How Sails Really Work

"The airflow diagrams in the sailing books are wrong!"

By Arvel Gentry

SAIL Magazine, April 1973

Arvel Gentry is a research specialist in transonic, supersonic and hypersonic vehicle aerodynamics at the McDonnell-Douglas company. He is also a successful ocean racing skipper and an amateur photographer.

So you think that you know how sails work: the slot effect, backwinding, stalling, and all that stuff. You've learned these "facts" of sailing from books and from magazine articles by the experts. Well, read on. You are in for a few surprises.

All the books give about the same explanation for how the main and jib work, and about slot effect. However, C.A. Marchaj in his book, *Sailing Theory and Practice,* states that "the interaction between sails is still a controversial subject and not fully understood." As a research aerodynamicist, I became very interested in this subject and set about conducting a study to, at last, resolve this problem.

In my research, I made use of three important tools. First, the Analog Field Plotter, a device for accurately determining the streamlines about any airfoil shape. Second, a new sophisticated computer program that is capable of calculating the pressures and air speeds on and about any airfoil combination. And third, a water channel where the flow patterns about airfoil shapes, including separation effects, can be observed under controlled conditions and photographed. The results shown in this and the articles that follow are, therefore, based on well-proven aerodynamic analysis methods.

My research has revealed the astounding fact that all the explanations in the sailing books on the interaction between the jib and main are wrong. In fact, if the air really went like many of these explanations say, then the resulting effects on the sails would be exactly the opposite of what is claimed!

It will take a number of articles to present the complete results of the research that has led to these conclusions. However, I like to think that each one of you will share with me a little of the excitement that I experienced when all the pieces of this puzzle started to fit together for the first time: the puzzle of how sails really work, how they influence each other, and most important, how to demonstrate clearly these effects. In this series, I will try to avoid unnecessary mathematics and technical terms; and though each article will deal with a particular aspect of the problem, a thorough understanding of it will depend upon the information contained in previous articles.

To understand fully the interaction of a jib and a mainsail, we must have correct information in a number of areas: (1) we must know how the air flows about the jib and mainsail when they are used separately, (2) we must know where the air flows when the two sails are used together, (3) we must know how the resulting changes in airflow affect the pressures on both sides of the sails, and finally (4) we must know how the air very close to the surfaces of the sails (the boundary layer) is affected by the changes in airflow and the changes in surface pressures.

Until recently, there has been no accurate way of obtaining all of this information. Actual test measurements are difficult to make, and when they are made, it is difficult to separate the effects of what happens in the airflow away from the sail surfaces from what happens in the boundary-layer air very close to the surface. The only approach in the past was to use "logical thinking" and "educated guesswork." However, the proper tools are now available to solve this problem and to provide a clear demonstration of the interaction effects.

As the first step in understanding how the air flows around sails, one must be able to draw streamlines that show the paths that the air takes. The concept of a streamline is very simple and we need only to look briefly at the accurately drawn flow about a single sail (Fig.1) 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, marked (S) in Figure 1, is the streamline that separates the airflow that goes on one side of the airfoil (the lee or top side) from the airflow that goes on the other side (the windward or bottom 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. The stagnation streamline is very important in understanding the flow about sails.

Once a complete set of streamlines is determined, we can make some very useful judgments as to how wind speed and pressure vary in the flow field about the airfoil. The relationship between speed and pressure is given by an equation called Bernoulli's equation. The Bernoulli equation shows how the pressure of the air and the speed of the air are directly tied together.

Wherever airspeed increases in flowing around the sails, the pressure goes down. Where the airspeed slows down, the pressure will be found to increase. Wind, well out in front of the boat, may be blowing at a certain constant speed (relative to the boat). However, when the air gets closer to the boat, its speed and direction begin to change.

