It’s not the Slot!

(How Sails Really Work)

By Bob Szczepanski

The physical size of a Victoria makes it a great platform to study and experiment with sail design, sail trim and the interaction between the main and jib. The sails are small enough to be easy and inexpensive to build, yet are large enough to study the effects of design and trim experimentation. Early in the process of trying to design the “perfect shape” for model yachts, I bumped into a classic urban legend that is applied equally to model and full sized sail theory.

Everyone has heard how important the slot between the jib and mainsail is relative to optimal sail trim and performance. It is generally thought that the slot increases airflow over the main thus improving its efficiency. Too open (not enough air squeezing) is bad, just as too closed (too much squeezing) is bad. Like Goldilocks, the squeezing has to be just right. Once while crewing on a full sized racing yacht, I was strongly admonished for standing in the slot area, because I was “disrupting the air flow” and, therefore, negatively effecting boat speed. All this is, well…..WRONG!

Most know that sails generate lift by creating a low-pressure area on the leeward side of the sail and a high-pressure area on the windward side. How this happens, it seems, is not widely understood. The phenomenon that really creates the lift is known as circulation flow. Circulation is the flow of air created around the sail due to its presence in the wind. Circulation flow makes the low pressure and high-pressure areas possible and creates lift per Figure #1.

You can see that the circulation flow opposes the apparent wind flow on the windward side, slowing it, thus increasing pressure. On the leeward side, the circulation flow speeds up the airflow thus reducing air pressure. Per Bernoulli’s Principle, we now have the formula for lift. If you have doubt that circulation flow exists (and many do), I offer the following homework assignment. Fill your bathtub with about six inches of water. When the water becomes calm, sprinkle ground pepper, or bath powder (anything that has small particles that float) over the entire surface area of the water. Take a small piece of cardboard and carefully bend it into the curved shape of a sail. Slowly put the cardboard “sail” in the water and then move it across the tub. Remove the “sail” when you reach the other end. Figure #2 is what you will see.

As the “sail” starts to move, it creates a vortex, known as the starting vortex, which initiates the circulation flow, which in conjunction with the apparent wind, generates lift. Both circulations will be visible. Visualizing or seeing the circulation flow also helps to understand upwash. The circulation flow that opposes the apparent wind causes upwash. The upwash causes some of the apparent wind to be pushed over to the leeward side of the sail speeding up the airflow, which further lowers the leeward side pressure. Increasing upwash increases lift and improves the efficiency of the sail. Understanding upwash will prove useful when sail trim is discussed later.

Now that we know, and maybe have seen, how a sail works, we can consider what is going on in the slot. Adding a jib to the earlier figure and drawing in the circulation flow yields Figure #3.

As you might expect, each sail has its own circulation flow, but wait….the flows actually oppose each other in the slot! It is another high-pressure area! The wind is not squeezed too much or too little, it is practically stopped. Therefore, the circulation flow relative to both sails looks like Figure 4.

The flow surrounds both sails and the slot essentially becomes no factor. The wind "sees" both sails like one big airfoil. How can this be? We have all seen backwinding of the main, caused by the jib, but it is not, like many think, from the size of the slot. The cause is the main either being set too full or not sheeted in enough relative to the jib, or both. What actually causes the backwinding is the jib's circulation flow hitting the leeward side of the main and partially distorting it's circulation flow. The fix is a combination of either flattening the main, or trimming the main in more, doing both, or easing the jib, if the main is already flat and fully trimmed in. These actions fix the flow so that it is again parallel to both sides of the sail and no backwinding occurs.

Knowing all this provides some interesting implications for sail trim. The circulation flow around the main increases the upwash of the jib, causing it to generate more lift than it would without the main. The jib, in turn, speeds up the wind on the leeward side of the main, further lowering the pressure and also increasing the lift that would occur without the jib. Since the circulation flow around both sails is similar to the flow around one (Figure #4), it makes sense to approach trimming both sails as one. Much like an airplane wing, the overall camber and position of both sails can be changed to fit the conditions. The jib can be thought of as the leading edge and the main can be thought of as the trailing edge of a wing and trimmed accordingly

In Position A, the airplane wing is in it's nominal shape for mid range flying speeds. This is similar to sails being trimmed for mid range winds as shown in Figure #6 Position A. Both sails have nominal camber and are set for the best lift to drag ratio. Lowering the flaps and changing the entry angle, in Figure #5, Position B on a wing, increases camber and therefore lift at low speeds. This too can be approximated with sails. Setting a more camber forward jib (tensioning the jib luff to either move draft forward, or at least preventing it from moving aft) in conjunction with lower forestay tension is similar to changing the entry angle on the wing. This jib trim, combined with a deeply cambered (eased outhaul) fully sheeted in main with draft more forward , replicates lowering the flaps. The result is a powerful overall shape suitable for light air as shown in Figure #6, Position B. To reduce lift and to minimize drag, while increasing speed, flaps on an airplane wing, are raised above the normal position to what is called a reflex position. (The entry angle is unchanged from the nominal position.) The sail trim approximation of this is flatter sails with the main trimmed closer to the rail, per Figure #6, Position C. The forestay and jib luff has max. tension and the main is set draft aft and has been twisted to open the leech and minimize drag The result is a high-speed shape suitable for high wind.

