Another Look at Slot Effect

"Arvel Gentry puts the old theories to rest"

By Arvel Gentry

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The "slot" effect," as we know it, is traditionally supposed to do three basic things:

First, the jib causes the air over the lee side of the main to have a much higher velocity, increasing the partial vacuum, and hence the sail's efficiency.

Second, the higher velocity air in the slot "revitalizes" the air over the main, which would otherwise be in a separated or stalled condition.

Third, the increased velocity in the slot results because the distance between the leech of the jib and the main is much less than the distance between the headstay and the mast, but it must accommodate the same flow per unit of time.

Sailing books, magazine articles by national champions and our leading sailmakers all have expounded on, and made use of, these ideas to tell us first, how the slot works, and second, to explain how we should trim our sails. These explanations of jib-mainsail interaction originally were derived from an aerodynamicist's description of how a wing with a leading edge slot works (Figure 1).

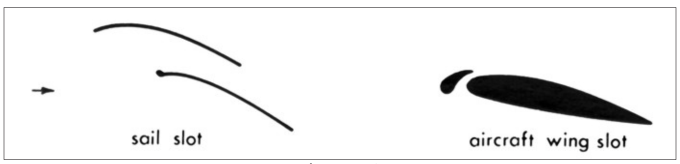

Figure 1

But in 1971 I obtained some results from a new and sophisticated computer program that indicated that the old explanations of how a wing slot works were entirely wrong. My results were accurate, detailed, substantiated by wind-tunnel data, and very conclusive.

Does this mean that the old explanations for slot effect were also wrong? The answer is yes!

My conclusion was not reached in haste for it is dangerous to say old ideas are wrong unless you have a lot of proof and can cover all the aspects of a problem. To test my theories I first made use of a device called an Analog Field Plotter that determines the flow streamlines about any airfoil combination (Figure 2). I studied single and multiple airfoil combinations to gain a basic understanding of the directions the air takes as it flows past the sails.

A number of sail angles and relative positions were investigated and the results were then backed up by more detailed and accurate answers from the computer. Next I conducted a series of experiments in a water channel to obtain photographic evidence of my findings. On top of all this, each new conclusion and explanation was subjected to the question, do they all make sense in terms of actual sailing experience? The answer continues to be yes!

In the first three articles of this series, I presented a number of very important and fundamental aerodynamic principles. In this fourth article, I will assume you already

