A Review of Modern Sail Theory

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Abstract

Popular concepts as to how sails generate lift, and how two sails interact with each other are discussed in light of modern aerodynamic research. Much of the old sail theory in the sailing references is shown to be wrong. The origins of these old ideas are discussed and the new and correct explanations presented. Applications of modern sail theory to practical sailing problems are discussed.

1. Introduction

Bruce Banks and Dick Kenny in their book "Looking at Sails" (Reference 1) state that "it is essential to anyone interested in sails, and indeed sailing, that the fundamental principles are thoroughly understood." They then follow with several pages of sail theory and repeat basic ideas that have appeared in the sailing literature for many years. Unfortunately, their explanations of the most important aspects of sail theory (how a sail gives lift, the interaction between the jib and main, the slot effect) are completely wrong.

Virtually all of the sailing references contain similar, but erroneous explanations when they discuss the aerodynamics of sails. References 1 through 5 are typical. These books and magazine articles were written by recognized sailing authorities, class champions, Olympic sailors, and famous sailmakers. How could these fundamental ideas on sailing be wrong, and how could they persist for so long? All of these people are certainly excellent sailors. They have learned from practical experience what it takes to make a boat go fast. But when they talk or write about the aerodynamics of sails, they get into trouble.

As a research aerodynamicist, I was dumbfounded when I first started reading the sailing literature as a beginning sailor and saw what a confused state sail theory was in. Even the basic explanations of how a sail generates lift were wrong. This I could understand, since even the popular aviation books were wrong in their attempts to explain lift. It is difficult to explain the generation of lift for laymen. The simplifications devised in attempts to do this seemed logical but usually turned out to be wrong.

The inconsistencies in the explanations for the interaction between two sails (the slot effect) also bothered me. However, in this case, even the technical aerodynamics literature seemed to be in trouble.

At that time I worked for a world renowned aerodynamicist, A.M.O. Smith. His group was doing advanced research in multiple airfoil theory (wings with flaps and slats). I was fortunate enough to learn from these people, have access to their digital computer programs and flow simulation equipment and be able to try some of the new ideas out on sails.

Eventually, the pieces began to fit together. The new multiple airfoil theories as applied to sails made all of the existing literature on the interaction between the jib and mainsail (the slot effect) obsolete. I presented the results of my research at the 3rd AIAA Ancient Interface Symposium in Redondo Beach, California in 1971 (Reference 6). Reference 7 contains some of the results for aircraft wings as prepared by A.M.O. Smith and his group.

However, the Ancient Interface Proceedings do not really reach the average sailor. Magazine articles and books still repeated the old theories. I was able to interest an editor at *SAIL* Magazine, Chip Mason, and he printed an extended version of my material in a series of articles starting in April

1973. The entire set of articles later appeared in the book "The Best of *SAIL* Trim" (8). The approach in these articles was to expand upon the technical information presented in the original AIAA paper, but the approach was still quite engineering oriented. At least, my ideas were now available to the general sailing public, although somewhat obscured with pressure distribution plots that were probably only understood by an engineer.

And how were these new theories received? Stephen Haarstick, of Haarstick Sailmakers, requested permission to make copies for use by people in his loft, and stated that "they are by far the best articles written on the subject for laymen to read." Similar requests were received from as far away as Australia. There was other evidence that some people did read the articles and found something of practical use. In one article I discussed the leading edge separation bubble phenomena (8), and proposed an array of short tufts starting right at the luff as an aid to windward sailing. This system soon began to appear on a few local boats. Although I did not expect that many hotshot sailors would pick up the idea, my mini-tufts later appeared on a world quarter-ton champion, in the Congressional Cup, on a maxi-boat, and on an America's Cup boat. However, in the sail theory area, most sailing "authorities" still stuck with the old ideas.

In one case, the reaction was rather negative. After only my very first article in the *SAIL* Magazine series, Peter Barrett of Yacht Racing Magazine (Olympic sailor, sailmaker, self-described as being trained "as an engineer specializing in fluid mechanics") had rather strong statements about my articles (9). He stated "that future articles will do little if anything to improve directly the performance of either a given class of sailboat or a reader. In fact, by implying that a major error in everyone's thinking is about to be corrected (and thus we will all, of course, be able to better utilize this airflow and race more successfully), I believe that a disservice is being done the reader."

I was at first shocked and angered by Mr. Barrett's comments, especially since they were made even before he had a chance to read the complete series. I was well prepared to defend the technical aspects of my theories. I had not expected Mr. Barrett's type of reaction. However, I certainly found one of his points to be true, "Few successful racing skippers pay much attention to the scientific articles." One bit of evidence of this was that new books by these same people kept appearing with the same old and completely wrong explanations of how sails work (10-13). Obviously, not everyone shared my interest in knowing the correct explanations for how their sails really did work.

Finally, in 1979, C. A. Marchaj published his new book "Aero-Hydrodynamics of Sailing" (14). Marchaj uses much of the material from my *SAIL* Magazine articles, and also states that "many problems concerning the interference between a mainsail and a jib were clarified by A. Gentry who explained correctly, for the first time, the jib-mainsail interaction effect."

With reference to the old theories, Marchaj states that "All one can say in defense of sailing theoreticians is that these misconceptions concerning jib-mainsail interactions were originally derived from the most respected and time honored, authoritative aerodynamic theories and faithfully reflected the state of affairs in this field."

As you have no doubt recognized by now, this is not the usual technical paper. The approach is to review the old theories, point out where they are wrong, and to contrast them with modern accepted sail theory. The format is a bit different also. Each part of the text goes with the figure printed immediately to the right. In many cases the discussion is quite brief, and technical terms and engineering plots are avoided when possible. If you want the technical details of modern sail theory, then read my articles in the "The Best of *SAIL* Trim" (8), or Marchaj's new book (14).

However, if like Mr. Barrett (9), you feel "that the average sailor, and indeed any serious racing sailor, will do himself far more harm than good by attempting to understand the theoretical streamline flow as defined by advanced fluid mechanics," then I suggest that you skip the rest of this paper and go watch TV.

2. Generation of Lift -- Old Theories

Figure 1

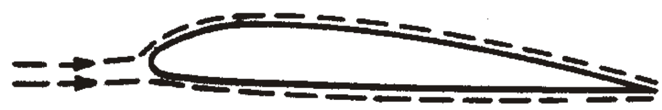


Figure 1. Stephen Colgate states that (15), "Because of the curvature of the upper surface of the wing, the air passing over that side has to travel a greater distance than that passing under the wing. Since it has to go farther, it has to go faster in order to reach the trailing edge at the same time as the air flowing past the underside of the wing." This is one of the oldest misconceptions about the generation of lift and seems to come from popular aviation books (16 for example). However, there is no physical law of aerodynamics that requires the air to flow as this theory states. You will not find this theory in any modern aerodynamics text book. In fact, exact calculations show that an air particle flowing over the upper surface gets to the trailing edge long before its brother particle that traveled by the lower surface route.

Figure 2

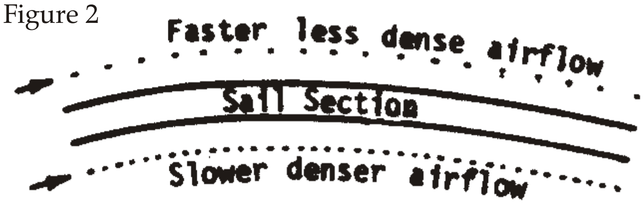


Figure 2. Some books (4) state that the density of the air is different on the two sides of an airfoil. This idea is completely wrong. Density is defined as the weight per unit volume (i.e., pounds per cubic foot). The density of air does not change as it flows around a sail. The forces on a sail are caused by other factors. The air would have to be blowing at jet-transport cruise speeds before density changes became important.

