How a Sail Gives Lift

"Arvel Gentry corrects this most misunderstood theory"

By Arvel Gentry

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How many times have you heard that a sail gives lift to drive a boat because, "the air travels faster on the lee side for it has farther to go than it does on the windward side. So the pressures are different and you get lift." Well, that is wrong! Even a perfectly flat thin airfoil, with the same distance on both sides, has lift when it is at an angle to the wind.

So try to forget everything you know (or think you know) about how a sail gets its lift. The real explanations of how a sail gives lift may seem a bit complicated at first, but once you get the idea it is really quite straightforward.

It is true that the pressures over much of the lee side of a sail are lower than the freestream pressure, and the pressures on the windward side are higher. These pressure differences do result from the air flowing faster on the lee side and slower on the windward side (Bernoulli's principle). But what causes the air to flow in this manner?

Early mathematicians tried to solve this problem and they derived a set of equations. The streamlines these first solutions gave are illustrated in Figure 1 for a simple flat airfoil at an angle to the flow Their equations and solutions were correct, but the flow lines were exactly the same on both sides of the airfoil (turn the page upside down and you'll see what I mean).

Because the flow lines are the same on both sides, the pressure forces therefore must be the same, and the airfoil would have no lift at all This would mean that man could not fly, and birds could not fly. But birds do fly, and early man-made gliders, even with flat, un-cambered wings also flew. Something obviously was missing from their solutions.

Examining the calculated flow around the edges of the airfoil gives the clue. Note that these mathematically determined streamlines in Figure 1 make sharp turns as they go around the leading and trailing edge of the airfoil (the luff and leech of our sail). For a thin airfoil this means that the air must have high velocities at these points in order to get around the sharp corners. The velocities around the luff can be reduced by bending the airfoil down into the flow (cambering the airfoil), but what about the leech?

In real life we find that the flow around the leech varies from that shown in Figure 1 as the air first begins to move past the airfoil. It changes so that the air leaves the airfoil at the leech smoothly with the same speed and pressures on both sides This fact of aerodynamics is known as the Kutta condition (named after the man who first discovered it in 1902).

You can understand this Kutta condition requirement if you stop and visualize what would happen if the Kutta condition were not satisfied, and the air coming off of the lee side of the leech were to travel faster than the air coming off the windward side (as is implied in the flow diagrams in many sailing books). If there were different speeds, we would have different pressures (from Bernoulli's principle) on the two sides of the line dividing the lee side and windward side flows downstream of the leech. With different pressures and the sail fabric no longer separating the two different speed regions, we would have nothing to keep the high-pressure air from taking over and pushing into the low-pressure region.

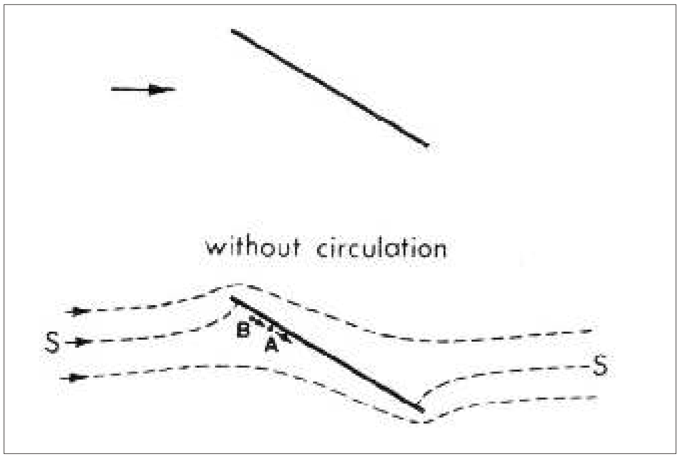

Figure 1

What happens in a real flow is: the total region around the airfoil adjusts itself so that the air flowing off the two sides of the airfoil at the leech has the same speeds and pressures. Again, this adjusting process is called the Kutta condition by aerodynamicists. It is an important principle to remember, for it influences the entire flow field about the sail.