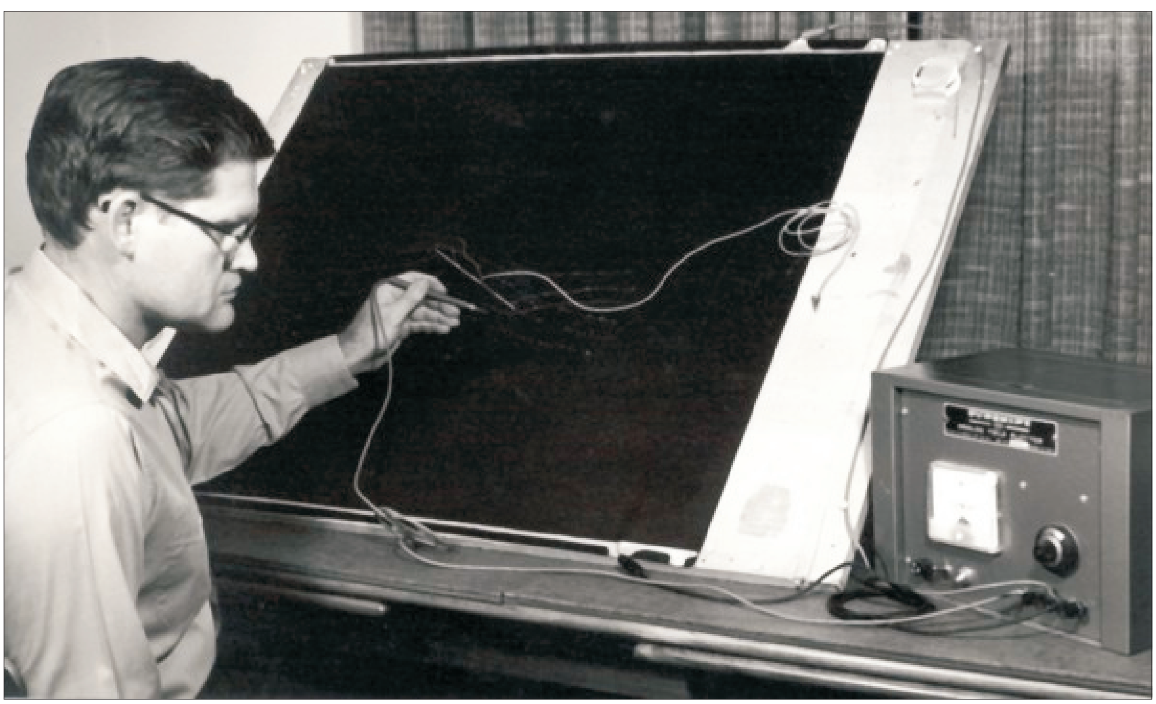

Figure 2.
Analog field plotter equipment.

have studied the first three parts. However, several items should be repeated as a review.

In the April issue I pointed out that most of the airflow diagrams in the sailing books violated some basic aerodynamic principles. In the may issue we learned that boundary layer separation on a sail results when the surface pressure is increasing too rapidly (the airflow is slowing down too quickly). And last month we learned about circulation and how lift is generated.

We saw that the airflow coming off both sides of the leech of a sail must be at the same pressure and speed (the Kutta condition). The airflow speed will be higher than freestream over the forward-lee portion of a sail, but it will return to near freestream speed by the time it reaches the leech. It is this slowing down of the lee-side airspeeds (and resulting increase in pressures) that causes the airflow to separate.

From the information I've presented so far, it is quite obvious that there are some serious misunderstandings about the old slot-effect explanations in the sailing literature. But if previous explanations for the slot effect are wrong, what are the right answers?

Until now, I've talked about general principles and about flow around a single sail. Now we'll begin the analysis of two sails together. The last article described how the flow about a lifting airfoil may be thought of as being the addition of a circulation flow solution and a non-circulation solution. The amount of circulation on the airfoil was adjusted so that the resulting airflow was in a smooth direction off the leech. But what about a case where we have two airfoils?

Figure 3 shows that both the jib and mainsail have their own circulation fields. The strengths of the two circulations must be adjusted so that the Kutta condition is satisfied at the leech of both sails (smooth flow off each sail). In Figure 3, note that the two circulation fields ***oppose*** and tend to cancel each other in the slot between the jib and main. This fact gives us a hint that we will not get all the increased air speed in the slot that is claimed by the old theories.

If the slot flow did give higher velocities that increase the partial vacuum on the main, would not this same "partial vacuum" on the ***windward*** side of the jib ***reduce*** its efficiency? As we will see later, what really happens is that some of the air we would think might go through the slot is actually diverted by the combined circulation fields so that it goes on the lee side of the jib.

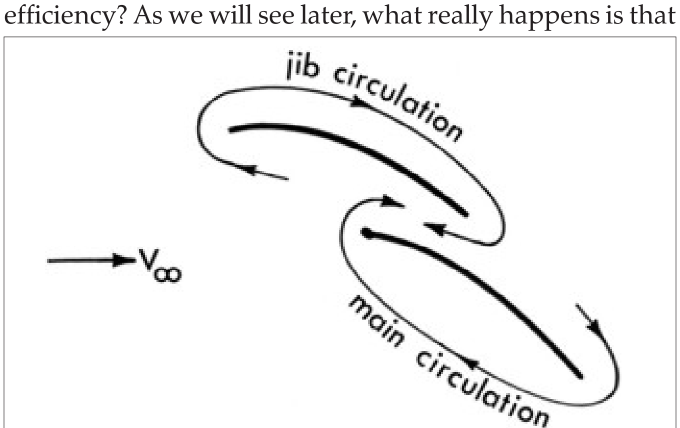

Figure 3

To examine the interaction between two sails, we will use a typical airfoil section of a mainsail and a matching section through the jib. The actual airfoil shapes and angles are not too important as long as they are reasonably representative of close hauled sailing conditions. In fact, for any conclusion to be scientifically correct, it must apply for almost any shape and for a wide range of angles, and I will illustrate the effect of different sheeting angles next month.

