The Aerodynamics of Sail Interaction

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Proceedings of the Third AIAA Symposium on the Aero/Hydronautics of Sailing
November 20, 1971
Redondo Beach, California

Abstract

This paper deals with the basic problem of the interaction between a mainsail and the jib. Since this paper is written for the sailor rather than the aerodynamicist, all aerodynamic terms and concepts are developed and explained as they are needed. The characteristics of the flow about the jib and mainsail airfoils when they are each used alone and when they are used together are discussed and illustrated. Results from these flow field studies give a very complete and accurate description of the jib-mainsail interaction problem.

1. Introduction

The general subject of the interaction of sails, both on the same boat and on boats sailing near each other, has been of interest to competitive sailors for sometime. The sailing literature abounds with attempts to explain just what is involved in the interaction between two sails. Such terms as slot-effect, Bernoulli's equation, the venturi effect, mast effect, and even safe leeward position appear frequently in what are apparently very rational explanations of this very basic sailing problem. However, the explanations are usually different in many respects and as a result, this general problem has been the subject of much argument and discussion over the years.

As an aerodynamicist by profession and a weekend sailor (by preference), I have been interested, amazed and amused by this situation. After talking to a number of sailors and reviewing both the sailing and aerodynamic literature, I realized that there were several reasons why arguments on this subject had persisted for so long.

First, some of the difficulties of the sailor in understanding this problem stem from some completely false and misleading ideas published in standard sailing references. Second, the explanations given in the literature were based on educated guesswork and practical experience and only a very limited amount of actual theoretical calculations or measurements, not from detailed test measurements or valid and accurate theoretical calculations. And third, attempts by aerodynamicists to properly explain the problem have not reached the sailor because of the technical language used and also because the aerodynamicist's descriptions were not always completely accurate themselves.

Although it is recognized that a single paper such as this cannot completely erase the years of argument to everyone's satisfaction, the most important effects that are brought about when two airfoils are used close together are illustrated and discussed. Important aerodynamic terms and concepts will be introduced and explained as they are needed. The results shown in this paper were obtained with the aid of some of the same techniques and tools used by the aerodynamicist in the design of modern jet aircraft. Any educated guesswork will be avoided or, at the least, clearly identified as such. Since this paper is written for the sailor, not the engineer, it will not dwell on the mathematical details of the aerodynamic theories used (this type of information is well-covered in the referenced aerodynamic literature).

2. Important Definitions and Concepts

A number of important terms and concepts should be clearly understood by the non-aerodynamicist before the main body of this paper is approached. A step-by-step development of this fundamental aerodynamic knowledge is necessary before the reader can appreciate the significance of the basic arguments and explanations to be presented later.

2.1 Division of Flow Regions

When the aerodynamicist studies the airflow about a shape, he recognizes that the flow can usually be divided into two basic types of flow areas, the external flow region, and the boundary layer region. These two flow regions are illustrated in Figure 1.

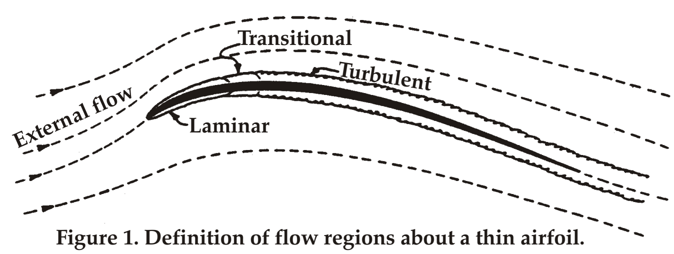

Figure 1. Definition of flow regions about a thin airfoil.

The boundary layer flow region is that layer of air that lies very close to the airfoil. The thickness of this layer of air is greatly exaggerated in the Figure 1 for clarity. Air has viscosity (even though it is very small when compared with other substances), and it is in the boundary layer that the viscous characteristics of air come into play. Because of this viscosity, the air that touches the airfoil is actually carried along by the airfoil (the air has zero speed with respect to the surface of the airfoil). The air just a small distance from the airfoil moves with some finite velocity with respect to the airfoil. The air at the edge of the boundary layer moves with the speed of the external air at that point on the airfoil. The remainder of the airflow will be identified as the external flow. The viscosity of the air does not affect the aerodynamic calculations for this part of the flow. The techniques used by the engineer in calculating what happens to the air in these two types of flow are different.

The boundary layer itself is usually divided into three separate types of flow. Near the leading edge of an airfoil there is a very smooth change of airspeed within the boundary layer from the airfoil surface to the edge of the boundary layer. This is the laminar boundary layer.

Eventually, because of the development of unsteadiness within the boundary layer and because of disturbances introduced into the flow by roughnesses (jib hanks, cloth seams, etc.), the smooth changes in speed within the laminar boundary layer start to give way to a much more erratic type of flow. This is called the transitional region of the boundary layer. After this short transitional region, the boundary layer becomes fully turbulent.

The external flow is not appreciably affected by this so the lift on the airfoil does not change much. The most significant effect is that the skin friction drag is greater in the turbulent area of the flow than it is in the laminar portion. For the portions of the boat that are underwater, great care is usually taken to keep the bottom clean and smooth to delay the transition from laminar flow to turbulent flow as far back on the hull or keel as is possible.

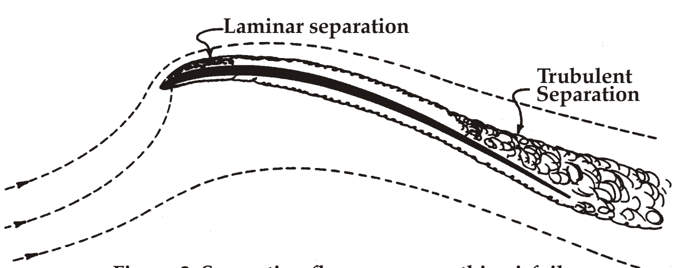

Figure 2. Separation flow areas on a thin airfoil.

Figure 2 shows another part of the airflow about a sail , separated flow. Separated flow regions occur when the boundary layer is no longer able to follow the surface of the airfoil. When this point is reached, the boundary layer separates from the surface and a very confused and mixed up type of flow is formed. (Note that from the aerodynamic standpoint, we refrain from calling this type of flow turbulent, since the word turbulent is reserved for use in describing the turbulent boundary layer. Instead, we will use to the term, "separated flow").

There are two types of separation: laminar separation and turbulent separation. A boundary layer will separate when the external pressure along the surface starts to increase too rapidly. The more rapid the increase in pressure, the more likely it is that the boundary layer will separate. The rate of change of pressure along the surface is called the pressure gradient. When the pressure is increasing, the pressure gradient is called an adverse pressure gradient.

Whether or not the boundary layer separates when subjected to a given adverse pressure gradient depends upon: the character of the boundary layer, laminar or turbulent, what has happened to the boundary layer before reaching the adverse pressure gradient, and what the speed of the airflow is a the edge of the boundary layer. The speed-distance factor is expressed by the aerodynamicist in a term called the Reynolds number.

In general, the laminar boundary layer is more prone to separation than the turbulent boundary layer. In some cases the separated flow will reattach itself to the surface of the airfoil. This is frequently the case for a laminar separation where a small separated bubble may form and the flow reattach as a turbulent boundary layer.

If the flow separates from the airfoil (either a laminar or turbulent separation) and does not reattach, we experience what is defined as a stalled condition. The lift on the airfoil no longer increases with angle of attack but actually reduces. We spot this situation by watching the yarn telltails on the lee side of our jib start to twirl wildly as we bear off from a close-hauled course.

The most important fact to remember from the above discussion is that we need an increase in pressure (an adverse pressure gradient) to cause separation. If the steepness of this gradient is decreased, then the probability of getting separation will be reduced. We will see the importance of this later on when we examine the influence of the jib on the mainsail.

