Tuning a Twin-Screw Rudder Installation

Subtle changes in the setup can make significant differences in how a fast powerboat handles and performs

by Donald L. Blount

The installation of a rudder on a conventional inclined-shaft propeller-driven powerboat *appears* to be a simple process. Many builders think all they need to do is mount the rudder aft of the propeller, place a tiller arm on the rudder stock inside the boat, and then set up the appropriate hydraulic ram so that the rudder moves to the desired angle when the boat is operating at speed.

It's not that simple! Subtle changes in the installation can make significant differences in the maneuvering and control characteristics of the boat.

I've geared the information below to steering systems for twin-screw, inboard-powered boats that track well at high speeds, are reasonably responsive to the helm, bank in turns, and maintain approximately 80% of their "approach speed" when reaching steady turning conditions. Now, a boat that tracks well is the result of two key factors: first, balanced design—that is, a longitudinal center of gravity (LCG) located correctly in relation to the hull lines; and second, a well-engineered and -executed rudder steering system.

Troubleshooting

To attain good steering in a fast powerboat, you must first be aware of steering problems in past designs of similar vessels. This analysis of previous models and their shortcomings will provide an historical basis for your decision-making. Let's look at a few examples of steering problems. Some of these problems are related to the steering system, and some to the hull design or LCG location.

Bow Steering (Yaw Instability)

Bow steering, technically described as *yaw instability*, is one of the most frequent complaints of captains and boat owners. The helmsman, sensing that the boat wanders off-course for no apparent reason, must frequently correct the rudder angle to hold the desired heading. This is a difficult situation, both for the helmsman and an autopilot, if there is one, because he, she, or it must work hard to maintain a straight course whether in calm water or following seas.

Often this instability is not a steering system problem, but the result of the boat's LCG being too far forward for the shape of the hull. To correct the problem, you might try adding fixed-skeg area aft, or fitting larger rudders. But, if the problem is in fact caused by a far-forward LCG, such alterations will not be successful. Instead, you may need to shift the LCG aft or increase the lift of the hull at the bow. Either of these changes will increase the running trim angle, which in turn reduces annoying bow-steering characteristics.

Another non-steering system problem that affects boat handling is caused by *rudder ventilation*, the condition in which large quantities of air get into the water-flow path to the rudders. The air path may come either from the bow aft to the rudders, or from the transom forward to the rudders. If ventilation is causing the problem, then, when the rudders are turned, the boat will begin to respond in a normal way but suddenly stop turning. The bow usually drops, and the boat may heel in an unexpected direction. The solution to rudder ventilation is to eliminate the air path to the rudders.

If the air path originates at the transom, you will be able to see a "hole" in the wake behind the ventilated rudders when you stand at the transom and look down into the water. There are a number of ways to correct the problem.

You can move the trailing edge of the rudder forward, either by cutting off the original trailing edge or by moving the rudder stock forward; you can remove the top, aft area of the rudder; you can lower the rudder and increase the distance from the hull bottom; or you can extend the length of the hull bottom aft.

When longitudinal spray strakes are located in the same transverse buttock plane as the rudder, the air path may come from forward. In this case, the solution is to remove, or if possible, *move* the spray strakes transversely to eliminate the offending air path.

Although the two examples above describe non-steering system problems, they are often misidentified as something mechanical. Mechanical problems with the steering system, however, are easier to find *and* correct. Two typical, prominent symptoms are: excessive force is required to turn the helm; or, the boat cannot attain full rudder angles at high speeds. Or both. Most mechanical problems are caused by too small or improperly installed actuators or pumps; air in the hydraulic lines; blockages of travel of the tiller arms or tie-rods; or improperly sited rudder stops. The solutions all require well-designed and properly installed equipment.

Rudder *vibration* may have several different causes. If the rudder vibrates at a single constant frequency—the natural frequency of the rudder—but only at certain propeller rpm's,

A 63' aircraft rescue boat carves a starboard turn at full speed, full rudder, within a turning diameter of 646'. The author's many years of engineering high-speed military craft such as this—and then systematically studying their performance—led to the design "rules of thumb" for twin-screw rudders on the following pages.

then you should change the number of propeller blades. This will prevent unnecessary rudder vibration at the normal operating rpm of the propeller.

If the rudder-vibration frequency increases with the propeller rpm, then the rudder is too close to the propeller, and you should increase the clearance between the leading edge of the rudder and the trailing edge of the propeller.

With the boat out of the water, you can easily see whether there is rudder erosion and what kind it is. Here are the various possibilities:

- *Propeller hub vortex* will cause erosion on the rudder in line with the prop hub. To solve the problem, install a shaped fairwater on the end of the prop shaft; this will force the water flow to diverge.
- *Tip vortex* will cause erosion in line with the propeller diameter. The solution is to change the prop design to eliminate or reduce the tip vortex.
- *Erosion on one side* of the rudder surface—outboard only or inboard only—means the rudder's alignment with the prop wake has not been set for best performance. You can see this condition in the photograph on page 98.

Most steering system problems can be avoided through thoughtful design and construction. The guidelines that follow are based on many years of personal experience designing boats that have good handling and maneuvering characteristics.