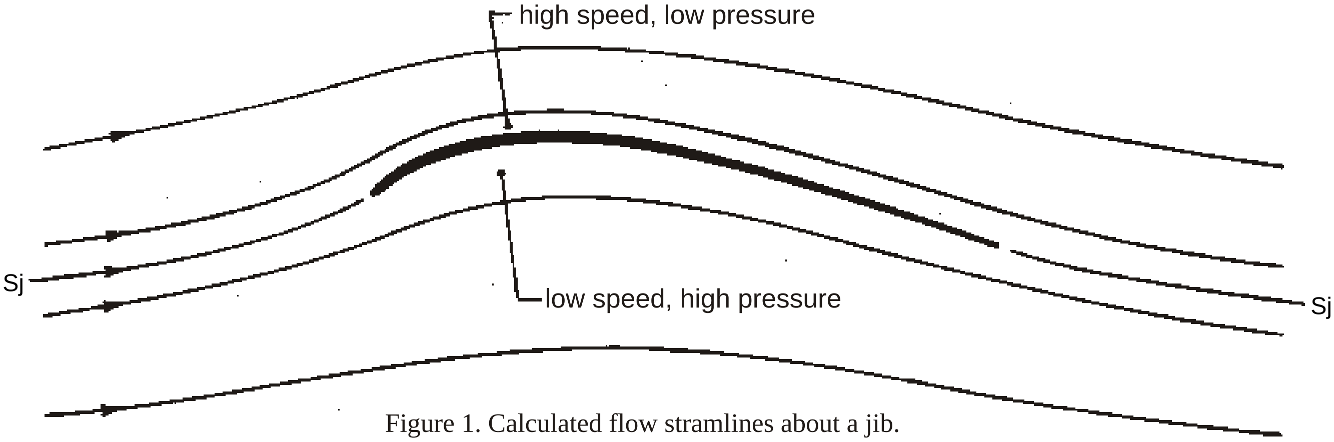

Figure 1. Calculated flow stramlines about a jib.

If we look at the streamlines in Figure 1, we see that sometimes they get closer together and at other times they spread farther apart. It is quite obvious that when two streamlines get close together or close to the airfoil surface, the air will have to speed up to get through the smaller area and the air pressure will be lower. Where the streamlines get farther apart, the air slows down and the air pressure becomes greater.

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. The sailing literature is full of these types of drawings. Unfortunately, they are just that, drawings of where the particular author *thinks* the air goes.

Figure 2 is typical of the airflow diagrams used in the books to explain the slot effect. There are a number of things wrong with this drawing, but I'll just mention the more obvious ones here. First, note that the stagnation streamline for the mainsail (S_m) shows a slight amount of upwash (bending of the streamline leeward to meet the sail). The air knows that it is approaching the sail and it starts to change direction even before it gets to the sail.

However, in Figure 2 the stagnation streamline drawn for the jib has no upwash at all. Apparently the wind knows that it is approaching the main but it doesn't know about the jib! That cannot be and this is the crux of the problem. The streamlines for both the jib and the main must show the proper effects of upwash. This cannot be determined by guesswork.

However, that's not all that is wrong with Figure 2. Look at the streamlines marked A and B on each side of the stagnation streamline for the main. Out in front of the sail, the A and B streamlines are the same distance from the stagnation streamline so the airspeed is the same in both tubes of air; but by the time they reach the leech of the main, the lee streamline, A, is closer to the leech than is the windward streamline, B. We would, therefore, have high-speed, low-pressure air on the lee side of the leech stagnation streamline, and air with a lower speed and higher pressure on the windward side.

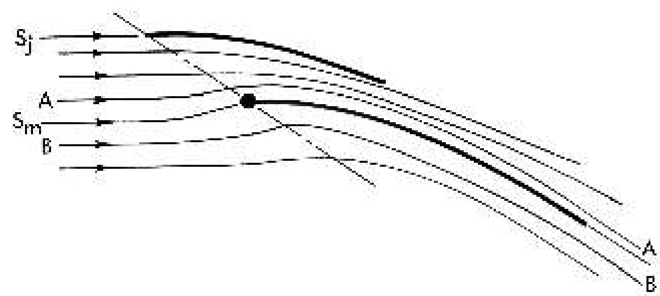

Figure 1. Typical wrong slot-effect drawing.

