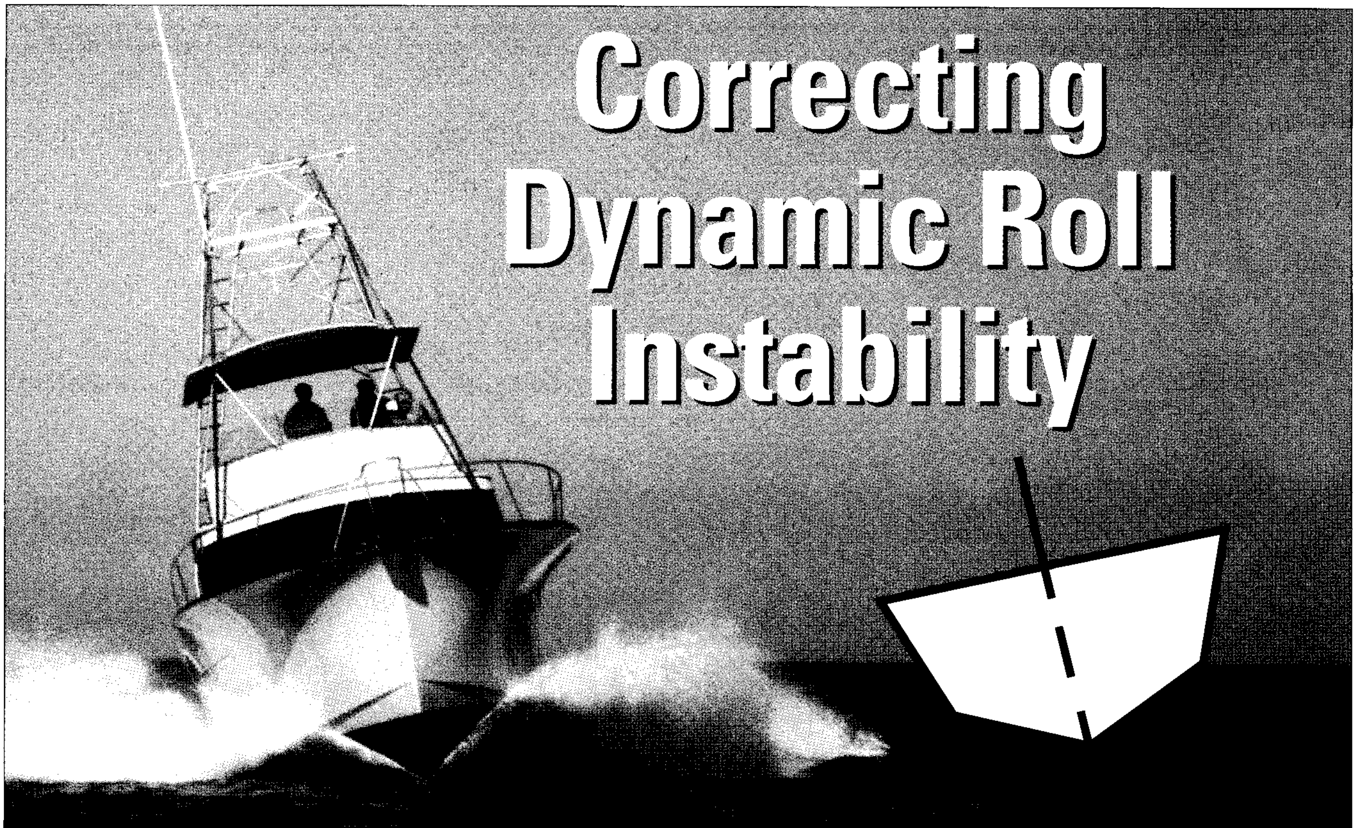
Correcting Dynamic Roll Instability



Low hydrodynamic pressure, or suction, at the forward hull bottom can cause some powerboats to lay over and "stick" at a certain angle of heel at high speed. We consider the causes of the problem, and approaches to fixing it.

