Boundary Layer Flow and the Headsail

Arvel Gentry continues to question old concepts

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Most sailing books describe the primary effect of the headsail on the mainsail approximately as follows: “The jib causes an increase in the velocity of the air on the lee side of the main. This higher velocity air in the slot revitalizes the air over the main and keeps it from separating and stalling."

Well, this may come as a surprise, but if the jib did cause a higher velocity flow over the main, then it would actually cause the flow over the main to separate rather than prevent it. But, I'm getting ahead of my story.

When the aerodynamicist studies the airflow about a shape, he recognizes that the flow can be divided into two basic types of flow areas: the external flow region, and the boundary layer region (Figure. 1). The boundary layer flow region is the layer of air that lies very close to the airfoil and the thickness of this layer is greatly exaggerated in the figure for clarity. Air has viscosity (even though it is very small), 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 speed with respect to the airfoil, and 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 is identified as the external inviscid flow. The viscosity of the air does not affect the aerodynamic calculations for this part of the flow, but the techniques used by an engineer to calculate 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 roughness (jib hanks, cloth seams, the headstay, etc.), and a certain amount of natural turbulence in the air, 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 flow in the boundary layer flow becomes very erratic, and we have what is called turbulent flow. The external flow is not appreciably affected by the change from a laminar boundary layer to a turbulent one, so the lift of the airfoil does not change very much.

The water channel photograph in Figure 2 shows another type of airflow that can exist about a sail, separated flow. We all have seen the evidence of this type of flow on our sails. As we bear off from a closehauled course with the jib in tight, the yarn telltales on the lee side of the jib

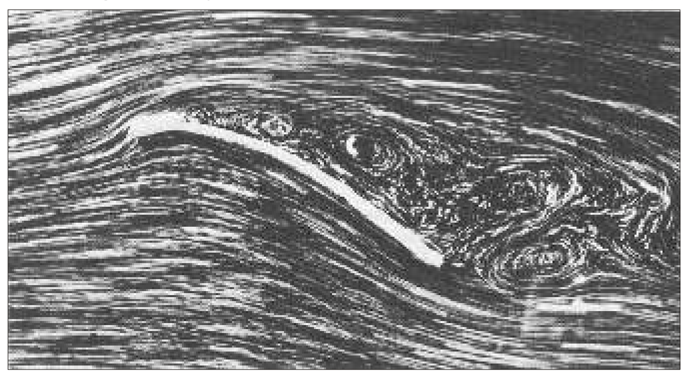

Figure 2

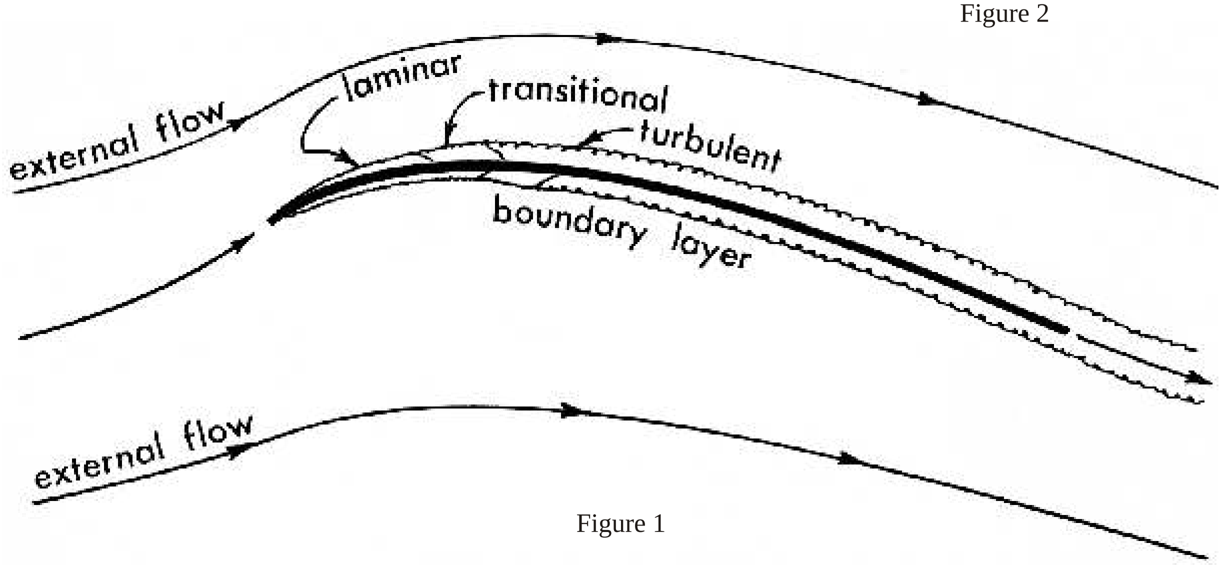

Figure 1

suddenly start to twirl wildly. The telltales are responding to the very mixed-up separated flow region that has formed over the lee side of the sail.