This situation cannot exist in the real flow about a sail. Instead, the entire flow about the sails would adjust itself so that the airspeed and pressures are the same on both sides just downstream of the leech. The streamlines should be equally spaced on both sides of the leech if they are equally spaced out in front of the sail.

Another important requirement is that the spacing of streamlines right at the leech of the main must be the same as the spacing of these streamlines out in front of the sails. In other words, the airspeed at the leech of the main must be about the same as the freestream speed. I am assuming the sails are properly trimmed and have no flow separation. You will see the reasons for this leech recovery-speed requirement in a later article (and also why it does not apply to the jib).

Check some of the drawings in your own sailing books. See whether the streamlines at the leech are drawn properly. Also, check the stagnation streamlines leading to both the jib and main for upwash. None of the drawings I have seen has both the upwash and leech streamlines drawn properly. Since these erroneous streamline drawings do exist, it is easy to see why the venturi explanation of the slot effect has persisted for so long (that is, a wide stream of air seems to enter the slot between the sails and simply speed up as the slot gets smaller).

Figure 3 shows a very accurately calculated set of streamlines about a main and jib combination. Contrast it with Figure 2. Note that the stagnation streamline for the jib (Sj) turns leeward as it approaches the luff and that it has more of this upwash than does the stagnation

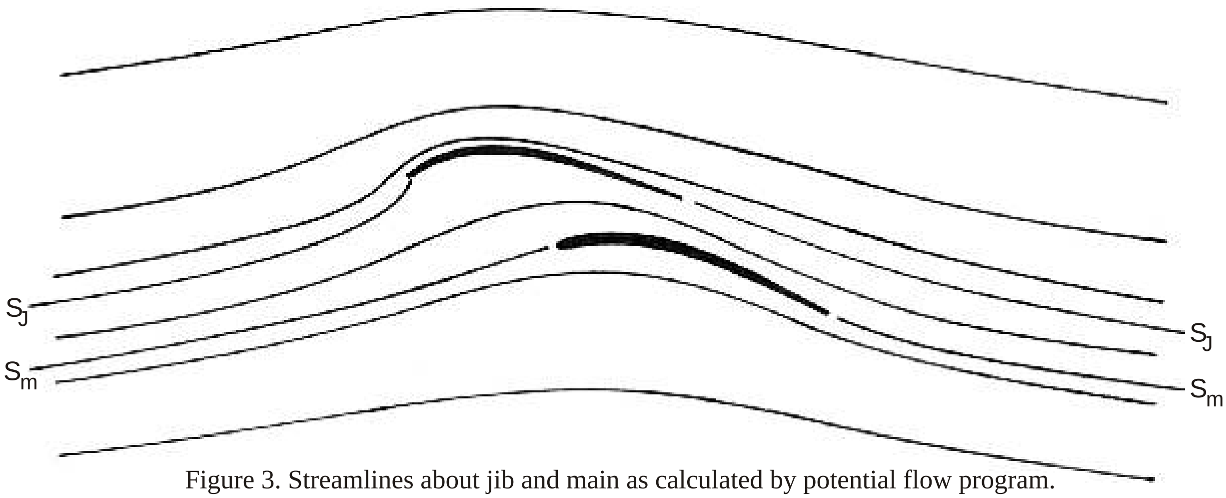

Figure 3. Streamlines about jib and main as calculated by potential flow program.

