The Balance of Hull and Sails

This is Part Four of a six-part series on Learning to Sail excerpted from Colgate's Basic Sailing, used as a text at the Offshore Sailing School. Steve Colgate calls upon a vast experience gleaned from teaching thousands of students and competing at some of the highest levels of the sport. His clear and straightforward approach focuses on reasons why a sailboat moves with the wind the way it does and seeks to allay the fears of beginning sailors. (Review Part Three.)

Knowing what's going on beneath the waterline lends insight into sail trim, especially in small boats.

Water flowing past the hull, keel, and rudder of a sailboat is subject to the same basic rules as air flowing past the sails. The only difference between the sails and underwater appendages is that the latter are symmetrical while the former are asymmetrical. But the angle of attack (which we call "angle of incidence" for wind hitting the sails and "yaw angle" for water hitting the keel) solves the problem of getting "lift" from the keel.

Due to the pressure of the wind in the sails, a sailboat sideslips a little as it goes forward. This is called "making leeway." Thus the angle between the direction that the boat is heading and an imaginary line indicating its "track" through the water is the "leeway angle" as shown in Figure 1. Since the water has to travel a greater distance on the windward side of the keel, an area of reduced pressure produces "lift" to windward. The more lift from the underwater surfaces, the less leeway the boat makes. In other words, it slips sideways less. Obviously, when sailing to windward we are trying to reach a destination upwind, and any sideslipping that pushes us downwind is undesirable.

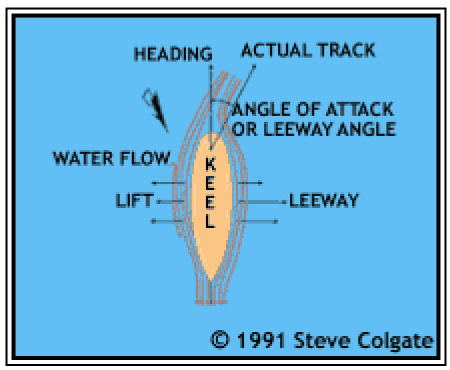

Figure 1

The more lift generated on the keel, the less leeway, or sideslipping.

The slower the velocity of the fluid flowing past the "airfoil," the less efficiency it has as a lifting surface. So when the boat is going slowly, it sideslips more. This increases the leeway angle and, up to a point, increases the efficiency of the keel. Past that point, though, the water becomes turbulent on the windward side of the keel and a stall results. A good example of this situation is a sailboat sitting on the starting line before a race in a close-hauled pointing angle but with sails luffing, waiting for the starting gun. At the gun, the crew trims in the sails to get the boat moving forward. Instead, the boat goes almost as fast sideways as she goes forward because the velocity of the water flowing past the keel is not sufficient to counteract the sideways push of the sails. Instead, the helmsman should have sailed on a slight reach, where the force of the sails is more in the direction of the boat's heading, in order to pick up speed and then harden up to close-hauled.

The sails of a boat sailing upwind create a forward and sideways force. The keel or centerboard resists the sideways force. Unfortunately, due to drag, they also resist the forward force. But to get into that opens a whole Pandora's box of how to reduce "form," drag, "frictional" drag, and the hull's "wave-making" drag, which is really the subject for a book on naval architecture, not practical sailing.

Balance In order to sail properly, and certainly to race successfully, one must take the "balance" of the boat in consideration. By "balance," we mean the tendency of the boat's heading to either deviate or to remain straight when the helmsman releases the tiller or wheel. If the tiller is released and the boat turns away from the wind, to leeward, it is said to have "lee helm." Conversely, if the boat turns to windward it has "weather helm." If it sails straight ahead, the boat is perfectly balanced.

"By "balance," we mean the tendency of the boat's heading to either deviate or to remain straight when the helmsman releases the tiller or wheel."

Though the above can be used as a guideline, older boats may have artificial weather helm. A boat will normally turn into the wind when the tiller is released because of the forces acting on the rudder. As water flows past the windward side of a rudder, "lift" is generated due to the angle of attack with the water flow. If the rudder post (which turns the rudder) is located on the leading edge of the rudder and attached to the trailing edge of the keel as on traditional sailboats, all the area aft of the post will be pulling to windward, thus tending to turn the boat into the wind. Since the water flow has traveled the full length of the keel to reach the rudder, though, the flow is not very effective as a "lift" factor.