Figure 3

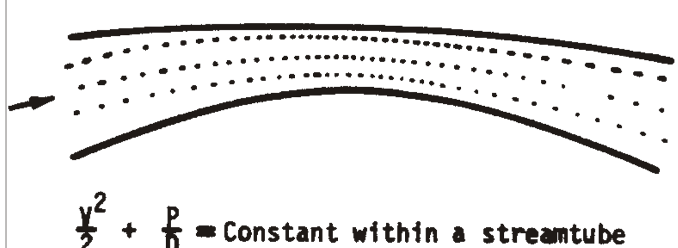


Figure 3. Bernoulli's principle is frequently cited in sailing references to help explain the generation of lift. Streamlines are drawn about an airfoil such as a sail. Then the Bernoulli principle is used to explain why the air travels faster where the streamlines are close together and slower where they are far apart. Bernoulli's principle states that one half the velocity squared plus the pressure divided by the density is constant along any stream tube of air. When the stream tube gets smaller, the air travels faster and the pressure goes down. This equation is certainly true. However, we first must know the stream tube shape. The sailing literature is filled with streamlines drawn by people unfamiliar with the laws of aerodynamics. As a result, the explanations that go with the pictures may seem correct, but in truth, they are usually completely wrong. The streamlines drawn in any reference quickly tell you how much, or rather how little, the author knows about aerodynamics.

Figure 4. The first attempts by scientists to calculate the lift of an airfoil used what we now call Newtonian impact theory. It was thought that the individual particles of air hit the surface and bounced off, and thus transmitted energy to the wing in an equal-and-opposite energy exchange manner. However, the lift that they calculated with this method was not very much, and the drag was high. Clearly, man would never fly, but how did the birds do it and why did small model gliders fly? These early scientists were treating air as a lot of small particles hitting the airfoil and not as a fluid flowing past the object. Some sailing books (17) still try to use this old but incorrect idea. In normal windward sailing, the air right at the sail surface is always flowing parallel to the sail. The shape and reaction of the sail is a result of the airflow and the surface pressures, and not as a result of particles hitting the sail like grains of sand. The impact effect is not useful until the airfoil is traveling at Space Shuttle reentry speeds.

Figure 4

3. Generation of Lift -- New Theories

Figure 5. It is not a simple task to explain how a sail or the wing of an airplane generates lift. Much of what is in the literature is an attempt to simplify a complex subject so that the layman can understand. Unfortunately, these simplifications are usually not correct. The explanation presented in this section sticks with modern lift theory as it is found in aerodynamic text books, but without the advanced mathematics usually found there. An experiment that you can do at home will help in understanding these concepts. The generation of lift baffled scientists many years ago. It is no wonder that the average sailor today still does not understand the generation of lift.

The correct theory for lift must hold for all conditions. It must work for regular airfoils like the wing of an airplane, for thin cambered surfaces such as our sails, and even for flat thin surfaces such as a flying barn door. I will start with the flat barn door airfoil since it helps demonstrate the important principles in a step-by-step manner. Two-dimensional airfoils will be used since the basic principles are easier to understand. The same concepts, plus some additional complicating factors, apply to three-dimensional sails.

Figure 5

Figure 6. If we were able to wave a magic wand and cause the air to have absolutely no viscosity, we would see some very unusual things happen. We would find that an airfoil, sail, wing, car, etc., would have zero drag. Unfortunately, we would also have no lift. In real life we don't have the magical power to check this out, but we can with our modern computer programs. Our "zero viscosity" air would flow about a flat plate airfoil as shown in the Figure 6. Note the symmetry of the flow. This causes all forces to cancel each other out, and give no drag, and no lift.

Figure 6

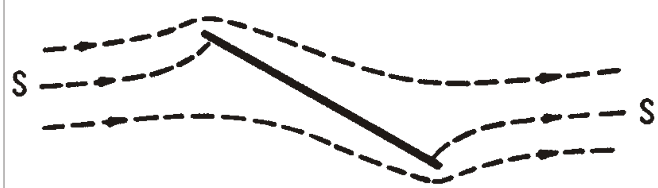


Figure 7. Note that the lower surface flow is able to turn the corner at the trailing edge and flow upstream a little until it meets the air on the upper surface. Even the air near the leading edge does some strange things. Some of it turns upstream and around the leading edge to the upper surface. The dividing lines between the upper and lower surface flows are called stagnation streamlines (marked S). In this inviscid model of the flow, the air right at the surface "slips" by the surface.

Figure 7

Figure 8. However, air does have viscosity and because of viscosity, the stream of air right at the surface will cling to it and not move at all relative to the surface. Figure 8 shows this phenomenon. A very short distance away, the air is moving relative to the surface. Once we get away from the airfoil surface, the viscosity of the air becomes unimportant again. The portion of the flow very near the airfoil surface is called the boundary layer. The change in the flow speed relative to the surface in the boundary layer is called the shear layer. It is this layer that causes skin friction drag on the sails, hull and keel.

Figure 8

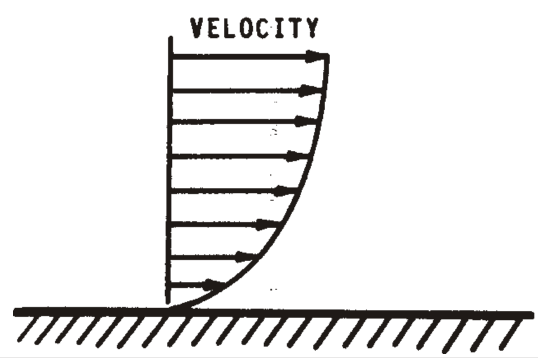


Figure 9. If we suddenly turn the viscosity on, the flow about our flat-plate airfoil will begin to change. The viscous boundary layer will start to form on the surface. In our magical inviscid model (Figure 8) the flow turned around the sharp trailing edge with a very high velocity right at the trailing edge point. Now with viscosity having an effect, the flow is not able to make this complete turn around the trailing edge. It at first tries to make the turn but then separates from the surface. This initial attempt to turn around the trailing edge causes a swirl of air to form. This starting vortex is swept downstream with the flow.

Figure 9

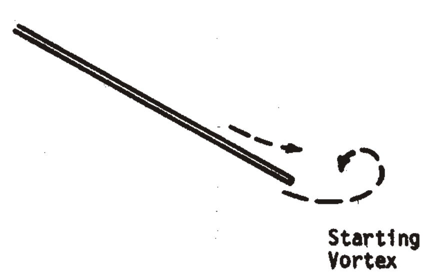


Figure 10. With the air no longer turning the trailing edge and flowing a short distance upstream, the upper surface flow now continues on toward the trailing edge to fill this void. With the upper surface air now continuing to the trailing edge, the leading edge flow adjusts itself so that more air is swept around to the upper surface so that there are no voids in the flow. This is shown by the shift in the stagnation streamline on the lower surface toward the rear of the airfoil. In fact, the entire flow about the airfoil adjusts itself so that much more air is flowing on the upper or lee side of the airfoil. After we turned on the viscosity with our magic wand, the air quickly adjusted itself so that both the upper and lower surface flows stream smoothly off the trailing edge parallel to each other (and at the same speeds). In aerodynamic jargon we call this trailing edge flow phenomenon the Kutta condition, after the man who discovered it.

