Studies of Mast Section Aerodynamics

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Abstract

This paper summarizes the studies that were conducted with the objective of obtaining a mast-section shape with improved aerodynamic flow properties for use on the 12-Meter *Courageous*. The project consisted of a theoretical study defining the basic aerodynamics of the mast-mainsail combination followed by both analytical and experimental studies of various mast-section shapes. A new 12-Meter mast-section shape evolved from these studies that demonstrated significantly improved airflow patterns around the mast and mainsail when compared directly with the conventional 12-Meter elliptical section. This new mast shape was used in constructing the mast for *Courageous* used in the successful 1974 defense of the America's cup against the Australian challenger *Southern Cross*.

1. Introduction

The mast has always been thought of as being an undesirable but necessary appendage on a sailboat. It holds the sails up but contributes considerable drag and disturbs the airflow over the mainsail so that its efficiency is greatly reduced. This popular belief has led to a number of different approaches in improving the overall efficiency of a sailing rig. Over the years many different mast shapes have been tried. Walking through any marina and observing the many different shapes used on today's boats certainly indicates that no definite and universal conclusion has been reached. Several designers have attempted to give the mainsail a clean leading edge by supporting the sails from an A-frame structure (and, I suspect, without even trying to account for the drag of the multiple masts and wires making up the A-frame). Still others have gone to completely rotating masts, and in the case of some catamarans, to replacing the mast-mainsail with a solid aircraft-type wing.

The concern for the mast-mainsail problem has apparently increased in the last few years. To a great extent this has been caused by the increasingly higher levels of competition being found out on the race courses. The various Ton-level classes are good examples. Sailing is also becoming a more technical sport with even the local racers seeing more and more all-out racing machines with special headstay foils, vast sail inventories, and complete sets of electronic sailing instruments.

The 12-Meter racing yachts certainly represent the highest level of such technical development. In the America's Cup the stakes are so high that people are willing to spend large amounts of money both in challenging and defending this piece of yachting history. The objective is to win and every part of the boat is searched for possible improvements.

In 1973 the Sparkman and Stephens design office was preparing a new 12-Meter design to be called *Courageous*. Bill Ficker, who skippered *Intrepid* in the 1970 defense, was slated to be the skipper of the new aluminum *Courageous*. Ficker and David Pedrick (S&S project engineer on *Courageous*) wondered if a new mast-section shape might lead to improved boat performance. This paper describes the work done in attempting to answer that question.

2. Basic Mast Section Studies

Recent studies on the aerodynamics of sailing have conclusively proven that many of the old theories describing how sails work are completely wrong (1, 2, 3). Because of this fact, it was necessary to approach the subject of mast-section aerodynamics with some caution. Obviously, old ideas and references on the subject could not be completely trusted. It was, therefore, necessary to first obtain a more fundamental understanding of the mast aerodynamics problem before attempting to arrive at an improved mast section shape.

One of the first facts to recognize is that a mast is not just a pole sticking up with the air flowing around it (although much of the literature talks about it as though it were). The mast is the leading edge of the mainsail and is important to the driving force of the sail, just as the leading edge is important to the wind of an airplane. However, the presence of the jib in front of the mainsail and the area of separated flow right behind the mast make the problem difficult to analyze. The point of flow separation on the mast depends upon how the air flows around the mast, and this is strongly influenced by the presence of the jib and the trim of the mainsail.

The strong effect that the jib has on the flow about the mainsail is documented in detail in Reference 4. Contrary to popular belief, the slot between the jib and mainsail does not cause a higher speed jet of air to flow on the lee side of the mainsail (the so-called venturi effect). In fact, the primary effect of the jib is to cause **lower** velocities on the lee side of the main. This fact is illustrated by the flow