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Have you ever been at the helm of a high-speed boat that would lay over on one side or the other, and stay heeled until you took some corrective action? Sometimes you can temporarily level the boat by adjusting differential trim tabs, or by "kicking" the rudders to turn the boat out of the heel. But usually you must throttle back to a slow speed before the boat returns to a level attitude.

This heeling problem is a *non-oscillatory dynamic roll instability*, and it's related to speed on vessels powered to exceed 25 knots. It's *not* related to number of shafts or boat size; in fact, early records describe 100′ to 200′ (30m to 61m) round-bilge military craft heeling at high speeds. "Non-oscillatory" means that the boat does not continuously cycle in roll, but seeks a new, steady, nonzero roll angle related to the speed of the boat. When the boat stops or slows to a displacement speed, it returns to a stable zero-heel angle.

What causes boats to "stick" at a certain angle of heel at high speeds is low hydrodynamic pressure, or suction, on the forward area of the hull bottom (see **Figure 1**). For a quick demonstration of how suction works, hold a spoon loosely in your fingers and touch its rounded bottom surface to water flowing from a faucet. The spoon is sucked into the water, not pushed away (see **Figure 2**). When a boat trims too flat (for which there could be several causes), the bow can be "sucked down" for the same reason the spoon is sucked into the flow of water from the faucet.

During sea trials conducted by a U.S. Navy test team on a U.S. Coast Guard boat exhibiting roll instability, suction pressures were in fact measured on the forward hull bottom—confirming our explanation. Still, it's very difficult to define just when the combination of buttock curvature and local water velocity results in dynamic suction pressures sufficient to overcome dynamic lifting pressures.

The 47′ (14.3m) sportfisherman pictured here, underway at 32 knots, will remain heeled until the helmsman takes corrective action—either adjusting rudders or trim tabs, or throttling back until the boat returns to level. A vessel experiencing dynamic roll instability does not continuously cycle in roll, but seeks a new, steady, nonzero angle related to the speed of the boat.

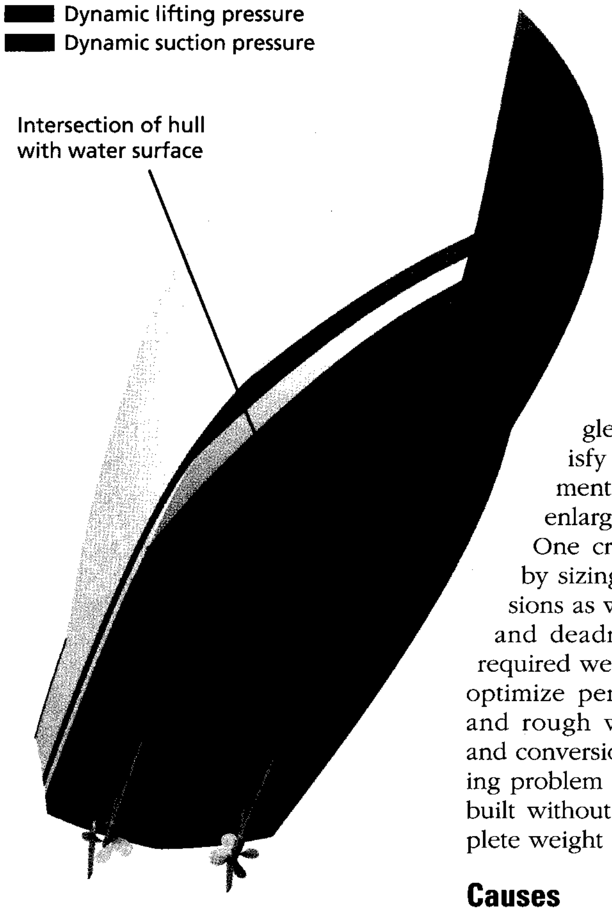


***Figure 1**—The arrow in the drawing points to the area of the vessel's bottom where the buttocks curve up. Suction pressures in this region can cause dynamic roll instability.*

Round-bilge hulls that are overpowered exhibit this heeling problem with greater frequency and severity than hard-chine boats. Also worth noting is that bow steering (poor course keeping) is often observed on a boat with dynamic roll instability.