Figure 10

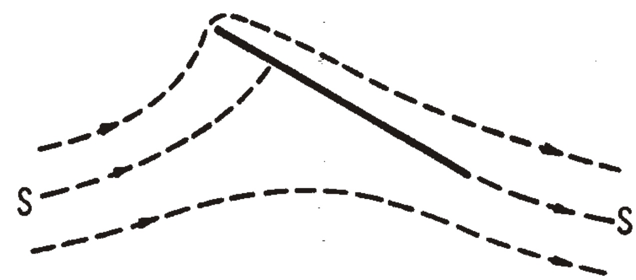


Figure 11. The airflow about the flat plate is now no longer symmetrical. The summation of the forces around the airfoil now will give a resultant force perpendicular to the flow direction. This force we call lift. Unfortunately, the scrubbing action of the boundary layer on the airfoil also causes drag. Now, however, the lift is substantial (much higher than the "impact theory" previously mentioned). Birds and airplanes can now fly, and we have a force to push our boats through the water! Without the viscosity of the air, we would have never gotten off the ground or away from the dock. In this figure we do have a problem with the air trying to flow around the sharp leading edge. That can be solved by bending the airfoil shape downward so that the leading edge meets the incoming flow.

Figure 11

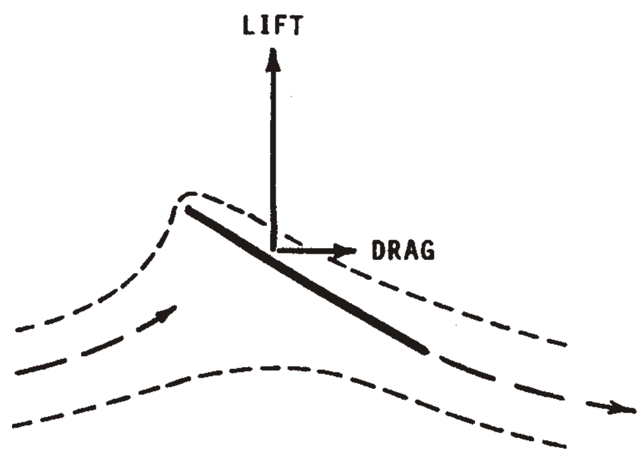
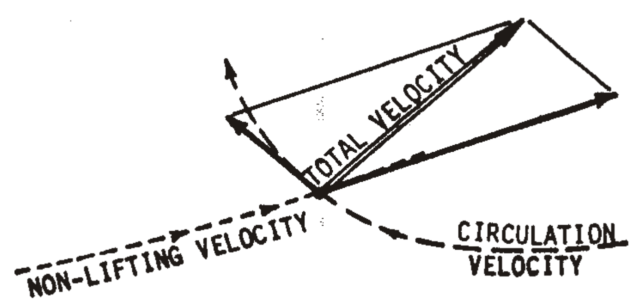


Figure 12. The flow about an airfoil really consists of two separate flows added together. One of these is what we call the non-lifting flow as illustrated in Figure 8. The other is a circulatory flow about the airfoil that is necessary to give smooth flow off the trailing edge. These two flows add together just as our boatspeed and true wind add together to give the apparent wind that we feel on the boat. The circulation flow is not an imaginary flow, or a mathematical trick. It is real, and can be visualized using the experiment described on the next page.

Figure 12



4. The Bathtub Experiment

Figure 13. If you have trouble understanding the circulation idea, try this experiment and see for yourself. Fill your bathtub with about two inches of water and let it set so that it is not moving. Now find something to sprinkle over the entire surface of the water so that you can better see the movement of the water during the experiment. Fine sawdust, talcum powder, or even pepper will work. We now need an airfoil. A four by six inch piece of stiff waxed paper cut from a milk carton makes a good airfoil. Bend the airfoil slightly so that it has about half the camber of a sail. Very carefully place the airfoil on the centerline of the bathtub as shown in the figure. The leading edge pointing toward the left should be slightly higher than the trailing edge (about a half inch) to give the airfoil what we call the angle of attack. Again let the water settle down.

Figure 13

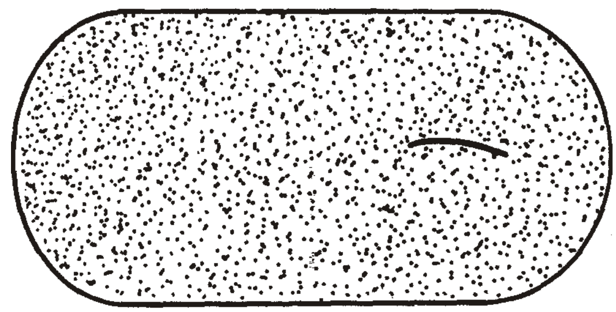


Figure 14. Now, grasp the airfoil carefully so as not to disturb the water. Start moving the airfoil down the centerline of the tub toward the left end. Watch what happens near the trailing edge of the airfoil as you first start the movement. The flow will at first start to make the turn around the trailing edge, then separate to form the starting vortex described previously. The starting vortex will stay at its starting position as we move the airfoil toward the left end of the tub. This is illustrated in the sketch. In this experiment in water, we have to keep the airfoil camber and angle of attack small in order to avoid excessive flow separation from the airfoil. However, all of the phenomena observed in the water experiment also happen in air.

Figure 14

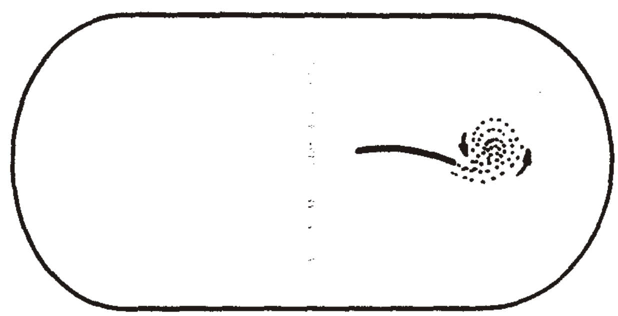


Figure 15. As the airfoil nears the center of the tub switch your attention to the flow in front of and around the airfoil. Note that the flow out in front of the airfoil somehow "knows" that the airfoil is coming, and starts changing its position to flow around the airfoil, even before it arrives. If the airfoil is being pulled precisely down the centerline of the tub, you will note some of the water in front of, and below the airfoil will actually end up flowing over the top of the airfoil. The upward flow out in front of the airfoil is known as upwash. You may have to repeat this exercise several times and concentrate on a different part of the flow field each time.

Figure 15

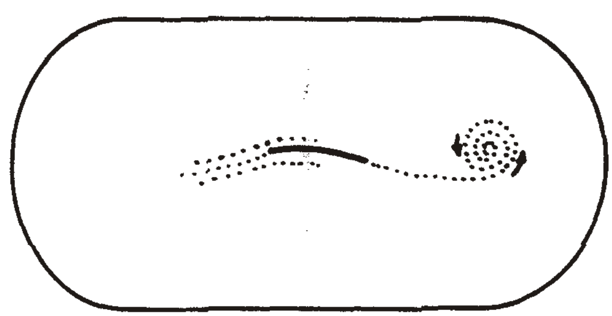
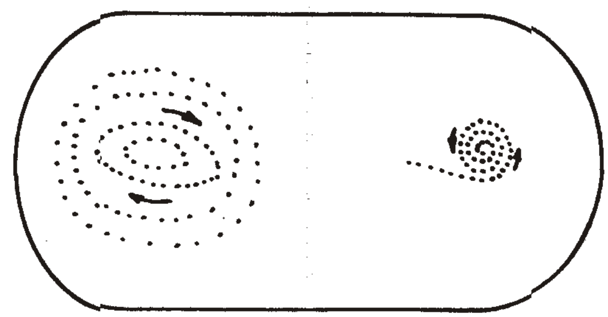


Figure 16. Now comes the key part of this experiment. When the airfoil gets within about one foot of the left end of the tub, suddenly lift it completely out of the water. What you have done by removing the airfoil is to remove one of the components of the two flow fields about the shape (this is like stopping a boat to measure the true wind). When you remove the airfoil all we have left is the rotational flows that are caused by movement of the airfoil. At the right end of the tub we see the starting vortex still rotating in a counterclockwise direction. At the left end of the tub we see a larger clockwise-spinning vortex. This is the "circulation" flow about the airfoil and is responsible for generating the lift. The forward motion of the airfoil and the circulation field are added together to give the final flow, just as adding the boat speed and true wind vectors give the apparent wind we see afloat.