Mathematicians found that the Kutta condition could be satisfied by adding another type of flow solution, called *circulation*, to that already determined and shown in Figure 1. Circulation is a special mathematical flow solution where air rotates around the airfoil. The direction of the circulation flow goes forward over the windward surface, around the luff and then toward the rear on the lee side of the airfoil. The circulation flow velocities are higher close to the surface and they decrease as you get farther away from the surface.

The combination of non-circulation flow and circulation flow is illustrated in Figure 2. When the two flows are added together, both the velocities and directions are taken into account in the entire area around the airfoil. They are added together just as one adds boat speed and true wind speed to get apparent wind strength and direction.

In the mathematical solution, circulation air speeds are

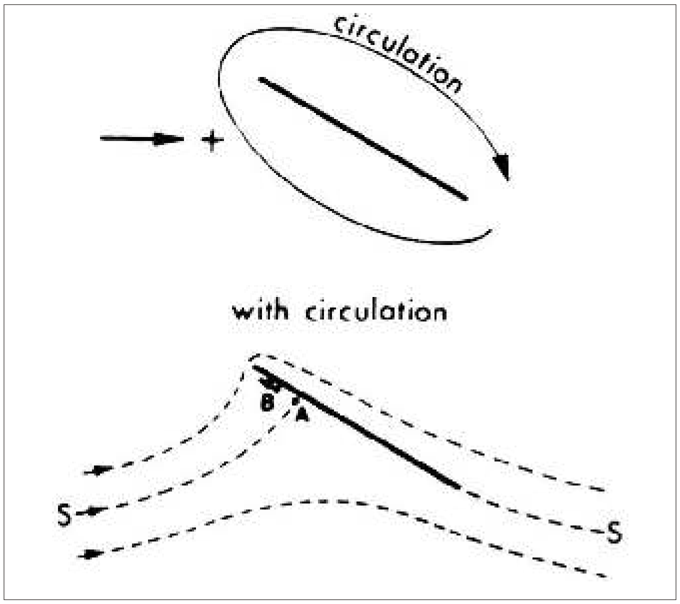

Figure 2

adjusted so that the Kutta condition at the leech is satisfied; the calculated air flow speeds and pressures are the same off both sides of the leech. The resulting air speeds of the circulation part of the flow are smaller than the non-circulation solution speeds. On the top of the airfoil, the circulation flow direction is the same as the non-circulation flow direction. This means that the two flows added together will give a higher speed flow.

On the bottom side, the circulation flow direction is against the non-circulation flow so the two flows cancel each other a little bit to give a slower speed flow.

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, which gives us the necessary pressure difference between the two sides of the sail to maintain the cambered shape and to give the lifting force to drive the boat.

You might ask if the results from this mathematical exercise (non-circulation plus circulation flow) are really meaningful. The answers are indeed accurate and they match test data almost exactly.

Examine the stagnation streamlines (marked S) in Figures 1 and 2. In Figure 1, the stagnation streamlines come into the airfoil close to the edges. Notice that at point A in Figure 1 the windward streamline is quite far from the airfoil surface.

At this point we should expect low speed flow in the direction indicated by the arrow. Circulation flow at this point is just equal to this speed and opposite in direction and it therefore cancels out the non-circulation flow. This point becomes the place where the new stagnation streamline comes into the airfoil when we have circulation as shown in Figure 2.

At point B in Figure 1 the flow on the surface has a slower speed than point A, so the circulation flow is not only able to cancel out the non-circulation flow direction, but can actually make the *flow go in the opposite direction* around the luff of the airfoil. From this we see that the circulation causes some of the air that was going to go on the windward side to be diverted around to the lee side. We can also see this from the fact that the stagnation streamline at the left side of Figure 2 is much lower than it was in Figure 1.

The Kutta condition must always be satisfied for any lifting airfoil. However, if the flow separates from the airfoil before it reaches the leech, the Kutta condition will not be satisfied at the leech of the airfoil itself. Instead, it will be satisfied at the trailing edge of the separated region – well behind the airfoil.