2.2 Potential Flow

The term potential flow is used by the aerodynamicist to describe airflow that is not affected by viscous effects (the boundary layer or by separation). Potential flow theory is a way of solving the external flow when we are able to neglect the boundary layer or separation. Since we always try to shape our airfoils (sails) so as to avoid separation and since the boundary layer is relatively thin, we will find that potential flow solutions have many very useful applications.

By the use of potential flow theory, we will be able to determine completely how the air flows past a single airfoil or around a combination of airfoils such as a mainsail and a jib. Potential flow solutions my be obtained with elaborate and advanced digital computer programs such as in Reference 1, or by the use of the rheoelectric analogy as applied with the analog field plotter. The use of the field plotter will be discussed in more detail later.

2.3 Streamlines

The concept of a streamline is very simple and we need only to look briefly at the example in Figure 3 on the next page to get the basic idea. The streamlines tell the direction of the airflow at different points in the flow field about an airfoil. The airflow between two particular streamlines will always stay between the two streamlines. The stagnation streamline is the streamline that separates the airflow that goes on one side of the airfoil (the top or leeward side) from the airflow that goes on the other side (the bottom or windward side). The stagnation streamline leaving the trailing edge or leech of the airfoil divides the airflow coming off the top of the airfoil from the air coming off the bottom. It is also called a stagnation streamline.

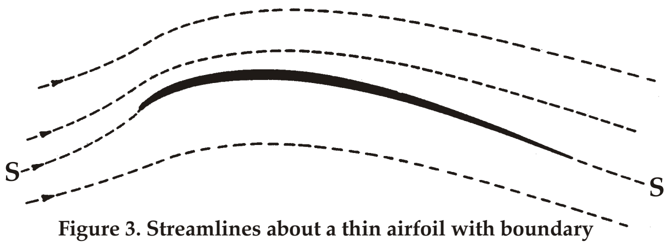

Figure 3. Streamlines about a thin airfoil with boundary layer and separation neglected.

2.4 Effect of Streamline Spacing

Once a complete set of streamlines are determined, we can make some very useful judgments as to how the wind speed and pressure vary in the flow field about the airfoil. It is quite obvious that when two streamlines get very close together, the air will have to speed up to get through the smaller area. Where the streamlines get closer together the air speeds up, and where the streamlines get farther apart, the air slows down. The next question is, what happens to the pressure as the air speed changes? The relationship between speed and pressure is provided by Bernoulli's equation:

$$P + 1/2\,\rho V^2 = H$$

where P = pressure
ρ = density of air (rho)
V^2 = local velocity squared
H = constant within a streamtube

The trade-off of air speed and pressure along a given streamline is governed by Bernoulli's equation and the fact that H, and therefore the sum of pressure P and $\frac{1}{2}\rho V^2$ must remain constant. Now this is all quite simple, but it is important to note that, before we can apply Bernoulli's equation, we must first know how the air flows about the airfoil. We must know where the streamlines go. All too often in the sailing literature, Bernoulli's equation is applied with only guessed streamlines and the conclusions drawn can be grossly wrong.

The aerodynamicist usually converts velocity or pressure into a pressure coefficient as follows:

$$Cp = (P - P_\infty) / (\tfrac{1}{2}\rho V^2) \quad \text{or} \quad Cp = 1 - (V/V_\infty)^2$$

Where Cp = pressure coefficient
P_∞ and V_∞ = conditions well in front of the airfoil

2.5 The Generation of Lift

We will now take a look at just how a sail generates lift. Here too, we find that some of the simple explanations in the sailing literature are wrong. One explanation of how a wing of an airplane gives lift is that as a result of the shape of the airfoil, the air flows faster over the top than it does over the bottom because it has farther to travel. Of course, with our thin-airfoil sails, the distance along the top is the same as along the bottom so this explanation of lift fails.

In the first early attempts by aerodynamicists to come up with a solution to the flow around airfoils, they found that their results were not very realistic. Their solutions met all the requirements of the governing equations, but the calculations indicated that the airfoil had no lift. The types of streamlines that resulted are shown in Figure 4.

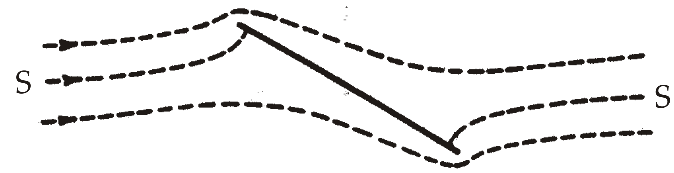

Figure 4. Flow field without circulation (no viscosity).

Note that these mathematically determined streamlines make very sharp turns in getting around the leading edge and trailing edge of the airfoil. For a thin airfoil this means infinite velocities at these points. The velocities around the leading edge can be reduced by bending the airfoil down into the flow (cambering the airfoil) but what about the trailing edge? In real life, we find that the flow around the trailing edge changes as the air first begins to move past the airfoil so that it leaves the airfoil in the same direction on the top and the bottom. This requirement that the airflow leave the airfoil smoothly at the trailing edge and in a direction determined by an imaginary slight extension of the airfoil, is known as the Kutta condition.

It has been found that the Kutta condition can be satisfied mathematically by superimposing another type of flow solution, called circulation, onto that already determined above. The superposition of these two different types of solutions is illustrated in Figure 5.

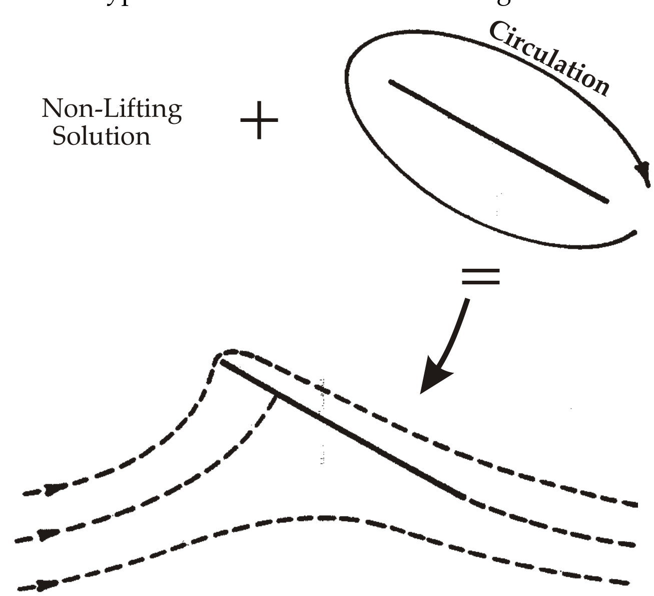

Figure 5. Superposition of circulation and non-circulation solution to give lift.

The strength of the circulation is adjusted so that the Kutta condition at the trailing edge is satisfied. Since the velocities from the circulation solution are smaller than the non-circulation solution, it is easy to see that when the two airflows are added together, the air on the top of the airfoil will be accelerated and that on the lower side will be retarded slightly. With slow speed flow on the bottom of the airfoil and high speed flow on the top, we get high pressure on the bottom and low pressure on the top, and the necessary pressure difference across the sail to maintain the cambered shape and to give the lifting force to drive the boat.

3. The Analog Field Plotter

Before we start examining the flow field results about some typical airfoils, a piece of equipment will be described that is capable of providing direct solutions of the potential flow problem. This equipment is called the "Analog Field Plotter" and uses what is referred to as the rheoelectric analogy. A picture and diagram of the equipment setup are shown in Figures 6 and 7.

