

Keel and Rudder Design

There is an art and science to good appendage design, with the emphasis on science. Here, the author reviews the basics of what's appropriate for modern cruisers, cruiser/racers, and pure raceboats.

Editor's note: This article is the first of a two-part series, based on an IBEX 2004 session titled "Practical Methods for Keel and Rudder Design," presented by David Vacanti, naval architect Eric Sponberg (St. Augustine, Florida), and Kevin Milne, president of Mars Metal Company (Burlington, Ontario, Canada). Here, Vacanti discusses the science of foil sections, planform shapes, lift and drag characteristics, and bulb and winglet keels. In the next issue, Eric Sponberg will look at keel and rudder engineering and construction, including calculating keelbolt sizes and rudderpost diameters. And, Milne will show examples of his company's manufacturing processes.

Text and illustrations by David Vacanti

If you're not an active member of the racing sailboat community, you may be unaware that a revolution in keel design is under way. It gathered momentum several years ago with the success of a raceboat called *Wild Oats*, fitted with an appendage system that has since been patented as "Canting Ballast Twin Foils" (CBTF).

Monohull sailboats with CBTF are attaining speeds previously reached only by sailing multihulls. It would appear at first glance that the long-accepted rule of displacement-hull speed limit, or hull speed—1.34 times the square root of the waterline length—has been somehow erased from the physics books. With CBTF, leeway angles have been reduced to zero, and some configurations of movable appendages are capable of lifting themselves to weather, permitting a sailboat to not only sail fast but also translate to weather as it does so. What's the reason for the much higher observed speeds?

First, let's review some keel and rudder basics to understand how this new technology has evolved, and how to apply the lessons learned to the design or redesign of keels and rudders.

Keel Design Criteria

In the design of powerboats, there are three basic tenets: (1) increased

engine horsepower will produce higher speeds; (2) lighter-weight engines and hulls are faster and more fuel efficient for a given horsepower; and (3) efficient hull designs make the best use of the power provided to them.

These principles are the same in sailboat design; all that's needed is to interpret them in sailing terms. The axioms of fast sailing designs are: (1) increased sail plan area (horsepower) increases speed; (2) lighter-weight hulls and keels produce faster boats; and (3) efficiently designed hulls make the best use of the horsepower produced by a sail plan.

Clearly, the designers of the clipper ships, or the J-class boats of the early *America's Cup*, pushed sail plan area to the limit in their attempt to achieve the highest possible speeds. Those vessels were indeed fast, but they did not break the barrier of the displacement-mode hull speed, for one simple reason: weight. The horsepower-to-displacement ratio was only modest.

Modern dinghy classes such as the Moth, International 14s, or the Australian 18s—with their clouds of sail, no ballast in the keel, advanced-composite hulls, and even horizontal keel and rudder lifting wings that allow them to fly altogether free of the water—are the ultimate in horsepower

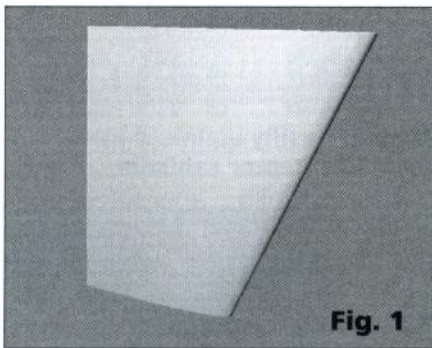


Fig. 1

Figure 1—A typical “standard keel” with all straight leading and trailing edges and no special treatments. Leading-edge sweepback angle is about 40°.

(sail area) to weight (hull, rig, and crew) ratio. These are perhaps the extremes of sailboat design. Let's explore the middle ground, where most boats reside.

Table 1 lists the key criteria for the design of keels for racers and cruiser/racers.

