Small-Craft Stability

The art of building an upright boat begins with a back-to-basics understanding of the physics of stability

by Dudley Dawson

Stability is perhaps one of the most complicated and misunderstood subjects in marine design and construction. And unfortunately, it's a lot more complicated and misunderstood for small craft than it is for ships. The U.S. Coast Guard, in NVIC 17-82, states: "Designers should be aware that no proven intact stability standards for small vessels exist today. Each standard has its own inherent limitations.... Since smaller vessels are inherently more vulnerable to wind and sea, it is recommended that a comprehensive approach to stability be taken by designers to enhance small vessel safety."

Above—*Jean-Pierre Mouligne perches on the deck edge of his 50' Finot-designed racer,* Cray Valley, *as the boat undergoes stability testing dockside in Portsmouth, Rhode Island. Mouligne is competing in Around Alone '98–99, formerly known as the BOC Challenge. Conventional stability testing does not call for careening the boat to 90°; but then, racing solo around the world in small craft is not a conventional contest.*

Before we get into the specifics of small-craft stability, it would help to define some of our terms. There's intact and damaged stability. There's static stability and dynamic stability. There's positive, negative, and neutral stability. Finally, there's dynamic instability, which is not the opposite of dynamic stability. The various terms sometimes refer to differing analyses of the same boat condition. Sometimes they refer to the same analysis method with differing boat conditions. And sometimes the boat and analysis method stay the same, but the

PHOTO ABOVE: BILLY BLACK

environment changes.

Confusing? You bet, so let's try to sort it out a bit. Throughout the article, stay focused on this simple fact: *Stability is the condition of being stable, or unchanging.*

Defining the Terms

Intact stability refers to an analysis of the stability of a boat when the boat's hull is intact (i.e., undamaged) and no flooding of the hull has occurred. *Damaged stability* refers to an analysis when the hull has suffered penetrating damage, such as a grounding or collision, and certain watertight compartments are open to the sea. In a damaged-stability analysis, the effects of the water inside the hull must be included.

Static stability refers to an evaluation of a boat in a still, or static, environment—no wind, no waves, no heeling out in a turn. It may not be strictly realistic, but it's the easiest to understand and analyze. *Dynamic stability* refers to an evaluation that includes a moving, or dynamic, environment—more real world, with wind and waves, but a bit harder to analyze. *Dynamic instability* refers to the aberrant behavior (porpoising, chine-walking, laying to one side) of some boats caused by dynamic loads while underway. These loads are related to the dynamics of the boat itself—hull shape, center of gravity, center of planing area, bottom loading, speed, etc. It is easier to discover, measure, and diagnose dynamic instability in calm water than in waves.

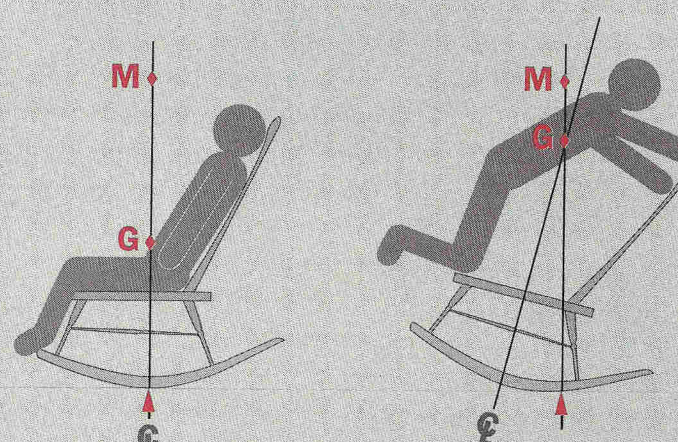
Positive stability exists when a boat is disturbed (for instance, by the wake of a passing boat), rocks a bit, and then returns to its original position after the disturbing force stops. We usually think of this condition with a boat floating upright, but as any sailor struggling to right a capsized dinghy knows, a boat can have a great deal of positive stability in an inverted position. *Neutral stability* exists when a disturbance causes a boat (or other floating object) to roll to some new position. When the disturbing force is stopped, the object stops and stays there, not returning to its original position. Logs, barrels, and basketballs have neutral stability. *Negative stability* exists when a disturbing force, even a very slight one, causes a boat to begin rolling, and then it continues rolling down even after the disturbing force is stopped.