In our professional practice *[see biographical notes at the end of this article—Ed.]*, we've noticed an increasing number of clients coming to us with with dynamic roll instability problems in their boats. What's happening? One possible explanation is that designers and builders are putting higher-horsepower engines in proven hulls without considering that the design balance has changed. Or, they are developing new models by extending hull length aft without relocating the longitudinal center of gravity (LCG). Or, they're "powering up" new models for higher speeds without changing the design and construction of the stern hull bottom and appendages.

As far as performance boats are concerned, it's our opinion that a single hullform will never satisfy multiple client requirements if the design is simply enlarged by geometric scaling. One creates a balanced design by sizing the overall hull dimensions as well as longitudinal beam and deadrise distribution for the required weight and LCG in order to optimize performance in both calm and rough water. Many new boats and conversions with a dynamic heeling problem have been designed and built without anyone preparing complete weight and LCG estimates.

Causes

In an ideal world, a designer who is given a specific set of symptoms would like to be able to say that the cause of the problem is ________ (reader may fill in the blank). Unfortunately, a symptom that appears while the boat is underway can often be due to a range of causes—each requiring different solutions (see **Figure 3**).

To resolve a heeling problem, the factors that result in the forward buttocks becoming and staying wetted at high speeds must all be corrected. In many cases, design and construction details at the stern hull bottom and appendages are the culprits. The table in Figure 3 summarizes the characteristics that can determine whether or not a boat will have a tendency to heel and stick at some speed above 25 knots. All the items listed result in wetting of the forward buttocks at high speed and development of suction. The following paragraphs will provide more detailed explanations of the causes listed in the table.

• ***Boat too heavy for its size.*** A high-speed boat can be too heavy relative to its bottom area for good all-around performance. A boat's being too heavy does not, by itself, result in dynamic roll instability. But, in combination with other design factors, it does greatly increase the boat's tendency to become unstable in roll. For example, it's widely known that very heavy boats tend to "get over the hump" more easily and attain maximum speed with a forward LCG. A forward LCG, however, can lead to dynamic roll instability. Moving the LCG forward to improve speed performance reduces running trim angle and thus brings the wetting of the forward curved buttocks into play—leading to a situation in which suction can develop.

The marine industry will probably never accept a definition of how heavy is too heavy. Our experience is that heavy hull loading becomes a factor that could result in dynamic roll instability for hard-chine boats when:

$$W^{2/3}/A_P \geq 2.91$$

For round-bilge boats, we suggest that one should be concerned about a boat's being too heavy when:

$$W/(L \times B)^{3/2} \geq 3.75$$

Where:
W = Full-load boat weight in lbs
A_P = Projected area of the planing hull bottom bounded by the chine and transom in sq ft
B = Waterline beam in ft
L = Waterline length in ft

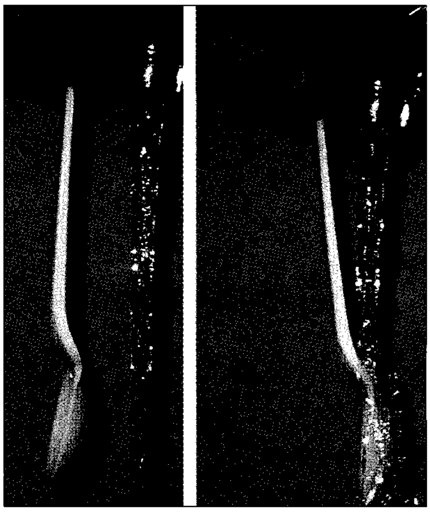


***Figure 2**—For a quick demonstration of how suction works, hold a spoon loosely in your fingers and touch its rounded bottom surface to water flowing from a faucet. The spoon is sucked into the water **(right)**, not pushed away.*

