What Goes Around Comes Around

The readers debate sailing's aerodynamics and the concept of circulation.

Last October and November, *Sailing World* published excerpts from *The Art and Science of Sails* by Tom Whidden and Michael Levitt (St. Martin's Press, 1990). The excerpts focused on aerodynamic theory, and the concepts outlined by the authors were complex. The underlying question, however, was basic: What really happens when wind and sails run into each other?

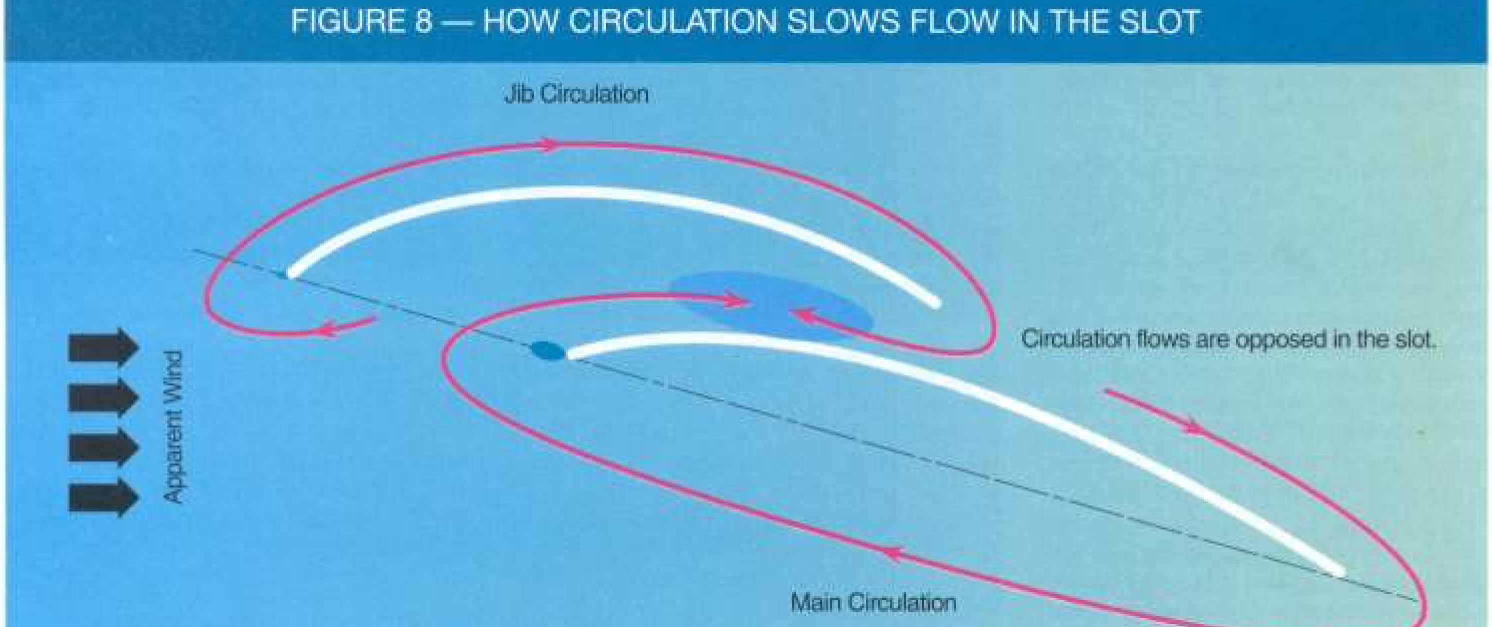
The excerpts prompted several *SW* readers to respond with long, detailed, and sometimes vehement letters disputing Whidden and Levitt's explanations. *SW*'s editors passed the letters along to Whidden and Levitt for a response; Whidden and Levitt in turn passed them along to Arvel Gentry of Boeing Aircraft, whose research and theories formed the basis of their aerodynamic arguments in *The Art and Science of Sails*.

