variables influencing the design of the hydrofoil system. The optimum hydrofoil configuration is nearly always vastly different from an aircraft's design.

—Gunther Migeotte

PAUL LEMMER

Unlike regular catamarans, hydrofoil-supported catamarans can be designed to lean into a turn much like monohulls. Somewhat counterintuitively, the foils do not impair handling or create directional-instability/broaching problems. This HYSUCAT Elan 8.5m (28') model at speed illustrates the type of surefooted tight turns in waves that can be performed.

the hydrofoils as appendages, so it is not necessary to complete such a detailed design for all applications.

Other Considerations

One of the most common questions about hydrofoils is "What happens when the foil hits something?" At Icarus Marine, our philosophy is to design the foils so that any impact that would normally not damage the hull should also not damage the foil system. Such a design criterion obviously excludes hitting rocks and the like. If the hydrofoils do hit an isolated rock that misses the hulls, it is preferable for the foils to break off without damaging the hull. This can be achieved by making the bolted connections the weakest link.

The main challenge is handling the smaller strikes with floating logs, sea animals (unfortunately), and beaching. Again, this is where a foil of duplex steel works so much better than one of aluminum. The photo on the facing page shows an aluminum-hydrofoil-supported boat with duplex steel hydrofoils that hit rocks just under the surface at peak tide. The foil "bulldozed" the rocks ahead of it. Surprisingly, even in this quite severe impact, the foil suffered only scratches, and the boat went back into service after a simple inspection.

An impact with floating logs is normally the worst-case scenario, especially in areas like Puget Sound in Washington State, which is known for


COURTESY GERHARD KUTT

This aluminum boat fitted with duplex steel hydrofoils bulldozed into a rocky ledge at speed. The steel foil suffered only scratches, and the boat was back in service after a brief inspection.

vertically floating logs, or "deadheads." A duplex foil can cut through smaller logs that will not damage the hull. Big tree trunks that would damage the hull, foils, and propulsion of any boat cannot be considered a design criterion.

In closing, a reminder that for any hydrofoil-supported project, it is imperative to follow a proper and detailed design process and to ensure a close cooperation between the vessel's designer and builder. Any changes to hull lines, propulsion, weight, centers of gravity, etc., need to be carefully evaluated, as they all affect the final performance. Welding distortion on the hull and foils is also important to check and compensate for in the final foil setup. PBB

About the Author: *Gunther Migeotte is part owner of Icarus Marine, a naval architecture firm in Cape Town, South Africa, specializing in the design of hydrofoil-supported catamarans and other types of high-speed craft. He completed his master's degree and PhD on hydrofoil-supported catamaran hydrodynamics under the supervision of K.G. Hoppe, the inventor of the HYSUCAT patent, at Stellenbosch University. He has designed, and written technical papers on, numerous hydrofoil-supported catamarans.*