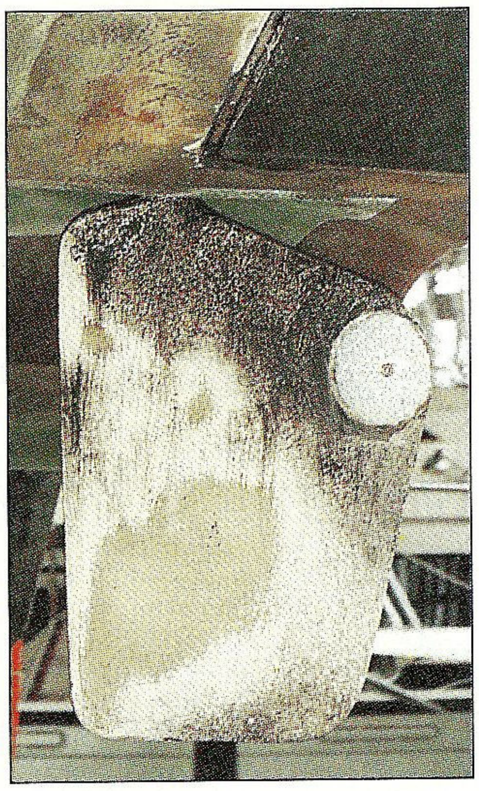
Rudder Size

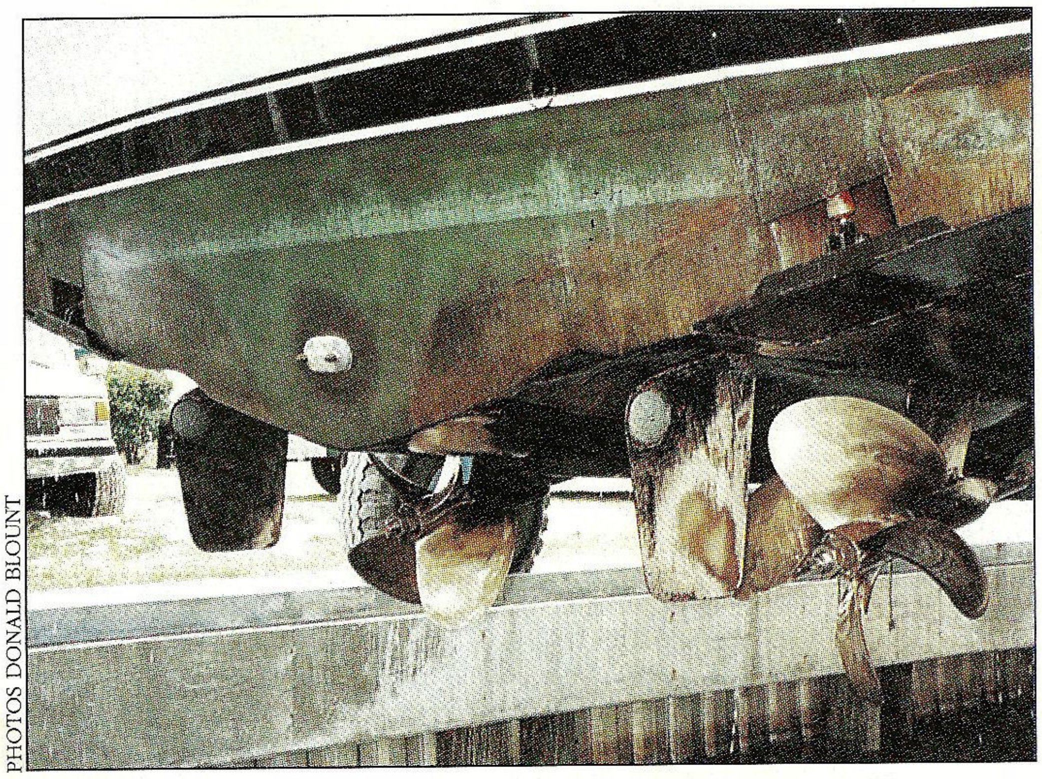
I use the term "size" to include all dimensional aspects of a rudder: area, length, width, rudder-stock location, and so on. Choosing the correct rudder size for a boat design is important, and you must determine it at the outset of a new design.

In selecting for rudder area, remember that boat weight and speed are both *primary* factors, while the length and width of the rudder blade are *secondary* factors—so you can vary the latter somewhat to suit the geometry and draft requirements of your specific boat design.

My experience with combatant craft that have good handling characteristics has provided me with useful design criteria for selecting rudder area, and I've listed specific recommendations in the accompanying rudder-sizing charts (see **Figure 1**) that will work for a wide range of boat weights and speeds.

Tuning continues





PHOTOS DONALD BLOUNT

The rudders themselves often reveal the cause-and-effect of improper installations. In the bottom photo we see the underwater setup on a fast twin-screw powerboat, with close-up views above. ***Top left***—*The leading edge of the inboard surface shows propeller tip erosion in the upper corner, and prop hub erosion at the base.* ***Top right***—*The outboard surface of its mate shows surface erosion attributable to incorrect toe-in.*

Rudder Geometry and Location

Figure 2 provides some basic definitions and a profile view of a typical rudder. The *projected area* is the single most important feature. The lever arm of the rudder—the distance between the rudder-stock axis and the center of pressure—controls the steering torque. Having the center of pressure aft of the rudder stock is a critical safety factor: Unless the center of pressure remains aft of the stock axis, steering-gear failure during high-speed operation could cause a snap turn.

