The Origins of Lift

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Abstract

The fundamentals of lift generation are presented with emphasis on their usefulness for understanding the flow around sails on a sailboat. These same concepts are applicable to conventional airfoils for aircraft. Well known basic aerodynamic principles are used to illustrate the starting vortex and the formation of a circulation flow field about two-dimensional airfoils that leads to the generation of lift. Three-dimensional effects supply additional flow complications but are not central to the fundamental origins of lift. The generation of lift requires that the fluid have some viscosity. An experiment with a fluid without viscosity has been conducted to prove this point. Without viscosity there would be no lift; birds and aircraft would not fly, and sailboats would not sail.

The wind is blowing nicely as I trim my sails and move smoothly across the water. A glider pilot searches for thermals to prolong his playtime in the air. The NASA space shuttle pilot makes his final maneuvers to line up with the runway and flares to make a nice landing. All of these situations have one thing in common; they all are able to generate a force that we call lift. For the sailor, lift is everything as long as the wind blows. For the glider pilot, it is almost everything but he needs help to get aloft. The shuttle pilot needs just enough lift to get back to the runway safely.

All of these vehicles are flying, and flight depends upon generating enough lifting force to avoid falling like a rock or, in my case, being left drifting with the tidal currents when the wind dies. But how is this lifting force generated? What is the fundamental explanation for the generation of lift?

1. To understand the fundamentals of how lift is generated, it is best to start with a simple two-dimensional airfoil. This allows us to get at the real essence of the origins of lift. Three-dimensional effects are just additional complicating factors and are not central to what really causes lift. Although the primary purpose of this article is to help sailors understand how their sails work, the concepts presented are exactly the same as for conventional airfoils used on aircraft. The emphasis here is on understanding more of the details of the airflow than is taught to the beginning pilot. The pilot has only minimal influence on the shape of his wing (control surfaces and flaps up or down). However, the sailor has rather complete control of the shape of his airfoils and frequently makes use of two or more flexible sails that must be constantly shaped to work together for best performance. Sailing also sometimes requires knowledge of the airflow patterns around boats in close proximity.

2. Air and water are fluids that have a small amount of viscosity. Viscosity effects are most apparent in the region of the flow very near the airfoil surfaces. We call this region the boundary layer. The boundary layer is responsible for creating skin friction drag on a surface. For most low speed flows, the fluid outside of the boundary layer (the external flow) may be viewed as inviscid (zero viscosity). When the pressure in the external flow near the boundary layer is increasing too rapidly, the normally well-behaved viscous boundary layer will separate from the surface. This leaves an unsteady chaotic region that distorts the external flow, decreasing lift and increasing drag (see Figure 1). Separation is a viscous effect.

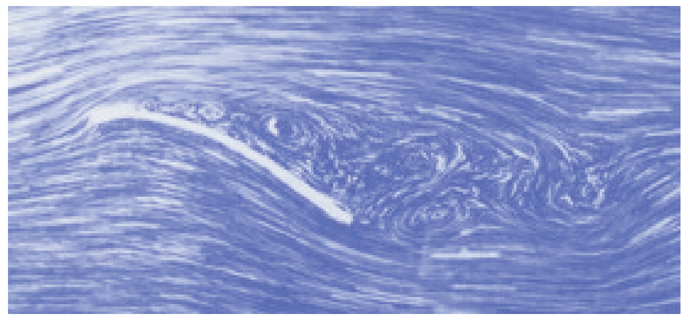

Figure 1. Water channel photograph showing separated flow.

3. Fluid flow without viscosity. Computed streamlines for the inviscid flow about a flat plate airfoil are shown in Figure 2. The flow is from left to right. Green streamlines that actually touch the surface are called stagnation streamlines. They divide the flow that goes on the top of the airfoil from the lower surface flow. In areas where the streamlines get closer together, the air speeds up and the pressure goes down (Bernoulli's equation, [Reference 1, page 226]). Where the streamlines get farther apart, the air slows down and the pressure goes up. If you rotate this flow diagram 180 degrees, you will see that it looks the same. The pressure force on the top will, therefore, be the same as the pressure force on the bottom giving zero lift and zero drag. This is known as D'Alembert's paradox [2, p 225]. A flat plate airfoil is used here to illustrate this. However, regardless of the airfoil shape, without viscosity the resulting lift and drag always turns out to be zero according to D'Alembert's paradox.