However, since the flow at the trailing edge of the separated region has a smaller angle to the freestream than does the actual leech of the airfoil, the airfoil with separation has less lift and much more drag. This is shown in Figure 3.

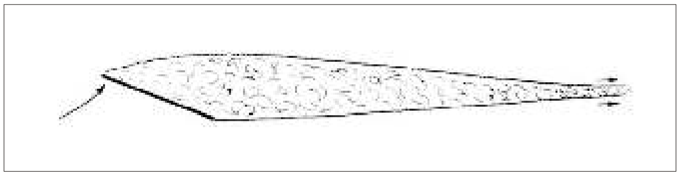

Figure 3

Note that nowhere in this discussion have I said anything about the density of the air, or about the air having farther to go on the lee side, or about the air actually striking the sail. The air just does not behave like that. Also note that the airfoil used was perfectly flat and thin. Of course our cambered sail is more efficient than the flat airfoil, but from the example given, we see that a sail does not have to have thickness, either real or imaginary, to have lift. The air flows about the sail, and the way that it flows is governed by the shape of the airfoil and it is basic non-circulation flow, plus the effects of the circulation that must be added to satisfy the Kutta condition at the leech.

Air does not strike the sail like so many grains of blowing sand. Instead, air behaves like a fluid as it flows past the sail. When air sees it is approaching the sail, it starts to move and change direction in preparation for passing the sail. But air also has a certain resistance to a change in direction. It doesn't want to change direction any more than it has to in flowing past the sail.

The stagnation streamline divides the air that is going to pass on the two sides of the sail. The air that is going to flow on the lee side does not move any further to leeward than it has to to get past the sail and still satisfy the Kutta condition at the leech. The lee-side streamlines, therefore, pass very close to the forward part of the sail. They have high velocities and low pressures in this region.

On the windward side, the air is a bit lazy; it doesn't want to move up into the convex region of flow that is formed by the airfoil and the stagnation streamline. The windward side streamlines spread out a bit, the air slows down and the pressure gets higher. But, the final airspeed, pressure, and direction of flow at the leech must be the same as on the leeward surface for the Kutta condition to be satisfied.

In Part 1 (*SAIL*, April 1973) we learned what is a correct streamline drawing. In Part 2, last month we introduced the boundary layer and separation effects. And so far in Part 3, we have learned how a sail gets its lift. Now let's put all this aerodynamic knowledge together to see how a single sail works.

Figures 4 and 5 show accurately drawn streamlines about an airfoil representing a jib at two different relative wind angles for the centerline of the boat (25 and 35 degrees). The stagnation streamline dividing the flow that passes on each side of the sail is identified by the letter S. The first lee-side streamline is marked A, and the first windward line is B.