Transverse stability refers to the heel and roll characteristics of a boat, and is evaluated by looking at cross sections of the hull. *Longitudinal stability* refers to the trim and pitch characteristics, and is evaluated by slicing the hull lengthwise.

A Kitchen Experiment

The concepts of *positive, negative,* and *neutral* stability can be demonstrated with a little experiment. Get a ping-pong ball, a bowl, and a flat table. Place the bowl upright on the table, and put the ball in the bowl. Move the ball slightly to one side of the bowl, and let it go. The ball will always return to the center bottom of the bowl. That's positive stability. Take the ball out of the bowl and place it on the table. Push it gently, and it will roll as long as you keep pushing, then stop when you do. That's neutral stability. Turn the bowl over, balance the ball atop the inverted bowl, and give it a gentle nudge. Away the ball goes, continuing until it has rolled completely off the bowl. That's negative stability. *—Dudley Dawson*

A Second, But Trickier, Experiment



The concept of *metacentric height, GM,* can be experienced with a rocking chair. Please do this carefully—we accept no responsibility for bruises or broken bones! Sit in the chair and rock. Then, carefully kneel in the rocker, and you'll find that you rock slower and more gently, but feel a little less secure. Finally, and be really careful when you do this, stand in the rocker. You're likely either to rock very, very slowly or to turn over. Why? Well, the chair's metacenter, **M**, is at the center of a circle defined by the rocker's curve. The flat part of the curve, at the back end of the rocker, has a high metacenter, and the center part, with more curvature, has a lower metacenter. As you went from sitting to kneeling to standing, you raised your center of gravity, **G**. The result: when you were sitting, your **GM** was larger, so you rocked faster and more safely. When you kneeled or stood, **G** went up and **GM** was reduced, so you rocked slower and less safely. And as you reached the tail end of the rocker where it flattened out, **M** went up as **G** stayed the same, yielding a larger **GM**, and hopefully keeping you from turning over. *—D.D.*

Applying the Definitions

As you may have surmised by now, these terms and conditions are often used in conjunction with each other. Let's take, as an example, a high-speed, self-righting rescue boat. We want to make sure that for both static and dynamic conditions, the intact transverse stability is neutral or negative when the boat is completely inverted, and positive otherwise. We also want to make sure that it is not dynamically instable, and that it has positive damaged stability. Huh? All that means is: that the boat should roll