Simple Planform Keels

The “simple” or “standard” keels such as the one shown in Figure 1 would include high-aspect-ratio keels as well as low-aspect shallow-draft keels. Both types have been the norm for a number of years. There have been many variations on the theme

that, while creative, have not materially changed the overall performance of sailboats. These variations include the “elliptical” keel with shortened root chord and exaggerated midchord lengths. The goal of that design was to reduce the hull-to-keel root chord interference drag. As I'll suggest below, though, there's a better way to minimize drag at the junction of the hull and keel root.

The surface of the hull provides a significant “end plate” effect, preventing lift forces developed by the keel surface from being lost and causing vortex drag. In calculating the lift and drag forces of the keel, a designer can assume that the keel is in effect “reflected” in the hull surface such that the aspect ratio is assumed to be twice the geometric aspect ratio. In contrast, the lift and drag of a rudder is calculated assuming that both the root and tip chords of the rudder are “open,” or unsealed; consequently, only the basic geometric aspect ratio is used in computing lift and drag. The transition of flow between the hull and keel at the root can result in some drag. Interference drag caused by the intersection of the keel and hull can be minimized by slightly extending the root chord into a fairing at the leading edge. The fairing requires that the root chord and its foil shape be extended to faithfully reproduce the chosen foil section; it cannot be done by simply adding an arbitrary “ramp” leading up to what would have been the nose of the root chord. (See **Figure 2**.)

Table 1. Keel Design Criteria	
High-Performance Racing	Cruiser/Offshore Club Racing
<ul style="list-style-type: none"> • High-aspect-ratio planform • High-accuracy surface • Computer numerically controlled (CNC) machining required • Very low center of gravity 	<ul style="list-style-type: none"> • Moderate-to-low-aspect ratio • Performance without surface maintenance <ol style="list-style-type: none"> 1. No waxing or polishing required • Modest to low center of gravity
Minimize wetted surface and frontal area <ol style="list-style-type: none"> 1. Choose high-area-coefficient foils 2. Keep maximum thickness at 9% to 10% of chord length 	Use all available draft <ol style="list-style-type: none"> 1. Maximize the span/draft for highest possible aspect ratio Use high-area-coefficient foils <ol style="list-style-type: none"> 1. NACA 00 Series a good example 2. Provides the greatest possible ballast volume for the least wetted surface and smallest frontal area
Achieve highest possible righting moment with least ballast weight <ol style="list-style-type: none"> 1. Lowest possible center of gravity 2. Bulbed keels 3. Canting keels <ul style="list-style-type: none"> • hydraulic rams with associated energy source for pumps 	Use only lead ballast <ol style="list-style-type: none"> 1. Lowest center of gravity 2. Least wetted surface 3. Highest aspect ratio <ul style="list-style-type: none"> • Use accurate molds and fairing tools • Winglets can help low-aspect-ratio keel performance <ol style="list-style-type: none"> 1. Winglets must be high aspect ratio 2. Not intended to carry significant ballast
Achieve highest possible side force with least wetted area <ol style="list-style-type: none"> 1. Consider trim tab/flap on main keel strut 2. Use flap that is 25% of chord at angles of 10° or less 	Do not use ballast bulbs on shallow-draft, low-aspect-ratio keels <ol style="list-style-type: none"> 1. For a fixed draft the bulb uses critical span and reduces aspect ratio and lifting surfaces significantly <ul style="list-style-type: none"> • Bulb adds wetted surface and frontal area to keel 2. Use high-area-coefficient airfoils <ul style="list-style-type: none"> • NACA 00XX Series • Maximizes volume for given keel area and wetted surface • Moves center of gravity as low as possible
Smooth, slick surfaces for low drag <ol style="list-style-type: none"> 1. Unpainted gelcoat 2. Polished metal finishes 3. Wax-shine all surfaces 	
Following is an explanation of some of the above terms. <ul style="list-style-type: none"> • Foil. One of the most misapplied terms regarding keels and rudders. Refers to the cross-section shape from leading edge to trailing edge of the keel or rudder. • Geometric aspect ratio. Ratio of the span to the average chord of a keel, not including bulb length. • High-area-coefficient foils. Ratio of the area of foil shape to a rectangle that just touches the outline of the foil at the maximum thickness points and the ends. Alternatively, area coefficient is the fractional percentage of the area of the rectangle area that is covered by the foil area. • Flap or trim tab. The 20% to 30% of the trailing edge of a foil that is arranged to move side to side for steering or added side force (lift). • Span/draft. Maximum dimension from root (top) chord to tip (bottom) chord of the main keel, not including bulb height. • Chord. Distance measured anywhere along the span from the leading to trailing edge. • NACA foils. The National Advisory Committee for Aeronautics defined foil types with predicted lift and drag data. Detailed information is available in <i>Theory of Wing Sections</i>, by Ira H. Abbott and A.E. von Doenhoff, published by Dover, 1980. ISBN 0-486-60586-8. 	