We always must check our results to see if a luffing condition would result. This check will insure that the results are correct even though the analysis does make use of rigid airfoils instead of flexible shapes.

First, look at the flow about the mainsail airfoil without the jib in place. The mainsail will be positioned at the same angle it will have when the jib is in place; the leading edge of the main is determined by the shape of the mast. For these studies, the area right behind the mast was filled in to represent the separated region that always exists immediately behind the mast. Separation effects from the mast are reasonably understood so I will not dwell on mast effects here.

The calculated streamlines for a main alone are shown in Figure 4. Note that the stagnation streamline (S_m) comes into the lower (windward) side of the sail. The calculated pressure, if no separation or stall occurs, is shown in Figure 5. Remember from last month that low pressures (high velocities) are represented by negative pressure coefficients, and that high pressures (low velocities) are shown as positive pressure coefficients.

Since the stagnation streamline comes in on the windward side of the sail (upwash), and we have a good pressure difference on the two sides of the surface, the sail will hold its shape and not luff. Even though the forward-lee part of the sail seems to be facing the freestream airflow direction way out in front of the sail, the upwash effect places the leading edge of the sail at a higher angle so that it will not luff. The sail only sees the local upwash flow directions.

Because the stagnation point is around on the windward side of the airfoil, we get a very high suction peak (large negative pressures) as the air tries to make the sharp turn around the mast to the lee side. The pressure then starts to increase rapidly toward the pressure it must attain by the time the leech is reached – to satisfy the Kutta condition. The boundary layer probably will not be able to withstand this steep increase in pressure, the flow will separate, and the airfoil will be in a stalled condition.

To prevent this stall, the sheeting angle of the sail is increased, either by letting out the mainsheet or moving the traveler to leeward. This is exactly what our experience is afloat when the jib is lowered. However, in the example shown in Figures 4 and 5, the mainsail is at the same angle at which it would be if the jib were present. And the

