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

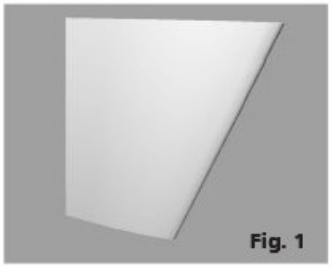


Figure 1—A typical "standard keel" with all straight leading and trailing edges and no special treatments. Leading-edge sweepback angle is about 40°.

(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
• High-aspect-ratio planform • High-accuracy surface • Computer numerically controlled (CNC) machining required • Very low center of gravity	• Moderate-to-low-aspect ratio • Performance without surface maintenance 1. No waxing or polishing required • Modest to low center of gravity
Minimize wetted surface and frontal area 1. Choose high-area-coefficient foils 2. Keep maximum thickness at 9% to 10% of chord length	**Use all available draft** 1. Maximize the span/draft for highest possible aspect ratio **Use high-area-coefficient foils** 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 1. Lowest possible center of gravity 2. Bulbed keels 3. Canting keels • hydraulic rams with associated energy source for pumps	**Use only lead ballast** 1. Lowest center of gravity 2. Least wetted surface 3. Highest aspect ratio • Use accurate molds and fairing tools • Winglets can help low-aspect-ratio keel performance 1. Winglets must be high aspect ratio 2. Not intended to carry significant ballast
Achieve highest possible side force with least wetted area 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** 1. For a fixed draft the bulb uses critical span and reduces aspect ratio and lifting surfaces significantly • Bulb adds wetted surface and frontal area to keel 2. Use high-area-coefficient airfoils • 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 1. Unpainted gelcoat 2. Polished metal finishes 3. Wax-shine all surfaces	

Following is an explanation of some of the above terms.
- **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 *Theory of Wing Sections*, by Ira H. Abbott and A.E. von Doenhoff, published by Dover, 1980. ISBN 0-486-60586-8.

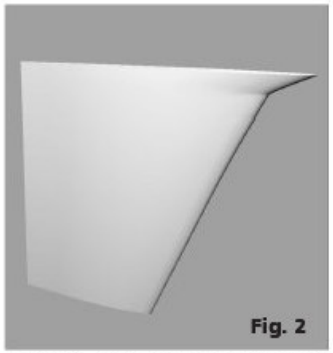


Figure 2—Interference drag caused by the intersection of the keel and hull can be minimized by slightly extending the root chord into a fairing at the leading edge, as shown here.

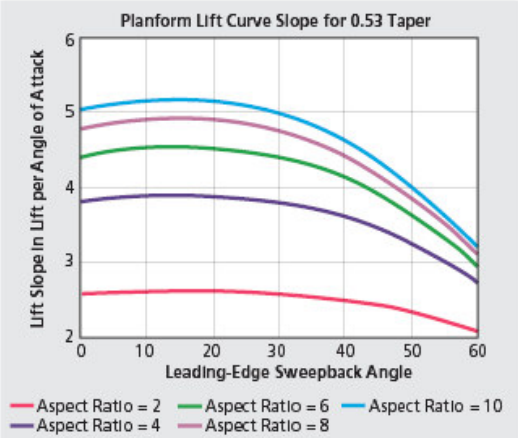


Fig. 3

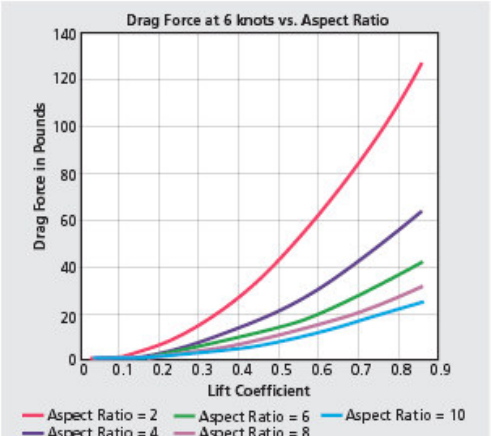


Fig. 6

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

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

$$C_{L\alpha_{J,K}} = \frac{2 \cdot \pi \cdot J}{2 + \sqrt{\frac{J^2}{\kappa^2} \cdot \left[1 + \left(\mathrm{Tan}\Lambda_{mid_K}\right)^2\right] + 4}}$$