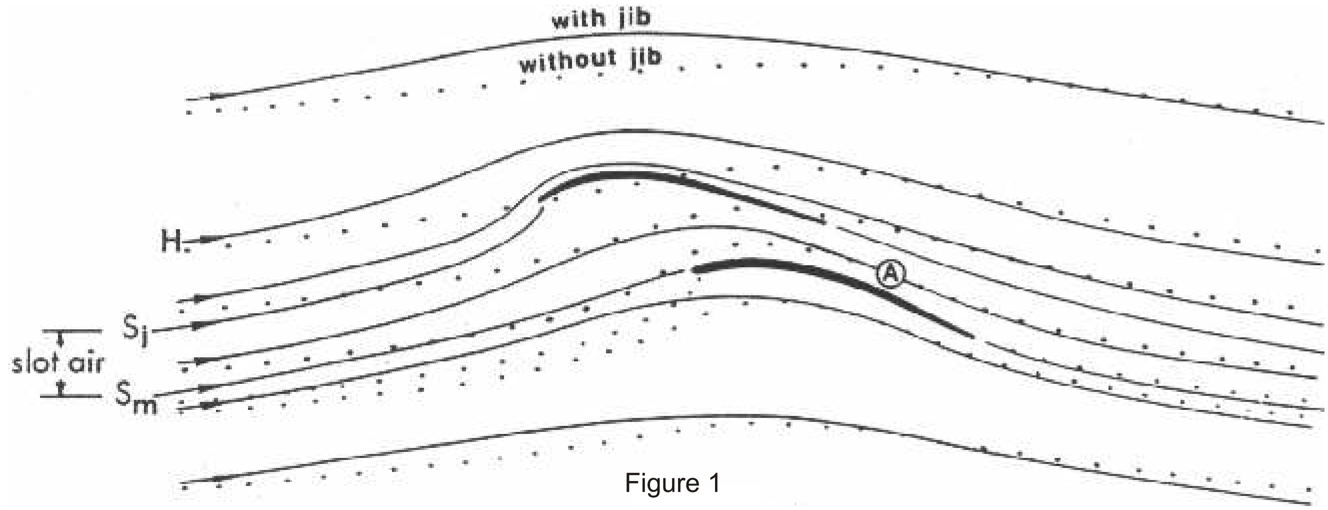

Figure 1

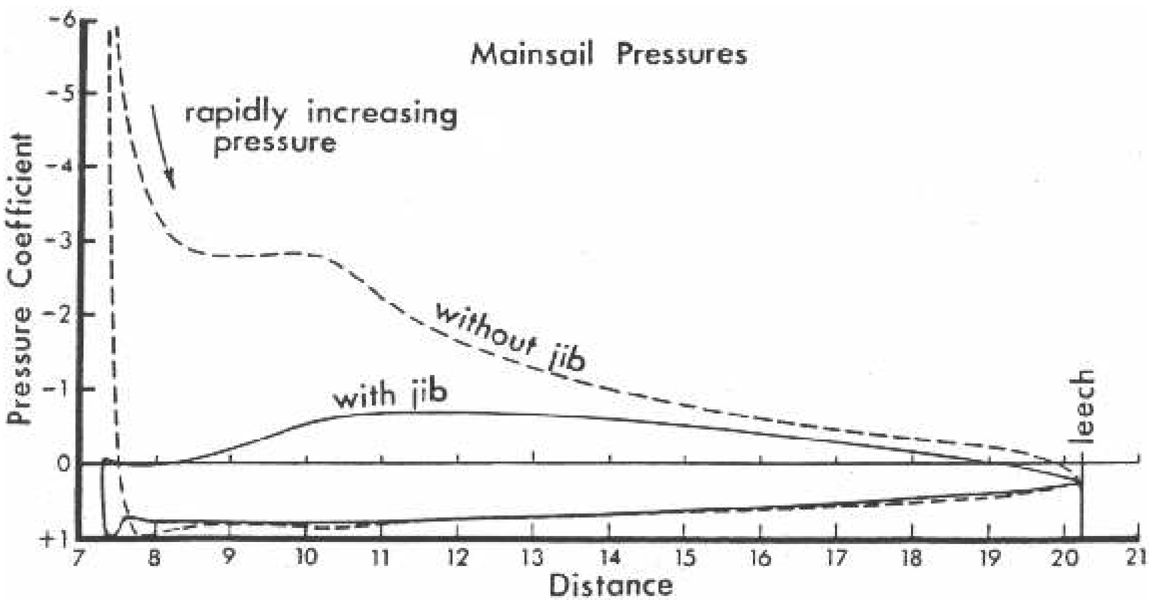

Figure 2

diagram shown in Figure 1, and the resulting pressure distribution about the mainsail shown in Figure 2.