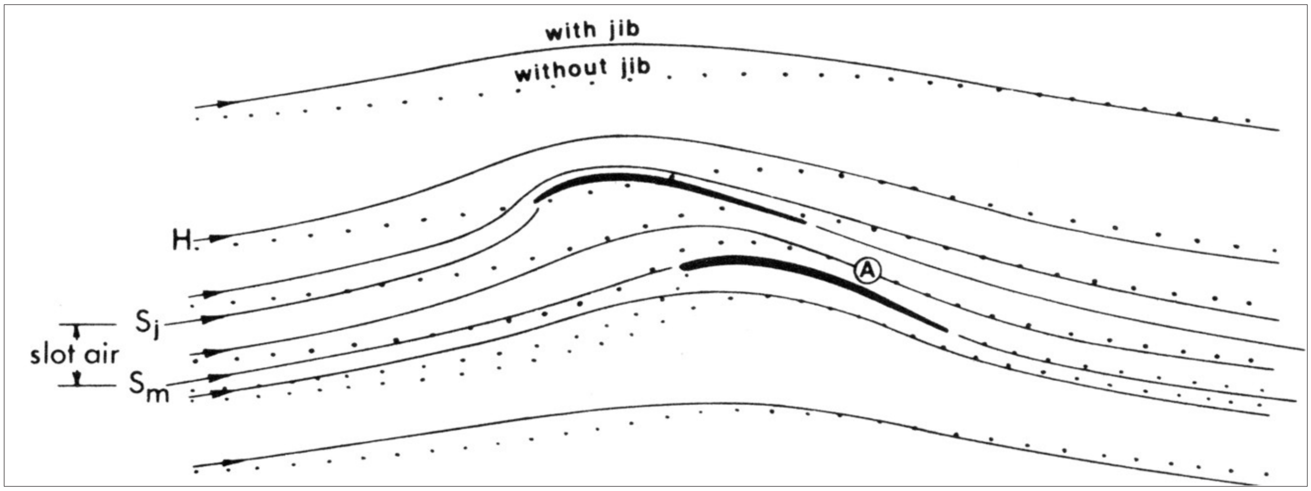

Figure 4

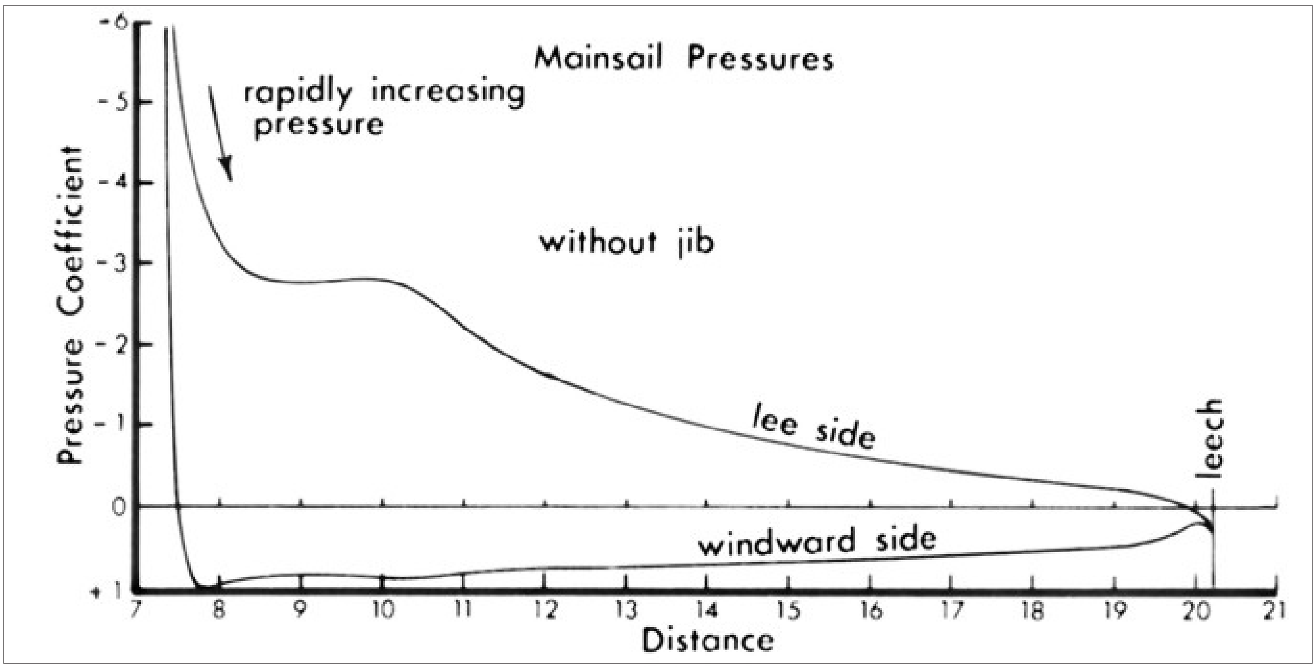

Figure 5

pressures shown in Figure 5 are what we get if the flow does not separate.

Carefully note the shape and position of streamline H in Figure 4. This line is selected so that it goes through the point (H) that will be the leading edge for the jib (the headstay) in our next example. The distance between the stagnation streamline S_m and the headstay streamline H at the left side of the figure is a measure of the amount of air that passes between the headstay and the mast without the jib being present and without any separation on the mainsail.

Now, let's introduce the jib. The streamlines, when both the jib and main are used, are shown in Figure 6. This figure is necessarily a bit cluttered so that the flow lines before and after the jib is added can be compared.

Figure 6 is the most important figure in this whole series, so study it carefully. The solid streamlines represent the flow when both the jib and main are used. For comparison, the streamlines that existed when the main was used alone are also given (the dotted lines). A number of important points come out of this figure.

First, the stagnation streamline for the mainsail when the jib is present (the solid line, S_m) goes smoothly into the leading edge of the mast instead of being down around on the windward side as was the case for the mainsail alone. The air, therefore, will not have to speed up as much to get around to the lee side of the main. This means that the airspeeds will not be so high over the forward-lee side of the main and the flow will not have to slow down so much to reach the final speed that is required at the leech to satisfy the Kutta condition.