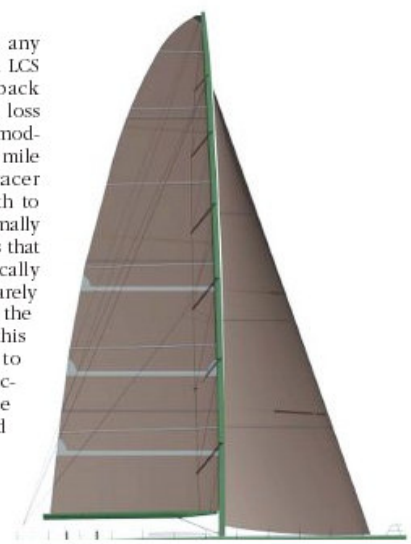
Fig. 4

AR = 2.304

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

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

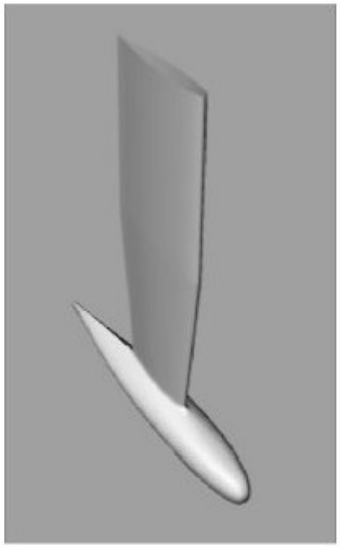
A fixed bulb keel with deep draft can easily achieve an aspect ratio of near 10:1. At this very high aspect ratio, a keel with a lift coefficient of 0.5 would generate over 400% less drag than a keel with a 2:1 aspect ratio, as shown in Figure 6. Taken another way, the 10:1 high-aspect-ratio keel will 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

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 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.

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.

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

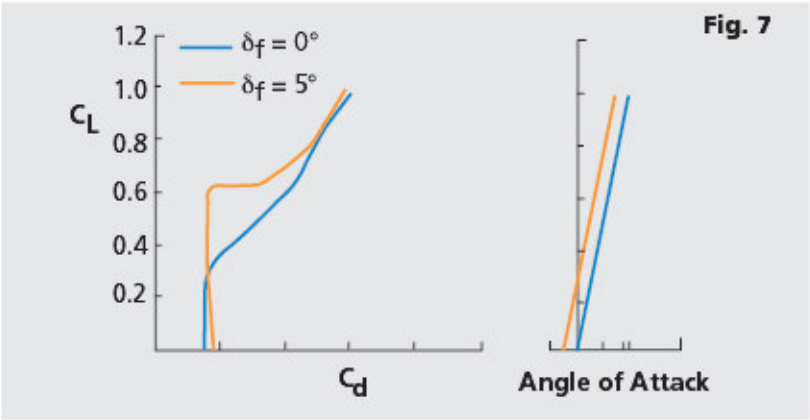


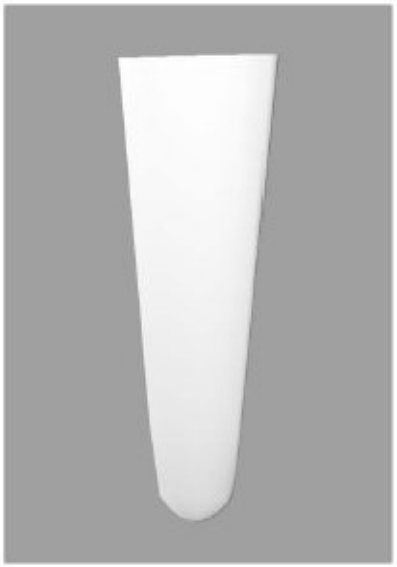
Figure 7—In these plots, drag coefficient of the foil type is plotted on the horizontal axis and lift coefficient plotted vertically. The trim tab has the beneficial effect of widening the low-drag region or "drag bucket" normally associated with whichever foil shape the designer chooses for the keel. This effect is seen clearly on the left side above, where the dotted line shows the much wider region of low drag versus lift coefficient for a trim-tabbed foil. The graph to the right plots lift coefficient on the vertical axis and angle of attack on the horizontal axis. The plot shows the positive lift coefficient generated by the foil at 0° angle of attack and 10° tab.

suspends a rudder on the trailing edge of an integral hull and keel. The trim tab would be appropriate only on a distinct keel with a specifically designed foil shape that is separate from a spade or skeg-mounted rudder.