Around the waterfront, there is some disagreement as to the best rudder balance. There are those who recommend values ranging from 15% to 25% of the rudder area forward of the stock; myself, I recommend 17% to 18%. Rudder balance, however, is also influenced by the rudder's section shape, be it an airfoil, flat plate, wedge, or parabolic in form.

In general, the location of the *vertical center of pressure*, combined with the side or turning force, should dominate your choice of size for stock diameter. The vertical center of pressure is typically 45% of the length of the rudder measured down from the top.

The placement of a rudder relative to the hull and prop is another key consideration. The guidelines shown in **Figure 3** are suitable for both single- and twin-rudder installations. I've established these relationships as design *rules of thumb*, based on my own experience with many boats. To make the dimensions that define the location of the rudder useful for various sizes of boats, I've presented them as ratios of the propeller diameter.

In order to prevent an airflow path that might ventilate the rudder when the boat is in a turn, you must ensure that the trailing edge of the rudder is forward of the transom. Unlike a fully wetted rudder, a ventilated rudder can reverse the turning forces and cause the boat *not* to respond to the rudder—indeed, the boat may refuse to turn until or unless you pull back the throttle.

The clearance between rudder and hull influences effective aspect ratio; that is, when there's a large gap, there is also a reduced turning force. To achieve the highest rudder force to turn the boat, keep this gap as small as possible.

The fore-and-aft distance between the prop and the leading edge of the rudder matters for several reasons. First, the pressures and wake from the propeller rotation can cause, or excite, vibration. Second, the fore-and-aft distance should be large enough to enable replacement of the propeller without removing the rudder. At the same time, locate the rudder stock such that it will be offset transversely from the propeller shaft. This has little effect on the boat's turning performance, and will allow propeller-*shaft* replacement without removal of the rudder.

Rudders in a Turn

When you study performance data, you can see that a boat is in an ever-changing state as it turns from a straight course until it reaches a constant turning radius at a steady speed. Having conducted many turning tests, I've made the following observations:

1. The velocity of water over the rudder is accelerated by the propeller.
2. Maximum steering torque occurs while the rudder is still moving and at about 85% of the maximum angle.
3. In a steady turn, the centerline of the boat will be at some angle relative to the tangent of the path of the boat's turning radius.
4. Maximum rudder angles are not usually used at high speeds because of large loss of speed, and excessive dynamic or centrifugal force induced while turning.

A high-speed boat in a steady turn is described in **Figure 4**. The side-slip angle (symbolized by the Greek letter *alpha*) is usually somewhere between 0° and 12°, with the bow inside the turning radius. In most twin-screw boats, the rudders are installed so that they turn at the same angle relative to the centerline of the boat, which means the outboard rudder actually exhibits a larger angle relative to the local water flow than does the inboard rudder. As a result, each rudder develops different turning forces. In other words, the inboard rudder operates at a lesser radius than the outboard rudder and needs a larger angle in order to have the same turning forces. This is not unlike the differential turning of the front wheels of an automobile.

Tiller Arm Toe-In and Toe-Out

Again, as stated above, the inboard and outboard rudders of twin-screw boats, designed for equal geometric angles, will have different angles relative to the water flow in a turn and, therefore, different rudder turning forces port and starboard. You can achieve *equal* rudder forces by attaching the tiller arms to the rudder stocks at an angle to the rudders. When the tiller arms are properly aligned, the port and starboard rudders will turn at different angles.

The differential needed between port and starboard rudders

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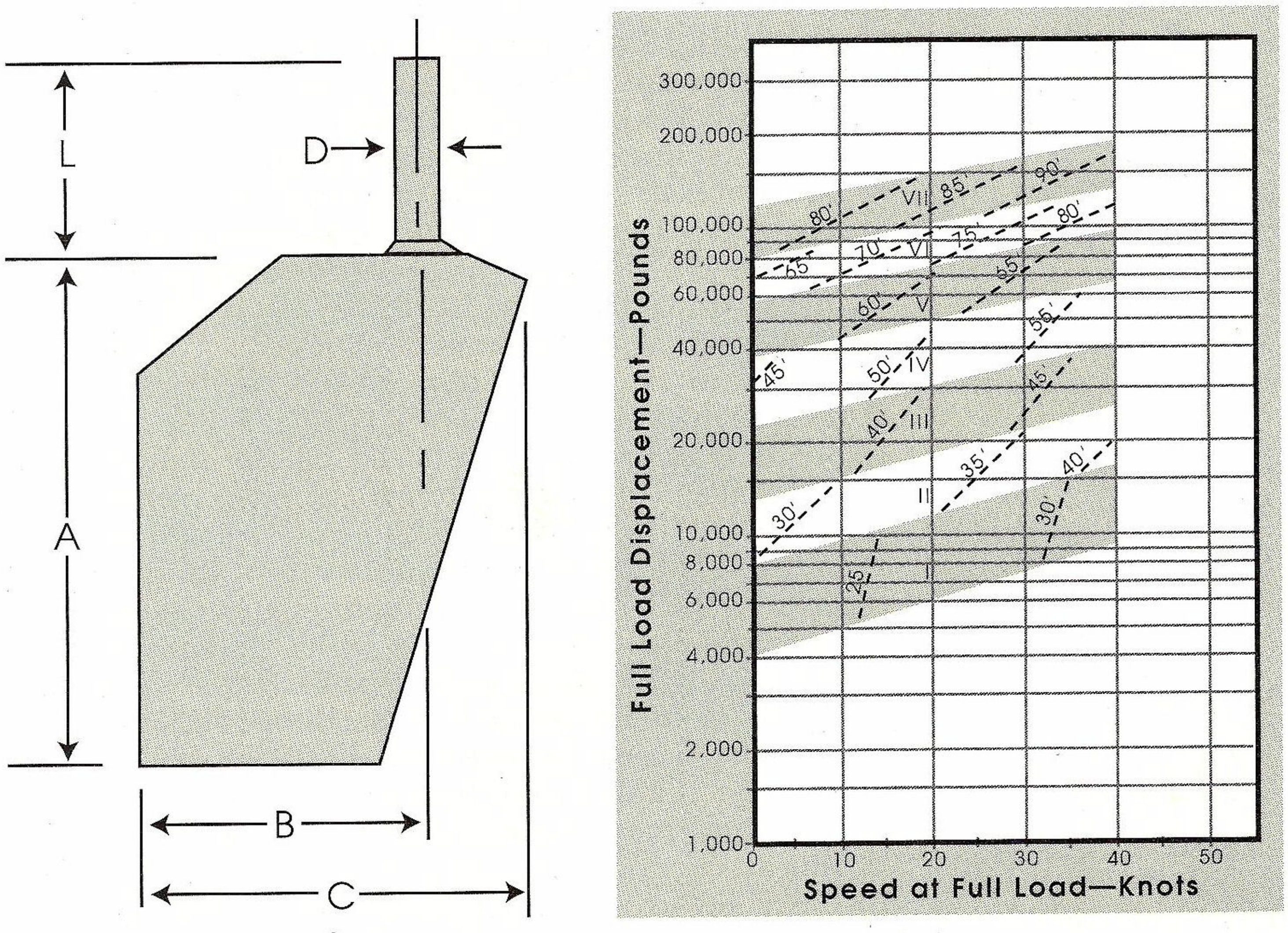