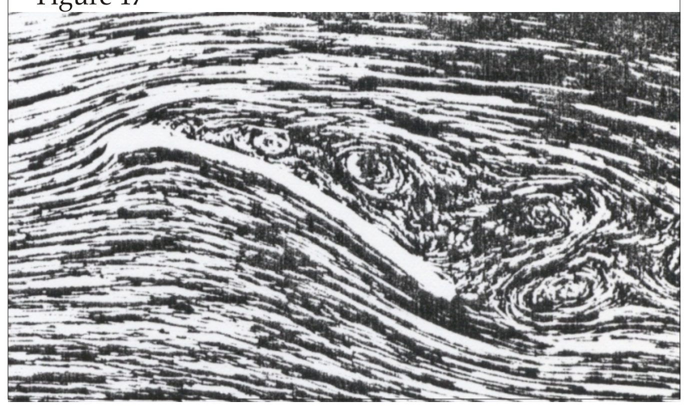
Figure 17



5. Flow Separation

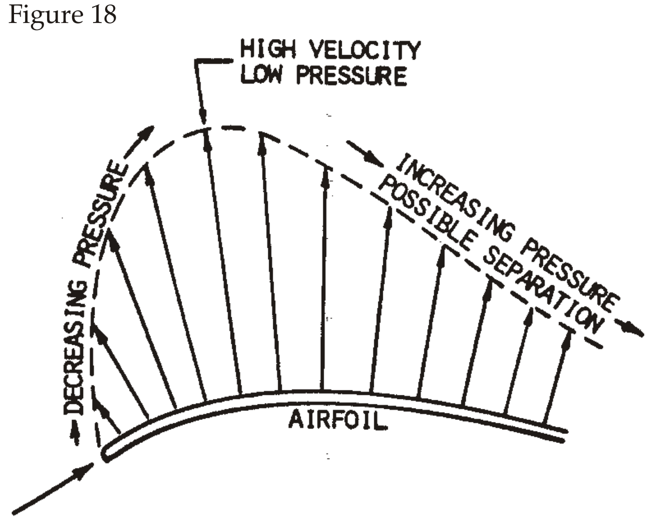
Figure 17. The flow separation phenomena are very important to the sailor. Few sailors, however, understand what causes separation. The current belief in the "venturi" slot effect is evidence of this. The photo at the right shows an airfoil in the fully separated stalled condition. Because of the stall, the airfoil has less lift and more drag. This photo was taken using a water channel (a fancier version of our bathtub). The camera moved with the airfoil and a long exposure was used to record the streaks made by the aluminum powder on the surface.

Figure 17



Figured 18. Flow separation is a viscous effect. It occurs when the boundary layer is no longer able to stay attached to the surface. The ability of the boundary layer to stay attached to the surface depends upon the local flow conditions and what has happened to the boundary layer previously. When the flow is accelerating along the surface, the pressure is decreasing. The boundary layer likes this kind of flow (it's like running downhill). When the flow speed is decreasing, the pressure goes up. This is called an adverse pressure gradient (the boundary layer is flowing against the increase in pressure). When the increase in pressure is too great, the flow will separate and become rather chaotic and unsteady.

Figure 18



6. The Leading Edge Separation Bubble

Figure 19. Several years ago while doing some research on rather thin wings for a fighter airplane, I was faced with what is known as the leading edge separation bubble phenomenon. As the airfoil angle of attack was increased, the flow separated right at the leading edge, but then soon reattached to the upper wing surface. As the angle of attack was increased more the separation bubble grew in length. Finally, when the flow could no longer reattach, the separation bubble would burst and spread over the whole airfoil causing a complete stall. It suddenly dawned on me that this same thing must happen on the luff of a jib. That weekend I taped 500 small telltales on my jib to check this out (we call them tufts in the aerodynamics business).

Figure 19

Figure 20. Just as the theory predicted, I found a small separation bubble all along the luff when the boat was sailed slightly off the wind. Sailing farther off the wind caused the bubble to be wider. Finally, the bubble would burst and the entire sail would be stalled. I searched the sailing literature but could not find any references to the leading edge separation bubble phenomenon. The leading edge bubble is discussed in more detail in my *SAIL* Magazine articles (see pages 97 and 254 of reference 8) and at great length in Marchaj's new book (14).

Figure 20

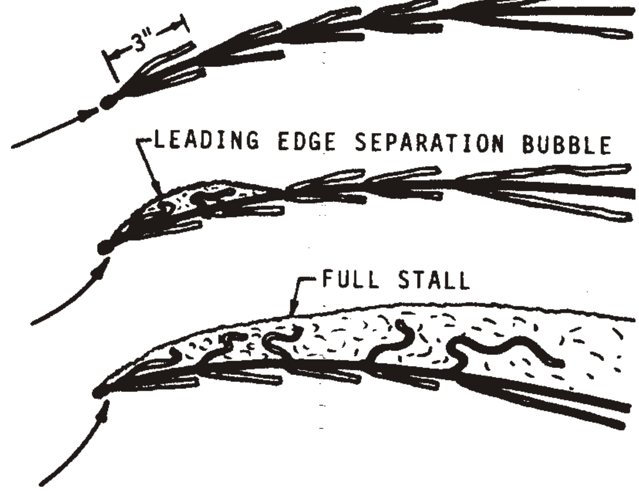
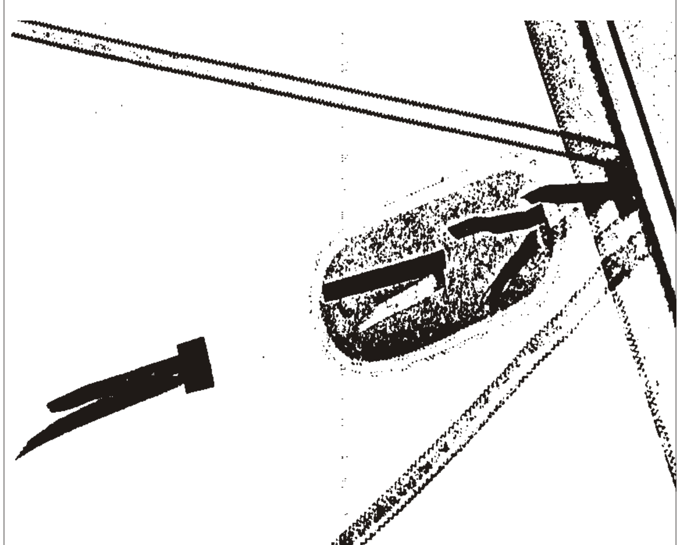


Figure 21. Most sailors use a yarn telltale located about 12 to 18 inches from the luff on the jib to tell when the sail stalls. However, this only tells you when the sail is stalled. You have already goofed, and gotten too far off the wind. But what if you put a series of very short tufts starting right at the luff and continuing to where you would normally put the standard long yarn telltale? I tried this idea and it turned out to be a tremendous help in keeping the boat at the best angle to the wind for windward sailing. Not only could you tell where you were between the luffing and the stalling condition, but you could also tell how rapidly you were changing from one condition to another. If you need more drive to regain lost speed, you simply bear off slightly so the first two or three tufts twirl, until the speed is back up. I found that even the beginning sailor could be quickly taught to sail to windward reasonably well with this new tuft system.