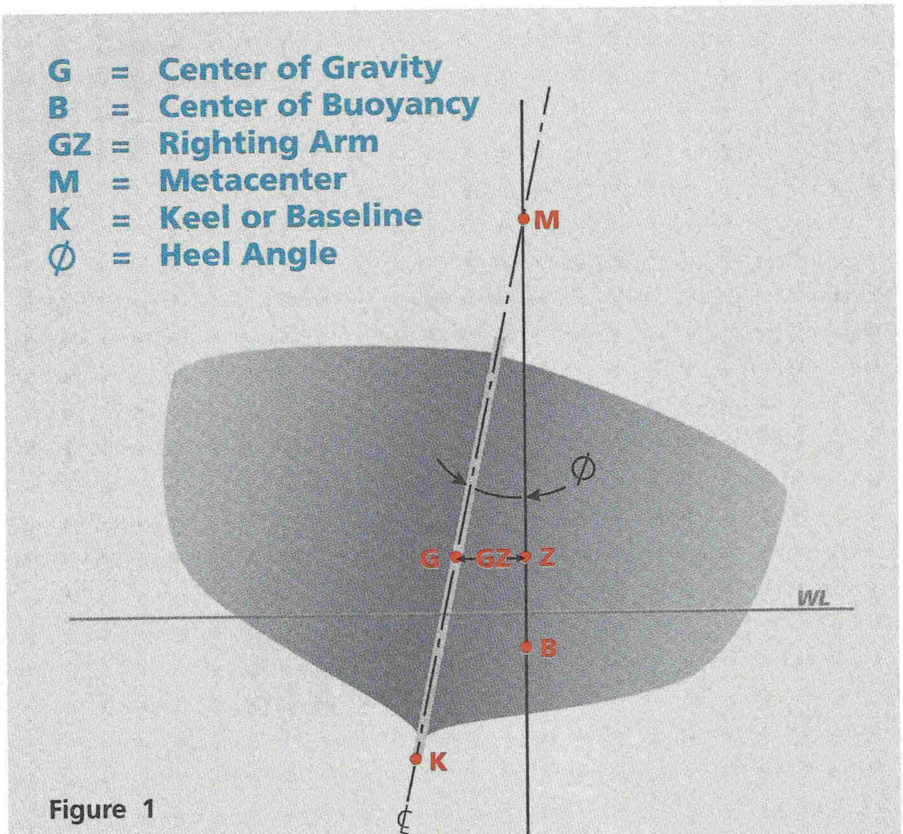


Figure 1

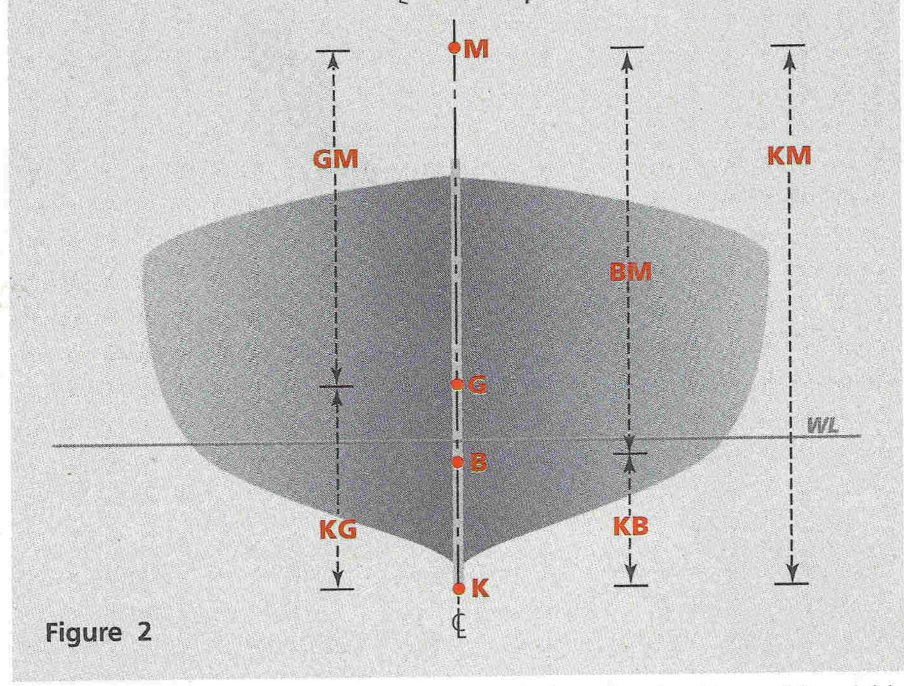


Figure 2

back upright after it's been rolled over, whether it's in waves or not; that it shouldn't do funny things when running at speed; and that if it's not damaged beyond certain limits, it will remain afloat and right-side up, even if it's leaning a bit.

Entire books have been written on these subjects, so we'll need to limit ourselves in this article. Dynamic instability was covered quite well by Lou Codega in *Professional BoatBuilder* No. 31, so we'll omit that one. Damaged stability (and the related subject of floodable length) is not often examined for yachts and small commercial craft, with the exception of certificated passenger vessels, so let's leave that for another time. We're primarily interested in transverse stability, since few boats capsize end-over-end, with the exception of sailing catamarans. Multihulls are a real complication, anyway, so let's just look at monohulls. What remains is static stability, which we'll examine in some depth, and dynamic stability, which we'll ignore for now in the interest of making things understandable.

Transverse static stability in the intact condition is the most commonly evaluated characteristic for small craft. If you're working with small boats and don't have access to curves of form for your hull, the best guidelines are found in the USCG stability regulations for commercial vessels, CFR 46 Subchapter S. Beginning with paragraph 171.020, the regs describe a simplified test method, also called a proof test, for evaluating the stability of boats up to 65′ in length.

The Coast Guard has prepared a seven-page data and calculation form that makes completing the simplified test a lot easier. Ask for form CG-4006, "Small Passenger Vessel Stability Test Procedure." This test establishes a test weight amount, based on assumed weather and passenger loads, and then measures the reduction in freeboard when the test weight is placed a certain distance off-center. The standard establishes a limit on freeboard reduction, and if you don't heel too much, you pass the test.

