More on the Slot Effect

"Arvel Gentry continues his discussion of jib-mainsail interaction"

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Last month we first studied the air flow around the main alone; then we added a jib, and this gave us a good picture of how the jib affects the mainsail. This month we will do just the opposite. First we will look at the airflow about the jib alone, and then add the main. By doing this, we will see that the main actually *helps* the jib to become the very efficient sail that it is.

If you have been following this series, you should be an expert at reading streamline drawings and pressure distribution plots, so let's jump right in. Figure 1 shows the streamlines about a typical jib-mainsail combination with the solid lines the streamlines when both sails are used, and the dotted lines the streamlines when the jib is used alone.

First, note that the dotted stagnation streamline for the jib alone (S_{jo}) goes right into the leading edge of the jib. However, when the main is also used, the stagnation streamline shifts to the position S_j so that it starts much lower (further to windward) and comes into the jib luff slightly on the windward edge. In this example the jib could be pointed a little closer to the wind without luffing.

From this we see that the mainsail shifts the jib stagnation streamline to windward (a lifting wind shift) and allows the boat to sail closer to the wind. This increased upwash on the jib is caused by the fact that the circulation fields for the two sails (*SAIL*, July 1973) add together to become stronger in the area in front of the jib. This is not a new fact, but at least now we see exactly how this jib wind shift occurs.

Another result is that the mainsail causes more air to be diverted around to the lee side of the jib. You can see this by comparing the levels of the two jib stagnation streamlines well out in front of the sails. The stagnation streamline of the jib when both sails are set (S_J) is much further to windward (lower) than it was without the main (S_{jo}). The distance between these two lines (L) represents additional air that the mainsail causes to flow on the lee side of the jib. Without the mainsail, this chunk of air would *pass on the windward side of the jib!*

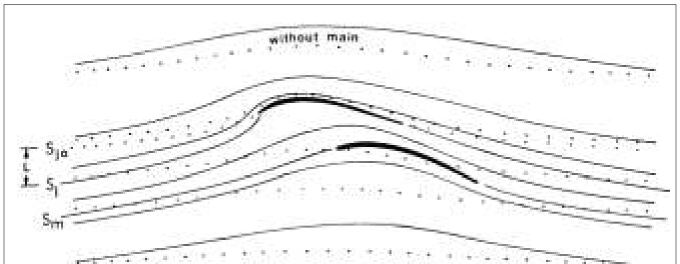

Figure 1

This diversion of air to the lee side of the jib has a very important effect. We know that the more air that flows on the lee side of a sail, the greater its lifting force. Because we have more air flowing to lee of the jib, it will travel at higher speeds and the lee-side pressures will be lower.

With lower lee-side pressures we have a larger pressure difference across the sail and more jib lift. This also can be achieved by a higher angle of attack, or it can be accomplished at lower angles with the help of the mainsail.

All this is illustrated in the jib pressure coefficient plot in Figure 2. The negative pressure coefficients represent pressures lower than freestream (suction pressures and high velocities); and the positive coefficients are higher than freestream (lower speeds).

Note that the negative pressures on the jib are much more negative when both the jib and mainsail are used. *The jib develops much more lift when it is operating in the flow field influence of the mainsail.* We would expect this to happen, however, for the jib is operating in the upwash field of the main. In an actual situation afloat, we can make use of this by sailing a bit closer to the wind. But this fact alone does not account for the great efficiency attributed to the jib in the presence of the main.

If we examine pressures near the leech in Figure 2, we will see a second reason why the jib is such an efficient sail. Note that pressures near the leech are slightly on the positive side (A) with a jib alone. This means the jib leech velocity, without a main, is near the freestream value required to meet the Kutta condition on a single sail.

However, the jib leech pressures with a main present actually are negative which indicates leech velocities higher than freestream (point B). In this case, the velocity at the leech of the jib is about 30% higher than freestream speed. How has this happened?

I have mentioned before that airspeeds must be the same on both sides of a single sail at the leech to satisfy the Kutta condition. For a single sail, the leech speed turns out to be close to freestream airspeed. When we have two sails,

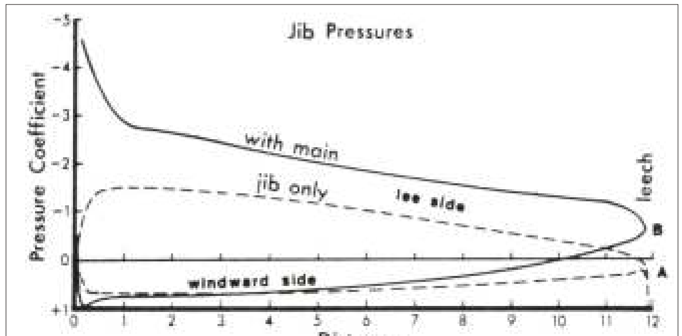

Figure 2

jib and mainsail, the airspeed at the leech of the last sail in the line (the mainsail) also will satisfy this Kutta condition and be near freestream values.