Within a couple of weeks there arrived at the *SW* offices about 30 pages of response from Whidden, Levitt, and Gentry, covering the 16 pages of questions and postulations sent in by readers. In order to lend some form to the substance of the debate, SW's editors have arranged excerpts from both letters and responses into a kind of dialogue.

Readers should be aware that all the parties to this debate had more to say than could be published in this limited space. *SW*'s editors have had to delete a number of points, counterpoints, and supporting arguments that would have interested even those few of our readers who might not be aerospace engineers or fluid dynamicists. We've tried to apply the editorial hatchet equitably, while dodging the pitfalls of quoting central scientific theses out of context.

Tom Whidden, President, North Sails: The primary subject of these letters is the aerodynamic term "circulation," as addressed in our book, and the appropriate expression for circulation

FIGURE 8 — HOW CIRCULATION SLOWS FLOW IN THE SLOT



Contrary to the old slot-effect theory, circulation flows around main and jib tend to cancel each other in the slot. Airflow in the slot is not only slower as a result, but a good deal is diverted to the lee side of the jib (see Figure 10).

All illustrations (used both in the November 1990 issue and in this article) are by Imagetek, based on Jay Goebel's original black and white illustrations from *The Art and Science of Sails*.

and the passion it engenders is, "What goes around comes around."

In 1973 Arvel E. Gentry, then a research specialist in aerodynamics at the Douglas Aircraft Company, said in the pages of *Sail* magazine that the jib reduces the velocities that would otherwise exist on the forward lee side of the mainsail. This amounted to sailing Darwinism; the end of the standard venturi/slot-effect theory. By the time he was through with his series of articles, other pet theories used to explain sailing would fall, too. From the beginning, it was hugely controversial. It was as if Gentry had said that man had evolved from apes, the earth was round, or the earth and planets revolved around the sun.

Peter Barrett, an engineer specializing in fluid mechanics, an Olympic medalist, and sailmaker, took on Gentry in his monthly column in *Yacht Racing* (now *Sailing World*) magazine: "When I wrote an article 10 years ago viewing sails from a fluid momentum concept instead of a pressure-velocity relationship, I stated near the end that 'the average racing skipper will probably not find many applications for sailing theory in its pure form.' I feel the same way today... I am willing to state categorically that [Gentry's] future articles will do little if anything to improve directly the performance of either a given class of sailboat or a reader."

That was in 1973. Since then, Gentry's theories have translated themselves into a number of practical applications — and have improved the performance of both sailboats and sailors. Speaking personally as a sailor, sailmaker, and author, I've found Gentry's theories immensely helpful in what I do. In *The Art and Science of Sails*, Michael Levitt and I worked hard to unite the latest aerodynamic theories with the age-old practice of sailing. We are the messengers, not the authors, of the theories. It was Arvel Gentry who provided the aerodynamic underpinnings for the book, and he is quite capable of defending himself.

Steven Bellavia, Islip, N.Y: I am very surprised that you would let the two subject articles be printed without being properly reviewed by an expert or professor in aerodynamics... It appears to me... that Mr. Whidden and Mr. Levitt have a poor understanding of the concept of circulation and lift, and have unfortunately inflicted this distorted view onto your readers.

Arvel Gentry replies: I started sailing in 1967 while I was working in the Aerodynamics Research Group at Douglas [see box for condensed curriculum vitae]. I read all the books and magazine articles I could find, and was dismayed to find that all of them gave the wrong explanations for how sails generate lift. Every college textbook on aerodynamics explains that lift is caused by the circulation about an airfoil that is necessary to satisfy the Kutta condition at the trailing edge of the airfoil. Unfortunately, this is buried in a lot of mathematics that are difficult to translate into simple terms for the average sailor.

Aerodynamics is not an intuitive science. It is a very complicated subject, and even most trained aerodynamicists tend to become specialists in a few specific areas, such as high-lift systems, computational fluid dynamics, stability and control, etc. Attempts to explain aerodynamic phenomena by well-intentioned non-aerodynamicists have resulted in wrong and often humorous results. However, there is no controversy as to the generation of lift on an airfoil. This phenomenon has been well understood by aerodynamicists for many years.