The trim tab has the beneficial effect of widening the low-drag region or "drag bucket" normally associated with whichever foil shape the designer chooses for the keel. This effect is shown clearly on the left side of **Figure 7**, where the lift coefficient C_L is plotted vertically and drag coefficient C_d is plotted on the x-axis. The solid curve represents the lift-versus-drag characteristics of a foil shape with no trim-tab deflection. The low-drag region in this case ranges between lift coefficients of 0 and 0.3 for a drag coefficient just less than 0.005. When a 25% long trim tab is deflected only 5°, though, the lift coefficient of the foil jumps to 0.3, with no change in leeway angle (seen in Figure 7), and the low-drag region now doubles its range to a lift coefficient just greater than 0.6. This means that a low-aspect-ratio keel on a cruising sailboat can be expected to generate about as much lift to counter sail forces at 0° leeway, as it would have at 3° leeway. A cruiser that would otherwise have been limited to sailing at leeway angles close to 8° to 10°

Table 2. Rudder Design Criteria

Planform Characteristics	Foil Characteristics
High aspect ratio 1. For geometric aspect ratio of 2 or more 2. Low drag, high lift per degree of rudder angle 3. More prone to stall, needs careful foil selection 4. Higher loads located farther from the hull	**Avoid very thin foil sections** 1. Not less than 9% thick 2. Causes rapid stall, flow separation, high drag, loss of control 3. Mechanical problems of thin foil sections limit shaft diameter and reduce safety margin
Root chord of rudder not considered "sealed" 1. Therefore, aspect ratio is computed as the geometric aspect ratio. **Greatest concern is to avoid stall and separation under all operating conditions** 1. Foils must have progressive, rather than sudden, stall characteristics 2. Large leading-edge sweepback angles with respect to the rudder shaft location cause "out of plane" rotation • The upper and lower sections of the rudder operate at very different angles of attack, with breaking action rather than lift-generated side force • Loss of control when under high levels of weather helm	**Avoid very thick foil sections** 1. Less than 15% best choice 2. Causes high drag, poor flow at low speeds **Avoid critical laminar flow foil sections** 1. Do not use NACA 65, 66, 67 Series foils 2. Drag and stall characteristics are very poor if not perfectly maintained and machined 3. Subject to humming/whining at speeds due to cavitation, bubble formation
Design leading-edge sweepback angle and taper ratio in the same manner as for keels 1. Leading-edge sweepback angle should be minimized, taper ratio between 0.4 and 0.6	**Use low Reynolds number foil shapes** 1. Short chords on rudders result in very low operating Reynolds numbers
Low-aspect-ratio rudder designs 1. Aspect ratios of 2 or less 2. Higher drag, modest lift per degree of rudder angle 3. Higher stall angles 4. Lower side loads on shaft	**Use foil shapes with maximum thickness located no farther than 35% abaft the leading edge** 1. NACA 0010, 12 Series; do not scale to more than 15% thick 2. Provide highest stall angles 3. Stall characteristics are gradual 4. Less likely to cause cavitation and vibration
Transom-mounted rudders 1. Prone to pulling air and turbulence from the surface down onto the planform • Reduces lift and control 2. Provide an anticavitation plate on the rudder a few inches below the water surface to stop the ingress of air from the surface 3. Cavitation will be manifest in humming or whining that, if severe, can cause erosion or structural problems	



A high-aspect-ratio "elliptical" rudder, as found on racing yachts. The rudder shape is designed to produce a distribution of lift along its span that generates an elliptical shape when plotted. Elliptical loading has been shown to generate the least vortex drag for lift produced.

would now sail closer to 5° to 7°, making substantial improvements in upwind performance. The cruising boat won't travel faster through the water, but the velocity made good will be measurably increased, and the capability to stay off a lee shore or skirt a storm is an excellent safety feature.

Here's one way to simplify a trim-tab installation on a cruising sailboat: couple the trim tab to rudder control such that the trim tab is set at a value that's a fraction of the main rudder command. Alternatively, a simple lever could be used to set the trim tab to a new fixed position for each tack. Offwind sailing would leave the tab at zero, and when the boat is lying a-hull in a storm, the tab could be set to help maintain a safe wind angle. Forgetting to move the tab on a tack would have only minor consequences.

Rudder Design Principles

Let's now consider efficient rudder design, and how to choose the best foil shapes to meet the goals of low wetted surface, low frontal area, and high aspect ratio. These principles apply with equal importance to keels and rudders. There are critical issues related to foil types for both keels and rudders that could cause an otherwise-optimal planform shape to exhibit less-than-stellar behaviors. See **Table 2** for the key criteria in designing rudders.