Figure 1—Rudder Size. *These charts provide the design criteria for selecting the appropriate rudder area for a wide range of boat weights and speeds.*

Rudder	Diameter (inches)	Length (inches)	Stock Weight (pounds per foot)	Rudder Weight Less Stock (pounds)	Rudder Length A (inches)	Stock Location B (inches)	Rudder Width C (inches)	Minimum* Rudder Torque 40 Knots (inch-pounds)
I.	1¼	15	4.17	19	13½	6 11/16	9 13/16	4,400
II.	1½	18	6.01	30	16½	8¼	12	8,100
III.	1¾	21	8.18	47	19	9⅜	13¾	12,200
IV.	2¼	24	13.52	82	23⅜	11⅝	17	23,300
V.	2¾	30	20.19	125	27	13⅜	19½	34,300
VI.	4	34	42.71	200	31	15⅜	22⅜	52,200
VII.	4½	38	54.05	275	34½	17	25	71,900

*Rudder torque has been increased 25% to allow for bearing friction.

Notes

1. The numerical value of the stock length (L) has been chosen arbitrarily.
2. Rudder weights are estimated.
3. Rudder torque is included so that the force required at the tiller arm can be estimated.
4. Dashed lines indicate approximate boat length.
5. Roman numerals indicate rudder size recommended.
6. Consult the manufacturer for rudder requirements outside those of stock design.