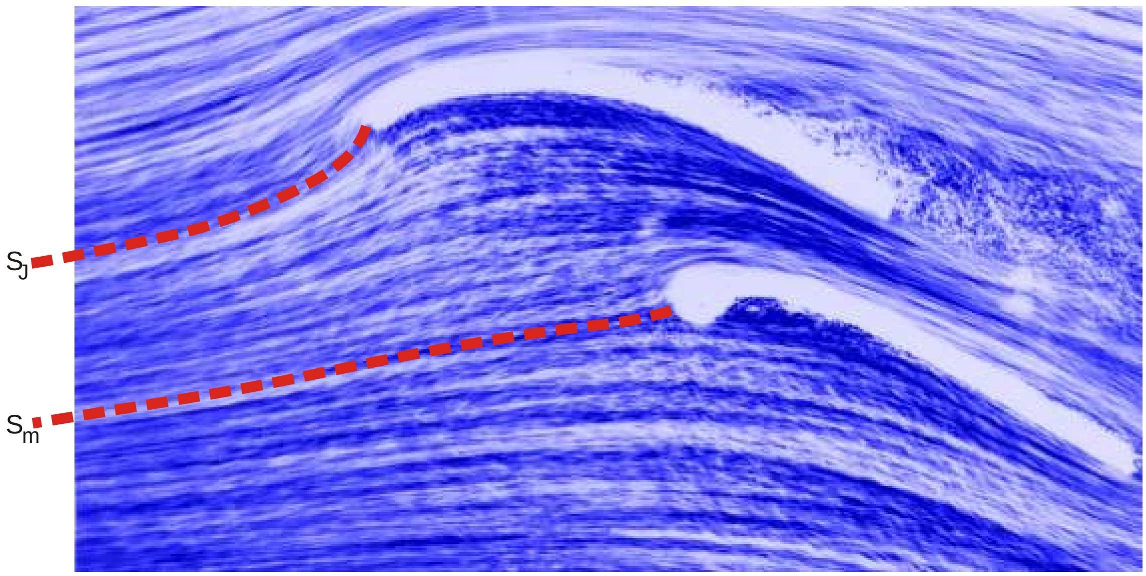

Figure 4. Water channel photograph of flow about jib and mainsail airfoils.

streamline for the main (S_m). The stagnation streamlines for the jib and main actually spread farther apart as they approach the space between the luff of the jib and the mast.

This is also substantiated in the water channel photo shown in Figure 4, and it is a very important point. It means that the air that is going to go in the slot between the two sails actually slows down as it approaches the sails. It slows down and only starts to speed back up as it approaches the leech of the jib.

This means that the old explanation of the slot effect in the sailing books, the venturi principle, is actually wrong. The slot does not act as a giant venturi with the air approaching the sails and then just speeding up in a high speed jet of air in the space between the sails (as Figure 2 erroneously indicates). Instead, the air first slows down and then is speeded back up in the slot.

Now this may at first seem like a trivial difference, but it is a very significant factor. The stagnation streamlines for the main and jib show how the air approaches the sails, how much air goes in the slot and, most important of all, how much air is caused to flow on the lee side of both the jib and main.

In a later article, we will see that the final airspeed in the slot near the leech of the jib is only about what it would be if the jib were not even present and the flow on the main does not separate. Exactly why the air behaves in this manner and how it affects the boundary layer will be described in the coming months.

Addendum to *How Sails Really Work*

This article appeared in *SAIL* Magazine in April 1973. I had thought a lot about how my *SAIL* series might be viewed by the expert sailors. These people were the authors of sailing magazine articles and books that frequently said that “It is important for every serious sailor to understand the basics of how sails work.” Now here I was about to point out that much of what they were saying was wrong.

I was well prepared to argue the technical aspects of my findings (I had reviewed my work with several co-workers including my boss, the famous aerodynamicist, A.M.O. Smith). However, I was not prepared for the reaction that I got from Peter Barrett. Barrett had competed in three Olympics and had won a silver in the Finn class and a gold with Lowell North in the Star. He wrote a monthly column called CARTE BLANCHE for *Yacht Racing* magazine and was quick to respond to my first article.

CARTE BLANCHE, by Peter Barrett
Yacht Racing Magazine, June 1973

Science and Racing

It is interesting to see how little the giant steps taken in expanding our reservoir of scientific knowledge have affected yacht racing. Although aerodynamics has very nearly become a science (40 years ago it was an art), and we have specialists like the author of a recent article in *SAIL* magazine, Arvel Gentry, who is a “a research specialist in transonic, supersonic, and hypersonic vehicle aerodynamics,” or like Jerry Milgram of MIT, whose Cascade sent the rule makers back to the drawing board, the sport of racing sailboats has in reality changed very little.