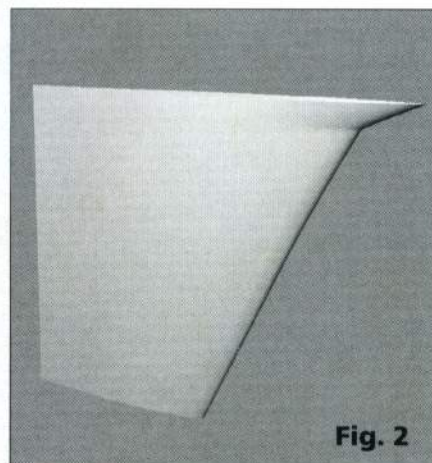


Fig. 2

Figure 2—Interference drag caused by the intersection of the keel and hull can be minimized by slightly extending the root chord into a fairing at the leading edge, as shown here.

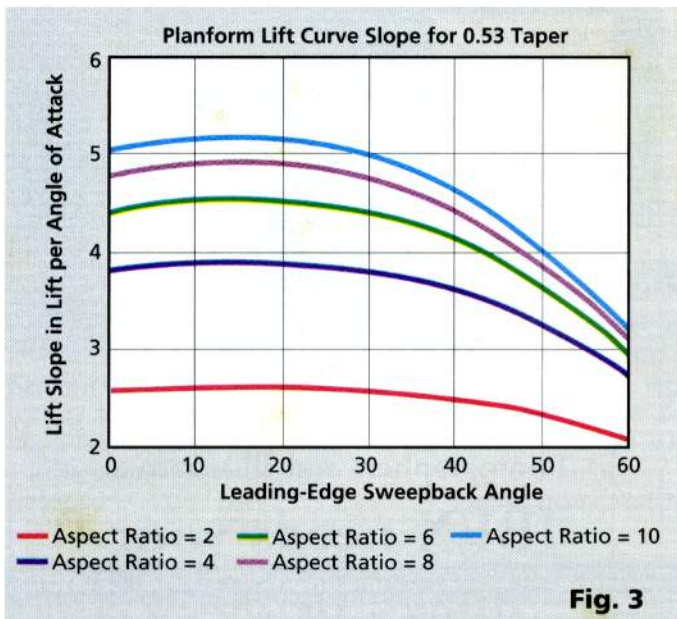


Fig. 3

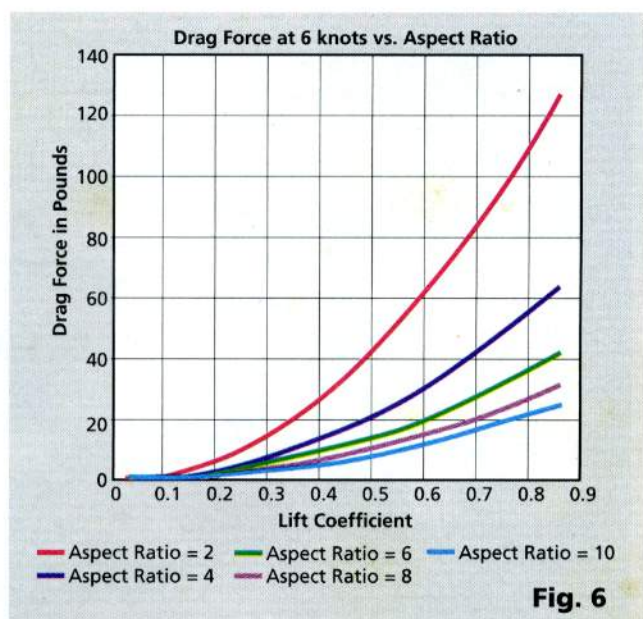


Fig. 6

For fixed taper ratio $\lambda = 0.53$ $\kappa = 1.003$

$$\tan \Lambda_{\text{mid } K} = \tan(k\text{-deg}) - \frac{4}{AR} \cdot \left[\frac{(1-\lambda)}{2 \cdot (1+\lambda)} \right]$$

$$C_{L\alpha_{j,K}} = \frac{2 \cdot \pi \cdot j}{2 + \sqrt{\frac{j^2}{\kappa^2} \left[1 + \left(\tan \Lambda_{\text{mid } K} \right)^2 \right]} + 4}$$

Fig. 4

AR = 2.304

$$100 - 100 \cdot \frac{C_{L\alpha_{2.41}}}{C_{L\alpha_{2.17}}} = 4.812 \text{ \% Loss}$$

Fig. 5

Figure 3—The lift curve slope, or LCS, is a measure of how rapidly the lift coefficient of the keel increases with increasing angle of attack. A higher LCS represents a more efficient keel. For any given aspect ratio, the maximum LCS is achieved when the sweepback angle is about 15°. **Figure 4** shows (to the mathematically minded) the impact of sweepback angle on the LCS of a keel for a given taper ratio, where taper ratio is the ratio of the tip chord to the root chord. K is the sweepback angle, and κ is a scale factor. **Figure 5**—Based on data from Figure 