Figure 3. Causes of Roll Instability

Problem	Approaches to correct problem
Boat too heavy for its size	Remove weight, especially forward of the LCG *or* redesign hull lines.
LCG too far forward relative to longitudinal distribution of chine beam	Rearrange location of components to shift LCG aft *or* redesign hull lines.
Hook in hull bottom near transom	Fill in hook or dished plates to achieve straight buttocks for aft 20% of hull bottom length.
In profile, the buttock curvature is too extreme near the bow quarter length or extends too far aft	Redesign hull lines *or* add flow-separating wedges to hull bottom.
Rudderpost ventilation	Cut off or redesign rudderpost to be flush with hull bottom.
Rudder ventilating near hull	The rudderpost must be designed to the minimum diameter consistent with hydrodynamic loads. (For more information, see "Rudder Design for High-Speed Boats," PBB No. 78, page 72.) Reduce rudder thickness to no more than that of rudderpost diameter. Parabolic, wedge, or flat-plate rudder sections are preferred. Lower rudder away from hull a distance greater than the stock diameter. Fairings filling the gap between the hull and top of the rudders, and attached to the hull ahead of and aft of the rudderpost, may reduce the tendency to ventilate.
Rudder toe-in/out not properly set	Set rudder toe-in/out with sea trials.
Trailing edge of rudder too close to or extends aft of the transom	Cut away top of the rudder aft of the stock, cut off trailing edge, lower rudder away from hull a distance greater than the stock diameter, extend a flat plate from the hull bottom over the rudder, or put a "fence" on the rudder.

• ***LCG too far forward relative to longitudinal distribution of chine beam.*** The location of the LCG relative to the hull lines is a very significant factor affecting dynamic roll instability. As stated above, forward LCG can reduce the running trim angle and lead to the development of suction.

• ***Hook in hull bottom near transom.*** Bottom hook near the transom (see **Figure 4**) creates dynamic pressures that lift the stern of the hull and reduce the running trim angle—again, leading to the development of suction forward.

• ***In profile, the buttock curvature is too extreme near the bow quarter length, or extends too far aft.*** As planing boats accelerate from displacement to high speeds, the principal forces that support the boat change from buoyant to dynamic. Hump speed is the point at which dynamic pressures become the predominant mode of support for the boat's weight, and the hull begins to lift out of the water. As speed increases above hump, it is the shape of the hull bottom below the chines relative to the total weight and LCG that defines the boat's calm- and rough-water performance. Most of the dynamic lift comes from the aft two-thirds of the planing bottom. However, as trim reduces with increased speed or as other factors result in bow-down trim moments, the forward curved buttocks become wetted, which can lead to suction pulling the bow down. Thus, the shape of the buttocks near the bow has a significant influence on whether or not dynamic roll instability will occur.

• ***Rudderpost ventilation.*** Some builders, especially (but not exclusively) of boats constructed of aluminum, extend the rudderpost below the hull bottom, as shown in **Figure 5**. This is just bad hydrodynamic practice for high-speed boats. To achieve good performance, it's important to eliminate or minimize the hydrodynamic influence of underwater appendages that might cavitate, ventilate, or cause bow-down trim moments at high speed.

In Figure 5, you can "read" the paint-removal patterns. The paint on the sides of the cylindrical rudderpost, as well as on the hull surface aft of the post, has been eroded by cavitation. The vapor pressure inside the cavity is about 0.5 psi (0.003 N/mm^2) until it extends to the transom. Then, air rushes into the cavity, filling it with atmospheric pressure at 14.7 psi (0.1 N/mm^2). This sudden increase in pressure adjacent to the hull bottom lifts the stern, lowering the running trim of the boat and wetting the forward curved buttocks.

• ***Rudder ventilating near the hull.*** Some fabrication techniques for joining the stock to the rudder blade can result in thick sections. Too-thick sections at the top of the rudder—especially on rudders with airfoil sections—can lead to cavitation and ventilation problems.