Rudderpost Location

One of the more important handling characteristics of a sailboat rudder is the feedback it provides to the helmsman. Experience has shown that placing the rudderpost about 17% abaft the leading edge is a good choice for a balanced helm. A well-designed rudder should have a nearly vertical leading edge and a rudderpost set as near vertical as practical. When there is excessive leading-edge sweep, rudder lift and drag performance will suffer in the same way as they will on a keel planform. But, rudder performance is more seriously affected by the rotation needed for steering. A swept-

back rudder and rudderpost cause the planform to rotate obliquely to the water flow. The greater the sweepback angle of the rudder, the more it functions as a brake and not as an efficient lifting surface that promotes steering through a true side force. The designer should also be concerned with how the taper of the rudder will affect the placement of the rudder shaft. A properly designed rudder should permit the shaft to lie at virtually the same percentage location aft of the leading edge for at least the upper 75% of the rudder span.

Rudder Planform Shape

It's common to draw racing rudders with highly tapered shapes at the tip. This practice is based on the valid principle that tapering a planform to match the characteristics of one-half an ellipse produces optimal lift distribution and the least vortex drag.

On a rudder, the elliptical planform creates some significant challenges. The very short chords produced at the tip must be accurately rendered with true foil shapes. It's not acceptable to manufacture a rectangular planform and simply round off the corners, as this completely destroys the foil shapes. An egregious example of this type of "fairing" is shown in the photo of a wing keel designed for a Six-Meter racer. The builder decided that he didn't like the profile of the keel, and ground off the leading edge at the keel tip chord to make it more appealing. The result is a blunt leading edge at the nose of the keel. This "fairing" process destroyed the foil characteristics of perhaps 25% of the keel span, particularly in the region of the winglets, and the boat sailed poorly as a result.

The author designed this wing keel for a Six-Meter sailing yacht. The keel is inverted with the tip chord longer than the root chord to place the lead as low as possible in the low-aspect-ratio keel. The leading edge of the keel is swept forward rather than aft in order to achieve the required lift distribution on the span. The builder, however, ground off the nose of the keel at the tip on the leading edge (see lower left), destroying the leading-edge shape for the lower third of the keel. The boat performed poorly.

Rudder shapes, which have very modest chord lengths to begin with, tend to be so small at the tip that they should be cast from a CNC-machined mold, or CNC finished after "over molding" with extra material to permit final shaping. If there were no intent to properly implement the foils along the entire span of the rudder

Table 3. NACA Foil Series Characteristics

NACA Foil	Maximum Thickness Location	Leading-Edge Radius	Area Coefficient
0010	30%	1.1%	0.683
63-010	35%	0.77%	0.633
64-010	40%	0.72%	0.634
65-010	45%	0.68%	0.650
66-010	50%	0.62%	0.675

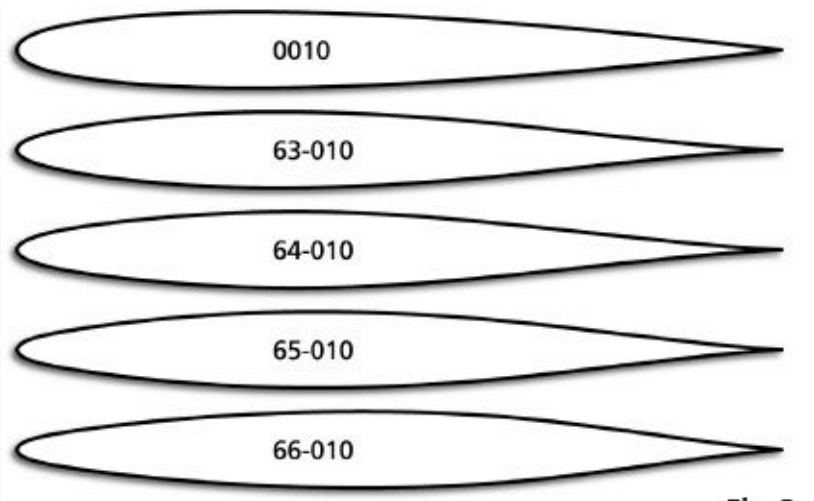


Fig. 8

Table 3 shows the basic characteristics of each of the foil series described in this article, and Figure 8 shows the shape of each foil.