3, this plot indicates percentage loss in lift as a result of using a 40° sweepback angle. **Figure 6** shows that aspect ratio dramatically impacts drag. **Below**—Nicorette III, a bulbed-keel, “triple-moving-foil” racer developed by Simonis-Voogd Yacht Design using the author’s software, took line honors in the 2005 Sydney-Hobart race. The forward rudder is a requirement in this arrangement, to provide side force when sailing upwind and the keel is canted.

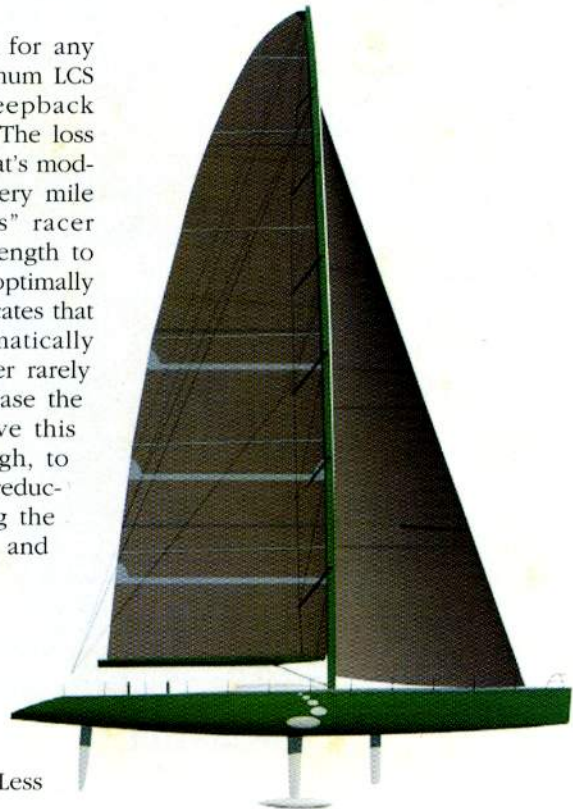
In addition to the characteristics listed for racer/cruiser keels in Table 1, the leading-edge sweepback angle is perhaps the single most critical design feature that can improve the upwind sailing characteristics of a keel. The example shown in Figures 1 and 2 is a typical keel design with a sweepback angle of about 40°. The effect of sweepback angle and aspect ratio on the lifting efficiency of a keel is computed as shown in the calculation of the lift curve slope ($C_{L\alpha}$). The lift curve slope, or LCS, is a measure of how rapidly the lift coefficient of the keel increases with increasing angle of attack. A higher LCS represents a more efficient keel. (See **Figure 3**.) **Figure 4** shows the impact of sweepback angle on the LCS of a keel for a given taper ratio, where taper ratio is the ratio of the tip chord to the root chord.