Note that from the aerodynamic standpoint, we refrain from applying the word *turbulent* to the separated flow, for the word turbulent is reserved for use in describing the turbulent boundary layer. To avoid confusion, we stick to the term separated flow. Almost all our sailing time is spent trying to avoid having separated flow regions on our sails, and this is why we must learn as much as we can about the causes and prevention of separation.

We all know what happens when we get separated flow on our sails; the sail loses some of its driving force and the boat slows down. But what causes separation? It is a well accepted aerodynamic fact that the boundary layer will separate only when the external pressure along the airfoil starts to increase too rapidly.

The more rapid the increase in pressure, the more likely it is that the boundary layer will separate. We should also note that the boundary layer will not separate if the pressure is decreasing along the airfoil.

The rate of pressure change along the surface is called the pressure gradient. When pressure is increasing, the pressure gradient is called an adverse pressure gradient. Whether or not the boundary layer separates when subjected to a given increase in pressure (adverse 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 the speed of the airflow at the edge of the boundary layer. The speed-distance factor is expressed by the aerodynamicist in a term called the Reynolds number.

The most important fact to remember from this is: pressure must be increasing along a sail to cause separation and stalling. This also means that local airspeed must be decreasing (remember, when pressure goes up, airspeed must go down).

We should also know (this will be covered in more detail in a future article) that high-velocity air on the lee side of the main must slow down and return to near freestream velocity by the time it reaches the leech. It is this slowing down of the air, and resulting increase in pressure, that tends to cause separation.

Now back to my opening statement; if the slot formed by the jib caused an increase in airspeed over the main, then the air would have to slow down even more rapidly to reach the required freestream speed at the leech. This greater pressure gradient would actually cause the flow to separate rather then prevent it.

But from sailing experience, we know that the jib does help keep the flow on the main from separating. Therefore, a *smaller* speed change in the air from the mast to the leech must occur to prevent separation (a reduced pressure gradient). Obviously, the proper explanation must be that the jib actually causes *reduced* velocities over the forward part of the main if this separation is to be prevented.

A complete explanation about how the jib creates reduced velocities over the forward part of the main will also be given in a future article.

Before I leave the subject of separation, I have an interesting new idea to propose. First, some background information; most competitive sailors use yarn telltales on their sails to indicate when the sail has stalled. The position of these telltales (12" - 18" from the luff of a headsail) has been determined from experience as being a true indication of when the sail has stalled (flow completely separated). The best point of sail is located somewhere between this stalled condition and the angle where the sail luffs. Usually it is close to, but not quite at, the luffing point.

Conventional telltales are merely stall-detecting indicators that tell when you have gone too far off the wind; the luffing of a sail tells you when you have headed too close to the wind. What is needed is a luff-stall *warning* device to tell us how close we are either to a luffing or a stalling condition. The behavior of the external air and the boundary layer near the luff of the sail can provide this information.

When a sail is set at an angle where it is just on the verge of luffing, the stagnation streamline comes smoothly right into the luff of the sail, and the flow on the lee side will be attached (unseparated). When the angle of the sail is increased slightly, the stagnation streamline will actually come into the sail on the windward side. The air will have to go very fast to make the sharp turn around the luff to get on the lee side, and then it will immediately start to slow down.

The boundary layer cannot withstand this rapid deceleration so it will separate right at the leading edge. However, the flow will then quickly re-attach itself to the sail and continue to the leech. What we have is a small separation region, or bubble, along the luff. If the angle of the sail is again increased slightly, the length of the separation bubble will increase also. The complete situation where we have also started to get separation near the leech is illustrated in Figure 3, although this leech separation does not always occur in practice. If we again increase the angle of the sail, the bubble will burst and the entire lee side will be separated as in Figure 2.

Here is my idea. The size of the separation bubble can be used to tell when a sail is between the luffing and stalled conditions. Several short three-inch pieces of yarn spaced end-to-end from the very luff to the position of the conventional telltale can be used to indicate the size of the leading-edge separation bubble.

When all the lee-side tufts are lying down, the stagnation streamline is coming in right at the leading edge and the sail is right on the luffing condition (Figure 4a).

If only the first tuft is twirling, the sail is near but not quite at the luffing condition (Figure 4b), and the separation bubble is very small. As the boat is headed further off the wind, the separation bubble will grow larger and the first two or three tufts will twirl (Figure 4c).