Figure 21



7. Characteristics of the Single Airfoil

Figure 22. The figure at the right shows the flow streamlines about a sail that has been adjusted so that the stagnation streamline, S, flows directly into the leading edge. Note that at the left side of this drawing the streamlines are angled up slightly (upwash). You have to be several airfoil lengths upstream, or downstream before the airflow is at the freestream undisturbed condition. In fact, a careful examination of the complete flow field would indicate that the level of the stagnation streamline far downstream of the airfoil is exactly the same as it was far upstream. These streamlines were calculated by a computer program with boundary layer thickness and separation effects turned off. With modern computer programs we are able to turn off the viscous effects (but still maintain the realistic flow condition at the trailing edge, the Kutta condition). With this kind of trickery provided by the program we are able to isolate and study the various factors that influence the flow.

Figure 22

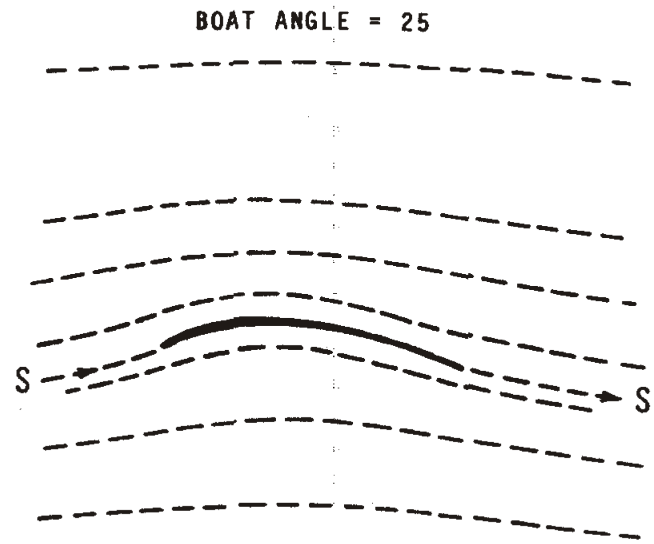


Figure 23. This figure shows the same sail at a broader sailing angle (35 degrees). Again, the program did not include boundary layer or separation effects. With the higher angle, more air passes to the upper (or lee) side of the airfoil. We see this because the stagnation streamline, S, starts and ends at a much lower level than it did in figure 20. The airfoil is able to generate more lift. Note, however, that the stagnation streamline hits the airfoil on the lower (windward) side near the leading edge. This will cause some problems when we consider the viscous effects.

Figure 23

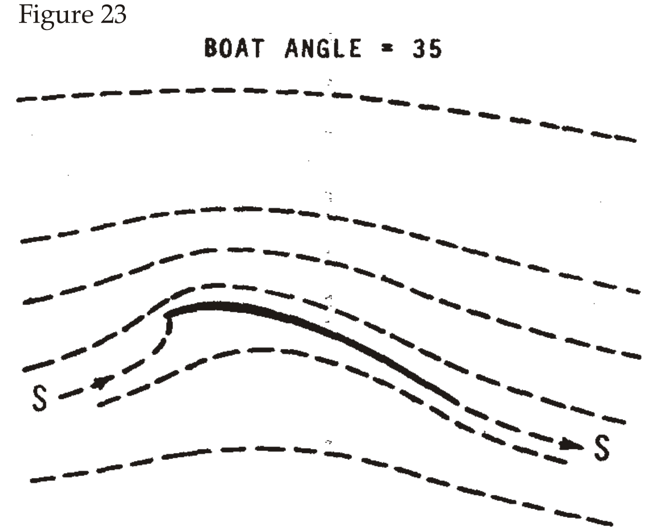


Figure 24. The calculated pressure distribution around the sail for the 25 degree boat angle condition is shown in this figure. The arrows pointing away from the upper surface represent pressures lower than atmospheric pressure ("suction" pressures). Long "suction" arrows also represent higher velocities in the flow. The arrows pointing toward the lower surface represent pressures that are higher than atmospheric pressure, and the slowest velocities. It is this pressure difference on the two sides of the sail that give us lift. We have the highest velocities on the sail where the upper suction arrows are the longest. The velocities are the lowest where the lower arrows pointing at the airfoil are the longest.

Figure 24

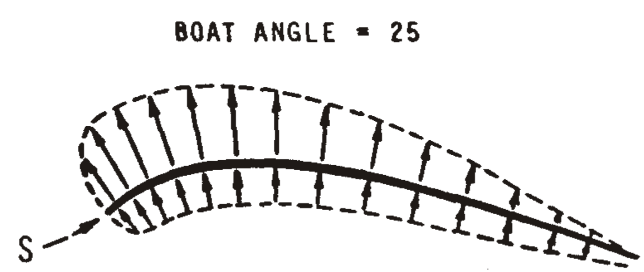


Figure 25. The pressures around the sail at the 35 degree sailing condition are shown in this figure. Note the very long (high suction, high velocity) arrows on the lee or upper side of the sail near the leading edge. The velocities are high here because the stagnation streamline is slightly around on the windward side of the airfoil. The air accelerates very rapidly as it goes around the leading edge from the lower side. The velocity then decreases as it approaches the trailing edge. The pressures are the lowest right near the leading edge and then increase as the flow approaches the trailing edge and slows down. The rapid increase in pressure near the leading edge will probably cause separation along the luff. If the increase in pressure is not too rapid near the leading edge, only a small separation bubble will form with the flow reattaching and continuing on. If the angle is too wide and the pressure increase too rapid, the entire leeside flow will separate and the sail will be in the stalled condition.

Figure 25

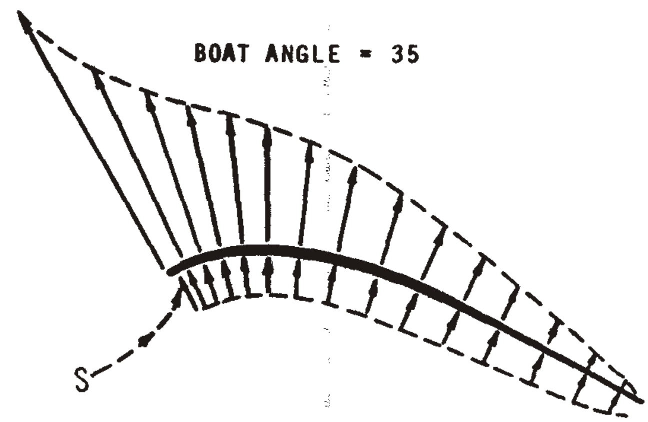
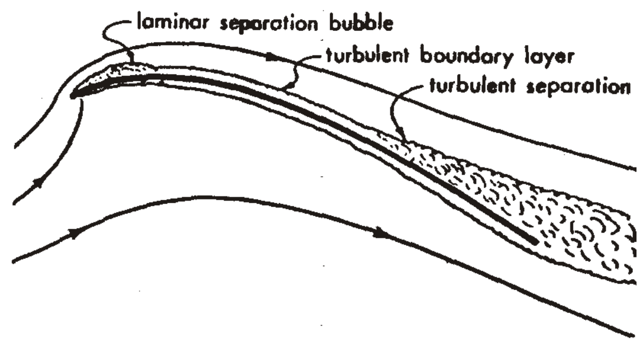


Figure 26. Separation can also occur at the trailing edge of an airfoil if the pressure increase is too great here. This will happen if the leech is hooked to windward or if there is just too much camber in the sail for the wind conditions. As we will see later, the jib has a strong effect on the separation characteristics of the mainsail and although it is not realized by many, the mainsail also influences the separation on the jib.