In the design shown in Figure 1, the sweepback angle is about 40°, the taper ratio is 0.53, and aspect ratio is

2.3. Figure 3 illustrates that for any given aspect ratio, the maximum LCS is achieved when the sweepback angle is about 15°, not 40°. The loss in LCS is 4.8% (**Figure 5**). That’s modest for a cruiser, but for every mile sailed, a “round-the-buoys” racer would fall about one boat-length to leeward of a boat with an optimally designed keel. **Figure 6** indicates that increased aspect ratio dramatically reduces drag. But, a designer rarely has the opportunity to increase the depth of the keel to achieve this benefit. It is possible, though, to increase the aspect ratio by reducing the keel’s width, forcing the ballast out of the main keel and into a bulb at the bottom.

Bulbed Keels for Cruisers or Racers

Lowering the center of gravity in a sailboat’s keel not only makes a more stable vessel but a faster one. Less



driving power is spilled from the sails if the boat remains more upright. The easy way to lower the center of gravity is to add a bulb to the bottom of the keel. It would be tempting to keep the draft and total ballast of the keel fixed, add a hollow sump to the top of the keel, and shift ballast material into a bulb that takes up some of the span of the original keel design, thereby substantially lowering the center of gravity and increasing the sail-carrying power of the boat. But, the designer would also have significantly increased the drag of the keel and reduced the LCS, resulting in a slower boat that points lower to weather. What happened? The addition of the bulb for a fixed draft reduced the available span of the keel, which in turn reduced the aspect ratio. Figure 3 also shows that aspect ratio dramatically impacts LCS. The added wetted surface and frontal area of the bulb were not offset by a corresponding reduction in the main keel wetted area or frontal area. A designer will know if a bulbed keel is efficiently designed when he or she can show that a bulbed keel carrying the desired ballast amount has an aspect ratio, wetted surface, and frontal area that are equivalent to or better than a nonbulbed design carrying the same ballast.

If draft is not a limitation, a savvy designer will quickly figure out two principles. The first is that increasing draft with a bulbed keel with short chords and near-zero sweepback angle will produce a keel with much higher aspect ratio (span-to-average-chord ratio) and increased sail-carrying power due to a lower center of gravity and higher righting moment. The higher aspect ratio and smaller surface area generate as much or more lifting force than did the original keel.

Second, a bulbed keel can carry less ballast and provide the same or greater righting moment as a fin keel, due to its lower center of gravity. A bulbed keel with greater depth and lower ballast weight for the same hull weight results in an overall increase in speed potential, for two reasons: the sail plan remains more nearly square to the wind, harnessing almost all the available power; and, the hull-keel combination is lighter. If the hull is designed to readily plane or surf, the boat will have the potential to

frequently exceed its theoretical hull speed.