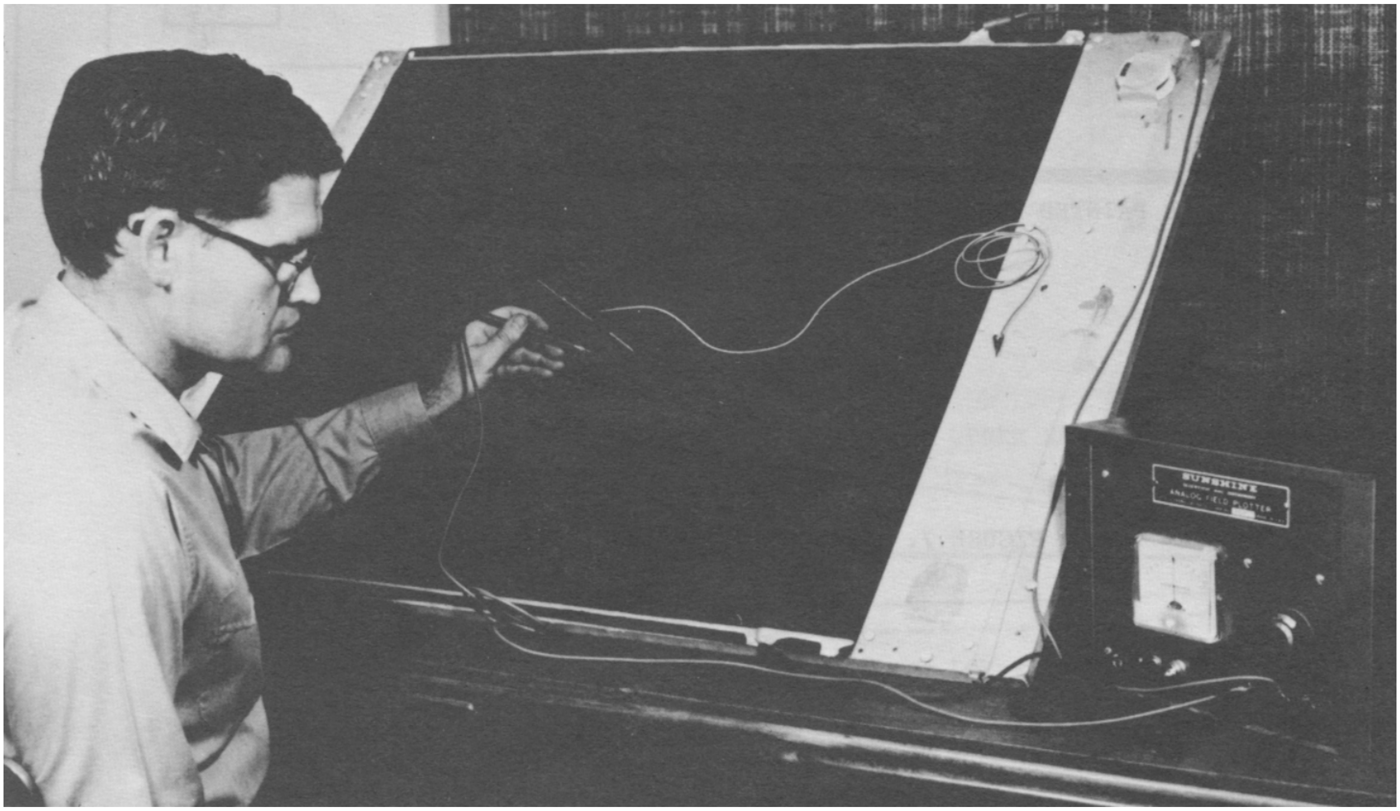

Figure 6. Analog field plotter equipment.

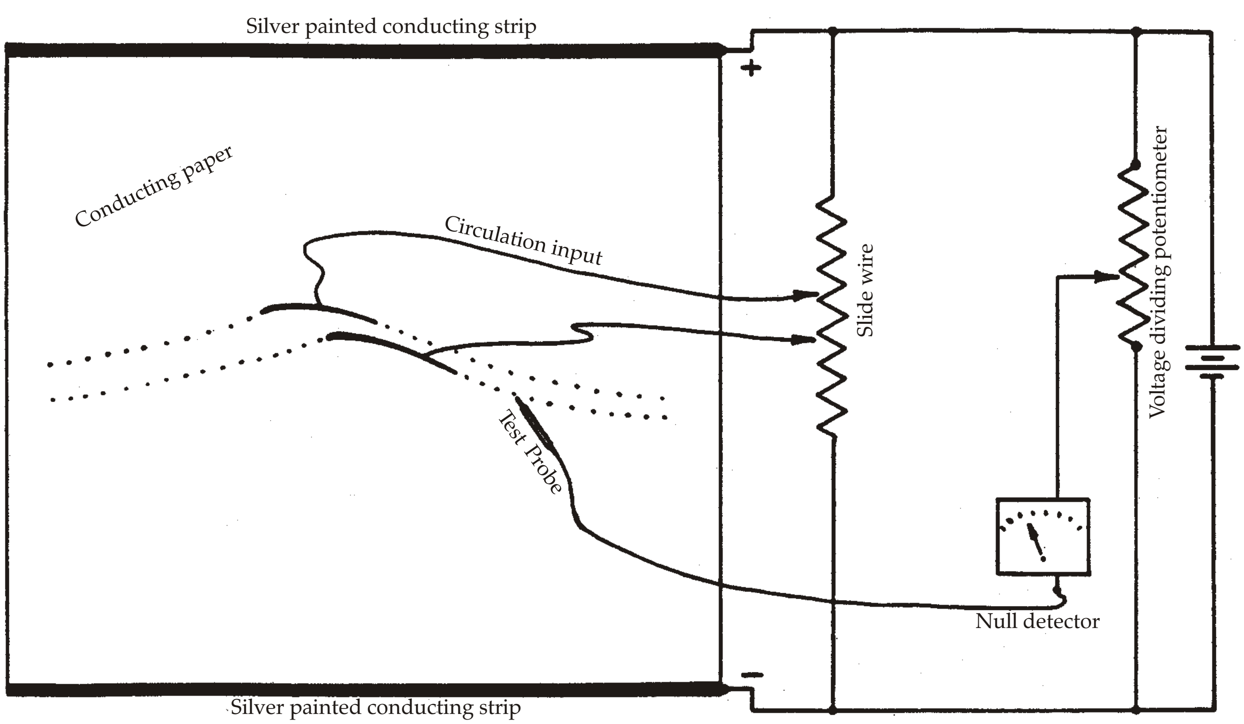

Figure 7. Diagram of analog field plotter.

The flow field recording surface is a special sheet of black conducting paper. An electrically conducting paint is used to paint a conducting strip across the top and bottom of the paper. The electrical control box contains a power supply that is attached to the painted strips across the top and bottom of the paper so that current flows through the paper from one strip to the other. Because of the resistance of the paper, we will get a voltage drop between the two strips. If nothing else is painted on the paper between the two border strips, the voltage across a horizontal line through the center of the paper would be halfway between the voltage at the top and the bottom. The control box contains a sensitive potentiometer, a null-meter and a probe device so that very accurate traces may be made of the lines of constant potential (voltage) within the paper. These lines may be marked with white chalk.

The airfoil shape to be studied is painted in the center of the paper at the proper angle as though the airflow were flowing from left to right across the paper. The presence of this highly conducting painted shape placed at an angle on the paper will cause all of the constant potential lines to be distorted. What we have accomplished at this stage of the equipment hook-up is to construct an exact analog to the flow about an airfoil with zero circulation (see Figure 4). The mathematical equations necessary to solve the airflow about the airfoil are exactly the same as the equations that describe the flow of electricity through the conducting paper.

However, the airfoil still has zero circulation as we have done nothing to assure that the Kutta condition is satisfied at the trailing edge of the airfoil. To do this, we first run a special resistance wire between the top and bottom strips. We then tap off of this with a conducting wire that is attached to the airfoil painted onto the paper. By sliding this tap-point to different spots on the resistance wire we can cause the airfoil to be at any potential (voltage) between the top and bottom strips.