Separated or "spade" rudders are standard now. The rudder is placed near the stern of the boat where it has the greatest leverage for steering. It is a lifting surface in itself, and since it isn't attached to the keel and is meeting fairly non-turbulent water, such a rudder is very efficient. These rudders usually are "balanced" so that the rudder post enters the rudder about one-fourth of the way back rather than being attached along the leading edge. Hopefully then, the center of the pull to windward will be right at the post and the rudder will remain straight. This reduces artificial weather helm. It also decreases true weather helm because the rudder, as a lifting surface, pulls the stern of the boat to windward to a small extent.

Excessive leeway also causes artificial weather helm. Take an extreme example of a boat slipping straight sideways through the water and making no forward motion. The water on the leeward side of the rudder aft of the rudder post pushes the rudder to windward giving the appearance of weather helm (the tiller goes to leeward as if the bow was turning to windward).

The way one can distinguish the artificial from the true weather helm is if the rudder has to be deflected from straight ahead in order to make the boat sail straight. In other words, if the tiller is being held constantly a few degrees to windward to make the boat sail straight, there is a true weather helm.

I've sailed on cruising boats with balanced spade rudders that the owners swore sailed fastest with a "neutral" helm and slowed down once they developed a slight weather helm. My observation was that though the helm felt neutral (there was no tug on it because the rudder post entered the rudder well aft of its leading edge), there was indeed a slight weather helm because the tiller was being held to windward a few degrees. When the weather helm developed to a point where the helmsman could feel it, the tiller was being held to windward at an angle large enough to increase rudder drag, thus slowing the boat down.

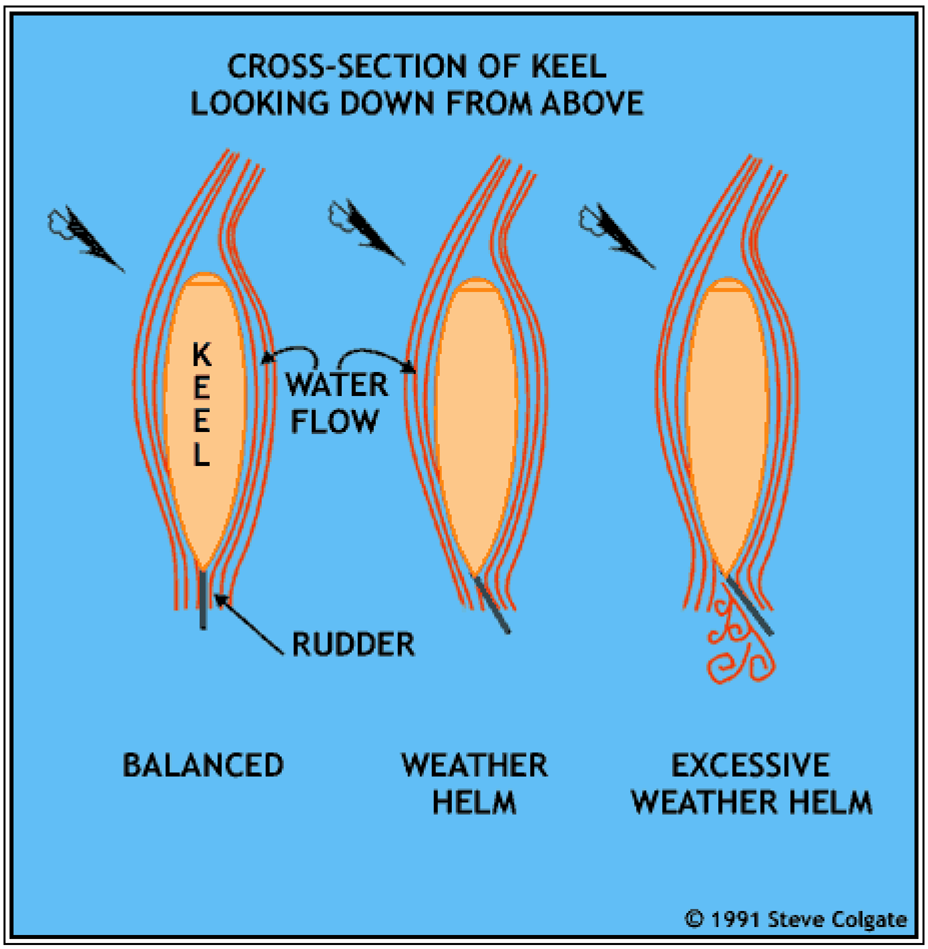

Figure 2

How the rudder feels provides the helmsperson with important sail trim feedback.