Yet, the leech of the jib is in a high speed region of flow created on the lee side of the mainsail; and detailed calculations show that the air flowing around the jib adjusts itself so that the Kutta condition is satisfied not at freestream conditions, but at a speed that blends with the high speed flow created by the mainsail in the region of the jib leech.

This high speed region would be there even if the jib was not present (providing the flow on the main is not separated), for airfoil shapes and angles used in my research show that jib leech airspeed would be about the same if the mainsail were used alone.

The Kutta condition on the jib must be satisfied in a high-velocity region created by the combined flows of the jib and mainsail (point B in Figure 2). The net result of this is that *the entire velocity distribution on the lee side of the jib is increased by a considerable amount*. These increased velocities mean lower lee-surface pressures and a resulting increase in jib lift.

In other words, the mainsail actually helps the jib, not only by giving it a lifting wind shift, but also by causing it to have much higher velocities on its lee side because of the Kutta condition requirements at the jib leech. While the aft windward side of the jib does lose some of its positive pressure, this is a small price to pay for the large increases in the suction pressure on the lee side.

This phenomenon will be referred to as the *dumping velocity* or *bootstrap* effect. The name bootstrap indicates that the main is actually helping the jib in this unusual manner.

What if a third sail were added forward and to lee of the jib with its leech in the increased velocity region of the jib? This third sail would have an even higher leech velocity and higher lee-side velocity distribution because of what the main is doing to the jib – and what the jib, in turn, does to the third sail.

The higher velocity flow that is forced to the lee side of the jib by the main has another important effect. These higher velocities all along the lee side of the jib mean that the boundary layer will be able to withstand more rapid increases in pressure (stronger adverse pressure gradients) without separating. The boat can be pointed at a higher angle (with the jib stagnation streamline coming in slightly on the windward side) without the whole jib separating and stalling.

Now let's examine the effects of four different jib and mainsail angles. Figure 3 shows four streamline drawings with only the stagnation streamlines appearing so that you can see clearly what happens to the slot flow as the sail angles are changed. Rather large sail angle changes of five degrees were selected so that the overall effects would be easier to illustrate.

Figure 3A has the sails at the same setting used in the jib-main flow study we already have discussed. In Figure 3B the jib has been moved five degrees closer to the mainsail, and as you can see by the number at the left, this causes a 60% reduction in the amount of air that flows through the slot.

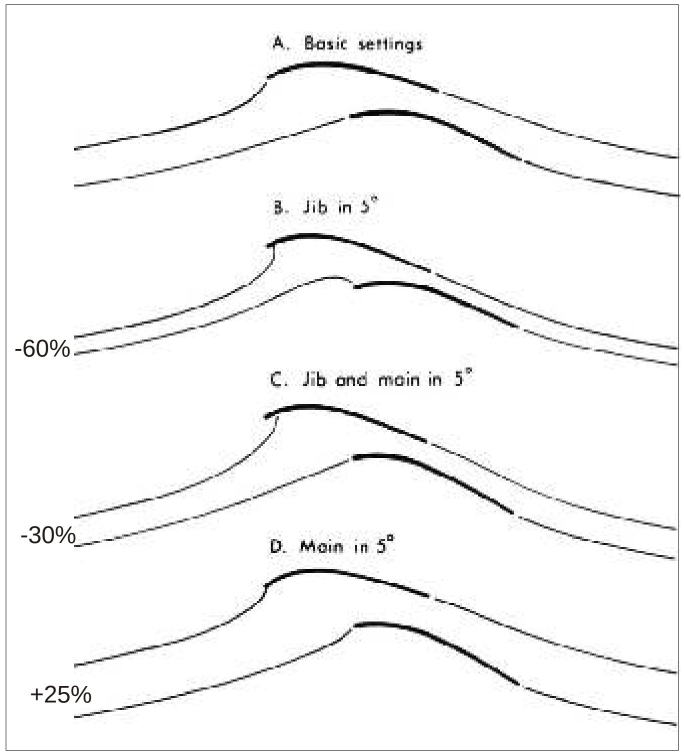

Figure 3

The stagnation streamline for the jib now comes into the sail on the lower, or windward, surface and the stagnation streamline for the main comes into the sail on its upper or lee side. This would cause higher pressures on the lee side of the main than on the windward side and the main would luff (carry a large bubble). As soon as the sail changes its shape, our nicely calculated streamlines become invalid, for the entire flow field changes a bit in response to the new shape of the sails.

But in Figure 3B we see what happens when we sheet the jib in too close. The slot-flow air is reduced; the pressures on the forward-lee side of the main become higher as the air flow becomes slower; and the mainsail loses more and more of its driving potential until we reach the point where it luffs. Even in this luffing condition, however, the main serves a useful purpose by causing an upwash in front of the jib. And it still contributes something, though less, to the bootstrap effect.