By a trial and error process, we keep adjusting the potential of the painted airfoil and each time trace the shape of the constant potential line that leaves the trailing edge of the airfoil. When we find the right setting that lets the streamline leave the airfoil smoothly at the trailing edge, we will have satisfied the Kutta condition. The mathematical equations that now describe the flow of electricity through the paper are exactly the same as those that are used to describe the airflow about the airfoil with circulation and, therefore, with lift.

Once this situation is achieved in our experimental apparatus we can proceed to use the sensing probe to determine complete pictures of the streamlines about the airfoil. Any number of airfoils may be studied simply by painting them on the paper in the proper relative positions and by attaching a wire to each airfoil so that the Kutta condition on each is satisfied.

The accuracy of the results obtained with the field plotter have been verified by the use of a potential flow digital computer program. The field plotter is also a very useful teaching device.

4. The Single Thin Airfoil

Now that we have the necessary aerodynamic background and the experimental apparatus we will look at the basic aerodynamics of the airfoils that are formed by our sails. The characteristics of the flow about a single airfoil representing a jib will be discussed first. The next section then deals with the flow about two airfoils such as a jib and a mainsail.

The airfoil shapes and relative position and sizes as selected for these studies approximate the airfoil sections on a mainsail and a genoa jib (both taken at the level of the first batten on the main). Of course, the thickness of the airfoils on our sails is virtually zero, while the thickness of the airfoils painted onto the field plotter paper is some finite value (about 1.5 to 3% thick) because of the size of the paintbrush used. This approximation will not significantly affect our answers. The initial discoveries for this study were made with the analog field plotter. The actual results presented here were determined later with a potential flow computer program.

Figure 8 shows the streamline patterns about an airfoil at two different relative wind angles for the boat. In the first case, the angle of the centerline of the boat was 25 degrees from the relative wind. This sail had a sheeting angle of 20.6 degrees from the centerline of the boat, so the airfoil itself had an angle of attack of 4.4 degrees. In the second case the angle of the centerline of the boat from the relative wind was set at 35 degrees. Still using the same sheeting angle, this case had an airfoil angle of attack of 14.4 degrees.

For the 25 degree boat angle case, we see that the stagnation streamline (identified by the letter S) goes smoothly into the leading edge (luff) of the airfoil. Streamline A goes on the top side of the airfoil (the lee

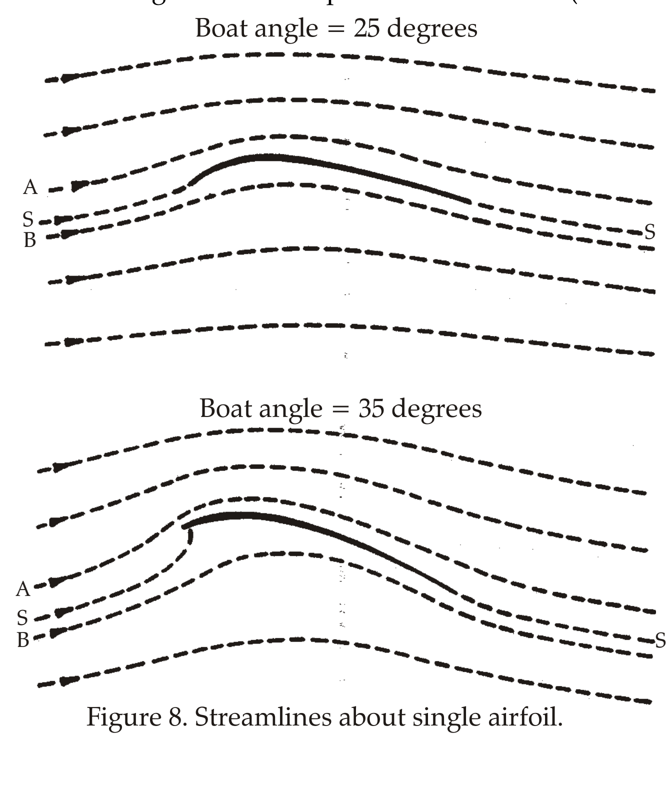

Figure 8. Streamlines about single airfoil.

side), gets close to the airfoil between the leading edge and the maximum camber point, and then moves away from the airfoil as the trailing edge is approached. From our previous discussions concerning velocities and pressures, we can see that the highest local wind speeds and lowest airfoil pressures (suction pressures) will be on the forward part of the sail. Since the stagnation streamline goes smoothly into the airfoil at the leading edge, we would expect to have a smooth increase in suction pressures over the first part of the airfoil.

Streamline B passes on the lower side of the airfoil (the windward side), gets farther from the airfoil surface near the cambered region and returns parallel to the trailing edge stagnation streamline some distance downstream. Since streamline B tends to move away from the airfoil surface, we get a decrease in wind speed and an increase in pressure in this area.

For the 35 degree boat angle case, we have a higher angle of attack of the sail and a significantly different streamline picture. The first thing to note is that the stagnation streamline does not go smoothly into the leading edge but instead actually comes into the airfoil on the lower surface, a little back from the leading edge. Streamline A passes very close to the leading edge and then moves away from the surface as the trailing edge is approached. We would, therefore, expect to see much higher velocities and lower pressures very close to the leading edge than was the case for the 25 degree boat angle condition.

The calculated pressure distributions on the airfoil for the two different boat angles are presented in Figure 9. In this plot we have used the usual aerodynamic convention of reversing the vertical scales so that the pressures lower than freestream are plotted at the top, and the pressures higher than freestream are plotted on the bottom. This allows us the convenience of having the upper surface pressures that are always negative on the top part of the curve and the lower surface pressures that are usually positive on the bottom part of the curve.

The difference between the upper surface and lower surface curves at a given point on the airfoil represent the pressure difference across the sail. Our reasoning concerning the pressures for the two angles is verified in these two plots. Note that the high angle of attack case has a very low pressure (high negative values) near the leading edge that is then followed by a steep increase in pressure. If the boundary layer cannot withstand this rapid pressure increase, the flow will separate, the telltail on the lee-side will twirl wildly in the separated flow and the airfoil will be in a stall condition.

One other key point should be made concerning the pressure distributions for these two cases. Note that the recovery pressures near the trailing edge of both airfoils (at about X=11) are the same. This means that the recovery velocities near the trailing edge are also equal. Calculations give values that are about 14% above the freestream velocity. This fact will become important when we use two airfoils together as will be discussed in the next section.