In 1969 I read a technical report on high-lift systems — airfoils with trailing-edge or leading-edge devices extended, such as flaps and slats. This report talked about the "high-speed flow in the slot between the leading-edge slat and the main wing as energizing the boundary layer." The authors did not give any equations to prove this statement. This was the same type of language that I had seen in the sailing books when describing the interaction between the jib and mainsail. These kind of statements did not match what I knew about the pressure distributions on airfoils and the boundary layers about them. I went to the high-lift specialists in the research group and also talked to the designers of the high-lift systems on the Douglas transports. They all agreed that this simple explanation was wrong. They had found that as the slat is moved away from the main airfoil in increments, the velocities increased on the forward lee-side of the main airfoil, the pressures got lower (more suction), the pressure change from the leading edge to the trailing edge got greater, and the boundary layer on the main airfoil began to separate. They had discovered this in their wind tunnel tests. They had also verified this when they applied their multi-element airfoil computer programs to their high-lift systems. (Computer programs that solve the flow about two or more airfoil components that are close together are usually called multi-element airfoil programs.)

I myself did not "discover" the correct explanations for how two airfoil components interact with each other. In essence, I too have been a "messenger." Although the standard aerodynamic textbooks did not cover the subject in sufficient detail, the aerodynamic specialists in high-lift systems at Douglas, at Boeing, and probably those at most of the other aircraft companies had already discovered how two or more airfoils interact with each other. Certainly, the availability of new multi-element airfoil computer programs at that time furnished the tools to explore all aspects of the flow about complex airfoil systems. The facts were known in the high-lift airfoil business, but had not been applied to sails.

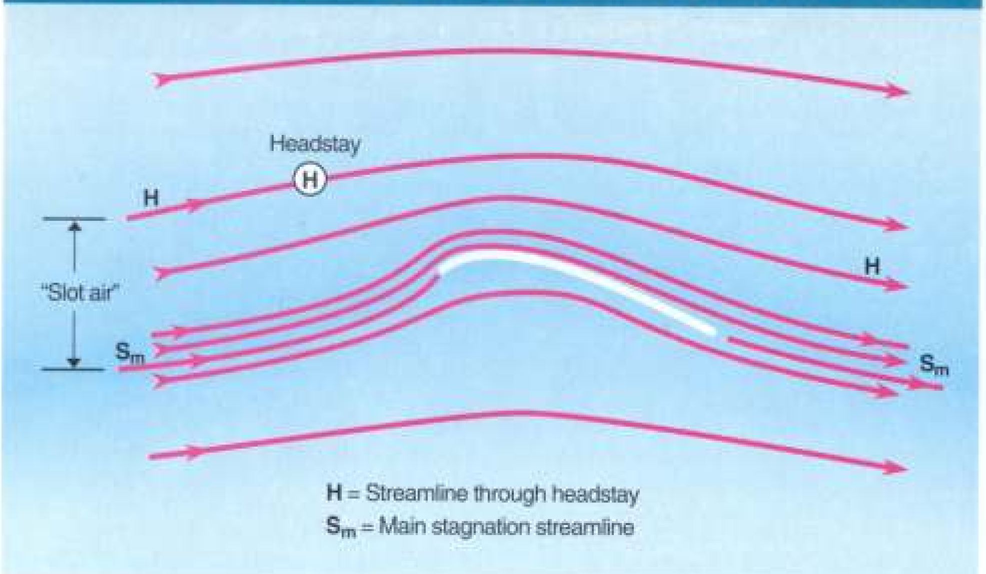
It was at this point that I decided to accept the challenge of trying to explain these complex interactions as applied to sails. Much of my spare time over the next two years was spent in preparing my explanation. I knew what I was letting myself in for. I was going to come out with the statement that all of the sailing books were wrong, and I had to build an iron-clad story.