When the top of the rudder ventilates, it can cause the boat to lay over. Also, when one side of the entire surface of the rudder ventilates, steering control of the boat can be lost or greatly diminished. In fact, when airfoil-section rudders fully ventilate, the boat may stop turning or even slowly turn in the opposite direction of that expected.

• ***Rudder toe-in/out not properly set.*** Rudder toe-in/out influences the running trim of a boat. Setting rudder toe-in/out such that it results

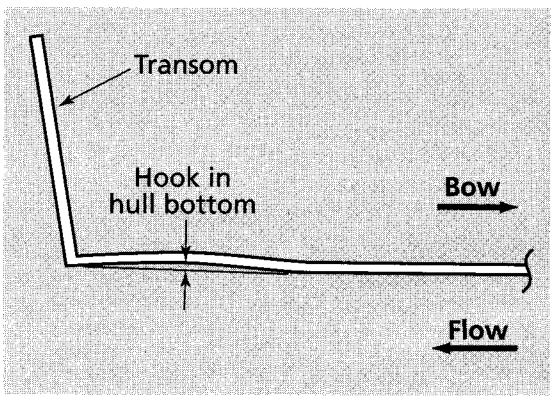


***Figure 4**—Bottom hook near the transom creates dynamic pressures that lift the stern and reduce the running-trim angle, causing suction forward. Hook can be unintentionally created during a boat's manufacture—on metal hulls, by plate distortion due to welding; on FRP hulls, by prerelease from the mold.*

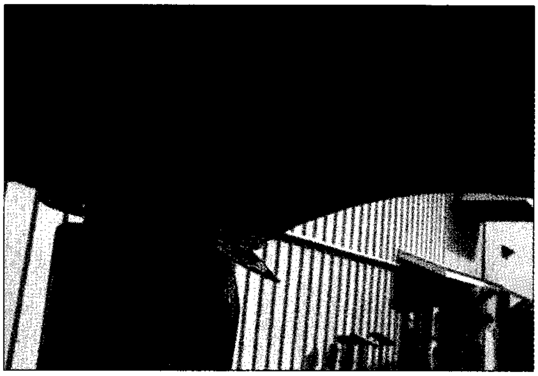


***Figure 5**—The rudderpost shown extends below the hull bottom—bad hydrodynamic practice for high-speed boats. It's important to eliminate the influence of underwater appendages, which can cause cavitation, ventilation, or bow-down trim moments at high speed. Note the paint-removal patterns to the right of the bearing: the paint on the sides of the rudderpost, and on the hull surface aft of the post, has been eroded by cavitation.*

in some bow-down trim could cause the wetting of the curved buttocks forward.

In general, twin-screw boats with outward-turning propellers (right-hand prop on starboard side and left-hand prop on port side) should have the trailing edges of the rudders farther apart than their leading edges. The best rudder angle relative to the centerline of the boat may be in the range of 2° to 4° for the zero steering angle to achieve the best speed and trim angle, as well as to minimize steering torque. Optimum rudder angle is determined during sea trials by adjusting the length of the tie bar connecting the tiller arms. *[For more on determining rudder angle, see "Tuning Twin-Screw Rudders," PBB No. 45, page 90—Ed.]*

• ***Trailing edge of rudder too close to, or extends aft of, the transom.*** One of the most common causes of rudder ventilation on high-speed boats is the trailing edge of the rudder being located very near, or extending aft of, the transom. When the rudder is properly under the hull, the hydrostatic pressure head of the water flow separating at the transom tends to seal off the cavity that can develop behind the rudder. If the top of the rudder at the trailing edge is very near the transom, the hydrostatic pressure head becomes insignificant, and the rudder will likely ventilate. Consequently, the stern is lifted, trimming the bow down and wetting the curved buttocks forward.

In some designs, it may not be possible to locate the rudders under the hull, given machinery arrangements and the position of the LCG. In that case, transom-mounted rudders are an option. They must have non-airfoil sections in order to function properly at high boat speeds.