WESTERN BRANCH METALS

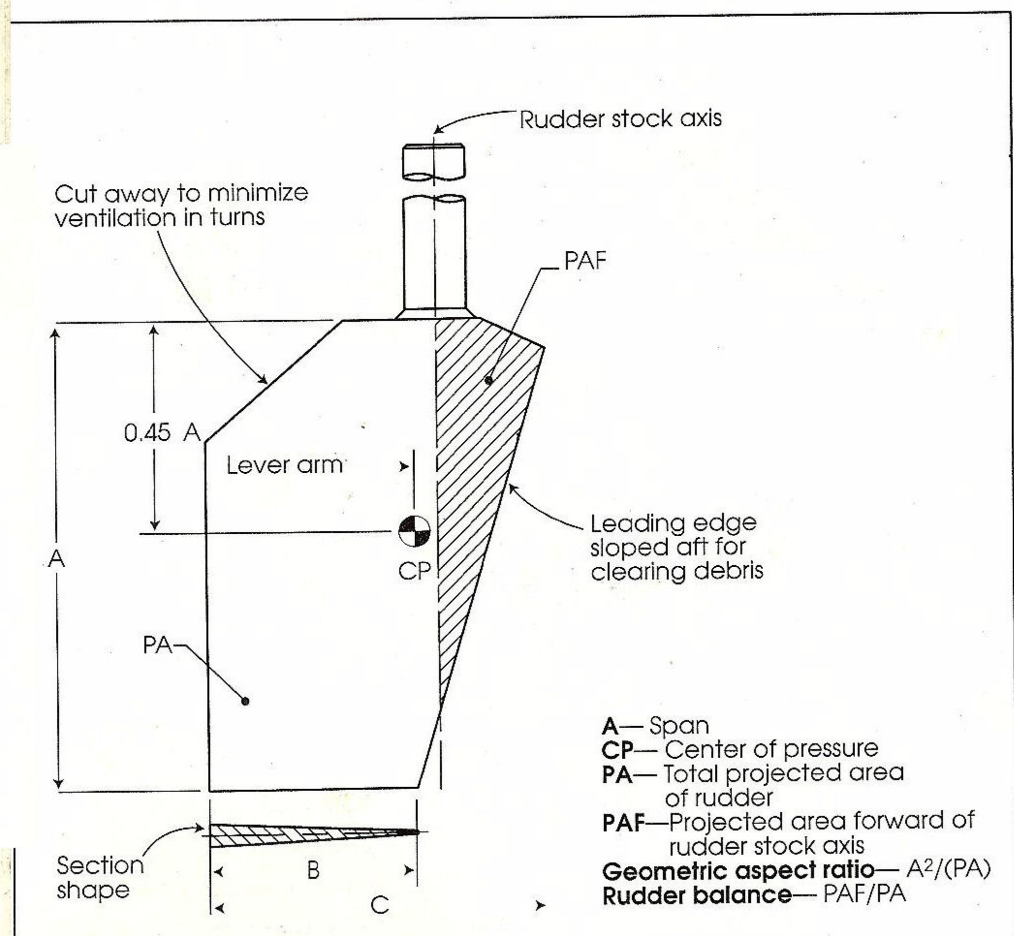


Figure 2—Rudder Geometry. *The projected area, says the author, is the single most important feature to consider.*

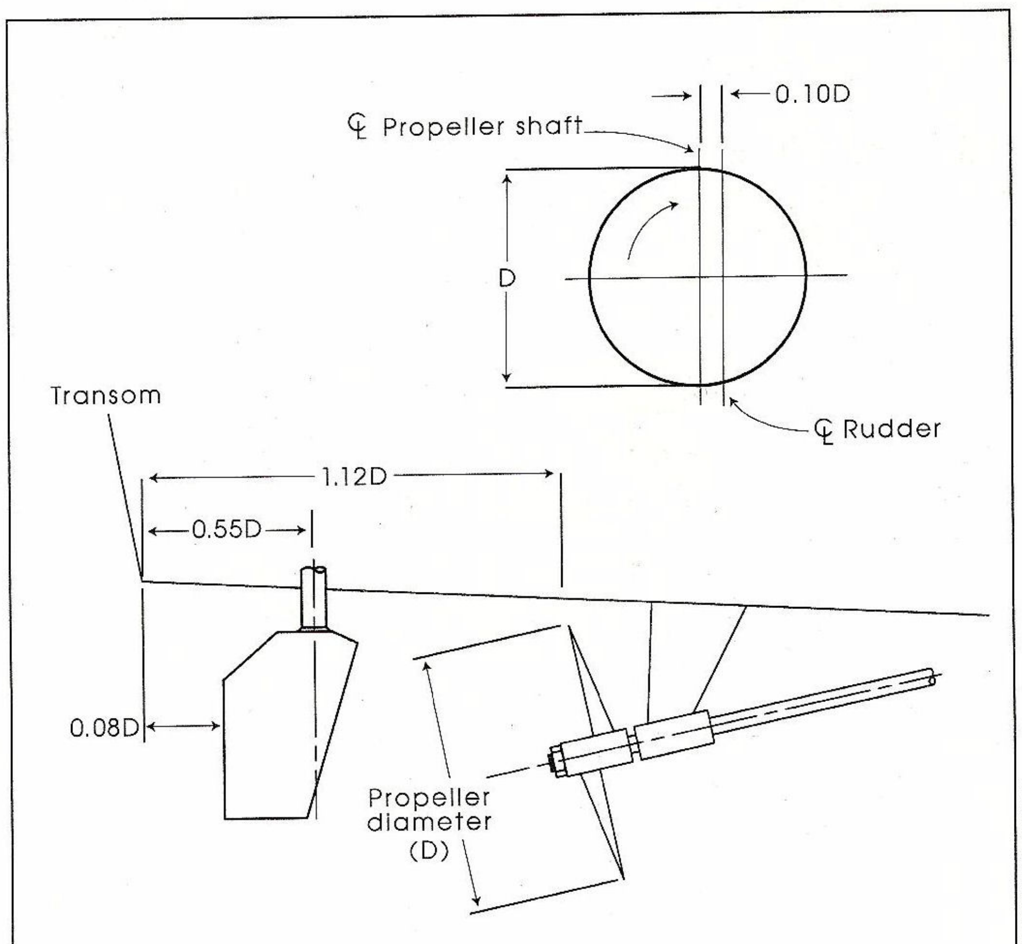


Figure 3—Rudder Location. *The guidelines shown here are suitable for both single- and twin-rudder installations.*