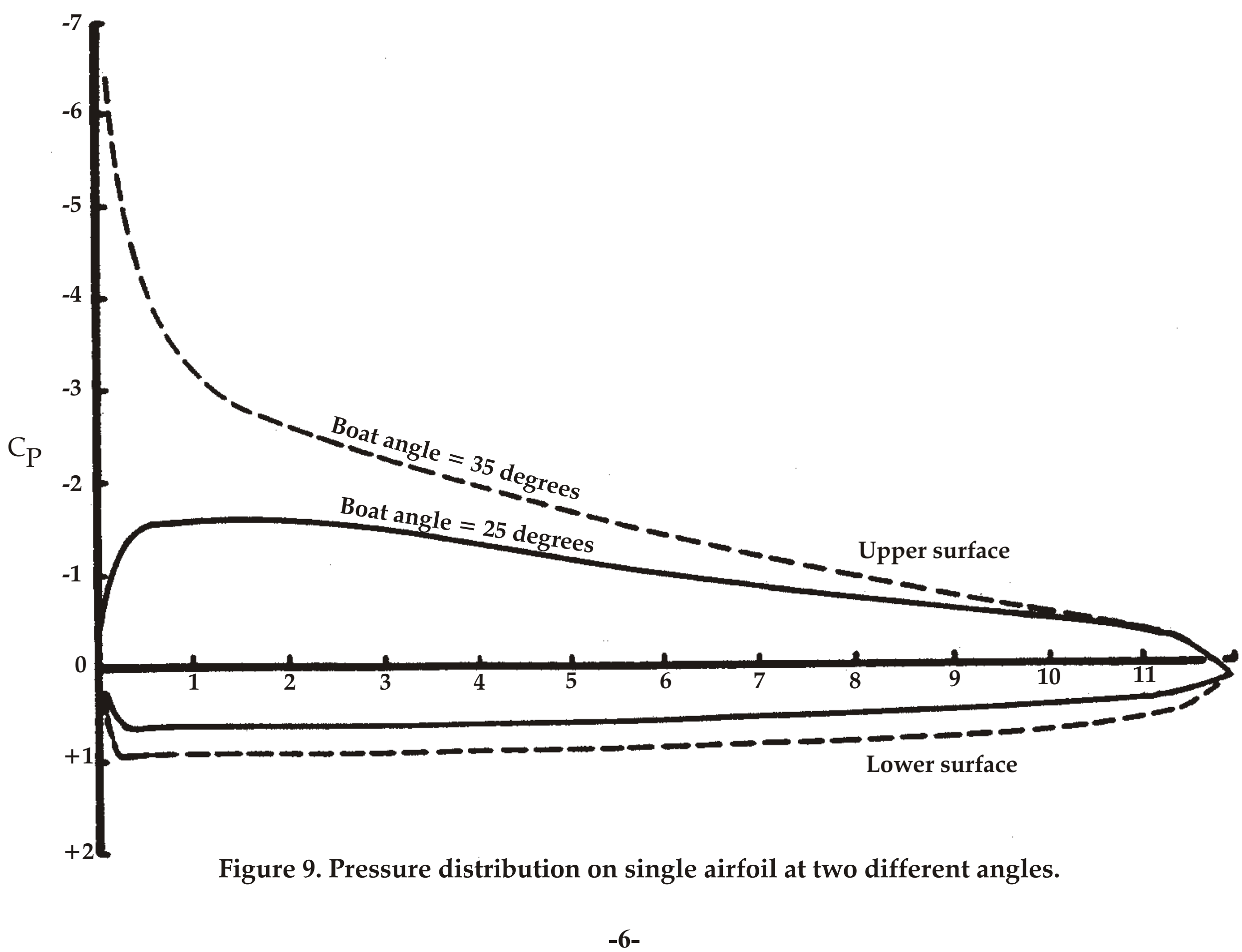

Figure 9. Pressure distribution on single airfoil at two different angles.

5. The Interaction Between Two Airfoils

We will now get down to the purpose of this whole exercise; to examine the interaction between two sails. To do this, we will use a typical airfoil section of our mainsail (at about the height of the first batten) and a matching section through the jib. The airfoil sheeting angles and the angle of the boat to the relative wind have been selected to represent a typical close-hauled sailing condition. The airfoils and angles used for this study are shown in Figure 10.

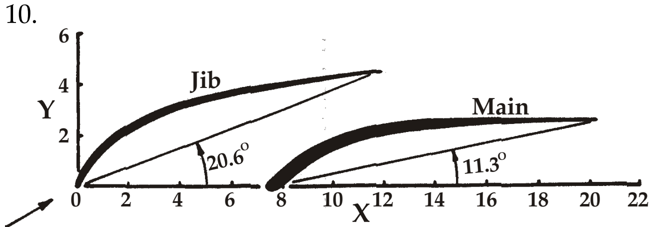

Figure 10. Plot of airfoils used in study.

5.1 Airflow on the Mainsail Alone

We will first look at the flow about the mainsail airfoil without the jib in place. The mainsail will be positioned at the same boat angle that it will have with the jib present, but at this stage in our study the jib is not yet in place. The leading edge of our mainsail (as painted onto the field plotter paper) is determined by the shape of the mast. The area right behind the mast will also be filled in to represent the separated region that always exists immediately behind the mast.

The streamlines for the mainsail alone are shown in Figure 11. Note that the stagnation streamline comes into the lower (windward) side of the sail. The calculated pressure distribution if no separation or stall occurs, is shown in Figure 12. Because the stagnation point is around on the bottom side of the airfoil, we experience a very high suction peak (large negative pressures), a very steep adverse pressure gradient right behind the mast, and a continuing adverse gradient as the flow goes back toward the trailing edge. The boundary layer would not be able to withstand these gradients, the flow would separate and the airfoil would be in a stalled condition. To prevent this stall the sheeting angle of the sail would have to be increased by letting out on the mainsheet or moving the traveler leeward. However, in our example shown in Figures 11 and 12, the mainsail is at the same angle that it would be at if the jib were present. This shows that, without the jib present, the stagnation point will be well around on the windward side of the mainsail. We have steep pressure gradients on the upper surface, and as a result, the flow will separate and the airfoil stall.

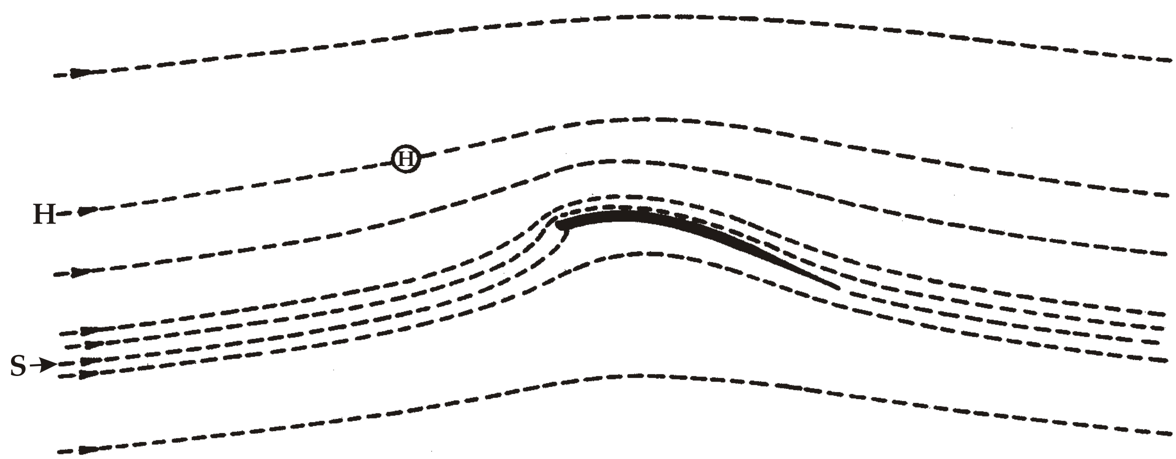

Figure 11. Streamlines about mainsail alone.

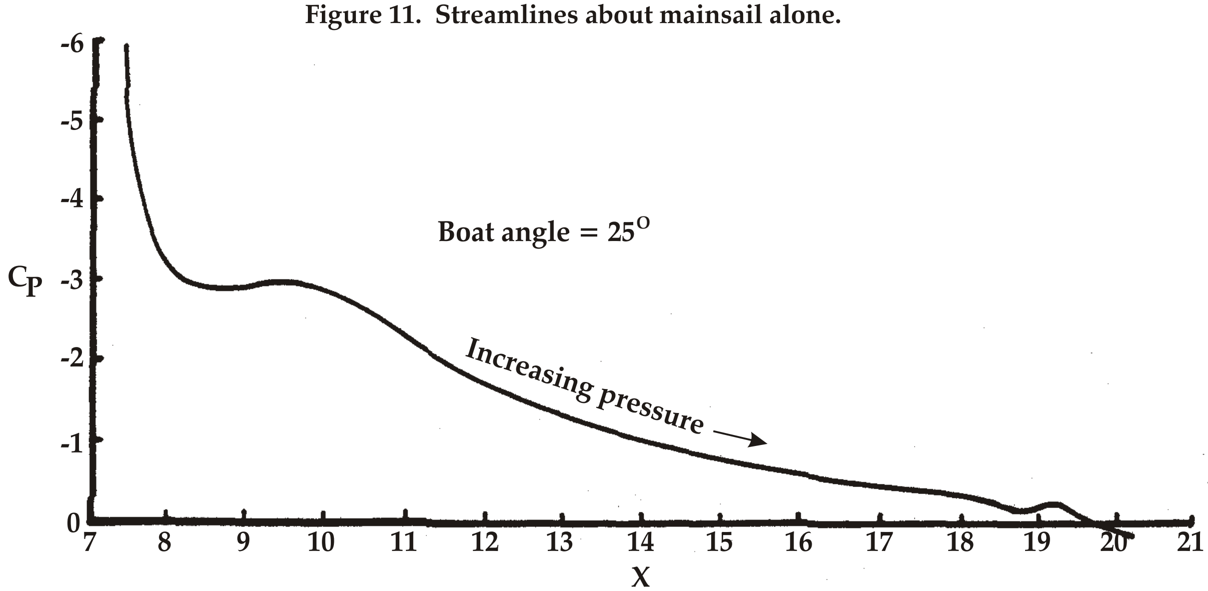

Figure 12. Upper surface pressure distribution about mainsail alone.