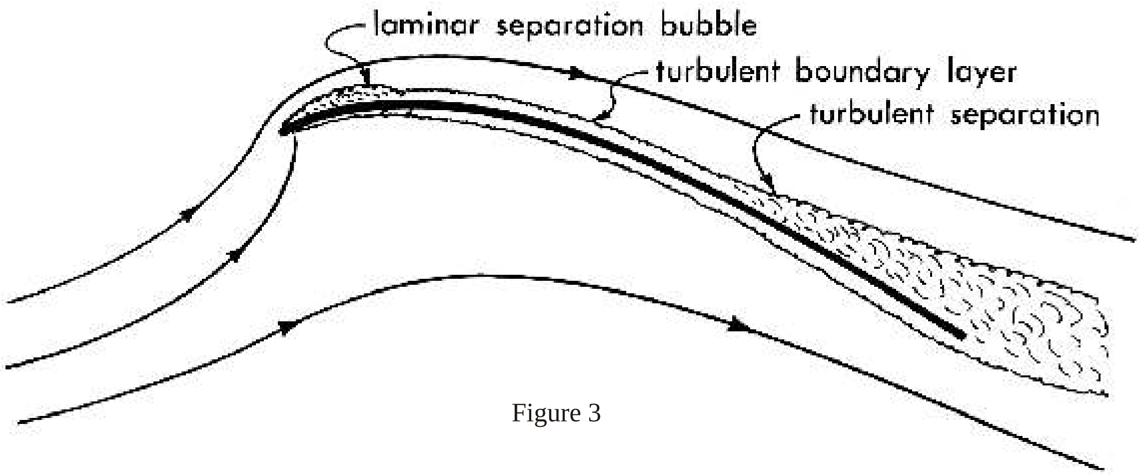

Figure 3

A further increase in angle will cause all the tufts to twirl (including the conventional telltale) for the sail has completely stalled (Figure 4d). The number of tufts that will twirl before the complete separation occurs will depend upon the length of the tufts used, and the characteristics of the sail.

Some of my friends who have used these short tufts near the luff (they call them "Gentry tufts") have reported that they are very useful, both in fine-tuning the sail trim and in staying on the best windward point of sail. It takes some practice in their use, but they provide a very sensitive warning of an approaching luff or stall. They are also valuable in improving a new helmsman's windward ability.

If I tell a beginner to sail to windward without luffing or letting the conventional telltale stall, he will do a bad job. He has several degrees of boat angle to play with, and the luffing or conventional telltale tells him only when he has already gone too far in one direction. However, if I tell him to sail with the first short lee tuft slightly agitated but with the rest all laying down, then he will sail a very good windward course.

When the first two or three leeward tufts start to twirl, he knows that he is getting too far off the wind, and he should come back up or the sail will soon stall. When all the leeward tufts settle down straight and even the first tuft is not shaking at all, the sail is on the verge of luffing. So far this tuft system has been used successfully on boats ranging in length from 23' to 63'.

As always, tuft visibility and the problem of the first tuft's wrapping around the luff are problems, just as they are with conventional telltales. However, multiple tufts on the leading edge and the use of a plastic window close to the luff with different colored tufts on each side solve these problems. Try this setup on your own boat; you may like it.

Next month: how lift is generated.

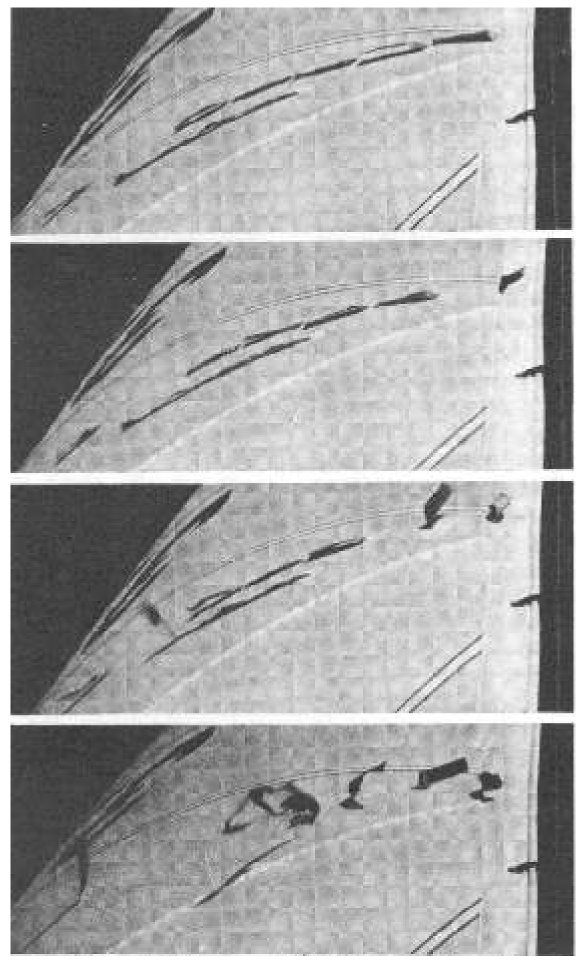

Figure 4