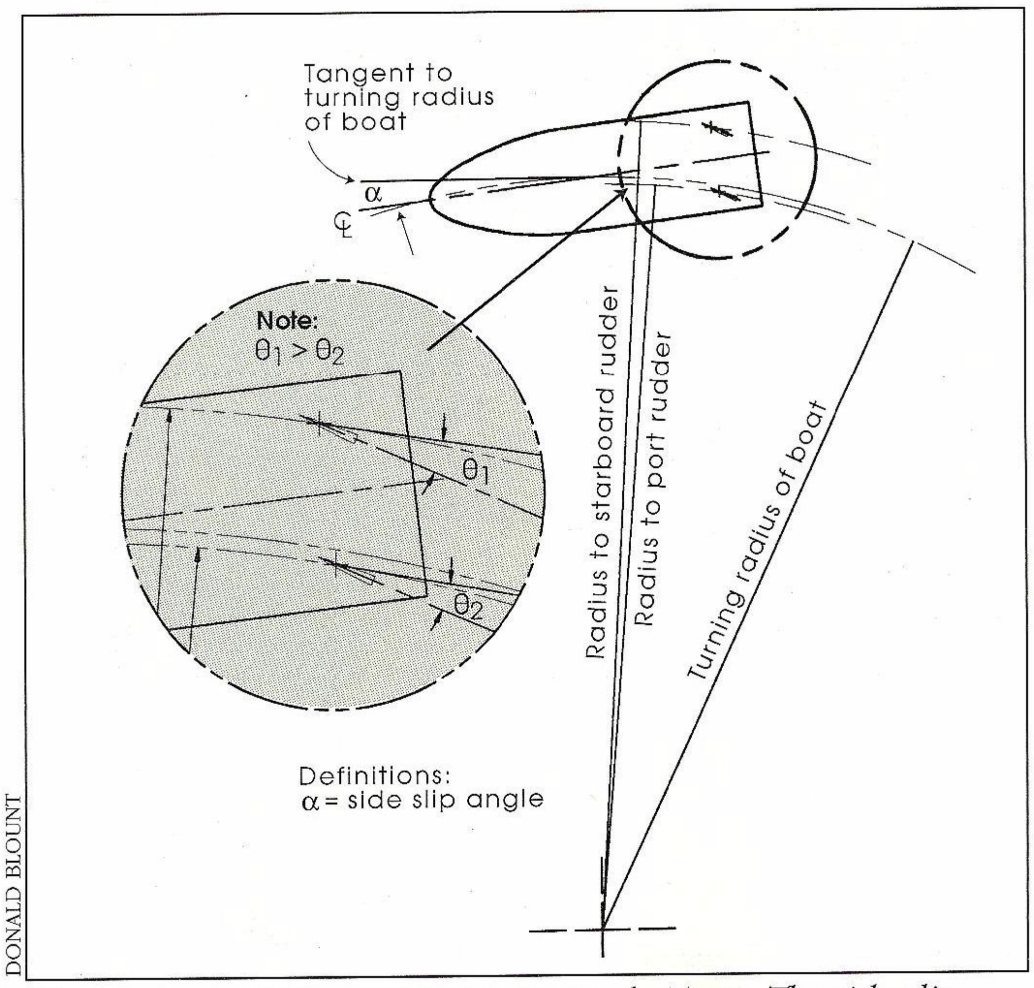
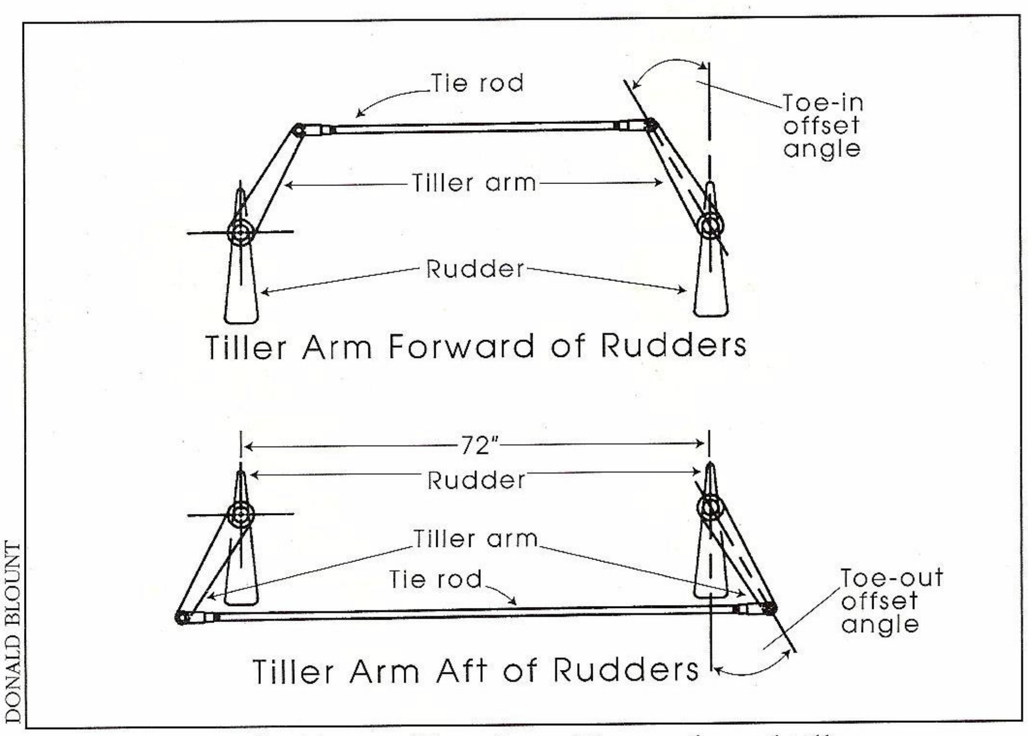
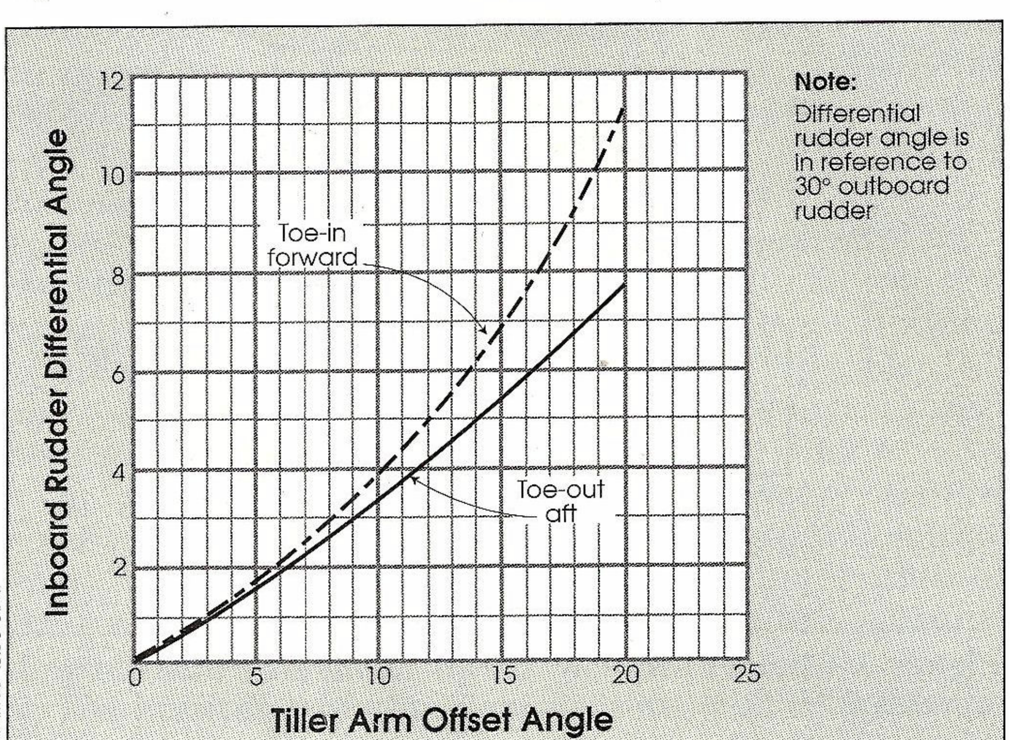