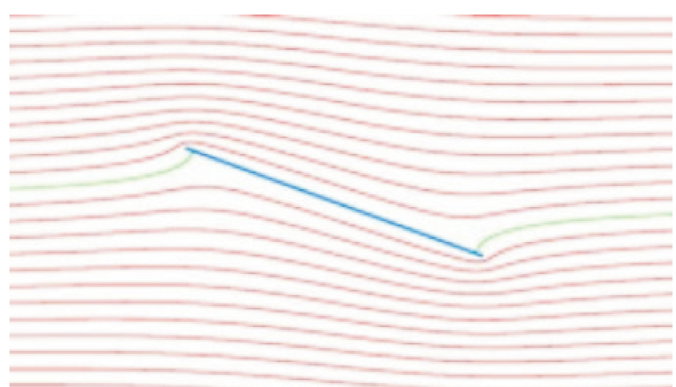

Figure 2. Non-lifting flow around a flat plate.

4. Formation of the starting vortex. However, air does have some viscosity! As the wind is initially turned on or airfoil movement is started, the flow on both the upper and lower surfaces near the trailing edge have some difficult maneuvers to make. As soon as the boundary layer develops, it will not be able to negotiate these maneuvers. The flow will separate from the surface and form the starting vortex as shown in the sketches in Figure 3 [1, p 393]. The external flow and the boundary layer will quickly adjust, and as stable flow is established, the starting vortex will be swept downstream. The same phenomena will also occur on a curved airfoil representing a sail and on a conventional airfoil such as used on aircraft. The starting vortex will eventually dissipate because of the fluid's viscosity.

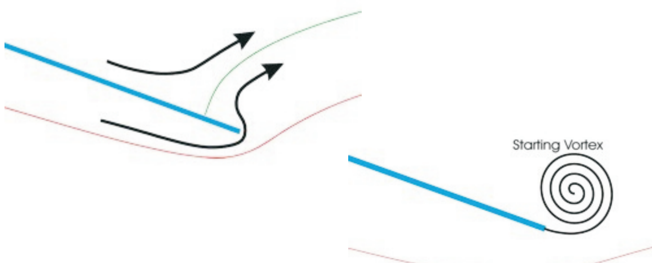

Figure 3. Formation of the starting vortex.

5. The vortex theorems. A set of vortex theorems by Hermann von Helmholtz and William Thomson (Lord Kelvin) play key parts in aerodynamics [1, p523]. The most important one in this situation is Thomson's circulation theorem. The application of this theorem in the two-dimensional airfoil case basically means that as the starting vortex is created in the flow field, there must be another vortex equal in strength and opposite in direction [3, p168-169].

In aerodynamic's terminology, this new vortex field is called "circulation" and it surrounds the airfoil. The circulation field emerges as the starting vortex is formed. This is a dynamic process that becomes stable when the starting vortex is swept downstream and the flow conditions at the trailing edge have become smooth and stable. This happens when the flow on both sides of the trailing edge have equal speeds (and pressures). This is known as the Kutta condition. The circulation flow field is equal in strength to the staring vortex and rotating in a clockwise direction (opposite to the starting vortex) as shown by the streamline plot in Figure 4.

Aerodynamics theory tells us that the airfoil lift is equal to the overall strength of the circulation flow field. The circulation flow field is the strongest near the surface of the airfoil and decreases at farther distances from the airfoil. When the non-

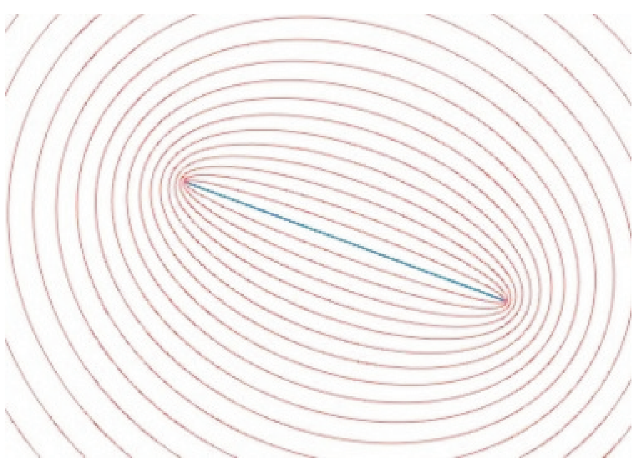
Figure 4. Circulation flow field.