Solutions

Where does one begin to look on a particular boat for causes of roll instability? First, gather the hull lines, as-built weight, and LCG (obtained from actual weighing, or calculated from draft marks). Haul the boat, take photographs of the underbody to document any paint-removal patterns from cavitation erosion, grab a comfortable chair, and sit down to analyze the hull and appendage design. (Digital photos work well here: it's quick and easy to e-mail them to a design professional for assistance.)

As we've discussed above, the problem of heeling may have two causes. First, displacement and LCG are inappropriate for the hull lines; and the hull lines themselves could have too much hook aft or too much forward buttock curvature. Second, hull appendages are located or shaped so as to encourage ventilation. One or both causes may be at work on a particular boat.

It has been our experience that the most fruitful and least costly approach is to tackle the ventilation problem first. If it is a contributing factor to heeling, correct it. If it's not, then turn to the inappropriate relationship of weight, LCG, and hull lines.

With regard to a heeling problem, the most frequent ventilation air path is flow forward from the transom to fill the cavities caused by disturbances under the hull. In some cases, hull recesses for trim tabs near rudders and/or rudderports facilitate the air path to fill a cavity. The second most frequent air path is from a disturbance at the bow (longitudinal spray strips, transducers, or through-hull fittings) near where the hull bottom, at speed, first comes in contact with the surface of the water. These two ventilation scenarios are illustrated in **Figure 6**. (Although not related to the heeling problem, appendages causing under-hull ventilation can result in propeller ventilation, possibly leading to severe propeller vibration.)

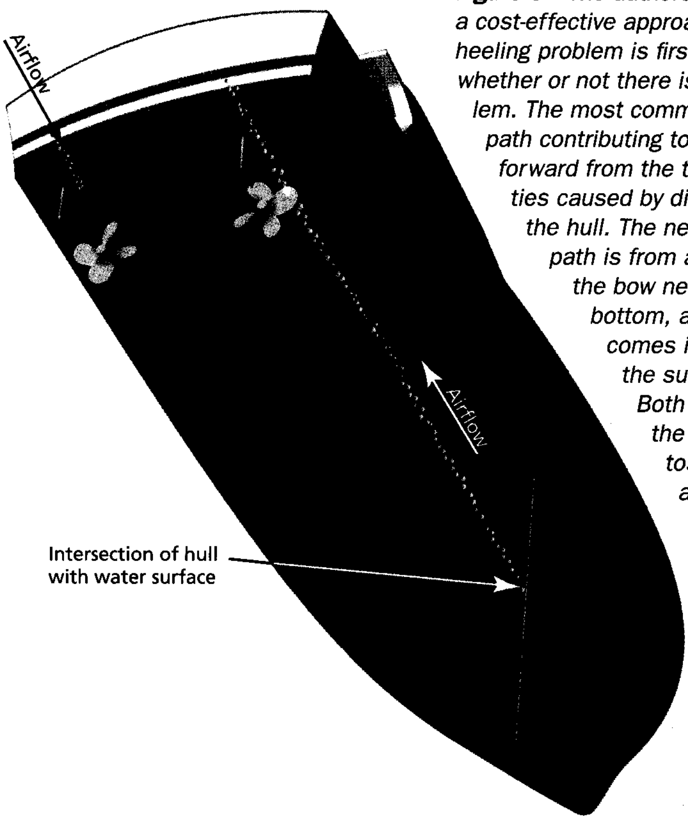
Figure 7 illustrates a ventilated rudder: a wedge-section rudder at an 8° angle, at a speed of approximately 36 knots, venting to atmospheric pressure. Flowing air from the top fills the full height of the base cavity; then air flows forward through the tip vortex and up into the cavity on the low-pressure side of the rudder blade.