I started with a device called an analog field plotter, which allowed me to accurately draw the streamlines about sail airfoil shapes. I felt this was important because many of the sailing books gave wrong conclusions and

Aerodynamics From the Experts

Tom Whidden and Michael Levitt's book excerpt "The Aerodynamics of Sails" (SW, Oct. & Nov. '90) was based in great part on the work of aerodynamicist Arvel Gentry, who this month responds directly to reader questions. Following is a condensed version of his curriculum vitae: Graduate of University of California, Berkeley, 1955; B.S in aeronautical engineering. Worked at NACA (pre-NASA) Flight Research Center at Edwards Air Force Base as undergraduate. Post-graduate work in flight test department at Lockheed in Burbank while studying for masters degree in Aeronautical Engineering at USC (1958). 1958-1977 worked at Douglas Aircraft Company in Long Beach, the last 10 years in the Aerodynamics Research Group under A.M.O. Smith; most of that time involved in developing computer programs used in aerodynamic analysis and design of aircraft. Moved to Seattle in 1977 to work in the Aerodynamics Research Department at the Boeing Commercial Airplane Group. Supervisor of Aerodynamics Computing Group, 1981-86; then worked for two years for Boeing Computer Services on new CAD/CAM system and on Navy contracts. Returned to Aerodynamics Research Dept. of Boeing Commercial Airplane Group late in 1989 to work on computational fluid dynamics methods (CFD) for the high-speed civil transport (HSCT). Named Associate Technical Fellow of the Boeing Company, December, 1990.

FIG. 9 — STREAMLINES FOR MAINSAIL FLOW ALONE



With main only, Arvel Gentry's calculated stagnation streamline (Sm) comes into the lower or windward side of the sail. The air between it and the streamline flowing through the headsail-less headstay (H) is the air that might reasonably be expected to flow through the slot once the jib were raised (see Figure 10).

explanations that were derived from hand-drawn streamline pictures that were obviously wrong. With the analog field plotter the effects of ignoring and then including the trailing edge Kutta condition could be easily simulated. I analyzed a great number of sail shapes and combinations. The analog field plotter was helpful in arriving at a number of streamline drawings that, when viewed in sequence, not only illuminated how lift is generated, but also showed the principles of how the jib and mainsail interact.

The streamlines were only part of the story. The next step was to apply a multi-element airfoil digital computer program to the final airfoil test sequence arrived at with the analog field plotter. The computer calculated even more precise streamlines, and also gave the resulting velocities and pressure distributions about the sail shapes. This was followed by a series of water channel studies at Long Beach State College. Some of the pictures are shown in Whidden and Levitt's *Art and Science of Sails*.

Up to this point all of my work had been done assuming two-dimensional airfoils. This is standard practice in aerodynamics. The next step was to study the effects of finite span, the three-dimensional factors. I made a few runs of full sail shapes on a three-dimensional lifting surface computer program, and the results verified all of my two-dimensional studies.

The final step of my research was to go sailing. I put about 500 tufts on my jib and main to observe the separation patterns, and used a special pressure probe attached to a telescoping pole to study the flow. A device that generated a continuous stream of soap bubbles was also attached to the pole and used to visualize the flow patterns about the sails.

After two years of work I was able to show in detail how the jib affected the main, how the main affected the jib, and the effects of changing the trim of the two sails.

The next step was to publish my results and subject them to the review of my peers in the scientific field. My paper, "The Aerodynamics of Sail Interaction," was presented in 1971 at the American Institute for Aeronautics and Astronautics (AIAA) Ancient Interface Symposium. Over the past 19 years I have not received a single criticism of the theories from anyone experienced in the aerodynamic high-lift business.

Starting in April 1973, I wrote a series of 11 articles on sail aerodynamics for *Sail* magazine. That year I was also asked by David Pedrick to conduct some research on mast-shape designs for the 12-Meter *Courageous*. The same tools and methods that I had used in my sail theory were applied to this problem and produced a new mast shape that when tested demonstrated improved aerodynamic flow. This mast was used to defend the America's Cup in 1974 and again in 1977. This design was also used on *Freedom* in 1980, and a slightly modified version was prepared for *Liberty* in 1983. The important part of these design studies was that the flow velocities on the mast are reduced by the jib, and that the optimum mast shape must be designed with both sails and all of the detail of the flow present (not just by studying a mast by itself in a wind tunnel).