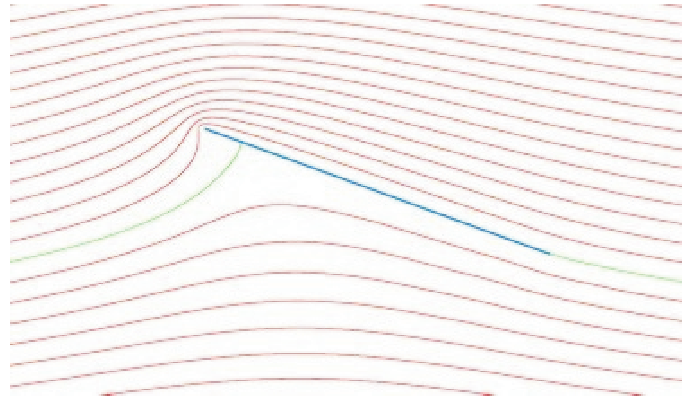
Figure 5. Lifting flow about flat plate.

lifting flow field and the circulation flow field are added together, you get the final lifting-flow streamlines shown in Figure 5. The circulation flow field is obviously the primary contributor to creating the upwash in front of the airfoil and the downwash behind the airfoil. The circulation flow field causes a large amount of air to flow on the top (lee side) of the airfoil.

The same amount of air is flowing between each pair of streamlines. The speed of the flow increases in areas where the streamlines get closer together such as near the leading edge of the airfoil. Higher speeds mean lower pressures. Where the streamlines get farther apart such as on the lower surface, the flow slows down and the pressures get higher. Lower pressures on top and higher pressures on the bottom mean that the airfoil now has lift.

With the proper computer programs, we can prepare accurate streamline drawings such as shown here to help us understand how the air flows around our thin sails or conventional airfoils. Again, the green streamlines are the stagnation streamlines and divide the flow that goes on top (lee side) from the flow on the lower windward side. Note that the streamline just above the airfoil passes very close to the leading edge and then gets farther away as it nears the trailing edge. This means that the flow will be the fastest right at the leading edge and then slow down as it approaches the trailing edge. The slowing down of the flow means the pressure is increasing. Remember that in real flow with viscosity, too rapid of an increase in pressure tends to make the boundary layer separate. Much of our sail shaping efforts are devoted to decreasing flow separation on our sails.

Note the distance between the two streamlines on each side of the green stagnation streamline right at the trailing edge in Figure 5. The streamlines are equally spaced. This means we have equal speeds and pressures on both sides at the trailing edge so no new starting vortex will be formed. The Kutta condition has been satisfied.

At this stage in our analysis, we have ignored the sharp turn around the leading edge of the simple flat plate airfoil. In the case of a sail, we would bend the leading edge of the airfoil down into the flow in order to avoid flow separation. For an airfoil on an airplane, we would give the airfoil some thickness with a round leading edge and possibly give the airfoil some overall curvature (camber).

The streamlines shown in Figures 2, 4, and 5 were calculated using conformal transformations as devised originally by Joukowski [4, p46]. The calculations and display of streamlines in these figures were accomplished using Boeing's Aero Grid and Paneling System (AGPS), see [5, 6]. Figures similar to 2 and 5 above may be found in a number of other references [7, p174, & 3, p174].

6. The flow field around an airfoil is the combination of two flow fields: The flow field without lift shown in Figure 2, and the circulation field about the airfoil. This concept is at first difficult to understand but a simple analogy might help. If you ride a bicycle in a crosswind, you feel only one wind on your face, the vector combination of the true wind plus a wind vector representing the speed of the bicycle. The same analogy applies to the sailor as he motors at an angle to the true wind. The new wind that he actually feels on his face is called the "apparent" wind. He only feels one wind, but he knows that it is a combination of the true wind and the boatspeed wind (Figure 6).

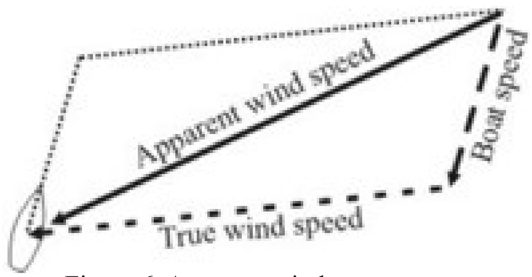

Figure 6. Apparent wind vectors.