This gives a smaller increase in pressure as the air flows toward the leech (a lower adverse pressure gradient) and helps prevent the flow from separating. If the jib were placed in the picture and had it caused higher air speeds over the forward-lee side of the main, as the old venturi explanation states, then it would give a steeper pressure gradient and actually ***cause*** the flow to separate, rather

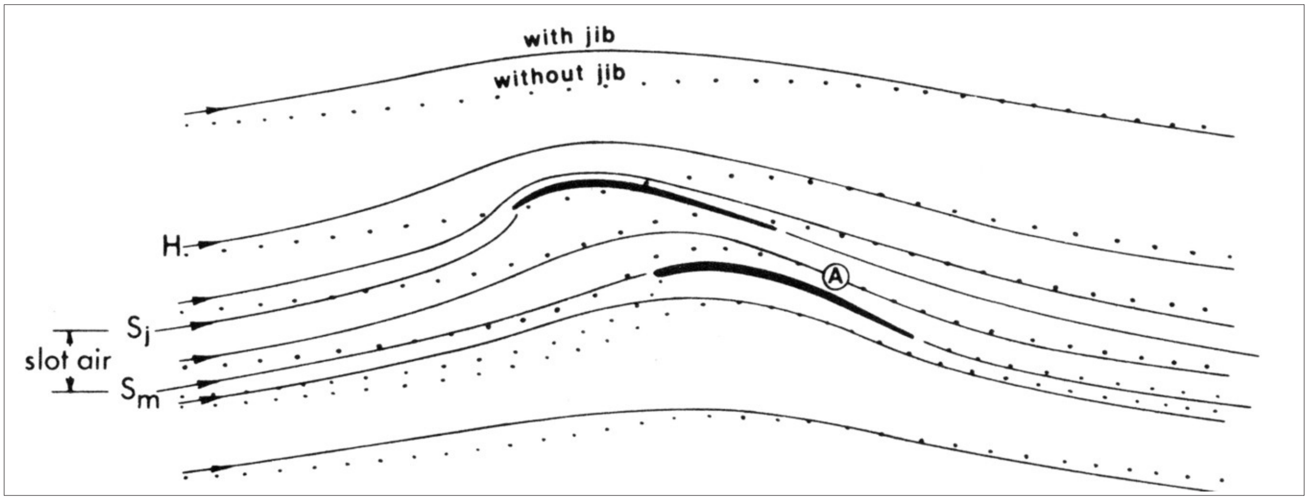

Figure 6

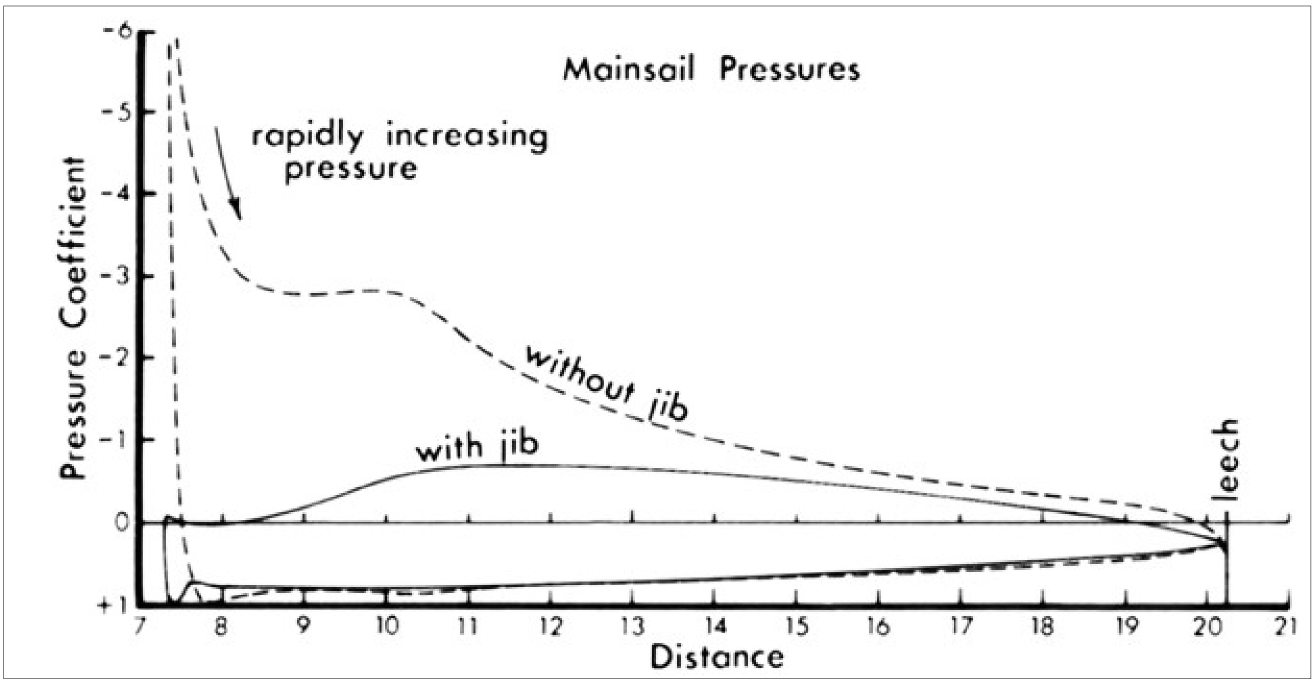

Figure 7

than prevent it.

Second, the streamline H that went through the headstay point when the mainsail was used alone now goes well above the surface of the jib. The new streamline through the headstay (the stagnation streamline for the jib, S_j) now is much lower than the headstay streamline, H, in the case of the mainsail alone.

The distance between the two stagnation streamlines (S_m and S_j) at the left side of the figure is a measure of the amount of air that now goes between the headstay and the mast (and therefore into the slot between the two sails) when both sails are present. You can see that ***much less air goes between the headstay and the mast when both sails are present than it does when only the main is used***. Much more air is being deflected around the lee side of the headstay (and therefore around the lee side of the jib) than when there was a mainsail alone!

Look closely at the solid streamline for the main and jib combination that passes in the slot between the two sails at point A. Note that at this point it is exactly the same distance away from the surface of the main as the dotted streamline is for just the main at point A. This means that at this point we have about the same airspeeds when we have a jib and main as we had for the main alone! In fact, on the surface of the main itself, Figure 7 shows slightly higher pressures (less negative) and therefore ***lower*** velocities when the jib is used than occurs without the jib. From all this, we have to conclude that the old venturi slot-effect explanation ***must be wrong***.

The calculated pressure distributions for the mainsail, both with and without the jib, are shown in Figure 7. The presence of the jib and a resulting shift in the stagnation point on the mainsail causes a drastic reduction in the high negative-pressures over the forward-lee part of the main. Since the pressure gradients are much lower, the possibility of complete flow separation on the mainsail is reduced, and the amount of theoretical lift being contributed by the mainsail is also reduced.