If a design office lacks access to a computational fluid dynamics, or CFD, program, then keel bulbs should be designed by rotating a NACA foil such as a 00 or 63 Series about the longitudinal axis of the bulb. (More on foil selection below.) The bulb should not exceed 15% maximum-thickness-to-chord ratio, and should have a very high ratio of length to maximum thickness in order to minimize wave drag caused by the underwater displacement of the bulb. The keel strut that supports the bulb should not be less than 9% thickness-to-chord ratio to avoid problems with stalling the main strut section in the turbulent flow of rough seas and heavy wind. Offshore sailing crews report hearing the keel shrieking or whining as it passes through the water at high speeds. This is an indication of cavitation, which may be caused by a poor choice in foil shape near the leading edge or a strut that is too thin. Cavitation from any cause should be rectified, as it can lead to corrosion or mechanical fatigue of the structure. To keep drag low, the strut should not exceed a maximum thickness of 15%.

Benefits and Limits of High Aspect Ratio

A fixed bulb keel with deep draft can easily achieve an aspect ratio of near 10:1. At this very high aspect ratio, a keel with a lift coefficient of 0.5 would generate over 400% less drag than a keel with a 2:1 aspect ratio, as shown in Figure 6. Taken another way, the 10:1 high-aspect-ratio keel will develop the same lifting force as a 2:1 low-aspect-ratio keel at one-fifth the leeway angle of the lower-aspect-ratio keel for the same speed through the water. But the far lower drag of the high-aspect keel will permit higher sailing speeds for a given amount of lift, and that higher velocity produces enough lift,

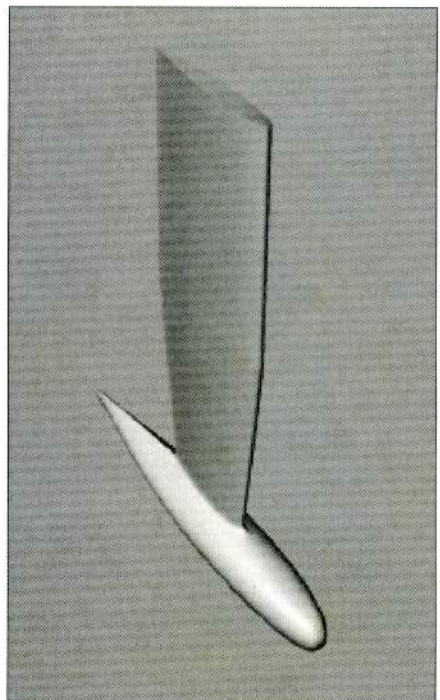
in turn, to permit a further reduction in leeway angle.

Very-high-aspect-ratio struts and keels have some serious downsides that cannot be overlooked. Consider the huge bending and torsional loads induced into the main strut by the bulb as it seeks its own path through the water. And, there are huge loads where the thin keel attaches to the hull. The keel may have to be attached by extending the strut into the hull to take the very large bending loads.

High-aspect wing structures are also prone to stalling at lower angles of attack or leeway angles than lower-aspect-ratio keels. When stalled, drag forces build up very rapidly, and structural loads can become excessive.

The Limits of a Bulbed Keel

The limit to the potential of a bulbed keel for improving performance is set by the available draft, and by the tensile strength of the keel strut, which is designed to cantilever tons of ballast weight away from the hull. One way to provide additional righting moment on hulls with extremely wide beam and shallow draft is to trade some of the ballast in the keel for water-ballast tanks. The price, though, is the complexity and time involved in moving the water ballast from side to side. Beware the accidental jibe when on a reach.



An example of a high-aspect-ratio bulbed keel, designed by the author. The limit to the potential of a bulbed keel for improving performance is set by the available draft, and by the tensile strength of the keel strut, which is designed to cantilever tons of ballast weight away from the hull.

The next logical step is to move the bulbed keel itself to windward by means of a matched pair of hydraulic rams—one pushing, the other pulling, the internal section of the “canting keel” to weather. This dramatically increases the righting moment of a keel for a given draft and ballast.