In most boats sailing to windward, a little weather helm is desirable. Where the rudder is attached to the trailing edge of the keel, as in Figures 2A and B, it is obvious that the couple of degrees of rudder needed to counteract a slight weather helm tends to give the keel "lift" and reduce leeway. Too much weather helm, however, will just cause turbulence and drag as in Figure 2C.

The same holds true with the spade rudder, which gets its lift from the angle of attack the rudder makes with the water. A little weather helm cocks the rudder to windward and increases the angle of attack.

There are many reasons for weather or lee helm, but foremost is the relationship between the "Center of Effort"(CE) of the sail plan and the "Center of Lateral Resistance"(CLR) of the hull shape. Imagine a sailboat drifting sideways down a river with the current. It hangs up on a tree stump under the surface. At all locations on the underwater body of the boat except one, it would pivot off the end of the stump and continue downstream. If it hangs up at that one spot, it will remain on the end of the stump in balance even with the current hitting the other side of the boat. This point is called the CLR.

By geometrically determining the point that is the combined center of all the sails that are set on the boat, we can find the CE of the boat. This is the center of all the forces acting to push the boat sideways against the center of all the forces resisting that push, the CLR.

Now imagine the boat as if it were a weather vane on top of a roof pivoting on the CLR. If the CE is directly above the CLR, the boat is in balance. So if the wind blows on this weather vane, it won't pivot.

However, by placing more sail area toward the bow of the boat, the CE moves forward. When it is forward of the CLR the tendency is for the bow of the boat to be blown to leeward. If you move the CE aft of the CLR by placing more sail area near the stern of the boat, the boat pivots to windward.

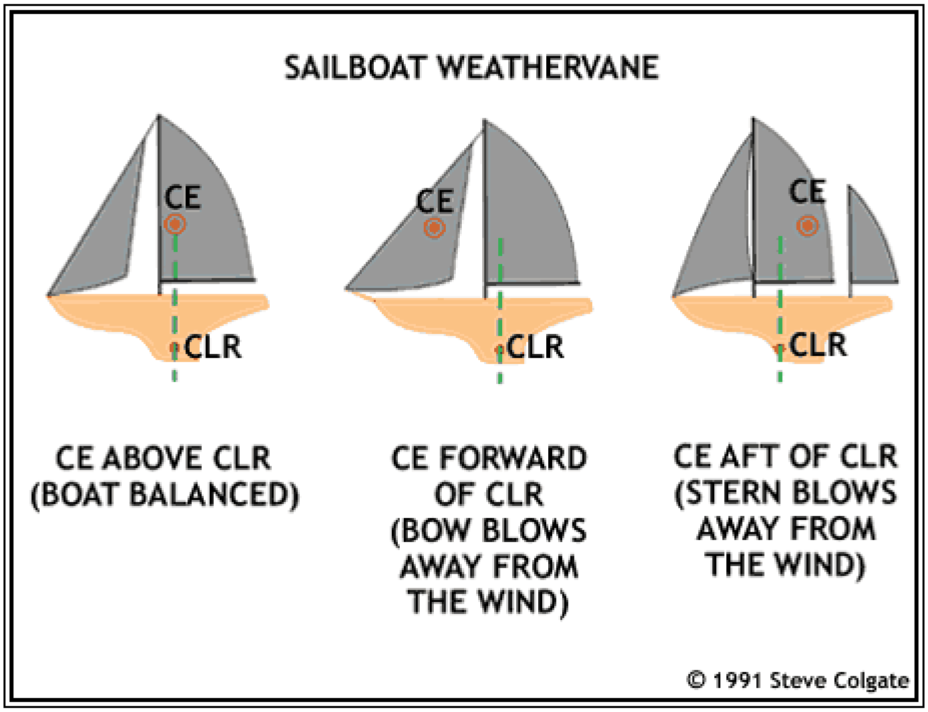

Figure 3

Whether the bow or the stern blows away from the wind illustrates the center of effort.