It is also important to note the shape and position of streamline H on Figure 11. This line is selected so that it goes through the point H that will be the leading edge of the jib (the headstay) in our next example. The distance between the stagnation streamline S and the headstay streamline H at the left side of Figure 11 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 airfoil.

5.2 Airflow on Jib and Mainsail Combination

We now introduce the jib airfoil into the picture. The streamlines when both the jib and mainsail are used are shown in Figure 13. The dashed lines represent the flow when both the jib and main are used. For comparison purposes, some of the streamlines that existed when the main was used alone are also given (the dotted lines). A number of very important points should be noted on this figure. First, the stagnation streamline for the mainsail now goes smoothly into the mast instead of being down around on the lower surface as was the case for the mainsail alone. Second, streamline H that went through the headstay point when the mainsail was used alone now goes well above the surface of the jib. The stagnation streamline for the jib is now much lower than the headstay streamline H for the mainsail alone case.

The distance between the two stagnation streamlines at the left side of Figure 13 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. We see that much less air goes between the headstay and the mast when both sails are present than was the case when only the main was used. Much more air is being deflected around the top of the headstay (and, therefore, around the lee side of the jib) than was the case for the mainsail alone.

It is interesting to note that the two sets of streamlines cross each other at a position about even with the trailing edge of the jib. This means that the airspeed at these crossing points are about the same for both cases. It is also of interest to compare the streamlines about the jib shown

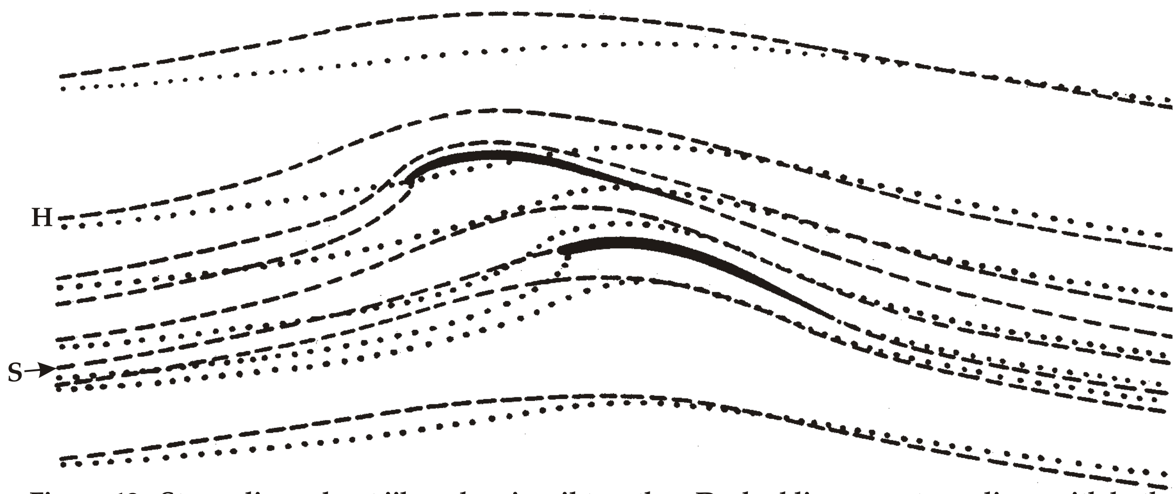

Figure 13. Streamlines about jib and mainsail together. Dashed lines are streamlines with both sails. Dotted lines are when the mainsail was used alone.

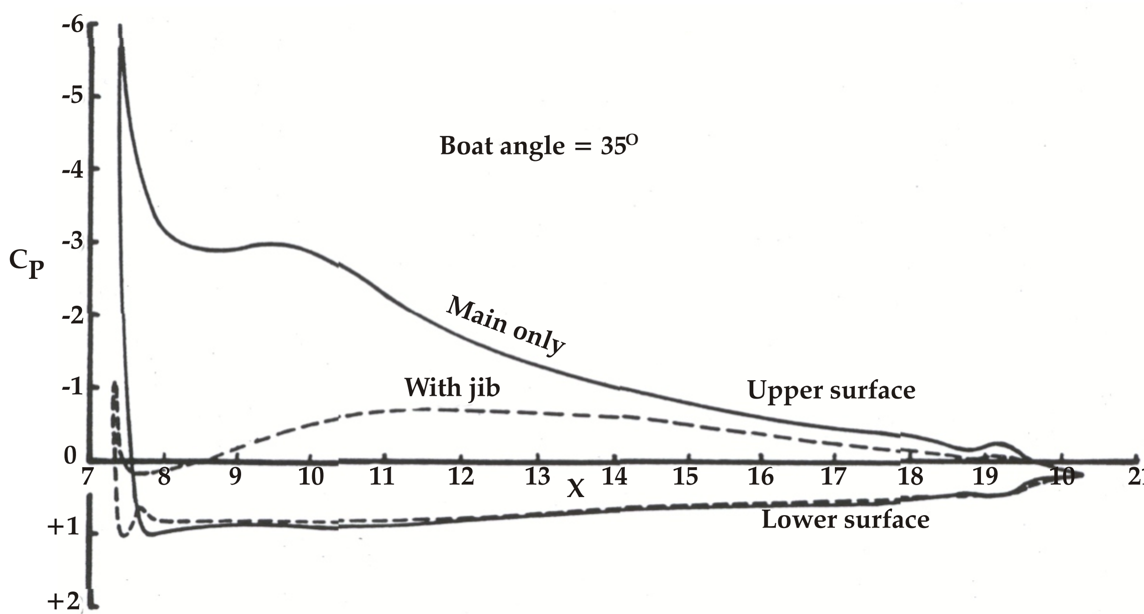

Figure 14. Pressure distribution for mainsail when jib is used. The mainsail in this example could have been trimmed closer to the centerline of the boat to load it up more, but still be able to avoid separation.

in Figure 13 with those on the lee side of Figure 8 where the jib was studied alone. The presence of the mainsail causes a shift in the stagnation streamline so that it goes into the windward side of the jib. This sail combination should, therefore, be pointed a little closer to the wind to avoid stalling the jib.

The calculated pressure distribution for the mainsail (both with and without the jib) are shown in Figure 14. Note that 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 front part of the main. Since the pressure gradients are much lower, the possibility of flow separation on the mainsail is reduced. The amount of theoretical lift being contributed by the mainsail is also reduced. Of course, as was mentioned previously, the mainsail alone case would have experienced separation and would not have been able to actually realize the amount of lift calculated theoretically when neglecting separation. We lose lift from the theoretical non-separated value but we now have reduced pressure gradients so the airfoil will not stall.