(or keel), then it would be better to avoid this type of detailed planform and simply retain a properly implemented rectangular planform.

Foil Characteristics

Determining the correct foil shape for a keel or rudder begins with identifying the most significant characteristics of the application, and then deciding which foil best provides the performance features that match that application.

For the sake of this discussion, I'll limit my comments to the basic NACA foils from the 00, 63, 64, 65, and 66 Series. There are many foil shapes available from various libraries of data provided on the Internet. And, there are several 2-D foil-design and -analysis programs with which

you can design original foils or modify existing ones, and optimize them for a specific application.

Foil types are generally differentiated from one another by nose radius and location of the maximum thickness abaft the nose of the foil. There are several other parameters, but guidelines for choosing a foil can be illustrated with this set and then extrapolated to others by the designer.

Table 3 shows the basic characteristics of each of the foil series described in this text. **Figure 8** shows the shape of each foil. Each foil type contains a set of foils for overall thicknesses ranging from 6% to 20%, with a specific set of offset data for each thickness. NACA 6X Series foils may not be scaled in thickness more than ±2%, or the desired flow characteristics will be lost.

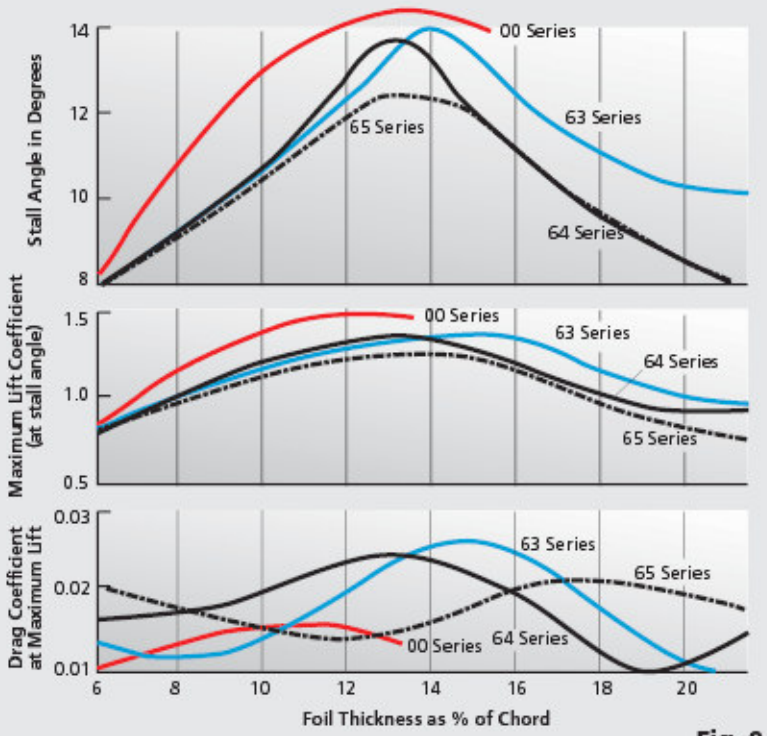


Fig. 9

Figure 9—The maximum lift coefficient or highest stall angle is achieved for all the NACA foils within the range of 9% to 15% overall thickness.