Figure 26



8. Sail Interaction -- Old Theories

Figure 27. The interaction between the jib and mainsail (the slot effect) is probably one of the most misunderstood aspects of sailing theory. Stephen Colgate's explanation for the slot effect (15) is typical of what appears in most of the sailing literature. “The jib funnels the air behind the main. The funneling action tends to increase the speed of the air flowing past the leeward side of the main.” The drawings, such as that shown at the right, seem to substantiate this theory. The jib does produce a flow header on the main, but the effect of this on the mainsail velocities is exactly opposite from this popular myth. In fact, if the primary effect of the jib was to increase the velocities on the lee side of the main, the effect would be to increase the possibilities of separation on the mainsail, instead of decrease it as we know happens in practice.

Figure 27

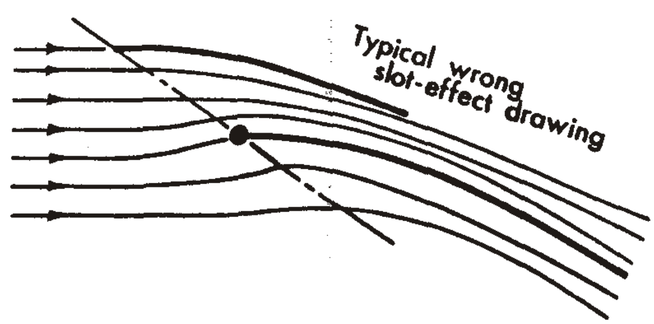


Figure 28. If the jib did cause a high speed jet of air on the lee side of the main, what would happen? First, the airflow off of the leech of a single sail is very near the freestream velocity well out in front of the sail. This means that the pressure near the leech is near the atmospheric pressure. If the jib caused higher speed flow near the leading edge of the mainsail, we would have lower pressures there also. If the pressures on the forward lee side of the mainsail are lower, then there must be a more rapid increase in pressure as the flow approaches the trailing edge. The flow would, therefore, be more prone to separation. Also, higher speed flow in the slot might help the main, but it would certainly harm the jib since the pressure would also be acting on the windward side of the jib.

Figure 28

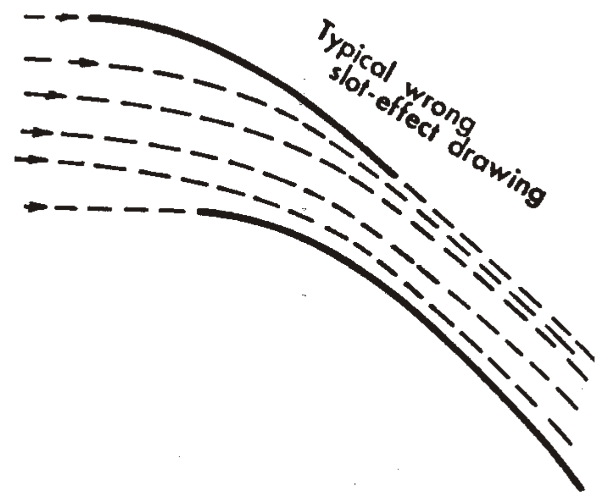


Figure 29. A sail, being a flexible surface, reacts directly to the air pressures around it. When the pressure is higher on the windward side than it is on the lee side, the sail will take the familiar cambered shape and exert a useful force on the boat. When the pressures are the same on both sides of the sail, the sail will shake. If the jib creates a higher airspeed on the lee side of the mainsail, then why does the mainsail shake along the luff when the jib is sheeted a bit too tight? If the smaller slot caused higher speed and therefore lower pressures on the mainsail, then the mainsail should have even higher pressure differences between the two sides of the sail, and it couldn't possibly shake. Only if the jib created lower velocities instead of higher, and higher pressures closer to the windward side values, could the mainsail react as we all know it does when we oversheet the jib.

Figure 29

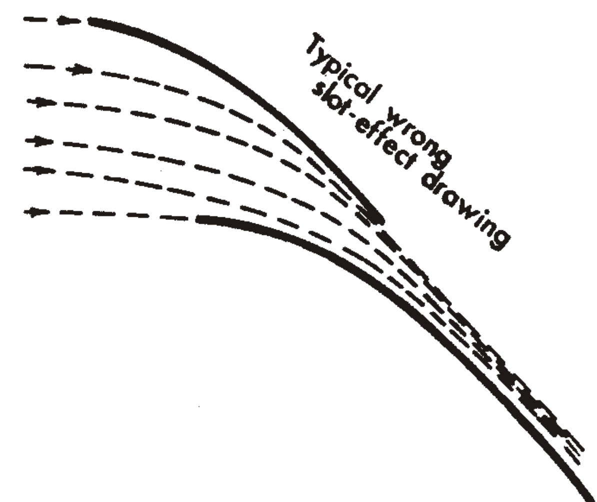
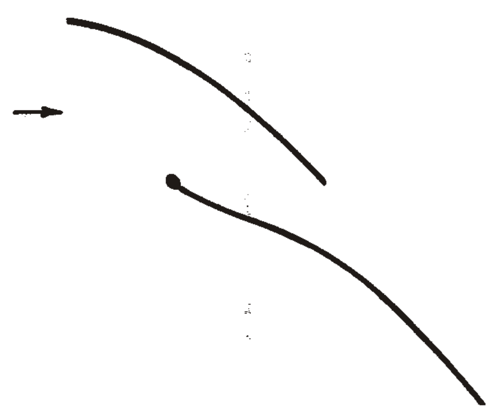


Figure 30. The figure at the right shows an effect that we often see on some boats. The trim of the two sails is such that the mainsail actually has a reverse camber in the luff area. Often, the "bubble" in the mainsail is quite stable. In this situation, the pressures over a portion of the lee side of the mainsail are actually higher than the pressures on the windward side of the sail. The old slot effect theory cannot explain this situation. We should by now begin to realize that the jib must actually cause the velocities on the lee side of the mainsail to be lower, instead of higher. We will now see why this is the case.

Figure 30



9. Sail Interaction -- Modern Theories

Figure 31

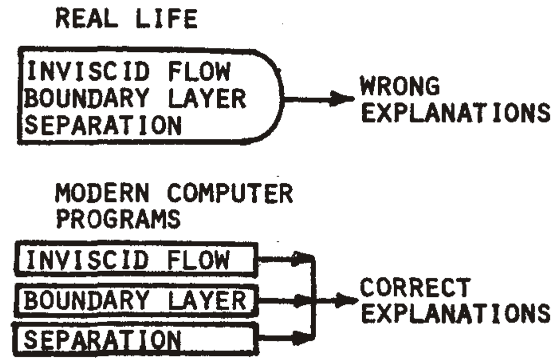


Figure 31. One of the main reasons why the slot effect has been misunderstood for so long is that we are unable to separate the various aspects of the flow while we are actually sailing. With modern computer programs we are able to separate each of the effects and to study them in a systematic manner. This allows us to understand the basic physics of the flow. Later, we can study how the boundary layer reacts to the various pressure distributions. These computational experiments tell us for sure that the old slot effect theories are wrong.