Figure 4—High-Speed Boat in a Steady Turn. *The side-slip angle (indicated by the Greek letter alpha) is typically between 0° and 12°, with the bow inside the turning radius.*



Figures 5 & 6—Toe-In/Toe-Out. *The preferred tiller-arm toe-in/toe-out angle differs for each boat design, and is based on the length of the tiller arm and the tie rod. Tiller arm toe-in/toe-out for the steering-system dimensions depicted above is plotted in the chart below.*



to satisfy local water-flow angles is typically 2° to 5°. For a given boat, the exact differential angle required for optimum performance depends on the turning radius. You can establish this differential with sea trials, but only if you have not yet cut a keyway in the rudder stock and/or tiller arm. The lack of a keyway allows adjustment of toe-in/toe-out for the boat, to give the boat a tight turning radius, or the least speed loss in a turn. After sea trials, you can cut the keyway for the desired tiller arm toe-in/toe-out, which is determined as follows.

First of all, the preferred tiller-arm toe-in/toe-out angle will be different for each boat design, and is based on the length of the tiller arm and the tie rod. (See **Figures 5 and 6**.) When the tiller arms are *forward* of the rudder stock, make the tie-rod length shorter than the distance between the stocks. With the tiller arms forward of the rudder stocks toed-in, the inboard rudder turns at a greater angle than the outboard one. This is consistent with the desire to equalize the turning forces between rudders. When the tiller arms are *aft* of the rudder stock, make the tie-rod length greater than the distance between the stocks (toe-out).

There is a difference between port and starboard rudder angles relative to the tiller-arm angles. For example, by setting aft-directed tiller arms at a 10° toe-out angle (relative to the rudder), you will cause the outboard rudder to turn about 27° while the inboard rudder turns 30°—a difference of 3°.

Rudder Offset Angle

You're unlikely to realize a boat's best performance or enhance response to the helm if the rudders are installed parallel to the centerline of the boat. Consider that, in many cases, the vertical dimension of the rudder places the rudder in the prop wake above the propeller shaft. Because the angular flow imparted to the water in the upper half of the prop wake is in the opposite direction of the lower half, the effective flow angle to the rudder will be influenced mostly by the upper propeller flow *and at a small angle relative to the centerline of the boat.* For twin-screw boats with outboard-turning propellers, your best choice of rudder angle for straight running is with the leading edge near the hull centerline at or about an angle of 1° to 3°.

To establish the best rudder angle for running a straight course, you need to conduct sea trials, using an adjustable-length rudder tie-rod. (See **Figure 6**.) Either fit a turnbuckle to the tie-rod, or mount end fittings that have enough thread length to adjust the rudder offset angle. You must also set engine throttles to the desired condition (cruise or maximum speed), and measure the speed accurately for each rudder offset angle. Then, record any observations regarding response to the helm. In particular, you're judging the force needed to turn the helm, and the vessel's response in turns. If possible, record the running trim angle, as well.

Another method for optimizing the rudder angle at high speed is to disconnect the tie-rod during a straight run—but this can be risky, because you will momentarily be without steering during the test. However, the now free-to-turn rudders will automatically center themselves relative to the flow direction of the water in the propeller wake. Measure the distance between the tiller-arm pins, adjust the tie-rod length to the measured distance, then fit and pin the tie-rod to the tiller arms.