Once the bulbed keel is canted to windward, however, there is nothing to resist the side force of the sails. So, a second planform must be added just forward of the main canted keel to provide the required lift to weather. The forward planform may be a fixed centerboard or a rudder. If implemented as a rudder, it can be placed at a higher angle of attack than the leeway angle of the hull. The adjustable angle of attack allows a smaller surface area to generate the required side force, and that results in a lower wetted surface area—but also in very high loading of the forward planform, typically called a canard. The high loading means that a smaller surface area set at an angle of attack produces much higher bending moments on the canard, resulting in

structural problems that must now be solved. It's also important that the combined drag of the canted keel and the canard be lower than that of the standard fin keel.

Carrying a forward rudder that pivots on a shaft and absorbs the side forces of the full sail plan makes for a severe structural problem. Some designers have decided to place the centerboard in a trunk and add a movable trailing-edge flap to adjust angle of attack. That allows the board to be raised downwind when the keel isn't canted.

Now the only remaining issue is the time required to move the keel from side to side and the energy source to power the hydraulics. Here's where the canting keel twin foil comes in—but, it has some serious caveats. The structural problems created by a canting keel were clearly demonstrated when the crew of a 90' (27m) maxi yacht were forced to abandon ship after the canting keel's hydraulic rams failed and allowed the keel to tear itself free of its mountings. The boat

rolled, and sustained severe damage to her hull.

Despite this structural failure, we've proven that maximizing horsepower and stability by optimizing hull displacement, ballast amount, and ballast location dramatically improves sailing performance. Any sailboat—whether a radical or a traditional design—can benefit from the application of these basic principles.

Winglets and Wing Keels

In 1983, the *America's Cup* went to Australia when the first efficient “wing keel” was implemented on a 12-Meter racing yacht. The key to the success of Ben Lexan's design was that the winglets themselves were efficient lifting surfaces correctly placed on the keel. It will surprise many to learn that the Wright Brothers were aware of the concept of placing end plates at the open end of a wing to prevent lift loss and reduce vortex drag. The brothers soon realized, however, that simple end plates contributed far more drag than they saved, and were not beneficial. NASA researcher

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Richard Whitcomb finally showed that end plates could be made to produce an overall reduction in drag if they were efficient wings themselves, rather than just plates. Whitcomb showed that a winglet must have a relatively high aspect ratio and must be placed at the trailing edge of the main wing surface, not at the leading edge, as some have done.

In designing winglets, keep the aspect ratio of each one at 2:1 or higher when computed as twice the geometric aspect ratio. Set the winglet angle of attack to be zero, meaning parallel to the water surface when at rest. This is not necessarily optimal, but is a reasonable placement when CFD programs are not available. Winglets should have their leading edge no farther forward than the point of maximum thickness of the main keel, and should extend to the trailing edge. Their maximum thickness should be between 9% and 12% of chord, and they ought not to be counted on to add significant amounts of ballast. And, they should follow the same rules as the main keel design for

An Islander 34 wing keel designed by the author. The wing design allowed 18" of span to be removed from the conventional keel, with no loss of performance.

sweepback angle and taper. The most advanced winglets in service on commercial jets today are known as "blended winglets," and are actually a bent-up extension of the main wing and not a separate planform. In these cases, the winglets are very-high-aspect-ratio extensions of the wing, where the designers had the luxury of producing lift in only one direction, in contrast to fixed keel designs. It's difficult to evaluate winglet performance, but in the Islander 34 wing keel that I designed (see photo, right), we were able to remove 18" (46cm) of keel span. When extensively sailed against a test boat with a standard keel, the wing-keel boat showed little or no difference in performance.



Trim Tabs

A possibility rarely considered in a cruising yacht is adding a trim tab to the trailing edge of a low-aspect-ratio fin keel—an option not available to a full-keel offshore yacht that already

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