Figure 32

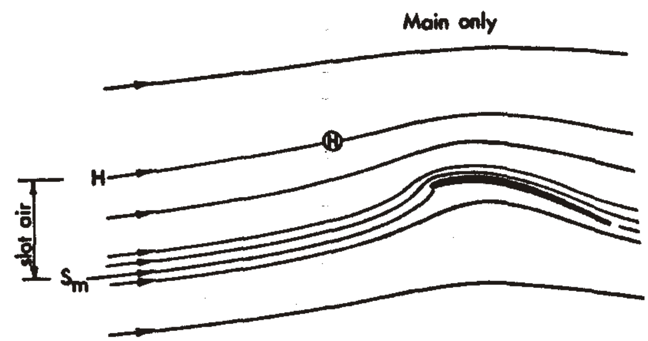


Figure 32. The figure at the right shows the streamlines about a mainsail alone. The stagnation streamline that divides the flow that goes on each side of the sail is marked as S_m. The streamline that passes through the headstay is marked with an H. The H with the circle around it indicates the headstay itself, and this is where we will later position the leading edge of the jib. The air that passes between the mast and the headstay is indicated as the "slot air" at the left side of the figure. Note that the stagnation streamline hits the mainsail on its windward surface. This means that there will be very high velocities, and low pressures, on the forward lee side of the mainsail. The pressure will then rapidly increase along the lee side of the mainsail. If viscous effects were present, the sail would stall.

Figure 33

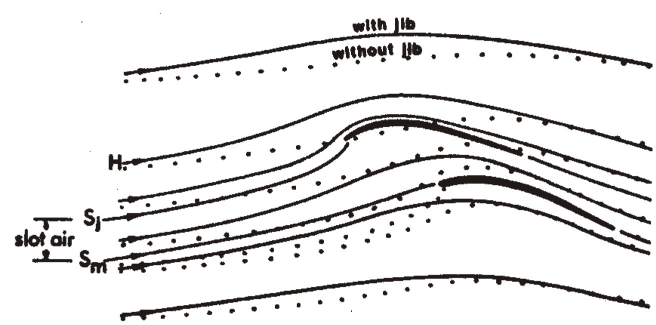


Figure 33. In this figure the jib is included. The solid streamlines are for the flow with the jib present. The dotted streamlines are for the mainsail only. The streamline that went through the headstay in Figure 32, H, now goes well to the lee side of the jib. The line that divides the flow passing on the two sides of the jib, Sj, we call the jib stagnation streamline. The stagnation streamline for the mainsail, S_m, has been shifted (headed) by the jib. The slot air is marked at the left side of the diagram. The amount of air passing between the headstay and the leading edge of the mainsail is now much less than was the case with the mainsail alone. We can see this because the width of the "slot air" stream tube marked in this figure is much smaller than that in Figure 32. Much of the "slot air" in Figure 32 with the mainsail alone now passes to the lee side of the jib.

Figure 34. The effect of various sail angles is shown in the four separate drawings at the right. The number at the left indicates the changes in the amount of slot air. In case B, with the jib sheeted in 5 degrees tighter, the amount of slot air is reduced by 60 percent. Look at the position of the mainsail stagnation streamline in case B. It hits the main on its lee side. Since we have taken most of the slot air and caused it to flow on the lee side of the jib, we do not have much left for the slot. Because this small amount of air must spread out to fill the region between the jib and the main, it will have to slow down (Bernoulli's principle again). The pressure in this region will be high. In fact it will probably be higher than the pressure on the windward side of the main. If our sail was flexible, it would adjust its shape (carry a stable bubble), or certainly shake in what we have always called backwinding.

In case C with both the jib and mainsail sheeted in 5 degrees, the slot air is reduce by 30 percent. The stagnation streamline for the jib now hits the jib well around on its windward side. This means that there will be very high velocities as the air negotiates the sharp turn around the leading edge of the jib. The jib would probably immediately stall. To prevent this we would either have to let the jib out some, or as we usually do, head the boat closer to the wind so that the jib stagnation streamline again comes in at the luff wire.

In case D, with the jib at its basic position and the main sheeted in 5 degrees, the flow in the slot is 20 percent more than the basic setting. The stagnation streamline for the main has shifted slightly around toward the windward side. The lee side velocities on the forward part of the mainsail would increase, and the pressure would go down. The flow on the lee side might separate at the mast. To avoid this we would have to sheet the jib in tighter to kill the higher velocities, or head the boat closer to the wind.

From these studies we see that the primary effect of the jib is to reduce the velocities on the lee side of the mainsail. This reduction in velocity will give an increase in pressure, a reduction in the pressure gradient on the sail, and therefore, lessen the possibility of lee side separation.

Figure 34

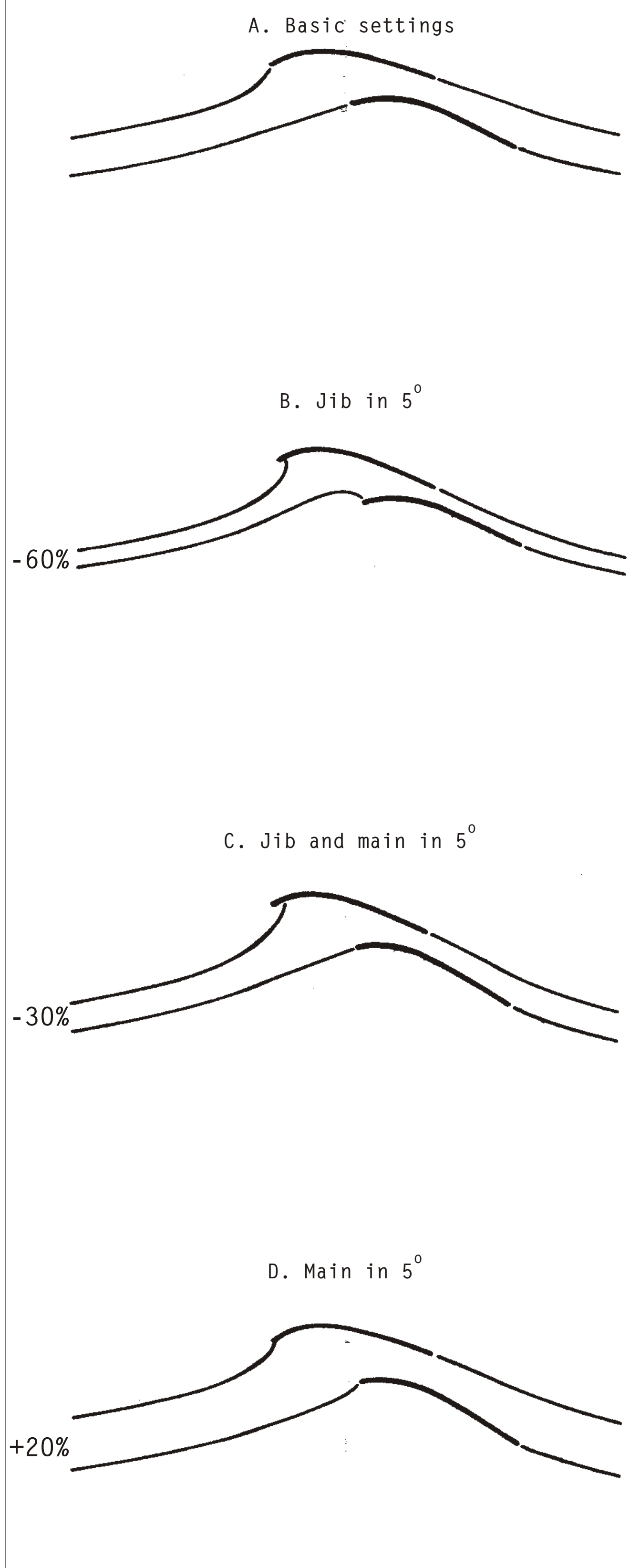


Figure 35. In the bathtub experiment we learned about circulation on a single sail. When we have two sails, we have two circulation fields that must be added together. Note in the figure at the right how the two circulation fields tend to oppose each other in the slot between the jib and the mainsail. This is further evidence that the jib really causes a decrease in the velocities on the lee side of the mainsail. The two circulation fields also add together to cause more upwash out in front of the sails, and give our boats better pointing ability.