This, of course, assumes that only the forward part of the main is carrying a bubble and that the aft part of the sail is loaded up.

In Figure 3C, both the main and the jib are sheeted closer to the centerline of the boat by five degrees. This causes a 30% reduction in the amount of slot air compared to the sails with basic settings in Figure 3A. However, in Figure 3C, sheeting both the main and the jib in closer causes even more upwash on the jib, and the stagnation streamline comes into the jib even further back on the windward side. Here the air is treated rather roughly as it makes the sharp turn to get on the lee side and will probably separate and cause the jib to stall unless the boat is pointed closer to the wind. Both sails in short, have been trimmed in too tightly for the boat angle being sailed.

In Figure 3D the jib is at its original basic setting but the main has been sheeted in five degrees to open up the slot. This causes a 20% increase in the amount of air that flows through the slot, and the stagnation streamlines for both the main and the jib have moved slightly around to the windward leading edge of the sails.

These comments do not pretend to show how sails should be trimmed for maximum speed; they are included only to show the general effects as the sail angles are changed. All these results, however, clearly indicate that the amount of air that flows through the slot between the jib and main will vary depending upon the relative sheeting angles of the two sails. The angles also have a direct influence over the way in which the stagnation streamline comes into the sails. And this, of course, affects the pressure distributions and determines whether or not the lee-side boundary layers will separate and the sails stall.

All my comments to date have primarily applied to a jib-mainsail combination having considerable sail overlap. A similar situation would have occurred if the sails had less overlap. The only difference would have been in the relative magnitude of the observed effect. With less overlap, a jib would not have such a strong effect on the mainsail, and the mainsail lee-side suction pressures would not have been reduced as much.

The downwash effect of the jib on the main also would have been smaller. With less overlap, the leech velocity on the jib would have been a bit lower and the bootstrap effect not quite so strong.

Of course all these comments also would apply to a single sail combination with varying sail shape and overlap from the deck to the top of the mast. Nevertheless, the basic conclusions still would be the same.

I now would like to classify the major jib-mainsail interaction effects. Although they are for the most part interdependent, I will segregate them into the effect of the jib on the mainsail, and the effect of the mainsail on the jib.

The major effects of a jib on the mainsail are:

1. The jib causes the stagnation point on the mainsail to shift around toward the leading edge of the mast (the header effect).
2. As a result, the peak suction velocities on the forward leeside of the main are greatly reduced. Since the peak suction velocities are reduced, the recovery adverse pressure gradients also are reduced.
3. Because of reduced pressure gradients on the mainsail, the possibility of the boundary layer separating and the airfoil stalling is reduced.
4. A mainsail can be operated efficiently at higher angles of attack without flow separation and stalling than would be the case with just a mainsail alone. This is caused by a reduction in velocities over the forward-lee part of the mainsail rather than by a speed-up in the flow which is the popular theory.
5. *Much less air* goes between the headstay and the mast when the jib is placed in the flow with the main. The circulations of the main and the jib tend to oppose and cancel each other in the area between the two sails, and more air is therefore forced over the lee side of the jib.
6. As the jib is sheeted in closer to the main, there is a continuing decrease in suction pressure on the lee side of the main. When pressures both to the windward and leeward side of the mainsail become equal, there no longer is the pressure difference across the sail necessary to maintain the airfoil shape, and the sail begins to luff.

The major effects of the mainsail on the jib are:

1. The upwash flow ahead of the mainsail causes the stagnation point on the jib to be shifted around toward the windward side of the sail, and the boat can be pointed closer to the wind without the jib stalling or luffing.
2. The leech of the jib is in a highspeed flow region created by the mainsail. The leech velocity on the jib is, therefore, higher than if the jib alone were used.
3. Because of the higher leech velocity, velocities along the entire lee surface of the jib are greatly increased when both the jib and main are used, and this contributes to the high practical efficiency of a jib.
4. The higher lee-surface velocities on the jib mean the jib can be operated at higher angles of attack before the jib lee-side flow will separate and stall.
5. Because of all this, proper trim and shape of the mainsail significantly affect the efficiency of the overlapping jib. Anything that causes a velocity reduction in the region of the leech of the jib (such as some separation on the aft part of the main) results in a lower driving force contributed by the jib.
6. The trim of the main significantly affects the pointing ability of the boat, for it directly influences the upwash that approaches the luff of the jib.
7. The mast in front of the mainsail always has been blamed for making the main less efficient than a jib. From my studies, I believe this is only part of the answer. Another, and probably equally important, factor is the increased velocity on the jib and the fact that its Kutta condition must be satisfied in a local high speed flow region that is created by the mainsail.