If you *don't* pass the simplified test, you have a few options: change the boat, change the load, or carry out a more detailed stability test and analysis, for which you'll need curves of form, and perhaps cross curves of stability. These are readily calculated from the hull lines by using specialized computer software.

To get started on this more detailed test and analysis, let's look at the 'midship section of a boat heeled to one side **(Figure 1)**, and label the important stuff. At the bottom is a reference point, or baseline, often at the base of the keel, and for that reason we label it **K**. Next is the vertical center of buoyancy, **B**, which is the geometric center of the underwater portion of the hull's volume. Keep in mind that **B** will be on the centerline for a boat with no heel, but will move farther away from the centerline as heel angle increases.

The location of the vertical center of gravity, **G**, is extremely important in stability analysis, and is determined by the distribution of the various components of the boat. Unless something unusual is going on, **G** should be on centerline. The more "boat" or gear that you put topside, the higher **G** will be, and the less stable the boat will be. The layman's term, "topheavy," is quite appropriate to describe this.

The locations of **K**, **B**, and **G** are fairly straightforward, but the next one, metacenter or **M**, is a little tougher. It is the point at which a vertical line drawn through the center of buoyancy intersects the centerline of the boat. For large angles of heel, it moves up or down noticeably, but at small angles of heel, it remains fairly constant, and that's an important point we'll come back to. Finally, there's **Z**. That's the point on a vertical line between **B** and **M**, directly outboard of the center of gravity. Thus, the line between **G** and **Z** will always be horizontal. That's it, just five key points to keep track of.

Measurements and Calculations

Using these points, we'll look at several critical measurements **(Figure 2)**. The distance from the center of gravity, **G**, to the metacenter, **M**, is abbreviated **GM**, and is referred to as the metacentric height. You may sometimes see it with a subscript, $\mathbf{GM_t}$, to indicate transverse metacentric height. The distance from **G** to **Z** is abbreviated **GZ**, and is termed the righting arm. This is because it is the distance factor, or arm, in the moment trying to right a heeled boat with positive stability **(Figure 1)**. We'll also use the distance from the baseline to the metacenter, **KM**, and from the baseline to the center of gravity, **KG**.

If you remember your geometry, you'll see that for a small heel angle, ϕ, the righting arm, **GZ**, is equal to the sine of ϕ times the metacentric height, **GM**.

$$\mathbf{GZ = GM \sin \phi}$$

It is this relationship that allows us to determine the metacentric height, **GM**, and the location of the vertical center of gravity, **G**, using a stability test. Although you can get an estimate of the location of **G** by carrying out a weight calculation, we need something better for a detailed stability analysis, as this location forms the basis for everything that follows.

The stability test is also called an inclining experiment, and was described by Eric Sponberg in PBB No. 42. For those readers who might want more information, a full description of the test procedure and the theory behind it can be found in the 28 pages of American Society for Testing and Materials Standard F 1321-90, "Standard Guide for Conducting a Stability Test." The ASTM standard contains a number of forms for completing the test and calculations, and similar forms can be obtained from the Coast Guard. (I also offered suggestions for simplifying the test procedures, in PBB No. 47.)

In a stability test, the freeboards or drafts are measured to determine where the waterline is. Then, a known weight, **w**, is moved from side to side on the