The overall general effect of the jib-mainsail combination is that more air is caused to flow on the lee side of the jib and less flow is left to travel in the slot between the jib and mainsail. The net effect is that the jib caused the stagnation point to shift closer to the front of the mast and, as shown in Figure 2, dramatically reduces the velocities and, therefore, the suction pressures on the lee-side of the mainsail. The suppression of the suction peak by the action of the jib is beneficial from the standpoint that it now gives a pressure distribution that the boundary-layer flow can better tolerate. Without the jib the rapidly increasing pressure on the forward lee-side of the mainsail would cause the boundary layer to separate from the sail and it would be completely stalled.

From the above statements, we see that the mast must be viewed in its proper environment; that is, as the leading edge of the main airfoil and with its velocity and pressure distribution strongly influenced by the presence of the jib.

In the analytical studies discussed above, the area behind the mast where we usually see separated flow was artificially smoothed over since the objective was to gain a basic understanding of the jib-main interaction problem. However, to design a better mast we must take a closer look at how the air flows around the mast and how the resulting velocities and pressure distributions influence the amount of flow separation in the area between the aft side of the mast and the mainsail.

First, let's look at some assumed flow situations past the mast. In Figure 3, it is assumed that the air flows around the mast without any lee-side separation at all. In Figure 4, it is assumed that the flow separates at the maximum-width point of the mast. In both sketches only the first two feet of the mainsail is shown. In Figure 3, we notice that the streamline on the lee side of the mast does not want to go into the hollow formed between the aft edge of the mast and the forward-lee surface of the mainsail. Because of this, the static pressure in this region gets rather high (since the streamline gets further from the mast-mainsail juncture). This gives a rather high pressure at the point marked "F" in Figure 3.

In Figure 4, it was assumed that the flow separates at the maximum-width point and that the air flows straight aft and reattaches to the sail at point "G". The static pressure in the separated region is approximately

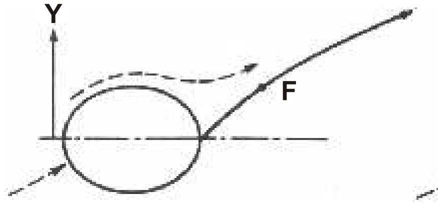

Figure 3

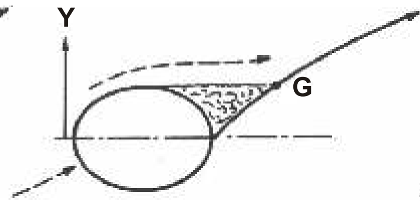

Figure 4

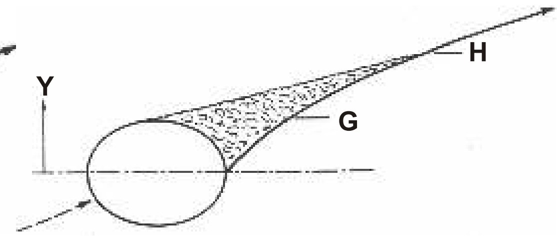

Figure 5

constant. That is, the same pressure that pushes forward on the back half of the mast is also pushing backward on the lee-side of the mainsail in the separated region. The two forces just cancel each other out. However, this same type of thing also happens in Figure 3 since the pressure in the juncture of the mast-mainsail is about the same on the aft part of the mast as it is on the forward-lee part of the mainsail.

Which flow situation would have the highest driving force, the one with no separation at all shown in Figure 3, or the one with the separation at the maximum-width point shown in Figure 4? There are three effects that determine the answer to this question. First, what is the difference between the forward suction forces over the forward facing areas of the mast? Second, what is the difference between the pressures on the mainsail itself from the points “F” and “G” to the leech of the sail? And third, what effect does the separated region have on the downstream profile drag of the sail?