In 1975 A.M.O. Smith published his famous "High-Lift Aerodynamics" paper. This paper gave a very complete scientific description of just about every aspect of high-lift aerodynamics and the slat (slot) effect, and should be studied by anyone doubting the material in my sail-theory paper and articles.

In 1976 C.A. Marchaj requested permission to use all of my material in his book, *Aero-Hydrodynamics of Sailing*. In the revised 1988 edition, Marchaj states: "Many problems concerning the interference between a mainsail and a jib were clarified by A. Gentry who explained correctly, for the first time, the jib-mainsail interaction effect."

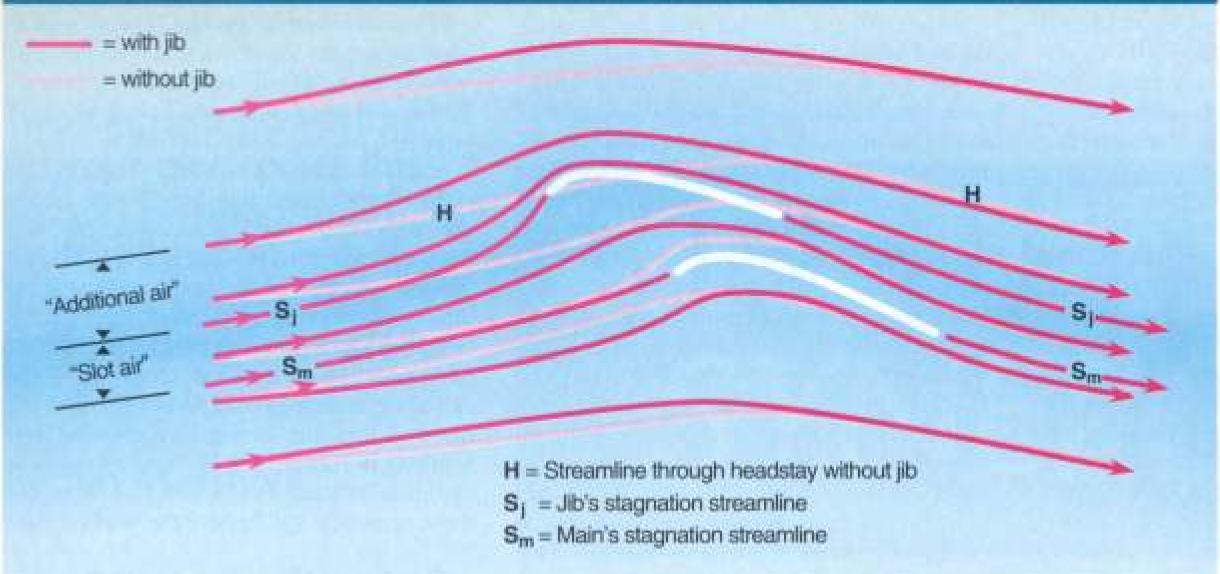
The correct explanation for the jib-mainsail interaction has by now been published in a number of other references, and most important, is backed up by a number of technical papers and wind tunnel tests. Over the years a number of sailmakers, sailing instructors, and college instructors have asked to use my material in their work and classes. The material has appeared in several different languages.

There is no longer any controversy over the slot effect and how sails work, any more than there are arguments that the earth is flat. However, while the physics and theory may not be in question, the best way of explaining these facts in simple terms is always open to discussion.

Bellavia: Since accurate in many areas, the articles are more misleading than incorrect, particularly [Figure 8] of the second article (November 1990)... To try to explain what circulation is or "looks like" would be equivalent to trying to show what the inertia of a rotating body looks like... Inertia is simply a property of a body, dependent on the mass of that body and the distribution of that mass [just as] circulation is the property of an airfoil dependent on the velocity field around the foil and the distribution of that field. The important thing is to understand how inertia affects the rotation of a body, or in this case, how the circulation affects the lift on the airfoil, and not what it might look like if you could see it. This is why I find Figure 8 very disturbing. I have actually had a sailing friend call me and ask why he has never noticed the windward telltales flowing in the opposite direction of the leeward telltales if this is how the air actually flows around the sail!