In addition to the misconceptions about the slot, setting sail twist is often approached incorrectly. It is a problem mostly prone to model yacht skippers. It is widely accepted and has been proven that the wind gradient (angle of the apparent wind) moves aft and increases speed as you move toward the top of the sail. Therefore, the sail must be twisted to accommodate the gradient change. This is completely true and a large factor, on full sized boats, when your mast is measured in feet. It is not the reason to set twist when your mast is measured in inches (model yachts). Most, if not all models, are sailed in the boundary layer. (Less than 10 feet above the water.) A very small wind gradient in this region does exist, but is completely negated, relative to the boat, by the apparent wind the boat generates by simply moving, even at very low speeds. Because of the small scale of models, the gradient force vector is so small, compared to the apparent wind vector, that it can be completely ignored. If this is true, why then, is setting twist correctly so important? The reason is the upwash that is created by the circulation flow that was described before. Upwash causes the apparent wind to move aft as you move toward the top of the sail, much like a wind gradient. Back sweep (the shape of the jib) increases upwash, while fore sweep (the shape of the main) decreases upwash. This is why jibs need to be designed and set with more twist than the main. More upwash requires more twist. For optimum trim, you need to twist the sails to accommodate the upwash being generated. Actually, very slight over twist set in each sail is preferred, since wind gusts and increased heel angles increase upwash. Slight over twist helps prevents stalling during these situations.

A last look at the circulation flows (Figures 3 & 4) yields another interesting conclusion. More air (upwash) will be created around the jib, if the sails are set as close to one another as practical. Being close, less air will leak through the slot. The increased upwash, in turn, increases the air speed on the lee side of the sails and the efficiency of both sails is improved! This is among the principle reasons why overlapping jibs (Genoas) are so effective on full sized boats.

The dynamics of the slot, turns out, is quite different than the urban legend holds. Understanding circulation flow, which causes lift, upwash, and defines how sails really work, provide useful insights for optimizing sail trim for performance racing.

Footnote: This article is based on observations from testing model yacht sails and the original work of Arvel Gentry, C.A. Marchaj and Martin Kutta.

SLOT FIGURES

FIG #1

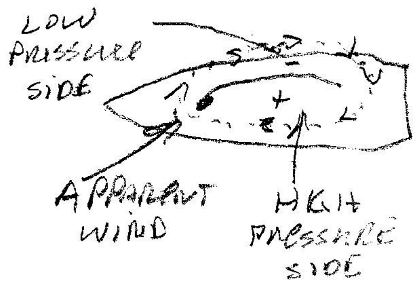

FIG # 2

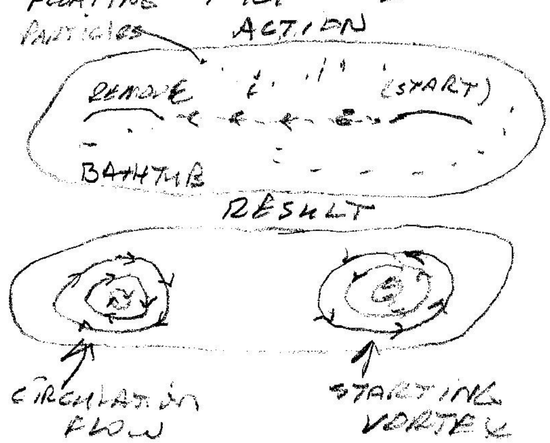

FIG # 3

JIB & MAIN CIRCULATION

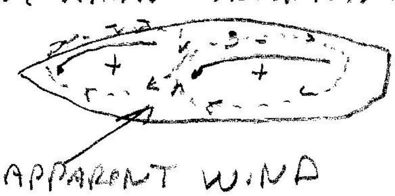

FIG # 4

COMBINED CIRCULATION FLOW

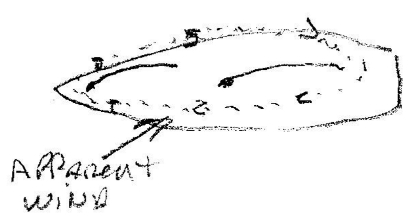

FIG # 5

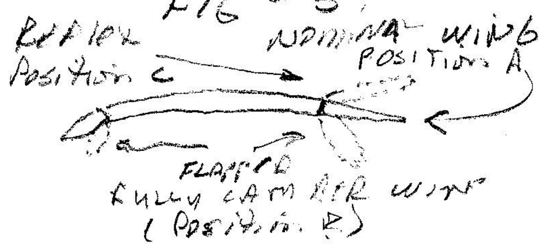

FIG # 6