In the computations made for this study, the suction forces on the forward face of the mast in Figure 3 were slightly higher than those on Figure 4. However, the suction force on the mainsail in Figure 4 from point “G” to the leech was much higher than it was in Figure 3 from point “F” aft. Neglecting any large effect of flow separation on the profile drag of the sail itself, the above results indicate that the flow situation shown for the mast in Figure 4 would have the highest forward driving force.

In any case, the important point to note here is that the driving force of the lee-surface of the mainsail between the mast track and point “G” is canceled out by the pressures on the mast between the maximum-width point and the mainsail track. This is because we have approximately constant pressure in this area and both the “G” point and the maximum-width point have the same Y-dimension.

Both of these sketches were shown to illustrate certain basic principals. However, the no-separation flow condition shown in Figure 3 is never found in real life because the boundary layer cannot withstand the rapid increase in pressure in the hollow between the mast and the mainsail. Even the velocity suppression effect of the jib is not able to help this situation. However, not only does the maximum-width flow separation situation in Figure 4 apparently give higher forward driving force, but it is a more realistic goal to strive for in the design of a new mast. Even this task is difficult since the flow around a mast usually wants to separate well before the maximum-width point is reached.

The flow situation that is usually found on a mast is illustrated by the sketch in Figure 5. The flow separates from the mast before it gets to the maximum-width point and reattaches to the mainsail at point “H”. Again, the pressure in the separated region is approximately constant. Also, again the lee-side area of the sail between the sail track and the point “G” does not contribute any driving force because the same pressure acts on the aft-part of the mast. However, the windward side of the mainsail from the track to the point “G” with its positive pressures does continue to contribute to the sail's drive.

The forward driving force of the flow situation shown in Figure 5 depends upon the amount of leading edge or mast suction over the front half of the mast, upon the suction pressure on the mainsail between point “G” and point “H”, and upon the suction pressures from point “H” to the leech. In the calculations made for this study, the forward mast-face suction force for the flow in Figure 5 was lower than it was for the forward face in Figure 4. Also, the suction pressures between points “G” and “H” and between “H” and the leech were not as high in Figure 5 as they were for the flow situation in Figure 4. In other words, the best flow situation was as shown in Figure 4 where the flow separates right at the maximum-width point of the mast. However, it is very difficult to get the airflow to remain attached to this point. This is because the peak-velocity point on the mast is always forward of the maximum-width point and unless something special is done to the mast and the boundary layer is tripped to turbulent, the flow will separate at the peak-velocity point.

The thrust-drag loop plot often used by the aerodynamicist is a useful tool for understanding the mast-mainsail forces. This type of plot is shown in Figure 6. This type of plot is a bit difficult to understand so some further comments are in order here. First, this is a plot of the pressure coefficient around the entire mast-mainsail airfoil from the leech to the lower surface of the main, to the mast surface, to the lee-side, and then back to the leech of the mainsail on the lee side. The arrows on the pressure line indicate this sequence. The Y-dimension is measured perpendicular to the centerline of the boat. The X-dimension is measured along the boat centerline. The pressure coefficient is plotted against the Y-dimension because it is only the Y-component of the mast or sail surface that contributes to the forward driving force. If we plotted the pressure against the X-dimension, all we would see would be the side force that tends to push the boat sideways through the water.

In Figure 6, we see that the pressure line forms several closed loops. These are called the thrust-drag loops. The