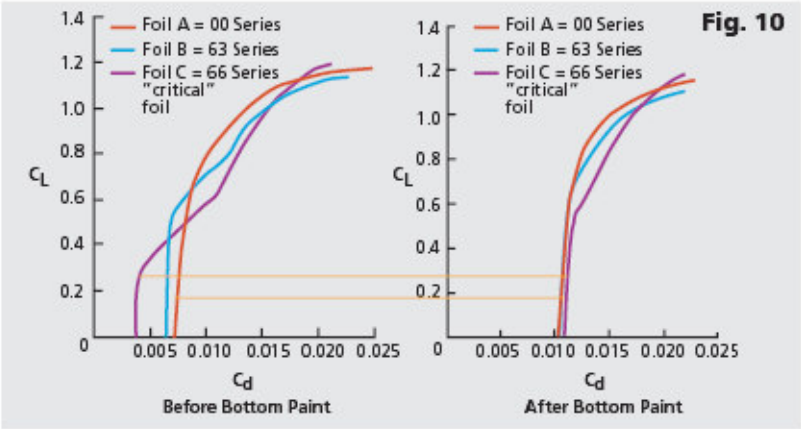


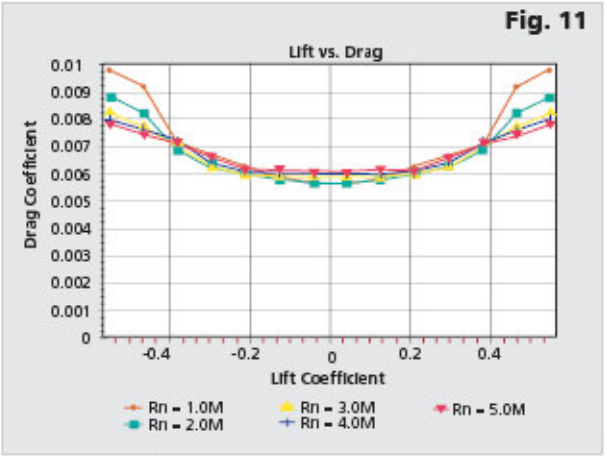
Figure 10 shows what happens when a critical foil shape such as the NACA 66 Series (Foil C) is coated with rough bottom paint or slime: its entire low-drag region is eliminated, and drag actually exceeds that of the more modest foil shapes (Foils A and B). The upper horizontal line shows the limit of the low-drag region of Foil C, and connnects it to the same location for Foil C after bottom paint is applied. The lower horizontal line connects the plots for Foil A before and after bottom paint; it's far less affected by the paint than is Foil C.

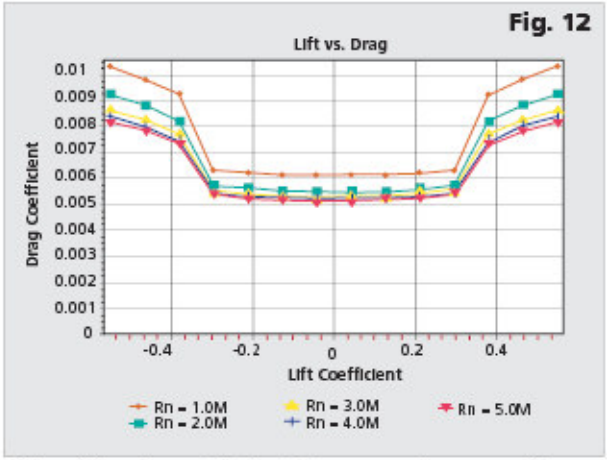
I've already noted that foils should range from 9% to 15% overall thickness. **Figure 9** illustrates that the maximum lift coefficient or highest stall angle is achieved for all the NACA foils within this range; lesser and greater thicknesses have rapidly declining performance outside it.

Foil Implementation Accuracy

Once a foil has been chosen for a particular application, how accurately must it be rendered on the keel or rudder to achieve the theoretical characteristics predicted by the lift and drag curves of a design program? For the sake of illustration, let's assume that a designer of a very-high-aspect-ratio, fixed-bulb keel for a high-speed racer has selected a NACA 66 Series foil for the strut—a reasonable choice, because the keel will operate in a narrow lift-coefficient range or small angles of attack. Therefore, the designer can assume that the keel will most often operate in the narrow but very-low-drag region of the foil between ±3°.

Refer to **Figure 10** and note what happens when a "critical" or "laminar flow" foil shape such as the NACA 66 Series is coated with rough bottom paint or an accumulation of slime or scum. The entire low-drag region is eliminated, and the keel performs no differently than if it had been a 00 Series from the beginning. So, this