David Mulkey, Las Vegas, Nevada: ...[regarding the slot effect] the authors are drawing diagrams, then using them to prove "the new view." First, if Sm is a "continental divide," how can it shift from center to leeward or windward? Compression of streamlines would be a more effective illustration, which would show increased velocity.

FIG. 10 — FLOW OF STREAMLINES WITH MAIN AND JIB



With main and jib, the mainsail's stagnation streamline has shifted up, or to leeward, showing that the presence of the jib causes the main to sail in a header. The jib's stagnation streamline (Sj) moves to windward (lower) of the old headstay streamline (H), showing that much less air is going through the slot than under main alone (Figure 9). Velocity in the slot is not speeded up by the presence of the jib, but the extra air going to leeward of the jib is moving at increased velocity and providing the jib with a lift!

Venturi, or slot effect. My telltales on the jib leech don't do what Figure 8 suggests would happen — flow into the slot...

Gentry replies: The lines and arrows in Figure 8 are not streamlines. They simply show the clockwise direction of the circulations about each airfoil. If you did calculate the detailed velocity vectors due to the circulations all around the airfoils, and then added these vectors to a similar set of velocity vectors that you would get for flow calculated about the airfoils without circulation, you would arrive at a complete velocity vector picture of the entire flow field (see p. 121 of R. Shevell's book, *Fundamentals of Flight*).

The streamline diagrams shown in Figures 9 and 10 in the November article were based on my 1971 AIAA technical paper. The lines divide the flow that goes on each side of the airfoils, and are called stagnation streamlines because these lines actually touch the airfoil surfaces, and the velocity at this precise point is zero. The location and shape of the stagnation streamline changes every time a change is made in the flow conditions, such as the addition of another airfoil, or a change in the angle of attack. These lines were not simply drawn by hand; they were calculated precisely by a digital computer program. The computations assumed that the boundary layer thickness displacement effect is negligible, which is a good assumption for this study. Under this condition the computational results produced by the program are exact. For some results with boundary layer thickness and separation effects included, see my paper, "The Application of Computational Fluid Dynamics of Sails" (1988).

Bellavia: [With regard to the slot effect] I would like Mr. Whidden and Mr. Levitt to conduct the following experiment: Place an air velocity meter (turbo, anemometer, etc.) in the center of the slot of a sailboat equipped with a knotmeter, a masthead-mounted apparent wind velocity meter, and a furling jib (away from the spreader so as to avoid the effect of the spreader itself). Keeping the jib furled, sail closehauled, trimming the main for attached flow, and record boatspeed, apparent wind velocity, and the "slot velocity." Now unfurl the jib, retrimming as necessary for attached flow, and record the parameters. What they should find is that Daniel Bernoulli (along with the laws of continuity, and conservation of momentum and energy) are indeed correct. The slot velocity increases with the jib, and in greater proportion than the increase in apparent wind velocity caused by the increase in boatspeed from the extra sail.

Gentry replies: Mr. Bellavia's test plan, with all of the sail retrimming and changes in apparent wind angle, will not help much in understanding the slot effect. He has too many variables changing. I suggest that the experiment be conducted in reverse order: Tape several horizontal rows of short telltales on the lee side from the mast to the mainsail leech. Start with the jib flying and the boat sailing closehauled. Under steady wind conditions maintain a constant heading. Measure the surface velocities on the forward lee side of the mainsail. Next quickly retract the jib only part-way and measure the mainsail pressures again. If this takes too much time, use the engine slightly to keep the same boatspeed. What you will see as the jib is moved away from the mainsail is that the velocities on the forward lee side of the mainsail will increase, not decrease as the old Venturi theories would imply. As the jib gets farther away, the increase in mainsail surface velocities over the forward lee part of the sail mean that there will be a more rapid increase in pressure as the flow slows down toward the trailing edge. This increase in pressure will cause the flow to tend to separate and eventually cause the mainsail to stall. With modern digital multi-element airfoil computer programs it is possible to study each of these effects one at a time, without having too many variables changing at once. I suggest that Mr. Bellavia study A.M.O. Smith's "High-Lift Aerodynamics" paper.