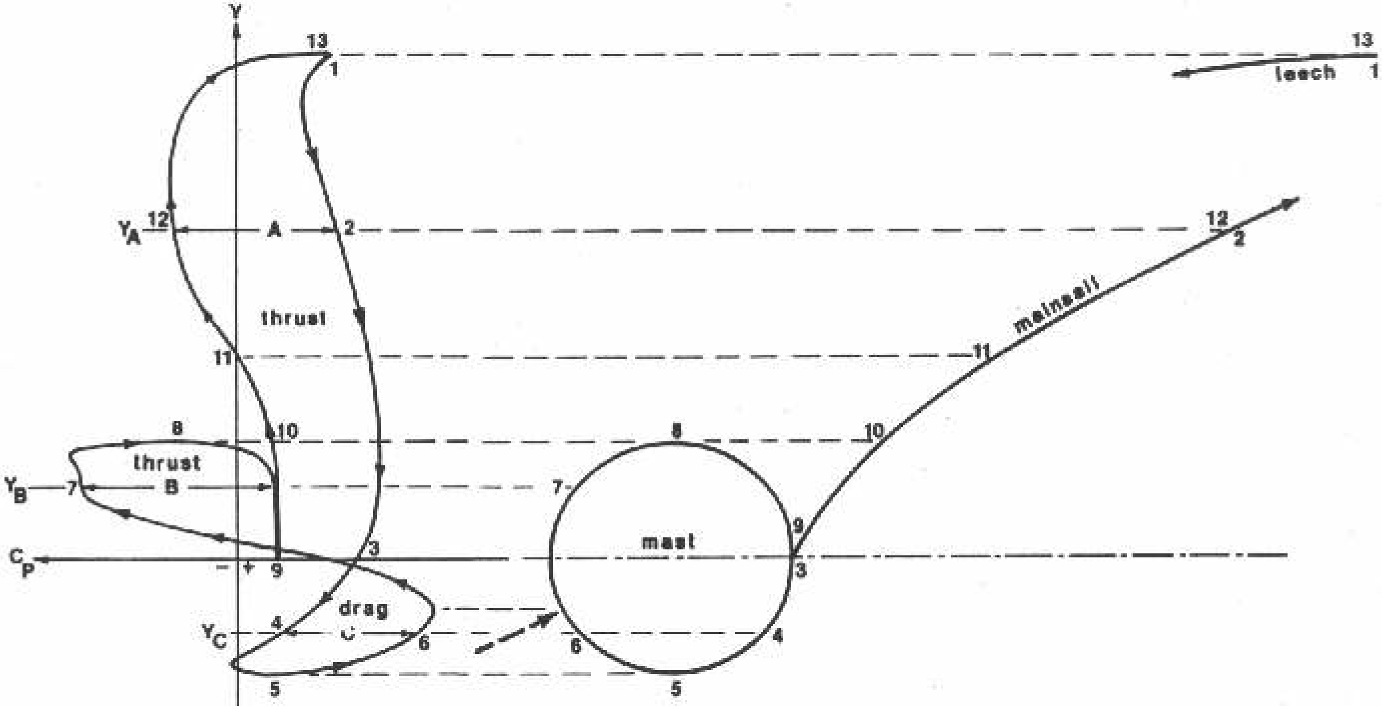

Figure 6

area formed by a closed loop going in a clockwise direction (such as for the lee-side of the mast) represents a forward driving force (thrust). The area enclosed by a counter-clockwise loop, such as on the windward half of the mast, represents a drag component. In Figure 6, the line "A" represents the pressure difference between the lee and windward sides of the mainsail at the Y-dimension Y_A. Line "B" is the pressure difference between the forward and aft side of the mast at Y_B. Line "C" is the pressure difference between the forward and aft half of the mast (drag) at point Y_C.

From Figure 6 we see that the mast-mainsail combination has three basic thrust-drag loops. Most of the windward side of the mast forms a drag loop while the lee side forms a thrust loop. The difference in the area between these two loops represents the net forward thrust or drag of the mast itself. It is important to note that the thrust loop formed by the lee side of the mast can actually furnish enough forward thrust to offset the drag from the windward side mast loop. This may help compensate for the adverse effect that the mast separation may have on the mainsail itself. The third loop is formed by the mainsail, and the clockwise direction of the loop indicates that we, of course, get thrust from the sail.

The driving force contributed by the mainsail is largely determined by the jib-mainsail interaction situation; that is, by how much the mainsail lee side velocities are suppressed by the jib. However, to a lesser extent, the separation from the mast also influences the mainsail drive. It does this by changing the shape of the pressure distribution between points 8, 9, 10 and 11 in Figure 6.

One other effect that has been ignored in the proceeding discussion is the effect of the separated region behind the mast on the boundary layer on the after part of the mainsail. Although we know that this must cause some increase in the overall drag of the sail, we have no way of realistically calculating it. This problem is probably significant on both the lee side and windward side of the mainsail. In the design of a new mast section shape, we will simply bypass this problem by attempting to design a mast shape with as little separation as possible on both sides of the mast and mainsail.