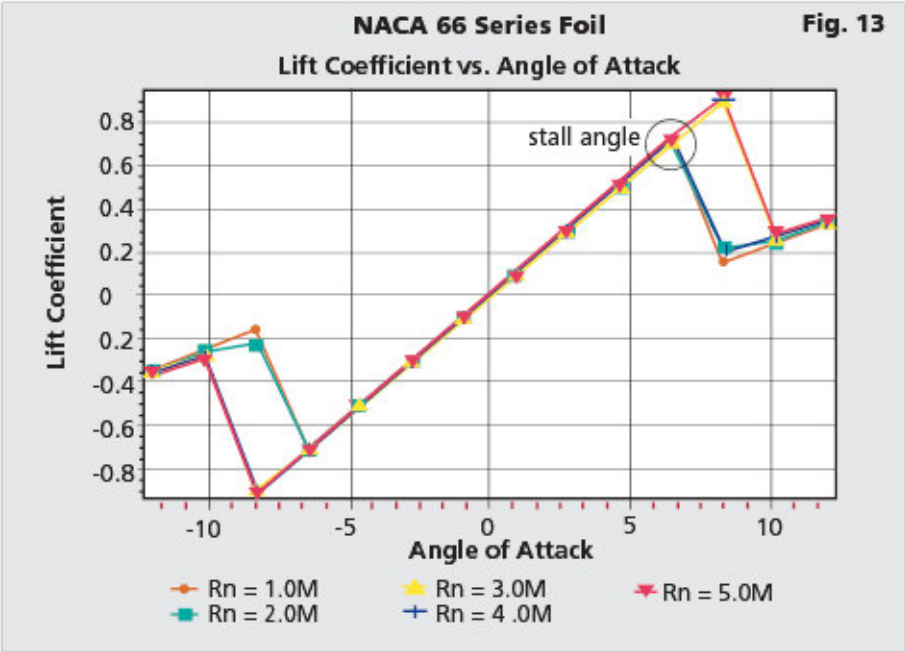




Figures 11, 12, 13, *and* ***14*** *illustrate the dramatic differences in lift and drag characteristics that occur as the nose radius and the position of the maximum thickness are varied among foil designs. Note in* ***Figure 11*** *the very broad low-drag region of the 0100 Series foil. The NACA 66-010 foil in* ***Figure 12*** *has much lower drag in the region between ±0.3 lift coefficients, but the 0010 has far lower drag outside this region.*

type of foil must be implemented with CNC accuracies, and must also be maintained with waxed gelcoat or as polished metal. Critical foils such as 65 and 66 Series are best chosen when a boat will be carefully maintained in dry dock or cleaned before each race. If this maintenance regimen cannot be followed, then a choice of a more moderate foil series from the 00, 63, or perhaps 64 Series is more reasonable.

Earlier, I mentioned that sweepback angles greater than 10° to 20° result in loss of lift and increased drag. Once again, a highly swept leading edge on any planform of 30° or more will result in even more



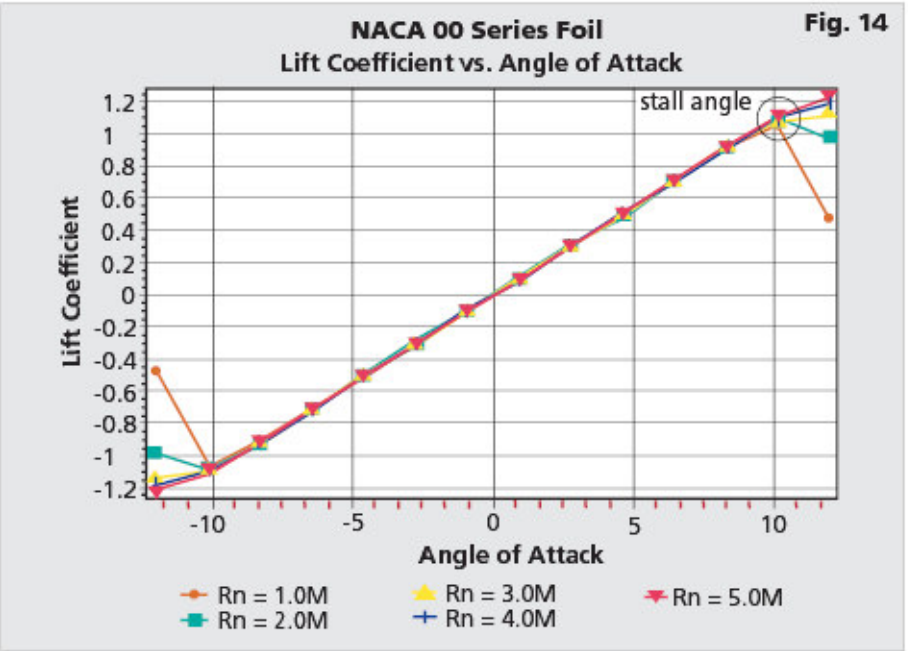
Figures 13 and 14 are good examples of how the maximum lift or stall angle of a NACA 66 Series is several degrees less than that of a 00 Series foil. Also, the NACA 66 Series stalls suddenly and severely while the 00 Series stalls gradually as angle of attack increases.

rapid deterioration of the low-drag behavior of critical 65 and 66 Series foils. Should there be any unfairness greater than 0.04" (0.016mm), or the accumulation of surface contaminants, the flow will transition from laminar to turbulent. Once this transition has occurred, the potential for cavitation, corrosion, and fatigue is more likely. A singing rudder or keel is the first indication of trouble.