The easiest way, in theory, to change the balance of a boat is to move the sail area forward or aft. If you move the mast (and along with it, the main and jib) aft, you increase weather helm—if you move the rig forward, you reduce whether helm or increase lee helm. Since most boats have varying amounts of weather helm and rarely have lee helm, any change that results in lee helm is usually just a reduction in weather helm for most boats and we tend to state it that way.

In practice, moving the whole rig fore and aft can be time consuming on a small boat and well-nigh impossible on a large one without extensive carpentry. An easier solution is to change the amount of sail forward or aft. A friend of mine had a yawl, that never seemed to develop any weather helm, so he replaced the mizzen mast with a larger one, bought a new mizzen and at long last achieved weather helm. Another friend owns a sloop that constantly developed too much weather helm. When nothing else seemed to work, he put a bowsprit on the boat and bought a larger genoa to achieve the desired results. The former brought the CE aft to achieve weather helm, while the latter brought the CE forward to reduce it.

Obviously, if changing the amount of sail area fore or aft changes the balance of the boat, changing the efficiency of the sails will have the same effect. If you sail without a jib your boat will have a strong weather helm from the mainsail, and if you sail under jib alone the boat will have a strong lee helm. If you luff the mainsail, thereby reducing its efficiency, the CE moves forward with a corresponding reduction of weather helm. If you luff the jib, you will increase weather helm.

By careful adjustment of the main and jib we can steer a fairly accurate course without even touching the tiller. This is good practice because one never knows when a rudder might fall off or a tiller break. One time we lost a rudder in the middle of a transatlantic race and steered the last 1,000 miles by adjusting the sails alone. For a close-hauled course, trim the jib fairly flat, and then play the mainsheet—luffing the main to head off and trimming it to head up.

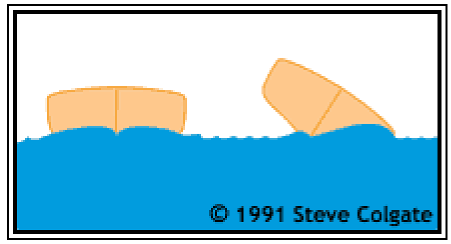

Figure 4

When a boat heels, the bow wave on the lee side becomes larger and tends to shove the bow to windward.

On a small boat, the distribution of your crew weight will affect balance. When a boat heels, the bow wave on the lee side becomes larger (Figure 4) and tends to shove the bow to windward.

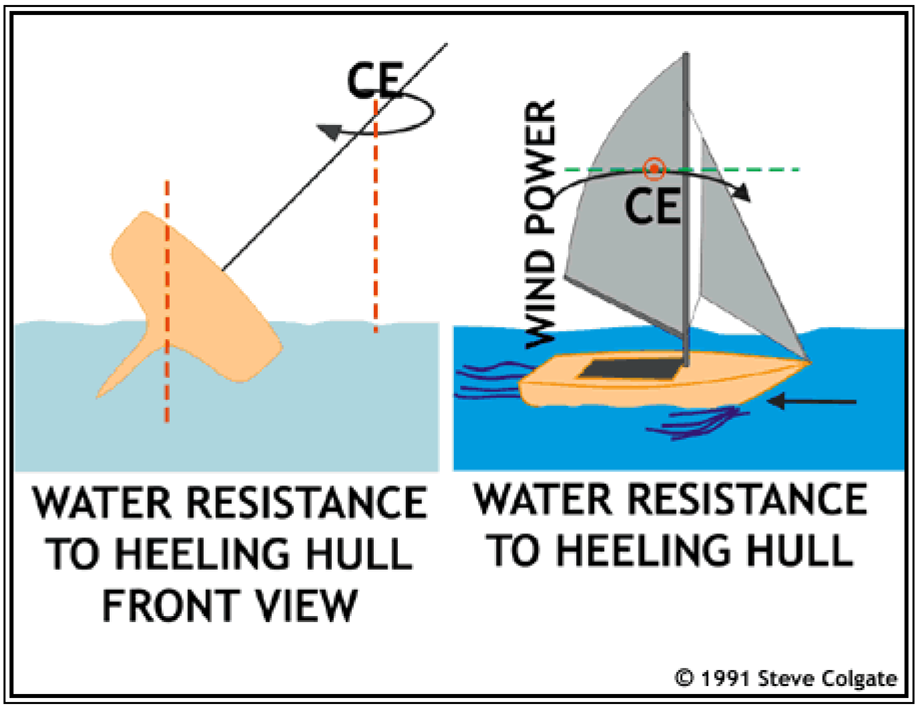

Figure 5

Additional weather helm develops when the center of effort is out over the water.