Yacht design may have advanced . . . certainly recent designs win over older ones, but they are racing under the IOR, a new rule, and the frequently heard rationalization that “new designs are faster than old ones, and boats would have been out-designed had we remained with the CCA rule” ignores the 10-year reign of the Cal 40, or the fact that the hottest boat in MORC may well be the Cal 25, a design which must be nearly 10 years old. So one must wonder whether designers are really able to create yachts which get from here to there faster than their counterparts of a decade or two ago, given a range of wind and sea conditions.

Also, if one looks at small boats, progress is questionable. The Snipe sails about as fast for its size and weight as any boat; although Lasers beat Sunfish in light and medium air, the reverse happens in a strong breeze; few if any modern designs can compete with either the Star or Thistle in light air, and 110s are able to give the much more sophisticated Flying Dutchman fits in heavy air.

Progress in sails and rigs is slow as well. The adoption of Dacron and aluminum have been real advances in speed and ease of maintenance, but improvements in the basic concept of a complicated and sophisticated rig like a Star or Flying Dutchman have been few in the past several years.

The primary reason for the perseverance of the status quo is the relatively high level of development attained many years ago, despite limited knowledge and primitive research tools. A Star or Snipe of the late 1930s was a pretty sophisticated wind-bending machine.

Although I have been trained as an engineer, specializing in fluid mechanics, I find my reaction to exciting claims in the field of air or water flow is usually a negative one. I wonder how the Federal Trade Commission can allow the advertisements for paints or bottom coatings which “improve speed five to 10 percent”. If any bottom treatment could consistently improve speed by two percent over a smooth fair untreated bottom, it would be on every racing sailboat in the world. Although Marchaj's book on the aerodynamics of sailing is far more detailed and accurate than Curry's, published in1925, I suspect that Curry's may do more for 95 percent of the world's yacht racers than Marchaj's. 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.

The best sailors, in general, are not scientists. Paul Elvstrom, Bud Melges, Rodney Pattisson; these people attack sailboat racing physically and emotionally more than they do scientifically. Although Pattisson's FD rigs are as aerodynamically clean as any rigs in use on any boat today, it is a result of a commitment to detail carried to the ultimate, and not any unique aerodynamic concepts. All of us know that windage and drag are bad, even if we were lucky in escaping high school science. Few of us practice our knowledge as thoroughly as Rodney.

Another step in a long line of published material which serves more to provide fireside conversation than to win races appears, as mentioned above, as the first of a series in *SAIL* by Arvel Gentry. I confess to being interested, although skeptical, when I read the editor's comment that “it is both disturbing and exciting to be told that all the books that describe how sails work are wrong . . .”. The article's subtitle continued the theme: “the airflow diagrams in the sailing books are wrong!” I was disappointed, but not surprised, to find that the sum total of the “astounding fact” in error in all the books is that the stagnation streamline for both jib and main is rarely drawn with enough upwash, and that the authors of material on the subject haven't thought it necessary to discuss the air flow on the windward side of the jib before reaching the mast, and particularly that the air isn't being accelerated in this region. Mr. Gentry promises more but I am willing to state categorically that future articles will do little if anything to improve directly the performance of either a given class of sailboat or a reader. In fact, by implying that a major error in everyone's thinking about air flow past sails is about to be corrected (and thus we will all, of course, be able to better utilize this air flow and race more successfully). I believe that a disservice is being done the reader.

Few successful racing skippers, as mentioned above, pay much attention to the scientific articles. The skippers who do worry about the technical aspects, pouring over Marchaj on countless cold winter nights, are rarely successful at winning races. And those who make the mistake of believing that a thorough analytical study of sailing, carried out by a research scientist in fluid mechanics, must lead to better racing performance (if only because our historical approach has so lacked in rigorous scientific approach) are doomed to doing the worst of all on the race course. The worst, that is, until experience shows them that sailboats are already perfected well past the point of, say an F-11 jet airplane, and that the major determinants of success are not turbulators on the mast, or slots in the spinnaker; but good starts, consistent tactics considering variants in wind direction and speed, a cool head, and a well-trained crew.