Of course, in the case of the mainsail alone, separation would have occurred in real life and you would not have been able actually to realize the amount of lift calculated theoretically when neglecting separation. You do lose lift from the theoretical non-separated value, but you now have reduced pressure gradients so the airfoil will not stall.

These findings are the keys to the often discussed phenomena of slot flow between sails. With accurately determined streamlines, you can see that the air passing between the two sails is quite different from the old "venturi effect" explanations many of us have grown up with. With both sails set, a large percentage of the air that was going between the headstay and the mast when the mainsail was alone now goes above and down the lee side of the jib. Less air is left to pass in the slot between the sails and this tube of air ***actually slows down*** (the streamlines spread out) as it reaches the line between the headstay and the mast.

Then, and only then, does it begin to speed back up as it approaches the slot between the jib and the mainsail. However, by the end of the slot, the speed has only accelerated back to about what it would have been at that point if the mainsail alone was used.

These flow diagrams also verify a couple of points that we all have observed in actual sailing experience. The jib reduces the upwash on the main (gives the main a header), and the main increases the upwash (a lifting wind shift) for the jib.

Thus we see that the primary effect of a jib is to cause ***reduced*** velocities over the forward-lee part of the main, rather than increased velocities. The slower velocities in turn give reduced pressure gradients that help prevent separation and stall rather than some higher speed "revitalization."

The velocities in the slot are determined by the total effects of the circulation fields around the two sails necessary to give smooth flow off the leeches (the Kutta condition). The flow streamlines for this condition should never be drawn by hand or guessed. Instead they must be accurately determined by an Analog Field Plotter or computer.

This month we have studied the main alone and then added a jib. It is equally interesting to do just the opposite: to look at the airflow about the jib alone, and then add the main. This is what we will do next month.