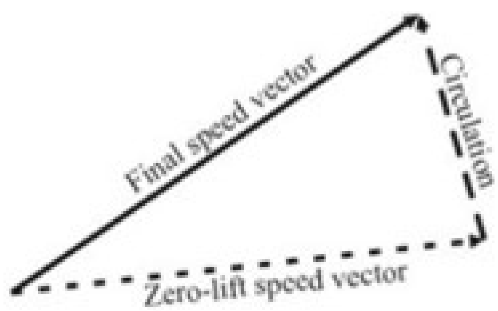

Figure 7. Circulation vector at a point in the flow field.

The two-dimensional airfoil as discussed above also feels the combination of two winds, the non-lifting inviscid flow field plus the circulation flow field caused by the starting vortex as shown in Figure 7.

However, the merging of two different flow fields is more complicated than the simple boat apparent wind problem. Both the zero-lift speed vectors and the circulation vectors vary in speeds and direction all over the flow fields around the airfoil. The example shown in Figure 7 is for a point on a streamline as it swings up toward the airfoil. In this example, the circulation vector has only a small effect on the final speed vector, but the flow direction is changed significantly by the circulation vector at that point as it redirects the air to flow up and over the airfoil. At a different location such as on top of the airfoil, the circulation vector would point in the aft direction and added to the non-lifting flow field gives a much higher final local wind speed. The circulation flow field effects get smaller as you get farther away from the airfoil as noted previously.

When the sails are raised and generating lift, the actual measured wind at the masthead that we loosely call the apparent wind is further complicated by the three-dimensional flow field around the sails (bound vortex and trailing vortex systems).

7. The bathtub experiment. The concept of circulation at first seems like mathematical trickery. However, the circulation flow field is real and there is an experiment that can be performed to visualize this whole process. This is described in one of my technical sailing papers, *A Review of Modern Sail Theory*, [8] and also in the book, *The Art and Science of Sails*, by Tom Whidden and Michael Levitt [9]. In this experiment, a thin airfoil representing a sail is slowly pulled through a two inch layer of water in a bathtub (see Figure 8). The airfoil should always be touching the bottom of the tub. Pepper sprinkled on the water surface helps visualize the movement of the water.

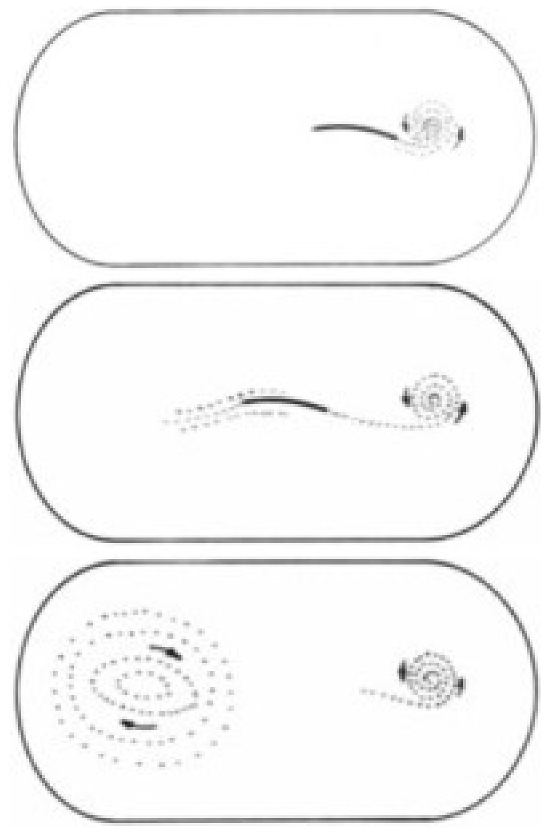

Figure 8. Bathtub experiment showing circulation field.

At the start of movement, we will see the formation of the starting vortex near the right end of the tub. It will be rotating in a counter-clockwise direction. Halfway down the tub, we can observe how some of the water is adjusting to flow on the top side of the airfoil. As we near the left end of the tub, we quickly remove the airfoil from the water. What we see left near the end of the tub is a circulation of flow in a clockwise direction. This is the circulation flow field. It is real!

In this experiment, it is important to use a thin curved airfoil at a relatively small angle of attack (about 5 to 10 degrees). Let the water settle down with no movement before starting the experiment. Try to keep the speed of the airfoil constant from the start until the end where it is quickly lifted out of the water. The airfoil should still be moving as you lift it out of the water. Each test run should take about 5 seconds. A number of tests may be required so you can concentrate on a key part of the experiment each time: the starting vortex, the upwash in front of the airfoil, the downwash behind the airfoil, and the circulation flow field. You will have to wait between tests in order to let all water movement stop.