I am not suggesting that Mr. Gentry is the successful scientist being an unsuccessful sailor pictured above. I enjoyed his article, look forward to the coming ones, and am sure that he is a good racing sailor (not because he has discovered that the air flow between jib and main slows before it speeds up, however). He undoubtedly had nothing to do with the attempt to present his articles as a major revelation contradicting the explanation of sailing to windward given in all the books.

Letter to Arvel Gentry from *SAIL* Magazine, May 30,1973

Dear Arvel,

You may already have seen Peter Barrett's latest column in the June issue of *Yacht Racing* but if you haven't I'm enclosing a copy.

I have no real argument with any of his comments; he's entitled to his opinions, except for the last few lines of the piece. Whether Barrett wrote them or they were added by the boys in the editorial department is not the issue here.

What is important is that we consider the series of articles you have written, and we are publishing, some of the most important research that has ever been presented.

His comments it seems to me are uncalled for and in my opinion attempt to backbite your findings. I don't care about the veiled reference to SAIL, but I care very much about how it relates to your own work. The fact is, it will be a major revelation to many of the readers and I think you too feel very strongly about this. At least that is what your own writing says.

You might want to write them a letter correcting them on this point.

Curiously in the same issue Ted Jones calls for more research in general. Confusion apparently reigns supreme!

With best wishes,
SAIL
Charles E. Mason III
Associate Editor

Yacht Racing, September 1973
Arvel Gentry Comments

Sirs:

In his June *Carte Blanche* column, Peter Barrett commented on my series of articles on sail aerodynamics in *SAIL* Magazine. After reading only the introductory article, Mr. Barrett wrote that he was "willing to state categorically that future articles will do little if anything to improve directly the performance of either a given class of sailboat or a reader. In fact, by implying that a major error in everyone's thinking about air flow past sails is about to be corrected (and thus we will all, of course, be able to better utilize this air flow and race more successfully), I believe that a disservice is being done the reader."

In fact, my articles do refute the old theories on how two sails work together and the slot effect, and they do explain the slot effect in a correct and iron-clad manner. This, it seems to me, is no disservice to anyone, particularly the readers of my articles. If Mr. Barrett will just wait for the rest of the articles he will see this.

Further, I did not imply that Mr. Barrett would, according to him, "be able to better utilize this air flow and race more successfully." Whether or not my articles will help a reader is not for Mr. Barrett to decide. Most sailors I know are interested in any new idea, even if it is of a scientific nature. My articles were prepared for those who are interested in learning the proper explanation for how sails work.

Mr. Barrett also had the temerity to say that, "The best sailors are, in general, not scientists." Yes, the best sailors are not scientists, or plumbers, or dentists, or teachers for that matter. They are people who, regardless of their original occupation, are somehow able to devote an exceptionally large amount of time to the sport as compared to the average sailor. Being originally involved in science, or engineering, or any other profession has little to do with it.

Mr. Barrett also stated that I might be a "good racing sailor (not because he has discovered that the air flow between jib and main slows before it speeds up, however)." Again he is wrong. My findings have been of great help in understanding my sails and their trim to improve boatspeed. And in any case, a correct explanation of how sails work should be of more help to the average sailor than old incorrect theories!

Finally, Mr. Barrett stated that I "undoubtedly had nothing to do with the attempt to present my articles as a major revelation contradicting the explanation of sailing to windward given in all the books." Barrett is totally misinformed on this point also. The editors, if anything, toned down my own enthusiasm for the subject. Barrett is not only wrong, he's certainly not entitled to make such a statement.

My confidence and enthusiasm on the material in my series is based on considerable research over the past two years and it is reinforced every time I pick up a new sailing book or magazine article and find them so totally inaccurate from an aerodynamic standpoint.

I suggest that Mr. Barrett read the entire series and if he then wishes to argue some technical aspect of my studies, fine. But he has no right to take a "so what" or "sour-grapes" approach after having read only the first introductory article. It will be the open-minded experts, the serious students of sailing, and time that will be the proper judge of my ideas, not Mr. Barrett alone.