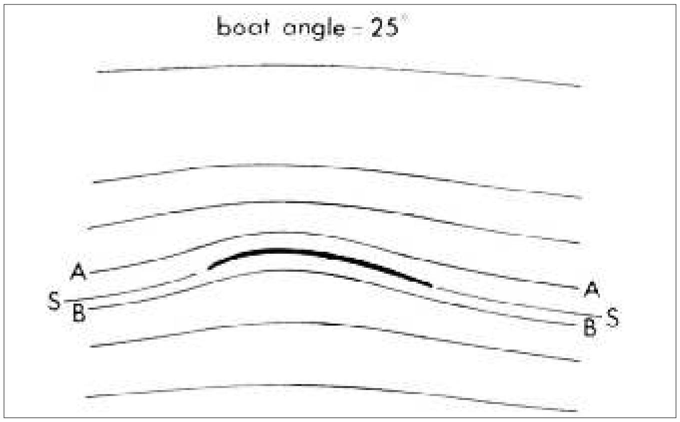

Figure 4

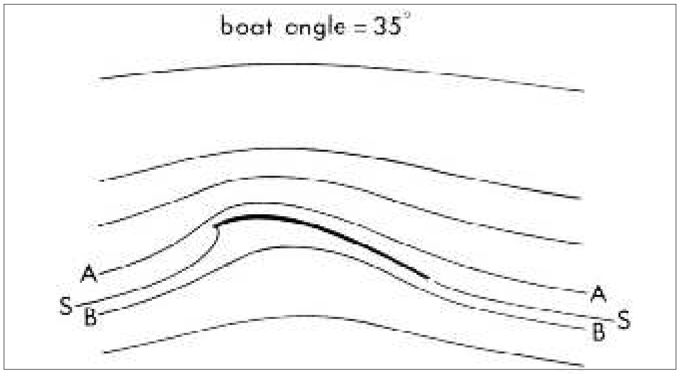

Figure 5

The detailed pressure distributions for the two boat angles are shown in Figures 6 and 7. In these drawings, the negative or suction pressures (less than atmospheric) are represented by arrows pointing away from the sail. The lower surface pressures are usually higher than atmospheric (positive pressures) and are represented by arrows pointing toward the sail.

Below each airfoil drawing is an engineering type of plot showing this same information in terms of pressure coefficient a long the surface of the sail. The difference between the lee-side and windward-side pressures at a given point on the airfoil represents the pressure difference across the sail fabric.

If you study Figures 4 and 6 together, you can see how all this information you've learned previously fits together. In Figure 4, the stagnation stream line S goes smoothly into the airfoil luff. Line A gradually gets closer to S and the airfoil surface as it approaches the maximum camber point. Line A then tends to move gradually away over the rest of the airfoil.

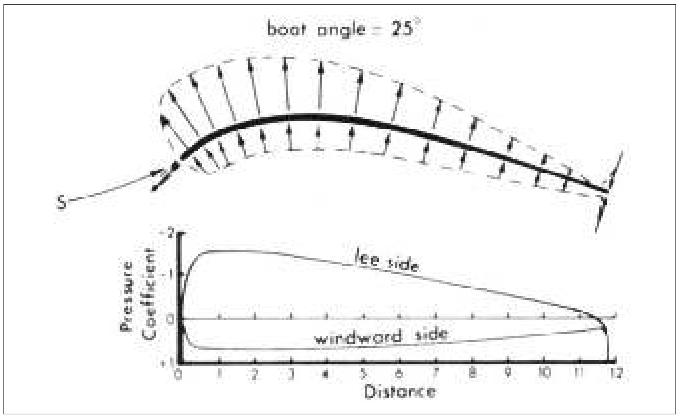

Figure 6

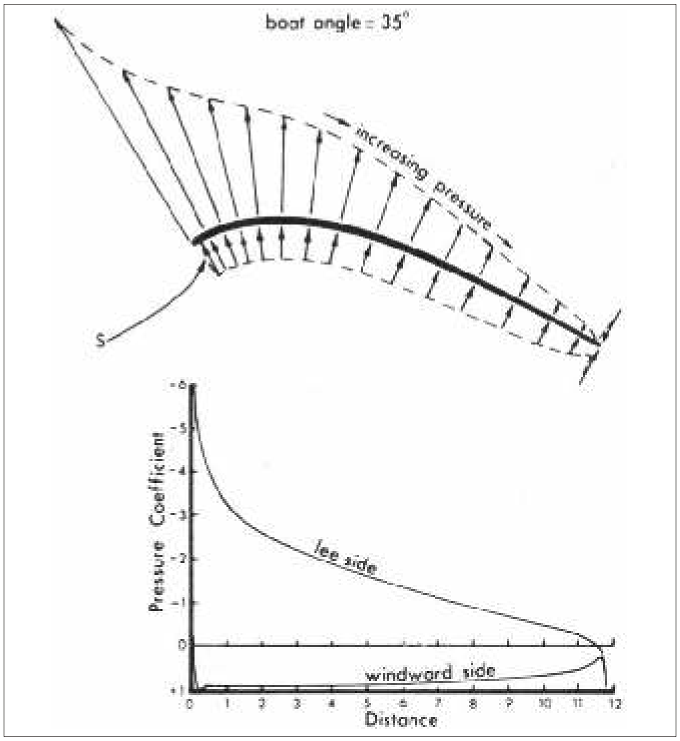

Figure 7

With this flow we would expect to have an increase in air speed to the point where streamline A is closest to the airfoil, followed by a gradual decrease in speed as the leech is approached. If you remember that air pressure goes down when speed goes up (Bernoulli's principle), you therefore get a decrease in pressure over the front lee-part of the sail, followed by a gradual increase in pressure toward the leech.