Foil Lift and Drag Characteristics

Figures 11, **12**, **13**, and **14** illustrate the dramatic differences in lift and drag characteristics that occur as the nose radius and the position of maximum thickness are varied among foil designs. Note in Figure 11 the very broad low-drag region of the 0010 Series foil. When

compared to the NACA 66-010 foil in Figure 12, it's immediately apparent that the 66 Series has much lower drag in the region between ±0.3 lift coefficients, but the 0010 has far lower drag outside this region. The implication should be clear straightaway that the 66 Series foil is not a candidate for a rudder that must swing through many degrees of steering range and will very frequently operate outside ±2.7° angle of attack. The clear choice for rudders is the 00 Series.



Recall that the Reynolds number, shown here in the figures as Rn, is directly proportional to chord length. The chords of all rudders are relatively short, and even at modest surfing speeds for a 36' (11m) racer will not often exceed 1M (million). Consequently, the red curve for Rn = 1M reaches the highest levels of drag for 66 Series foils, but the 00 Series shows almost no preference for low Rn from 1M to 5M. I know of a project in which a noted designer specified a 66 Series foil on a high-speed catamaran. The rudders sang and vibrated as they rapidly hit the high drag and turbulent flow that so readily occur on this foil. Changing

to the relatively mundane 00 Series with the same planform shape eliminated the vibration and gave better control.

In another example, a well-known yacht had a strong tendency to nosedive when running before the wind, and required all hands to be in the cockpit to prevent submerging the bow. The problem was not poor buoyancy in the bow but very poor foil selection on the keel. When the keel was redesigned and accurately faired with a more rational foil family, the yacht suddenly regained its composure downwind and won its class in the next major race it sailed. Foil selection *does* matter.

Another discriminator between foil families is the maximum lift coefficient. **Figures 13** and **14** are good examples of how the maximum lift or stall angle of a NACA 66 Series is several degrees less than that of a 00 Series foil. Not only that, but the NACA 66 Series stalls suddenly and severely while the 00 Series stalls gradually and serenely as angle of attack increases. The gentle and gradual nature of the 00 Series stall characteristic makes it suitable for rudder applications where the designer can expect very wide angles of control. All designers should note that while they may design for a small weather helm on the rudder, operation in rough water with even modest winds

problems for control and steady operation in waves.

The Canting Ballast Twin Foils design concept represents the state of the art in sailing efficiency. Nevertheless, its complex and expensive mechanical systems intrude into the cabin space and are not yet totally reliable. Still, these systems are justified for the highest levels of racing performance. CBTF also promises that optimal design can result in a more exciting product that offers speed and efficiency, without extremes of implementation. By adhering to the basic principles outlined in this article, the next generation of designs should prove safer and more efficient.

Keel and rudder design and analysis are beyond the capability of a simple spreadsheet. A design team should equip itself with at least basic keel and rudder design software that can provide integrated lift and drag characteristics as well as hydrostatic computations.

The team should carefully evaluate the planform shape according to available draft, mechanical limitations, and intended levels of maintenance. Cost of manufacture to achieve low-drag, high-lift performance can be substantial. High performance must be paramount in the design brief in order to justify the cost.

True comparative engineering evaluations of keel and rudder designs are done only for the most demanding racing projects such as the *America*'s Cup and other high-profile venues. The common person's sailboat is frequently adorned with the most dreadfully inappropriate appendages that fortunately or unfortunately (depending on your perspective) pass through the water sufficiently well to not draw too much attention to themselves. There is no simple means to know what performance might have been had the appendages been done correctly. Motorsailing speeds might increase one-half knot, and sailing upwind might be better by a boat length or two every couple miles sailed. The upwind or offwind broaching caused by a stalled rudder with a highly swept leading edge and stock might never have occurred. But these limitations are not readily observed or recognized. Only the most egregious errors show themselves with poor handling characteristics such as a narrow steering region where the boat feels right, or a singing rudder or keel on a multihull or planing dinghy. PBB

About the Author: *David Vacanti is the principal of Seattle-based Vacanti Yacht Design, which primarily develops computer software for boat design and analysis. He started writing code for marine applications some 20 years ago, and now provides technical support for more than 3,000 users of his software worldwide. He's authored a number of papers on keel, rudder, and foil design, and has designed—and redesigned—production and custom appendages for offshore and Great Lakes cruisers and racers. He is also an aerospace engineer, with a half dozen patents in radar and avionics.*