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

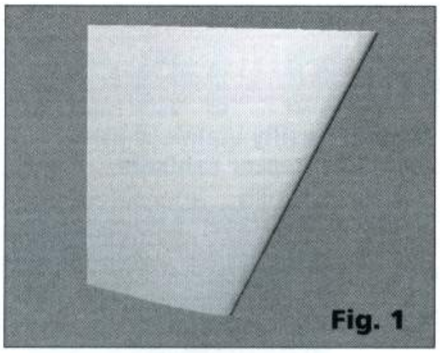

***Figure 1**—A typical "standard keel" with all straight leading and trailing edges and no special treatments. Leading-edge sweepback angle is about 40°.*

(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.

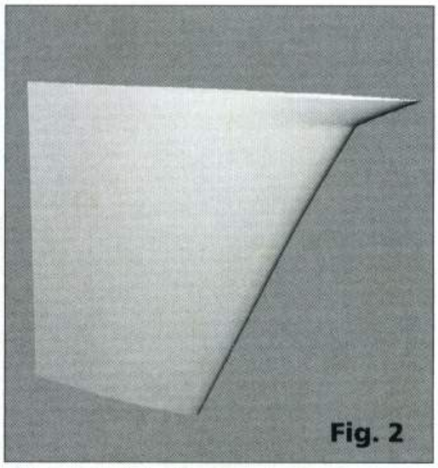

***Figure 2**—Interference drag caused by the intersection of the keel and hull can be minimized by slightly extending the root chord into a fairing at the leading edge, as shown here.*

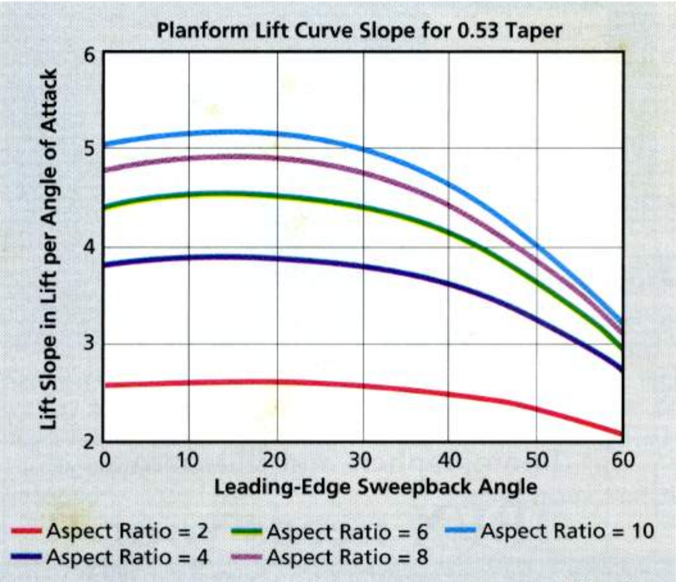

Fig. 3

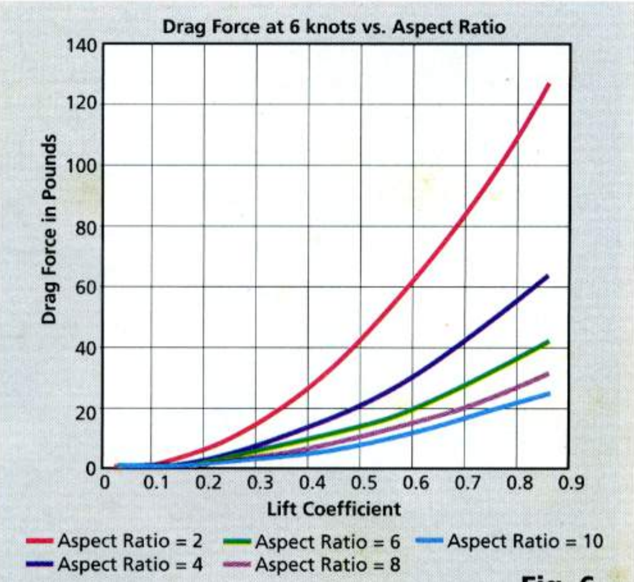

Fig. 6

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

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

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

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