Also, the center of effort (CE) is out over the water (Figures 5A and 5B). Imagine a sailboat in a dead flat calm with the mainsail and boom way out over the water as if it were running free. If you come along in an outboard motorboat and push the end of the boom in the direction that the boat is pointing, the boat will turn away from you (into the imaginary wind). The reason, of course, is that the push is out on a lever arm, at the other end of which is the drag of the hull. So, you can see that additional weather helm develops when the CE is out over the water when you are reaching, running, or heeling.

By shifting the crew weight from one side of the boat to the other, a small sailboat can be steered without using the rudder if the breeze is light enough. Hike out to produce lee helm or place the crew on the leeward side to produce weather helm.

The center of effort can be moved in a few other more subtle ways. If a mast is raked aft the sail area is moved aft. Raking a mast means leaning it, and is not to be confused with bending it. To lean it aft, the headstay is eased and the backstay is tightened.

Sail shape also has a great deal of effect on balance. For instance, if the mainsail has a tight leech (one in which the batten ends are pulled slightly inboard, to windward), weather helm will be increased.

Another way to change the balance of the boat is to leave the CE in one place and move the center of lateral resistance forward or aft. Since the CLR is the center of the underwater lateral plane of the boat, the only way (without a centerboard) to move it is to submerse less or more of the boat. If you depress the bow of the boat by moving crew or equipment forward, the CLR moves forward and weather helm increases. The opposite results if you depress the stern, allowing the bow to lift higher out of the water. Imagine the bow being blown to leeward by the wind as more of it is exposed. This is only a memory aid and not the cause of the lee helm.

Sailboats that have centerboards can move the CLR more easily. Since a centerboard pivots on a forward pin it describes an arc as it is lowered. Thus the area is farther aft when the board is halfway down (angled aft) than in its full-down position (vertical under the pin). So to move the CLR aft, just raise the board partway if it's all the way down, or lower it partway if it's fully housed in the centerboard trunk (all the way up). This will have the effect of reducing weather helm.

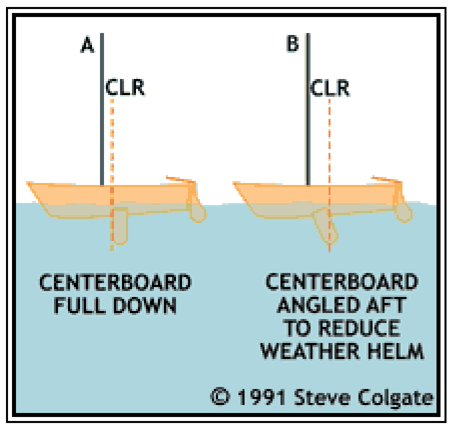

Figure 6

Moving the centerboard aft reduces weather helm.

A well-designed boat will have a slight weather helm which increases as the wind velocity increases. The weather helm creates "lift" for the rudder, and also gives the helmsman some "feel" for the boat. The slight tug allows the helmsman to ease pressure on the tiller in order to let the boat come up closer to the wind. Increased pressure on the tiller makes the boat fall off away from the wind. In other words, steering is in only one direction, while the boat steers itself in the other direction. A boat is very difficult to steer well if it has to be steered up toward the wind as well as away from the wind. It is said to have no "feel."

Another reason it is desirable to have some weather helm is the fact that with it the boat will automatically head up in the puffs. This reduces heeling and maintains the angle that the wind originally made with the sails, because the apparent wind comes aft in puffs.

To recap, counteract excessive weather helm by (1) adding more sail area forward, (2) reducing sail area or sail effectiveness aft, (3) moving the mast forward, (4) reducing mast rake, (5) moving crew or equipment aft, (6) reducing heeling by hiking, or (7) place the centerboard in the halfway down position.

In Part Five—Hull Speed Demystified of the Learning to Sail series, Steve Colgate clears up the mysteries of hull speed.