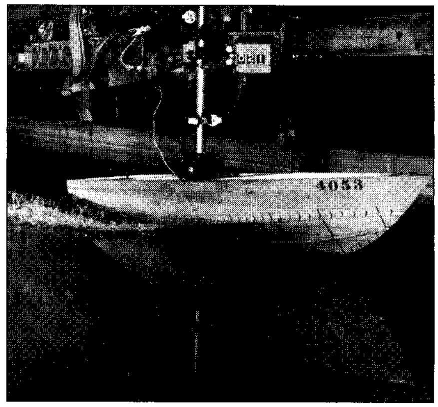
Well-documented sea trials will provide a lot of clues to identify the problem(s) that cause a boat to lay over. It's critical to know the accurate weight and LCG for the condition of the boat at the time of sea trials. The sea trials should be conducted without using trim tabs, beginning at slow speed and increasing engine speed with 100-rpm increments up to wide-open throttle. Measure and record boat speed, rpm, and running trim angle. The accuracy of the trim-gauge readings needs to be at least 0.2° with zero trim set when the boat is floating at rest.

Sea trials on twin-screw boats—with and without rudders—provide invaluable information on running trim angles versus speed, and help determine if rudder ventilation is contributing to the problem. Since operating without rudders can pose safety hazards, conduct sea trials in an area free of other traffic, and have a chase boat with you. Don't attempt a rudderless sea trial with a single-screw boat.

Figure 8 shows experimental change-of-trim versus speed from sea trials of two different boats of the same size. Both boats were troubled by laying over at speeds above 25 knots. Also included for comparison are model test data for an untroubled boat. Arrows labeled "A" and "B" in the figure point to speeds where there are changes of slope or wiggles in the trim-versus-speed curves for the two troubled boats. (There are no such changes in the slope for the boat without a heeling problem.)

It's the change of slope in these curves that tells a story. The region to which the A arrow points occurs at a





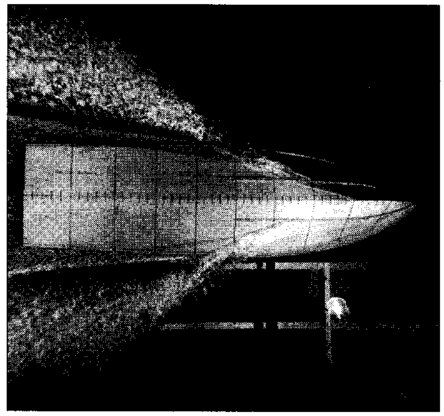


***Figure 6**—The authors have found that a cost-effective approach to tackling a heeling problem is first to determine whether or not there is a ventilation problem. The most common ventilation air path contributing to heeling is flow forward from the transom to fill cavities caused by disturbances under the hull. The next most-common path is from a disturbance at the bow near where the hull bottom, at speed, first comes into contact with the surface of the water. Both are illustrated in the drawing. The photos **(right)**, taken in a test tank, show two views of a model with an air path initiated by a spray rail.*

speed lower than that of the maximum trim. That means the forward curved buttocks of the hull are wetted and developing suction, which holds the trim down until increased boat speed creates sufficient dynamic lift to overcome it. Suction development at semi-planing speed forecasts the potential for suction at high speed, pulling the bow down and laying the hull over on its chine.

A second slope change or wiggle in the trim-versus-speed curve may be present at speeds greater than that of maximum trim at hump, as seen in Figure 8 at the region marked by the B arrow. This slope change is likely to result from ventilation of appendages such as a rudder-post or rudder. If this change in slope is seen in the sea trial results, a repeat test is in order, after one of the following steps is taken: rudder-posts are cut off flush with the hull; rudders are removed and holes plugged; rudders are dropped away from the hull a distance greater than the post diameter; or a bottom plate extending aft of the transom is added