3. 12-Meter Mast Section Studies

With the basic ideas from the studies outlined above, it was next possible to attack the original problem posed by Bill Ficker and David Pedrick to attempt to design a new 12-Meter mast section shape that would have improved aerodynamic properties over the conventional elliptical section used on most previous 12's.

A 12-Meter boat mast is not exactly an average sailboat mast. It is about 90 feet long and its cross-sectional area at different heights is closely controlled by the 12-Meter rules. The width and fore-and-aft dimensions are controlled also. The net result is that you are confined to a rather fat shape with the fore and aft dimension being only about 24% greater than the width. The basic 12-Meter elliptical mast section used on many previous 12's measures 11.925" by 9.625".

The 12-Meter mast studies described in this paper were only concerned with the determination of the mast external cross-sectional shape. The structural design of the mast, rig, fittings, etc. was accomplished by S&S.

The mast studies for *Courageous* were conducted in a number of phases as outlined below.

(1) Analytical studies to determine how different mast shapes influenced the velocity and pressure distributions around the mast-mainsail and genoa combination.

(2) Analysis of the above data to arrive at the flow

characteristics that would be desirable in a mast shape.

(3) Development of a mast section test technique and preliminary sailing tests on several new unusual shapes.

(4) The design of a family of new mast shapes.

(5) Sailing tests where the new shapes were compared directly with the standard 12-Meter elliptical section. These tests were made on the author's Ranger 23 using 60% size sections.

(6) Further analysis and refinement of the most promising sections and more tests on the Ranger 23. This was repeated a number of times.

(7) The construction of three full-scale test sections for testing on an Ericson 46.

(8) Sailing tests with the standard elliptical shape and the two new sections (identified as sections G-4 and G-5) on the Ericson 46 *Bright Star* with Bill Ficker. This test resulted in the selection of the G-4 section for use on *Courageous*.

(9) Analytical and experimental studies to arrive at a suitable surface mounted transition strip device.

There were two basic aerodynamic objectives to be reached in the design of a new mast-section shape. First, it was desirable to reduce the size of the separated flow region behind the mast as much as possible. Here the concern was with the way that the pressure distribution builds up around the mast and how the boundary layer reacts to the pressure changes. And, second, it would be desirable to have a mast with high leading-edge suction pressures so as to improve the forward thrust of the mast itself.

An examination of the flow around the standard 12-Meter elliptical section shown in Figure 7 will help illustrate these factors. The pressure distribution around the ellipse is shown in Figure 8. In this figure the pressure coefficient, C_p, is plotted against the surface distance, S, measured around the surface of the mast. It will also help to keep in mind the relationship between the pressure coefficient and the surface velocity as given by the following equation.

$$u_e/u_\infty = \sqrt{1 - C_p}$$

where u_e = surface velocity

u_∞ = freestream velocity

C_p = surface pressure coefficient

$= (p - p_\infty)/(\tfrac{1}{2}\rho u_\infty^2)$

p = surface pressure

p_∞ = freestream static pressure

ρ = air density

From the above equation, we see that the more negative the C_p is, the higher the velocity. In examining Figures 7 and 8, we see that the air accelerates rapidly and smoothly from the stagnation point (where $C_p = +1$) and has a maximum speed and maximum suction pressure (most negative C_p) at the point marked $C_{p_{peak}}$. Then the flow starts to slow down and the pressure builds up (toward the + side) even before the maximum-width point on the mast is reached. Since the boundary layer on