All of these findings are very significant since they are the keys to the often discussed phenomena of "slot-flow" between sails. With these accurately determined streamlines, we see that what really happens to the air that passes between the two sails is quite different than the old "venturi effect" presented in much of the sailing literature. 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 on the lee side of the jib. Less air is left to pass in the slot between the sails. This tube of air that goes between the sails actually slows down (the streamlines spread out) as it goes by the front half of the jib. It then begins to speed back up as it approaches the slot between the jib and the mainsail. 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 were used alone (and the flow on the main had not separated). This fact is impossible to demonstrate afloat because the mainsail would be stalled. However, field plotter and theoretical results are able to identify and explain these basic effects.

Another important point is shown in Figure 15. This plot shows the pressure distribution on the jib when it is alone and when both the jib and main are used. The pressures on the jib are much higher (more negative) when both the jib and mainsail are used. The jib develops much more lift when it is operating in a flow field created by the mainsail. To a certain extent we would expect this to happen since the jib is operating in the upwash field of the mainsail (the jib experiences a shift in the oncoming air corresponding to a lift, and the mainsail experiences a header caused by the jib). In the actual situation afloat, we compensate for this by sailing closer to the wind, so this alone does not account for the great efficiency attributed to the jib.

In our discussion of the single thin airfoil, we mentioned that the velocities near the trailing edge were about 14% above the freestream value. In our case now with both the jib and main used, we find that the trailing edge of the jib is in a high speed region of flow created on the lee side of the main. The air coming off of the trailing edge of the jib must be at the same velocity as the surrounding flow. This velocity has been demonstrated as being about the same at the trailing edge point as we measured when the mainsail was used alone. The Kutta condition on the jib must, therefore, be satisfied in a different and much higher velocity region created by the

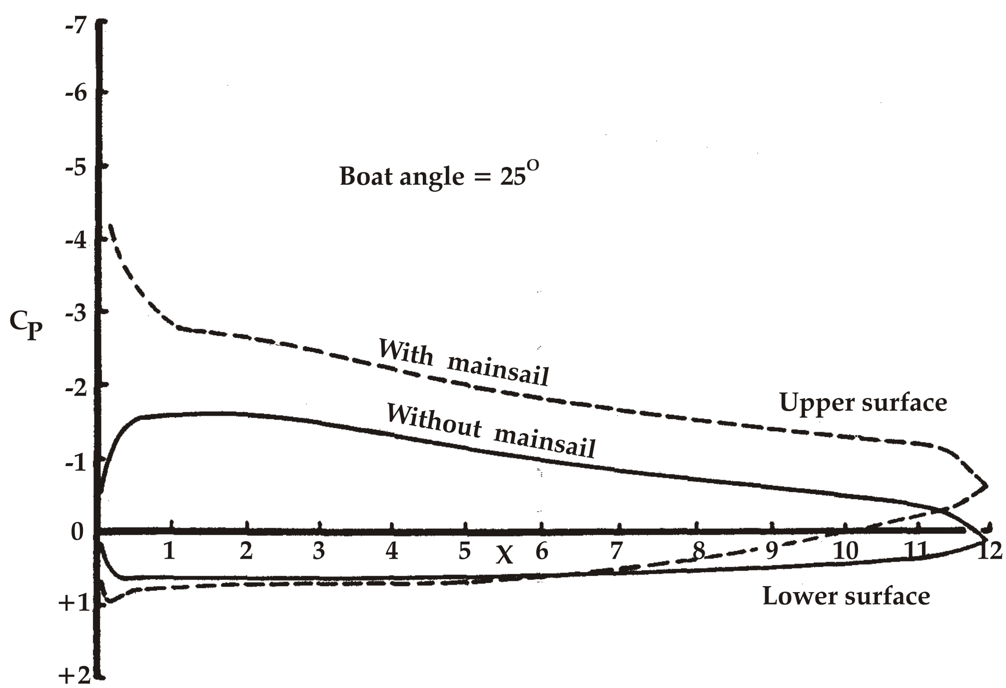

Figure 16. Pressure distribution for jib with and without the main being present.

mainsail. The net result is that the entire velocity distribution on the lee side of the jib has to increase by a corresponding amount so that the jib Kutta condition is accurately satisfied. We, therefore, get a large increase in the driving force of the jib.

The idea and importance of the trailing edge velocity condition as it affects the leading airfoil was first pointed out to me by A.M.O. Smith in his work on slats at the Douglas Aircraft Company. To demonstrate these effects he suggested that the velocity distribution on a leading airfoil (such as a wing slat or a jib on a boat) be normalized by dividing the airfoil dumping velocity (the velocity at about 90-95% of the chord). The resulting normalized velocity distributions should be about the same with and without the main airfoil present if the above theory is true. This fact is verified in Figure 16. For this plot the velocity at X=11 was taken as the dumping velocity (V_D).

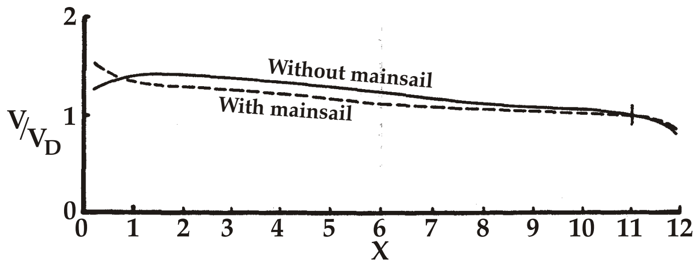

Figure 16. Velocity distribution for jib when normalized by the trailing edge dumping velocity.

6. Summary of Jib-Mainsail Interaction

At this time we have enough information to assemble a very good summary of the major jib-mainsail interaction effects. Although these are, for the most part, interdependent effects, we will classify them for convenience into effects of the jib on the mainsail, and effects of the mainsail on the jib.

6.1 Effect of Jib on the Mainsail

The major effects of the jib on the mainsail are as follows:

1. The jib causes the stagnation point on the mainsail to shift around toward the leading edge of the main (the header effect).
2. As a result of the above, the peak suction velocities on the lee side of the main from the main leading edge to the area of the jib trailing edge are greatly reduced. Since the peak suction velocities are reduced, the recovery adverse pressures are also lower.
3. Because of the reduced pressure gradients on the mainsail, the chances of the boundary layer separating and the airfoil stalling are reduced.
4. The mainsail can be operated efficiently at higher angles of attack without flow separation and stalling than would be the case with the mainsail alone.
5. As the jib is sheeted in at closer angles to the centerline of the boat (or as the mainsail is sheeted farther out) we would get a continuing decrease in the suction pressures on the lee side of the mainsail. When the pressures on the windward and leeward side of the mainsail become equal we no longer have the pressure difference across the sail necessary to maintain the airfoil and the sail begins to luff.
6. Much less air goes between the headstay and the mast when the jib is placed in front of the mainsail. The circulations of the mainsail and the jib tend to oppose and cancel each other in the area between the two sails. More air is, therefore, forced over the top (lee side) of the jib.
7. The mainsail in the example used in this study could have been trimmed closer to the centerline to load it up more.

6.2 Effect of Mainsail on the Jib

The major effects of the mainsail on the jib are as follows:

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. The boat must, therefore, be pointed closer to the wind with both main and jib raised to prevent the jib from stalling.
2. The trailing edge (leech) of the jib is in a high speed region of the flow about the mainsail. The trailing edge velocity on the jib is, therefore, higher than if the jib is used alone.
3. Because of the higher trailing edge velocity, the velocities along the entire lee surface of the jib are greatly increased when both the jib and main are used. This contributes to the high efficiency of the jib as observed by sailors.
4. Because of the above items we would expect that the proper trim and shape of the mainsail can significantly affect the efficiency and amount of driving force obtained from the overlapping job. Anything that would cause a reduction of velocity in the region of the trailing edge of the jib would result in a lower driving force contribution from the jib.
5. The mast in front of the mainsail has always been blamed for causing the main to be less efficient than the jib. From the above studies we have seen that this is only part of the answer. The other, and probably equally important factor, is the increased velocities on the jib because its Kutta condition must be satisfied in a locally high speed flow region created by the mainsail.