How much will offsetting the rudder angles improve performance? On some boats, optimum offset rudder angles have increased speed by as much as one-half knot in comparison to when the rudder angle was parallel to the centerline of the boat. But, there are two additional benefits to be gained: steering forces at the helm will be lower, and the running trim of a boat can change by about one-half degree.

The table in **Figure 7** documents sea trial results from a

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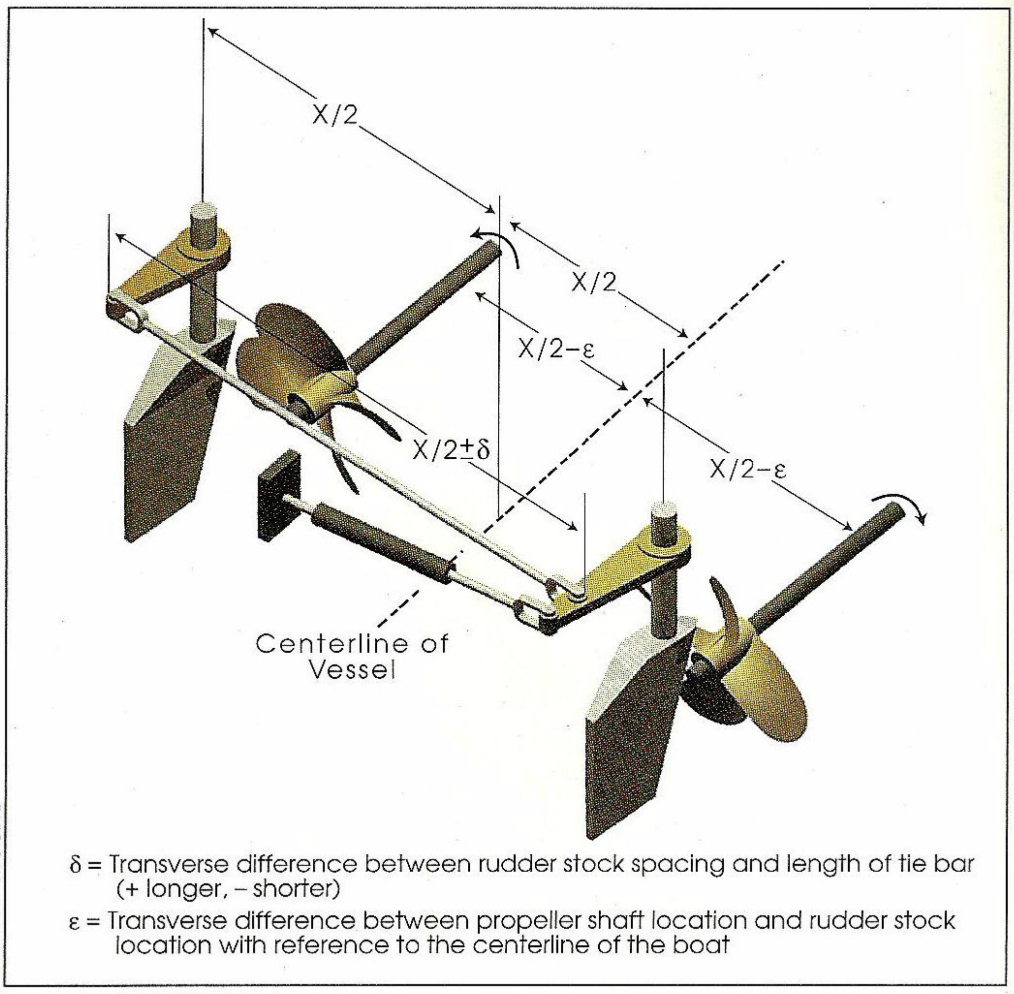

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Figures 6 & 7—Tuning the Installation. *The optimum rudder angle for the boat is best found by running a straight course in sea trials, using an adjustable-length rudder tie-rod. The table below documents the results of sea-trialing a 48-footer this way, recording variations in rudder offset angles.*

Rudder Offset Angle (+ Leading Edge Inboard) in Degrees	Speed Knots	Trim Bow Up Degrees	Comments
+4.8	34.4	7.3	Steering hard to port and stbd.
+2.4	34.7	7.2	Steering easy
+1.2	34.8	7.0	Steering very easy
0	34.8	7.0	Rudders parallel to boat center line
-1.2	34.8	6.9	Steering hard to port and stbd.
-2.4	34.6	6.9	Steering very hard, boat will not respond to turn

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48', twin-screw boat employing an adjustable length of rudder tie rod to achieve variations in rudder offset angles. This example indicates that changes in the rudder offset angle do make a difference in how the boat handles and performs.

Summing It Up

Rudder systems are vital to the safe maneuvering and control of a fast powerboat. By paying careful attention to installation details, designers and builders working together can deliver boats with outstanding maneuvering characteristics.

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About the Author: *Don Blount is the principal of Donald Blount and Associates, a marine design, engineering, and project-management firm located in Norfolk, Virginia, which specializes in technologies for high-speed boats, including sportfishermen, motoryachts, and patrol craft. He is the former civilian head of the U.S. Navy's combatant-craft engineering department. (His firm's Web site is http://ourworld.compuserve.com/homepages/dlba.)*