Peter R. Fenner, Richardson, Texas: [In the October 1990 excerpt] I find a statement which implies that if fluids did not have viscosity there would be no lift. I find this statement to be misleading, if not totally wrong. Much of my understanding of why sails work comes from an article in the predecessor of *Sailing World* [*One-Design & Offshore Yachtsman*], published in the 1960s by Peter Barrett. As with many physical phenomena, there is more than one way to mathematically describe the forces involved. Peter, being an engineer, explains the force created on a sail as a result of changing the direction of the air mass flow. Under that view, only a fluid flow with no mass would produce no lift.

Gentry replies: I suggest that Mr. Fenner study chapters 8 and 9 of the famous book by Richard Von Mises, *Theory of Flight* (1945 and 1959). He will see that the key piece of knowledge that first allowed scientists to calculate the lift on an airfoil was the Kutta condition (in 1902). The Kutta condition stated that there must be a finite velocity at the trailing edge (Von Mises, p. 201). The physical reason why this is true is that the viscosity in the air will not permit an infinite-speed flow around an airfoil trailing edge, as explained in the Whidden and Levitt articles. Without viscosity the Kutta condition would not exist; there would be no circulation field to add to the non-lifting onset flow, and there would be no drag and no lift.

Charlie Small, Worthington, Ohio: [excerpts from a 10/18/90 letter to *SW*] ...The theory of rotary circulation around an airfoil reminds me of the medieval astronomers' attempts to explain the motion of the planets. They started with the assumption that the earth was the center of the universe. The theories and mathematics became more and more complex but they failed because they did not examine their basic assumption... The fact that, after all these years, there is still any question about how a sail works suggests that somewhere we've started with some wrong assumptions. One of these assumptions is that a sail is the same thing as an aircraft wing and that data from wind tunnel tests is applicable to a sail.

I have trouble with this assumption on two counts. First, an aircraft flies by putting energy into the air, while a sailboat must take energy out of the air, and second, that the air flow conditions are similar. In wind tunnel tests, bathtub tests, and in actual flight the true wind and the relative wind are coming from the same direction. On a sailboat the true wind and the relative wind (when going to weather) are about 15 degrees apart. This creates a set of conditions that have minimal similarity to an aircraft.

To dispense with all the mathematics and theorems, the simple fact is that the thing that makes a sailboat go is a difference in pressure from one side of the sail to the other. On the weather side the air... can no longer continue in its flight path, so it is piling up against the sail. In this pile-up the momentum of the wind is converted into positive pressure (which pushes the sailboat forward and also produces heel).

On the leeward side the air wants to continue on its original flight path and speed, but to do so would create a void, so it responds by expanding. This expansion serves to fill the void and the reduced pressure "pulls" the sail along.

Since air (or any fluid) will tend to move from a higher pressure region to a lower pressure region, there will be a tendency for flow to occur around the foot, leech, and luff of the sail, which is easily demonstrated by using telltales. So what we have is a mound of high-pressure air on the weather side of the boat and low-pressure (expanded) air on the lee side.

It's not difficult to imagine the effects that this produces. First the mound of high pressure to windward is trying to flow into the lower pressure area behind the sail, thus creating the "upwash" effect at the luff that Whidden refers to. Also the increased windward pressure is squeezing air out through the slot between the main and the jib, which creates an eductor [*sic*] effect like a paint-spray gun (i.e. the flow through the slot tends to pull air off the lee side of the jib to join its moving stream), which gets the two airstreams moving at the same velocity. So if there is acceleration of the air in the slot it is due to the high pressure to windward. This is demonstrated in high winds by the backwind bubble along the luff of the main, which cannot be avoided if the boat is to move well.