In Figure 4, streamline B tends to resist moving up into the convex region formed by the airfoil and the stagnation streamline so that it gets further away from the airfoil surface. Therefore there is a decrease in wind speed and an increase in pressure in this area. Figure 6 shows how all this turns out in terms of the pressure along the airfoil surface.

For the 35 degree boat angle case in Figures 5 and 7, we have a higher angle of attack for the sail, and a significantly different streamline picture and resulting surface pressures. The stagnation streamline comes into the airfoil on the windward surface a little way back from the luff. Streamline A passes close to the luff and then immediately starts getting farther from the surface over the rest of the airfoil. All the air between lines A and S must pass through the little space at the lee side of the luff.

We would expect to see much higher air speeds and lower pressures close to the luff than we had for the lower boat-angle case. We would also see a rapid increase in pressure as the flow continues downstream from the luff, since streamline A moves rapidly away from the surface. The pressure drawings and plot in Figure 7 show that this is exactly what happens.

Previously it was learned that the boundary layer does not like rapid increases in pressure and it tends to separate under these conditions. In real life, the boundary layer for the high-angle case shown in Figures 5 and 7 would probably separate and the airfoil would stall. As soon as this happens, the streamlines shown in Figure 5 would no longer be true, for we would get a completely different flow picture about the airfoil (similar to Figure 3).

However, by being able to calculate the airflow with the computer as though there was no separation, we are able to study just what causes the separation to occur, and what can be done to prevent it from separating.

In the streamline drawings in Figures 4 and 5, the lines A and B are the same distance away from the stagnation streamline S at the leech as they were way out in front of the airfoil. This means that the airspeeds and pressures on both sides of the leech are about the same as the freestream speed.

The detailed calculated results show a speed, at 95% of the airfoil length, about 14% higher than freestream velocity, with the speed and pressure recovering to near freestream values by the time the trailing edge is reached. These facts will become very important when I describe two airfoils together.

Another important point can be inferred from the data presented in these figures. Because all sails are very thin, with relatively sharp leading edges, they are very sensitive to the angle of the wind.

An increased angle of attack will cause the stagnation streamline to come into the windward side of the sail. This will cause excessive pressure gradients on the lee side as the air tries to recover from its rapid turn around the leading edge and return back to near freestream values at the leech. As a result, the flow will separate and we will have a stalled condition.

As the angle of attack to the wind is reduced (the boat headed up), the stagnation streamline will shift around to the luff and then the lee side of the sail. The resulting pressure distribution will cause the sail to change its shape since there may be a higher pressure on the lee side than on the windward side. It is in a luffing condition.

Note that the air is not actually striking the sail like so many grains of sand and making it shake. It is just that the fluctuating pressure and unstable shape of the sail cause it to shake as it responds to the pressures created by the flow. Obviously, the term *backwinding* of a sail is not really a very good descriptive term for it implies that air "strikes" the sail. And now we know that air does not behave in this way.

You should also note in Figures 6 and 7 that the higher-angle case would have higher lift – if the flow did not separate. Where does this higher lift come from? The streamlines in Figures 4 and 5 clearly illustrate this. The higher angle of attack requires a higher circulation to satisfy the Kutta condition at the leech. Higher circulation means that more air is diverted to pass on the top or lee side of the sail. We can see this from the fact that the stagnation streamline in Figure 5 is lower (further to windward) than it is in Figure 4. Again, to get more lift we must cause more air to pass on the lee side of the sail.

If you have read carefully the first three parts of this series, you should be able to predict what will happen when two sails, the jib and main, are used together. Between now and next month, look at some of the drawings in the sailing books that “show” how the slot works, and read their explanations. Then see if you can figure out why they are wrong.

Next month: jib, mainsail, and the slot effect.