This experiment can be done with a conventional thick airfoil to illustrate the starting vortex and the upwash flow. However, the view of the circulation itself will not be very good with the thick airfoil because of the inrush of water to fill the volume space when the thick airfoil is removed. To do the experiment correctly, use a thin rectangular piece of metal or part of a milk carton for the airfoil.

8. The generation of lift. The resulting circulation flow field causes some of the fluid that would normally go below the airfoil to be redirected to flow on the top side. This is most apparent out in front of the airfoil where the circulation vector is in an upward direction. Some of the fluid in front of the airfoil starts changing direction so that it will pass on the top side (to the lee side of a sail). In aerodynamics we call this "upwash".

On the top side of the airfoil, the circulation vectors are in the same direction as the free stream direction, therefore causing the flow to speed up. This increase in speed means lower pressures (according to Bernoulli's equation). On the bottom side of the airfoil, the circulation vector is opposite the general flow direction so the fluid tends to be slowed down resulting in increased pressure. The difference in pressure forces between the top and bottom sides of an airfoil are what gives us lift.

The concept of circulation not only helps explain how and why the fluid flows about an airfoil as it does, but it turns out to be a key concept in correctly explaining the "slot effect" between the jib and the mainsail. With two sails, each airfoil has its own circulation flow field. The two circulations appose each other in the slot between the sails and add to each other in the region to lee of the jib. More air is caused to flow on the lee side of the jib. Also, each airfoil has its own Kutta condition. The flow at the trailing edge of the mainsail nears free stream conditions. This is called the dumping velocity. The trailing edge of the jib, however, is under the influence of the flow around the mainsail and, therefore, does not return to near free stream conditions. Its Kutta condition is satisfied at a higher dumping velocity, thus reducing the possibility of flow separation. This means that the flow on the jib is improved by the presence of the mainsail. The jib helps the mainsail by reducing the peak suction pressure near the mast so the sail will not stall. These effects were first properly understood by visualizing the respective circulation flow fields. For more details see *The Aerodynamics of Sail Interaction* [13].

9. Three-dimensional effects. With our simple two-dimensional airfoils, if you draw flow streamlines starting way out in front of the airfoil and also extend them way downstream, you would find that at the extremes they are at about the same level. The circulation flow field causes some of the fluid to flow up and around the airfoil and then return to the same condition downstream. With three-dimensional wings, the circulation and lift changes along the span, and wing tip effects cause another set of vortex systems that greatly complicate the picture and creates a trailing downwash flow field. Gliders have very long wings in order to minimize the 3-D effects. However, 3-D effects are not central to understanding the basic origins of lift.

10. Physical proof? If the fluid has no viscosity, our aerodynamic theories indicate that we would have no lift and no drag. But is there any physical proof of that? **Yes!** There is a fluid with zero viscosity, **super-cooled helium** [10]. I really got excited when I learned of this for I had been saying for years that without viscosity we would have no lift. I did some research to learn more, then contacted an expert in superfluid helium at the University of Oregon to get final verification:

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To: Prof. Russell J. Donnelly
Sent: Thursday, November 04, 1999 10:14 AM
Subject: Quantum Fluids
   I am a retired Boeing aerodynamics engineer. I am
searching for information on an experiment performed
a number of years ago at Caltech, called "the
flies'-wings experiment." I learned of this in the
book GENIUS, the Life and Science of Richard
Feynman, by James Gleick (page 302).
   In this experiment "Tiny wings, airfoils, were
attached to a thin quartz fiber hanging down through
a tube. The superfluid was pulled through
vertically. A normal fluid would have spun the
wings like a tiny propeller, but the superfluid
refused to cause twisting. Instead it slipped
frictionlessly past. In their search for lighter
and lighter airfoils, the experimenters finally
killed some local flies, or so they claimed, and
the investigation became known as the flies'-wings
experiment."
   A quantum liquid may be pushing the definition
of a "real fluid" a bit, but I have thought that
this experiment might help illustrate the fact
that a fluid's friction properties are responsible
for the generation of lift. Without friction,
there would be no Kutta condition at the trailing
edge of airfoils, and therefore no drag and no
lift. Birds could not fly, airplanes would not
fly, and sailboats would not sail!