7. Flow Field Effects on Other Boats

One last look at the flow field created by a jib-mainsail combination should give us some idea of the wind speed and angles that would be encountered by another boat sailing nearby. The local velocities and flow angles for a number of points about a boat with a jib and mainsail are shown in Figure 17. The freestream speed has been selected as 10 knots for these calculations. The local wind speed in knots is tabulated above the local wind direction. Positive flow angles represent a lift flow field, and negative angles represent a header flow field. From the numbers on the left side of this figure we see that the wind speed and direction have changed significantly from the freestream values of 10 knots and zero local angle. We would have to go several boat lengths upstream (and downstream) before the freestream values would be reached.

Note that a boat sailing in the safe leeward position (ahead and to the lee of the sails shown in the figure) would experience both a favorable change in local wind direction and a slight increase in wind speed. The suction velocities on both sails of the boat in the safe lee position would be increased slightly because of the presence of the boat to windward and behind. The boat in the safe leeward position is actually being helped by the other boat in the factors of a more favorable wind direction, increased wind speed, and increased sail loading because of the higher local trailing edge wind speed. The boat behind is hurt by a heading wind shift and by reduced wind speeds. Of course, the sails of both boats would have to be included in the analysis to get an accurate assessment of the local speeds and angles for this situation.

8. Three-Dimensional Effects

All of the above conclusions have been based on studies of simple two-dimensional airfoils. Our real sails, however, are three-dimensional. The airfoil chord lengths, shape, angles of twist, and amount of overlap, all vary from the deck to the top of the sails. This real life situation can be studied only with the aid of a large lifting surface digital computer program such as described in Reference 2. The field plotter such as used for the present studies can only be used on two-dimensional airfoils (the theory of the analog field plotter is discussed in more detail in Reference 3). The relative importance of the various effects discussed in this paper will vary from the foot of the sails to the head because of the variations mentioned above. However, it is felt that the effects and conclusions reached in this paper through the use of the field plotter and potential flow theory are still valid.

Footnote:

It should be noted that the basic understanding of the flow phenomena presented in this paper were first discovered through the use of the analog field plotter (Reference 3). However, all of the figures and plots presented in this paper were actually prepared using the computer program described in Reference 1.

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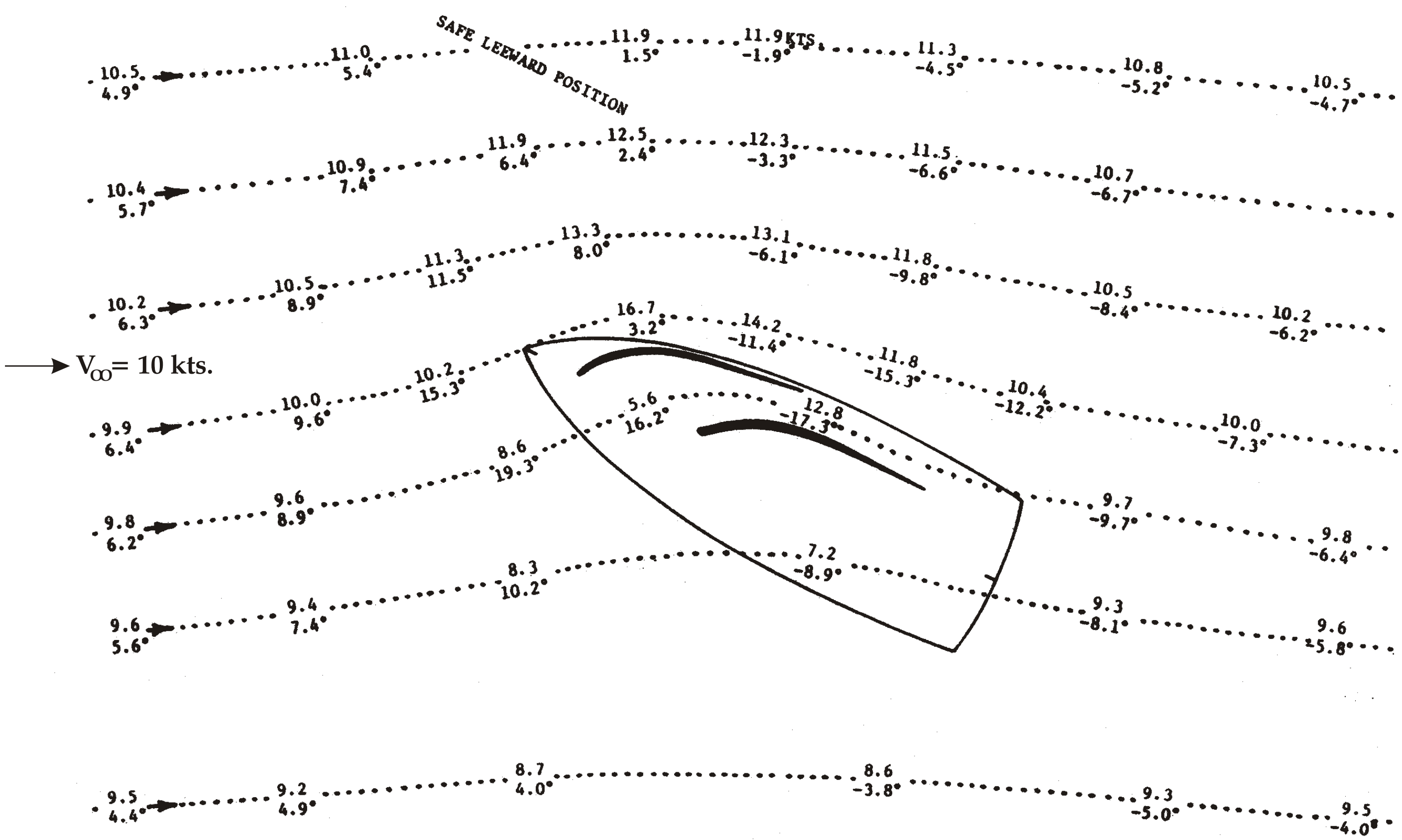

Figure 17. Streamlines about jib and mainsail showing local wind speeds and flow angles.

Biography:

Name: Arvel E. Gentry
Educational Background:
B.S., Mechanical Engineering, 1955, University of California at Berkeley
M.S., Aeronautical Engineering, 1958, University of Southern California
Present Position:
Chief, Applied Research Group Aerodynamics Research, Douglas Aircraft Company, McDonnell Douglas Corporation, Long Beach

Douglas Experience:

Mr. Gentry joined the Douglas Company in 1958 and has participated in supersonic and hypersonic design and research projects in both the Aircraft and Space Divisions. His past activities have included serving as senior aerodynamics engineer on the early Douglas supersonic transport project, and three years on the Aerospaceplane project. On these projects he served as coordinator for all aerodynamic section activities, developed many of the analysis techniques used in the aerodynamic and performance evaluation, and conducted supporting wind tunnel test programs. He has since served as a research specialist in transonic, supersonic, and hypersonic aerodynamics and performance analysis. He was principal investigator on the development of the Douglas Hypersonic Arbitrary-Body Aerodynamic Computer Program (HABP) that is currently in wide use in both government and industry agencies on the space shuttle project. He is currently principal investigator on an ONR contract on Transonic Maneuvering Problems.

Sailing Experience:

Mr. Gentry is a member of Seal Beach Yacht Club. He currently races Cal 20 #1177, ***Kittiwake***, in both class and handicap events. Previously he owned Lido 14 #86. In December he will take delivery of a new Ranger 23, also to be named ***Kittiwake***.

Sailing Publications:

"Downwind Tacking", SEA and Pacific Motor Boat Magazine, February 1970.
"Rigging and Handling the Spinnaker", SEA and Pacific Motor Boat Magazine, April 1970.