[excerpts from a 9/13/90 letter to *SW*] ... When the air has no energy (velocity) the boat does not move, but when the wind is blowing the air has momentum energy and the boat reacts well. The force that drives the boat comes from converting wind-speed energy into pressure acting on the sail. The more efficient the process, the less speed energy is left in the air when the boat passes. Thus the idea that the wind speeds up while it travels around the sail is totally contrary to what has to happen to get energy out of the air.

... Viscosity, boundary layers, and Bernoulli have little to do with what is going on, and if anyone knows how to regularly achieve the Kutta condition I hope to hear from them. My mainsail leech streamers always want to bend around the lee side and stream forward.

Gentry replies: Fascinating! I've never heard quite these arguments before. Every one of Mr. Small's statements is wrong — so wrong that I almost think he's pulling our leg... Apparently Mr. Small has never seen a small airplane come in for a landing in a crosswind... The lift and drag that an airplane or our sails experience are a result of the apparent wind that is a vector combination of our movement over the earth plus the moving air. The airplane in a crosswind, the sails on our boats, an airplane or sail rig in a wind tunnel — all are governed by the same laws of fluid dynamics.

As for air "piling up" or "expanding," or having an "eductor effect" in the slot, I'm sorry, Mr. Small. Air at the speeds that we sail in is virtually incompressible. Every cubic inch of air on the windward side of a sail has the same density as a cubic inch on the leeward side. Air does not "pile up." It slows down, or speeds up, according to the well-understood laws of fluid dynamics. The result is that the flow is as described in the *Sailing World* articles, and not by any "paint-spray gun" effect.

Mr. Small, the backwind bubble along the luff of your mainsail is caused by the fact that the jib has reduced the velocity and increased the pressure so much in the slot that the pressure on the lee side of the luff is higher than the pressure on the windward side. And your leech streamers that "always want to bend around the lee side and stream forward" are only trying to tell you that the air flow on the lee side of your mainsail near the leech is separated, causing reduced lift and more drag.

Mulkey: [regarding how the jib affects the main] If the streamlines were properly drawn, they would be apart at the luff of the jib and together in the body and leech (to windward, or in the slot), resulting in thicker boundary layers pointing forward and thinner ones pointing to leeward. Conversely, the closer streamlines would be at the luff of the main to leeward, decreasing pressure and resulting in forward lift. With a keel in place, net lift is forward. This is how sails work, for those of us who still believe the world is flat.

Gentry replies: First, Mr. Mulkey, you clearly do not understand how boundary layers work. Second, you must have gotten your information from some of the old sailing books with streamlines that were simply drawn by hand and not based on any detailed analytical or test work. The detailed velocity field and resulting pressures about the jib and main depend upon the shape of the sails and the angle of attack. The shapes and conditions for the detailed calculations that produced Figures 9 and 10 are good representations of actual sails. A boat trimmed for windward sailing will have the jib stagnation streamline coming in right at the luff wire, or slightly on the windward side if it is driving off a bit. This will cause the peak velocities and suction pressures to be the highest over the forward part of the sail. The streamlines on the aft leeward side of the sails must slowly diverge from the sail surface, since the flow must slow down to finally match the windward-side speeds and pressures at the leech. All of this has been verified by detailed computer calculations, by wind-tunnel tests, and by actual measurements afloat.

Whidden—Summary: What goes around comes around. In the 1960s Peter Barrett wrote an article in *One-Design & Offshore Yachtsman* that stuck firmly in Peter Fenner's mind. In the 1970s, Barrett dismissed Gentry's theories as possibly true but ineffectual. Back then Michael Levitt, my co-author, was an editor at *Yacht Racing*, and Barrett was vice-president of North Sails, where I am now president. Last year Michael Levitt and I relied on Gentry to provide the foundation for the aerodynamic theories discussed in our book; excerpts from which were published in *Sailing World*. Today, the excerpts have provoked several readers, including Peter Fenner, citing Peter Barrett, to argue the same points in the pages of the same magazine. Now that's circulation!