From: Russell J Donnelly
Sent: Saturday, November 06, 1999 4:43 PM
To: Arvel_Gentry
Subject: RE: Quantum Fluids
   You are right.  You might consult my book
"Experimental Superfluidity" for a
discussion of some of these matters.
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I obtained Russell Donnelly's book [11] and also studied other references on superfluidity. One very enjoyable book was by E.L. Andronikashvili, *Reflections on Liquid Helium* [12]. It was interesting that the introduction in this book was by none other than the same Russell J. Donnelly from the University of Oregon.

It can be argued that the formation of the starting vortex at the sharp trailing edge of an airfoil is a result of the very high velocities that would be necessary to flow around the airfoil and not due to viscosity. However, even an airfoil with a thick and rounded trailing edge to avoid the high local velocities still has a starting vortex and generates lift under the definite influence of viscosity and flow separation. In the case of objects with blunt trailing edges, the resulting separated flow region may be thought of as a rough extension of the original airfoil, and a starting vortex will be formed and circulation developed. "The aerodynamic lift forces and most other contributors to the forces and moments on aircraft and other bodies moving through fluids do not exist in the absence of vortices" (McGraw-Hill Encyclopedia of Science & Technology Online).

11. Other theories. Note that in this entire discussion I have not once mentioned anything about (1) the air having farther to go on the top side of an airfoil, or (2) Newton's laws of motion, or (3) about getting lift by "deflecting the air downward".

In the first case, there is nothing in aerodynamics requiring the top and bottom flows having to reach the trailing edge at the same time. This idea is a completely erroneous explanation for lift. The flow on top gets to the trailing edge long before the flow on the bottom because of the circulation flow field.

As for Newton, his laws are included within the aerodynamic theories discussed.

And on the "deflecting the air downward" idea, that is a three-dimensional effect. In our 2-D case, the circulation flow field causes the air out in front of the airfoil to be directed upward around the airfoil and then back down to about the same level as it started out in front. Yet due to viscous effects and resulting circulation, lift is generated. Yes, we can't fly with a two-dimensional wing and, therefore, are influenced by three-dimensional effects caused by a complex trailing vortex system. We can reduce these 3-D effects by using very long wings such as on gliders or the around the world aircraft design by Bert Ruttan. On an infinitely long wing, the 3-D effects are gone and we are essentially back to looking at two-dimensional airfoil aerodynamics. If we can reduce the 3-D effects, then "deflecting the air downward" is not essential to the origins of lift.

12. Multi-element airfoils. My first technical paper on the aerodynamics of sails was published in 1971, *The Aerodynamics of Sail Interaction* [13]. The primary objective of that paper was, for the first time, to properly describe how two sails, the jib and the main, worked together. It used circulation concepts to discover how the circulation flow fields about multiple sails interact causing even more air to flow on the lee side of the jib, while at the same time helping prevent the mainsail from stalling. The old "slot effect" theory was dead. That paper also made it clear that the old theories as to how slats and slots on the leading edge of aircraft wings worked were also wrong.

In 1974, A.M.O. Smith, the famous aerodynamicist at Douglas Aircraft and my boss at the time, published his Wright Brothers Lecture, High-Lift Aerodynamics [14]. AMO's paper, Section 6.3 and subsequent sections, describes how previous theories were wrong. They also provided more detail as to how circulation fields are important in properly understanding multi-element airfoils and, therefore, how our sails work. AMO's paper is also in the book, *Legacy of a Gentle Genius, The Life of A.M.O. Smith*, edited by Tuncer Cebeci [15].

However, old ideas are slow to die. A recent book on how airplanes fly [16] contains a very old and incorrect explanation for how slots and slats work ("The high-pressure air below the wing is drawn up through the slot and flows over the top of the wing. This energizes the boundary on top of the wing."). Apparently, the authors of that book, which includes a college aerodynamics professor, have not seen AMO's 1974 paper! Unfortunately, many of these old incorrect slot effect explanations also still appear in the sailing literature when discussing the flow about the jib and the mainsail combination.

13. Conclusion: Fluid viscosity is the fundamental reason why birds and airplanes can fly and why sailboats are able to sail. Fluid viscosity causes the formation of the starting vortex which leads to the creation of the circulation flow field. Understanding the characteristics of the flow about our sails (and keels) is important in adjusting the airfoil shapes for maximum performance.

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