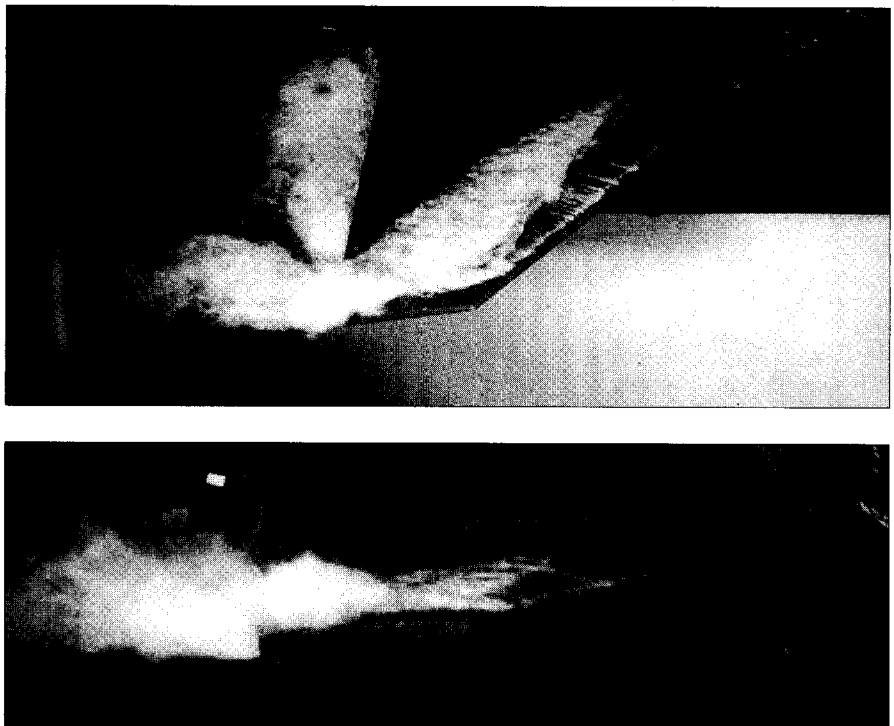


***Figure 7**—These photos, also taken in a test tank, illustrate a ventilated rudder. (The **top** view is in profile; the **bottom** view is from underneath, looking up.) The rudder is a wedge-section, at an 8° angle, at a speed of approximately 36 knots, venting to atmospheric pressure.*

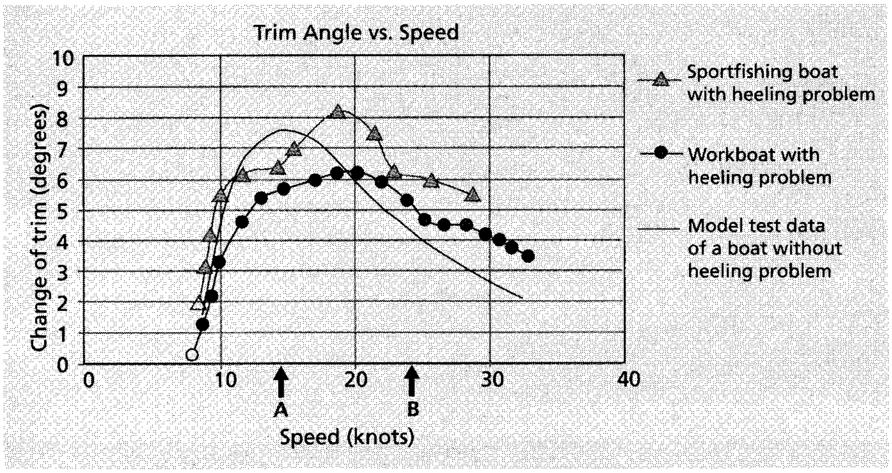


Figure 8*—Experimental change-of-trim versus speed from sea trials of two different boats of the same size, both with heeling problems at speeds over 25 knots. A third boat, with no heeling problem, is included for comparison. The arrows point to speeds where there are changes of slope or "wiggles" in the trim-versus-speed curves for the two troubled boats.*

to seal off the ventilation path. The change in slope at speeds above that of the maximum hump trim should diminish or disappear if appendage ventilation was in fact the source of the heeling problem.

Don't hesitate to discuss dynamic roll instability problems with industry professionals. Unfortunately, the problem is not rare, but it's one of the marine industry's many little secrets. It can generally be fixed when it occurs, but it's much cheaper, easier, and less stressful to avoid the problem at the design stage rather than fix it after launch. PBB

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For additional detailed information on the dynamic stability of high-speed boats, see PBB No. 31, page 20.