Figure 35

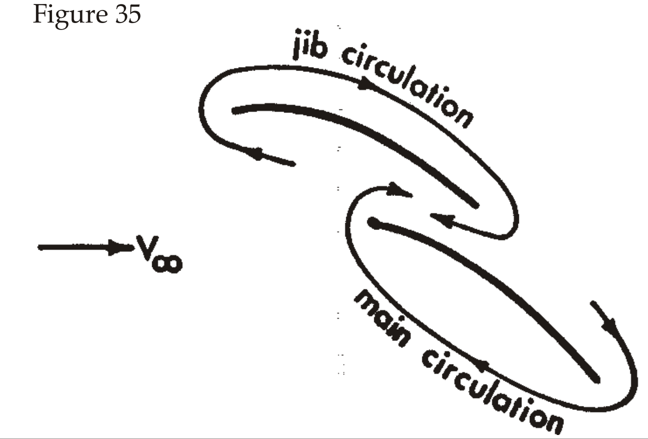


Figure 36. One primary effect remains to be investigated, and that is the effect of the mainsail on the jib. We all know what a powerful sail the jib is relative to the mainsail. This is sometimes blamed on the separation from the mast, but this is not the whole story. We have already seen how the mainsail can cause an increase in the upwash at the leading edge of the jib.

One effect not covered previously is the fact that the trailing edge of the jib is located in a high speed region of flow created by the mainsail. I have mentioned that the airflow at the trailing edge of the mainsail must return to conditions near the freestream conditions. This is not the case with the jib. The airflow at the trailing edge of the jib only has to return to the speed of the air present on the lee side of the mainsail.

Figure 36

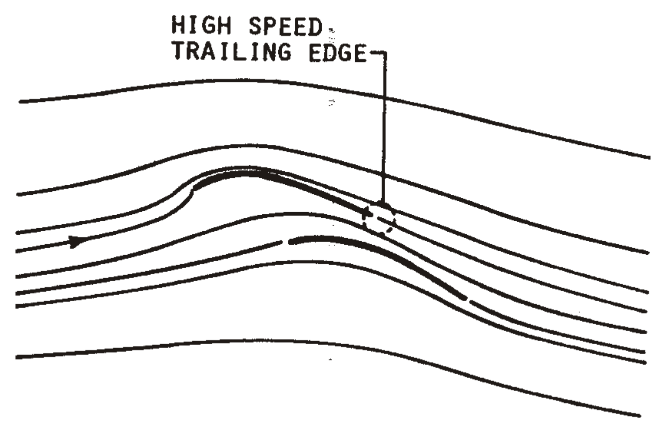
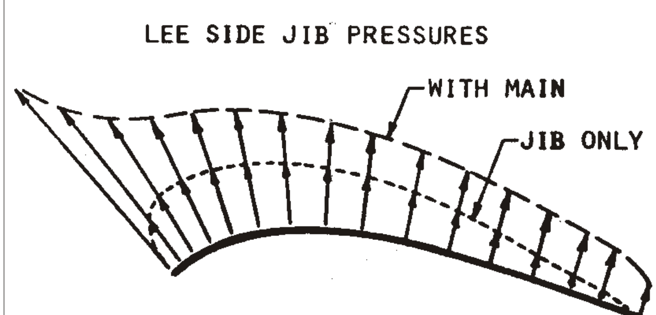


Figure 37. The single sail has a circulation field that, when added together with the non-lifting field, satisfies the condition for smooth flow off of the trailing edge. When two sails are present we have two circulation fields that add together to create the total flow picture. We have seen how the mainsail causes more air to flow on the lee side of the jib. These higher velocities to lee of the jib, plus the fact that the jib trailing edge flow returns to a higher velocity than the mainsail, means that the jib will have a much higher pressure difference across the fabric and higher lift. The higher trailing edge velocities on the jib also mean that there is less possibility of flow separation on the jib. All of this can be turned into more forward drive, or to better pointing ability.

Figure 37



10. Summary of Sail Interaction

Although they are for the most part interdependent, the major jib-mainsail interaction effects will now be segregated into the effect of the jib on the mainsail, and the effect of the mainsail on the jib.

10.1 Effects of the Jib on Mainsail

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 lee side 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. With the jib present, 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. The two circulation fields are in the same direction out in front of the sails and on the lee side of the jib. This forces more air to flow over the lee side of the jib.
6. As the jib is sheeted closer to the main, there is a continuing decrease in suction pressure on the lee side of the main (exactly the opposite of the popular venturi myth). When the pressures on the windward and leeward side of the mainsail are equal, there is no longer the pressure difference across the sail fabric to maintain the airfoil shape, and the sail begins to luff.

10.2 Effects of the Mainsail on the Jib

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 high-speed 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 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 affects 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.

11. CONCLUSIONS

The lift generation for a sail is shown to be caused by the combination of two flow fields. One is the flow that would be present if the air had no viscosity. The other is a circulation field about the airfoil. This circulation field is an indirect result of the fact that air has viscosity. The initiation of the circulation flow field occurs simultaneously with the formation of a starting vortex off of the trailing edge. The old theories that rely on impact theory, density changes in the air, or the different distances on the two sides of the airfoil are all wrong.

The interaction between the two sails is much more complicated than the old theories imply. The flow about the jib and mainsail are a result of two circulation fields which add together. These two circulations oppose each other in the slot between the jib and mainsail. The primary effect of the jib is to slow down the flow on the lee side of the mainsail, reduce the pressure gradients and, therefore, prevent separation on the mainsail. If the effect of the flow was to speed up the air, as the old venturi theory states, it would increase the possibility of separation, rather than decrease it. The old venturi explanation for the slot effect is completely wrong.

These modern theories have proven useful in developing aids for sailing to windward (the mini-tufts). The sail interaction ideas should help to understand the requirements in achieving optimum sail trim to windward. The sail interaction concepts should also be useful in selecting and setting staysails to help the flow around the mainsail. The proper understanding of the sail interaction played a large part in the author's research that led to an improved mast section shape that was used on the America's Cup boats ***Courageous***, ***Enterprise***, and ***Freedom*** (18 & 19).

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BIOGRAPHY

Arvel Gentry is presently a research supervisor in the Aerodynamics Research Department at the Boeing Commercial Airplane Company. He has raced his own boats very successfully (primarily in Southern California), and has extensive crewing experience on larger ocean racing yachts. He has authored numerous magazine articles on sailing aerodynamics and sailboat performance. He has conducted research efforts in support of America's Cup projects, and designed the mast section shape used on ***Courageous*** and ***Freedom***. He has also developed specialized sailboat performance recording equipment and served as a sailing performance test engineer on Jim Kilroy's ***Kialoa*** maxi-boats.