Barrett's Reply *Yacht Racing* September 1973

Mr. Gentry objects to my comments on his series exploding all the old myths about air flow past sails. That is his right, as it is my right to object to headlines and editorial comment implying that at last the real, the true, the irrefutable words about sail aerodynamics are about to be presented when his series, in my opinion, adds very little if anything to the state of the art. My credentials aren't untouchable, but include a Master's degree in engineering mechanics and completion of all course work for a PhD in same, specializing in fluid mechanics; teaching college level fluid mechanics, and using an analog field to plot streamlines, as Mr. Gentry did, well over a decade ago.

I think our differences of opinion can be condensed to two issues:

1. Mr. Gentry thinks that increasing the upwash in the streamlines approaching the jib, and hence emphasizing the fact that less air passes between the jib and main than would pass between headstay and mast if there were no sails (and the corollary that the free air slows down as it prepares to pass between the jib and main) to more closely conform to theoretical flow conditions is an important point and one that previous writers have been in error in discussing. I believe previous writers have considered the precise amount of upwash so unimportant that they have simply never even worried about drawing these streamlines exactly right from an analytic point of view.

2. Mr. Gentry feels that these slight changes in theoretical streamlines, "should be of more help to the average sailor than old incorrect theories!" I feel that the average sailor, and indeed any serious racing sailor, will do himself far more harm than good by attempting to understand the theoretical streamline flow past a sloop rig as defined by advanced fluid mechanics. It has been my observation, that the more a racing skipper becomes fascinated by purely theoretical concepts (as evidenced by sails covered with telltales, strain gauges in the rigging, smoke and cameras to visualize air flow, and discussion [oral and written] of fluid mechanics applied to sailing), the worse his racing results.

As my *Carte Blanche* column in this issue suggests, the determinants of racing success are not an understanding of the Kutta condition, or "circulation," but good starts, an empathy with the wind and sea, especially the wind, concentration on steering and speed and instantaneous tactical decisions which usually turn out to be correct. Preoccupation with anything else works to the disadvantage of the racing sailor.

To draw analogies, the Grand Prix driver who is a research thermodynamicist specializing in the Otto cycle, or a PHD in vibrations, is a rarity (probably non-existent); the pro basketball star will find advanced study in body mechanics, muscle and bone structure, etc. a handicap.

Sports which depend on pushing oneself to the limits of human endurance, such as distance running or swimming, are simple enough so that a serious competitor can devote a great deal of attention to pure scientific fundamentals without hurting his performance, perhaps even assisting it. But a complex sport like sailing, with the key factors so far removed from analytic study, is best approached with a very pragmatic viewpoint.

Mr. Gentry, I mean no offense. Let us disagree with tolerance and good humor; perhaps I am mistaken. I wish you much success in your sailing endeavors.

Peter Barrett
Pewaukee, Wisconsin

What Goes Around Comes Around

In October and November 1991, *Sailing World* Magazine published two articles on *The Aerodynamics of Sails*. These were primarily extracted from Chapter 5 of the book, *The Art and Science of Sails*, by Tom Whidden and Michael Levitt. Chapter 5, *A New View of Sailboat Aerodynamics*, was based on material that I had furnished to them back in 1989 for their book.

The two *Sailing World* articles in 1991 prompted a number of people to write in with their own ideas on sail aerodynamics, just as had happened back in 1973 when my original articles were published in *SAIL*. *Sailing World* decided to publish another article with answers to some of the questions. They had received 16 pages of questions and postulations sent in by readers. "Within a couple of weeks there arrived in the *SW* offices about 30 pages of response from Whidden, Levitt, and Gentry." The Editors arranged excerpts from both letters and responses into a kind of dialogue. The article, *What Goes Around Comes Around*, was published in the April 1991 issue of *Sailing World*.

Tom Whidden was aware of my disagreement with Peter Barrett back in 1973 and mentioned it in some of his comments used in the *What Goes Around Comes Around* article.

"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.

(Back in 1973) Peter Barrett dismissed Gentry's theories as possibly true but ineffectual. Back then Michael Levitt, my coauthor, 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."