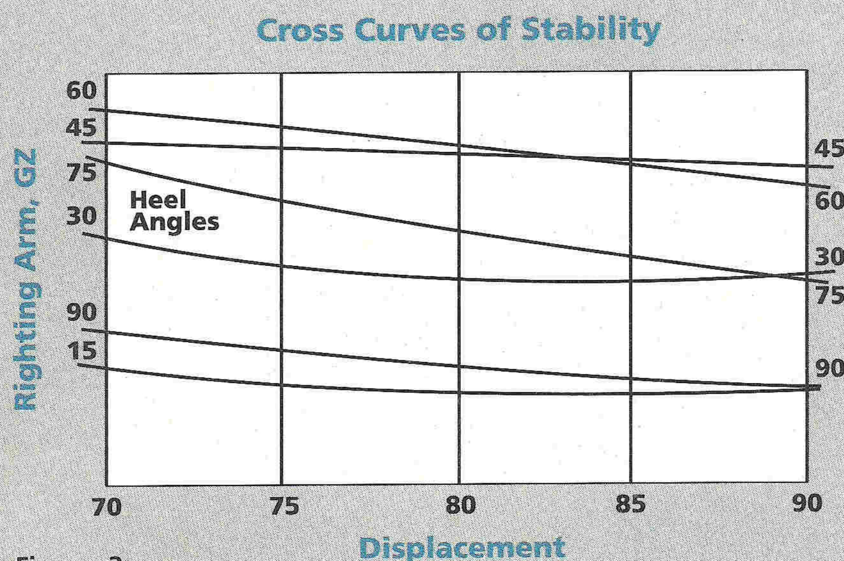


Figure 3

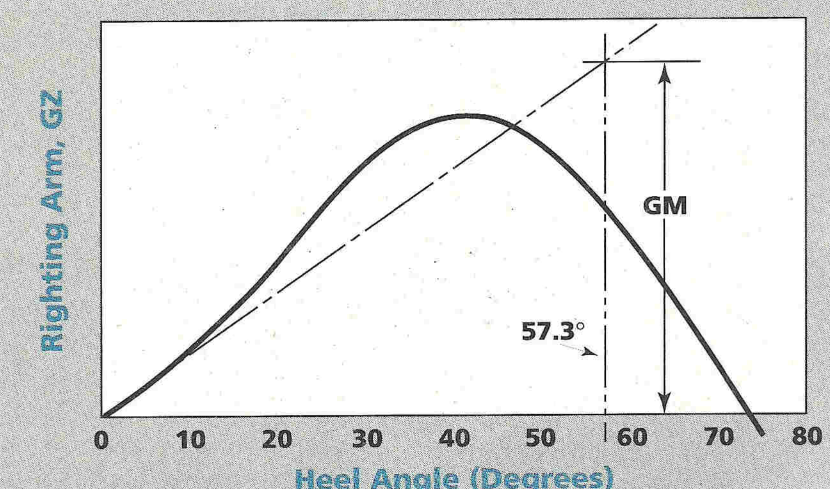


Figure 4

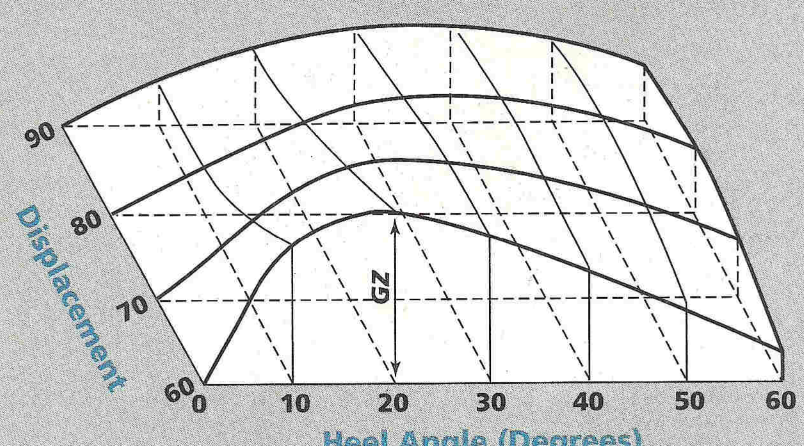


Figure 5

Stability cross curves ***(Figure 3)*** *show the righting arms for a range of heel angles and displacements, while the middle graph* ***(Figure 4)*** *shows the righting arm for a particular displacement and center of gravity. The relationship between the two types of curve can be plotted as a 3-D "contour map"* ***(Figure 5)*** *illustrating the boat's stability over a range of conditions.*

boat a known distance, **d**, and as the boat rolls, the heel angle is measured. The weight times the distance that it is moved creates a force trying to roll the boat over, and is known as the heeling moment (when corrected by the cosine of the heel angle, since the weight moves along the heeled deck, not horizontally). For a boat in equilibrium (at rest), the heeling moment has to equal the righting moment, which is the force trying to roll the boat back upright. The righting moment is equal to the weight (displacement) of the boat, Δ times the righting arm, **GZ**:

$$w \times d \times \cos\phi = \Delta \times GZ$$

Remember, earlier we indicated that for small heel angles, usually limited to 2° during the test, $GZ = GM \sin\phi$. If you make the substitutions and do the math (see a naval architecture textbook if you're interested in the details), the formula becomes:

$$GM = \frac{w \times d}{\Delta \times \tan\phi}$$

You have **w**, **d**, and ϕ from the stability. test, and you can get Δ from the curves of form, using the drafts and/or freeboards you measured. Plug these into the formula and solve for the metacentric height, **GM**. Now, back to the Coast Guard standards, and we find a couple of benchmarks for minimum values of **GM**, one starting at paragraph 170.160, and another starting at paragraph 171.045—again based on weather and passenger loads.

Having gone through all of that, however, it is unfortunately true that the Coast Guard **GM** standards are more applicable to *ships* than to small craft. If you really want to understand your boat's stability picture, you need to go further. The starting point for that is the vertical center of gravity, **G**. Referring to **Figure 2**, note that **KG = KM – GM**. If you've already solved for **GM** using the formula above, just get **KM** from the curves of form and solve for **KG**. You can also solve directly for **KG** with the test data and the following formula:

$$KG = KM - \frac{w \times d}{\Delta \times \tan\phi}$$

Now that we know the exact location of the center of gravity, **G**, the real fun begins. Most of the computer software packages used for deriving curves of form will also derive stability cross curves and righting arm curves for particular loading conditions—i.e., light, partial load, and full. Stability cross curves **(Figure 3)** show the righting arms, **GZ**, for a range of heel angles and displacements. Righting arm curves **(Figure 4)** show righting arms for a particular loading condition (displacement and center of gravity). It is interesting to note the relationship between the two types of curves on a 3-D plot **(Figure 5)**, which becomes a "contour map" of the boat's stability over a range of conditions.

Quantifying and Interpreting

Referring to the righting arm curve, or **GZ** curve **(Figure 4)**, positive stability is indicated by values above the horizontal axis, and can be quantified by a number of measures. First is the slope of the curve at low angles. A steep slope indicates a high **GM** and a very "stiff" boat, which doesn't heel much but can be uncomfortable because rolling is very quick (high accelerations). This is generally not suitable for a seagoing boat, but may be just fine for a tour boat in protected waters. A shallow slope indicates a lower **GM** and more gentle rolling, but if it's too low, it may indicate a stability problem. This slope can be quantified by taking a straight-line tangent to the curve at 0° and extending it out to 57.3° (1 radian); its height at this point is equal to the value of **GM**.

The second quantifier from the **GZ** curve is the location (heel angle) and **GZ** value at the peak of the curve, which is the point at which stability starts to drop off. The Coast Guard standards list values for both minimum angle and minimum **GZ** value in paragraph 170.173, with 25° to 30° and 0.66′ as the general rule.

The third quantifier is the area contained under the curve, which is a measure of how much stability the boat can generate to resist weather and passenger loads. Referring again to paragraph 170.173, the general area standards are 10.3 foot-degrees between 0° and 30°, 16.9 foot-degrees between 0° and 40°, and 5.6 foot-degrees between 30° and 40°.

Finally, it's good to see how far the curve extends before it crosses the horizontal axis and goes into the realm of negative stability. This is referred to as the *range of stability*, and the angle is known as the *angle of vanishing stability*. Seagoing powerboats generally have a range in excess of 70°; sailboats, sometimes well in excess of 100°. Self-righting craft, by definition, have a range of 180°.

Standards, Here and Abroad

While we've referred to U.S Coast Guard standards in this article, they are not mandatory unless you're building a *certificated* commercial vessel. Mandatory stability standards are largely nonexistent for recreational craft right now, at least in the United States, but the ISO (Organization for International Standardization) is working to develop standards that will become mandatory CE requirements for recreational boats sold in Europe. At this point, the standard, **ISO 12217**, is not completed, but the draft version is in three parts: Part 1, for non-sailing craft over 6m (19.7′) in length; Part 2, for sailing boats over 6m; and Part 3, for boats up to and including 6m. We hope to cover the entire subject of the new ISO and CE requirements in an upcoming article, so I won't go into details of the stability standard here; if you need current information, it can be obtained from which is coordinating United States activities in this technical area. PBB

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