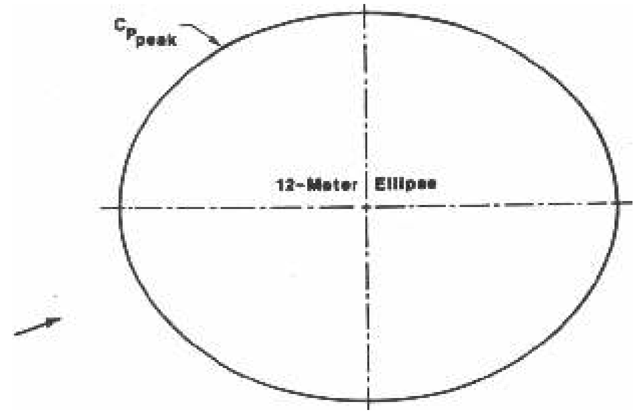

Figure 7

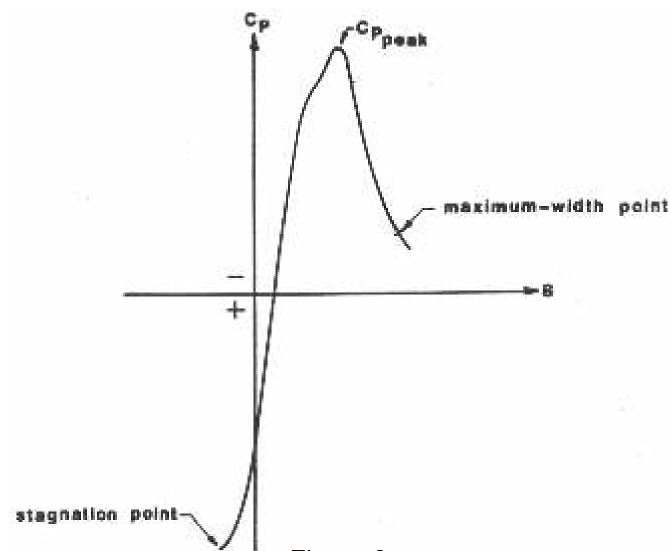

Figure 8

the surface of the mast does not like sudden increases in pressure the flow will probably separate right after the peak velocity point is reached and before it gets to the maximum-width point. A line drawn tangent to the mast at the peak-velocity point and extended until it hits the mainsail gives an indication of the large area of separated flow that will exist behind the mast and on the forward lee part of the mainsail.

If the boundary layer could be made to trip from the laminar state to the turbulent state before the peak velocity point is reached, then it would stay attached longer. This is because a turbulent boundary layer is more tolerant of pressure increases than is the laminar boundary layer. However, the flow between the stagnation point and the peak-velocity point is continuously accelerating (a favorable pressure gradient) and the boundary layer will not want to change from laminar to turbulent in this region. However, it is possible to artificially trip the boundary layer to the turbulent state with the aid of a surface mounted roughness strip. For the trip device to be most effective, it should be positioned near the highest velocity point. If it is positioned too close to the peak velocity point, premature separation may occur at the trip itself. A trip position closer to the front of the mast

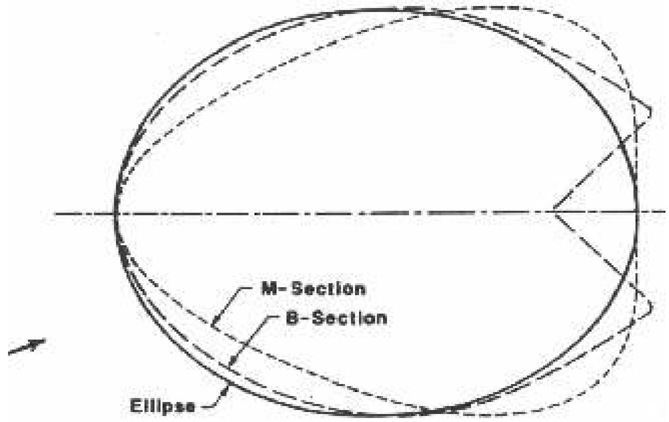

Figure 9

would also tend to be less effective because the velocity is lower (lower Reynolds number). Of course, it usually is possible to trip a boundary layer to the turbulent state, but when the conditions are not favorable for this, it may be necessary to use an unusually high trip device.

At this point we see that the standard 12-Meter ellipse has two basic features that tend to reduce its aerodynamic potential. First, the peak velocity is not as close to the maximum-width point as would be desired. Second, the shape of the velocity distribution is such that it is not favorable for tripping the boundary layer to the turbulent state without an excessively large transition trip device. Obviously, a circular mast would be worse then the 12-Meter ellipse because each of these unfavorable characteristics would be even more pronounced.

In attempting to arrive at a mast shape with improved aerodynamic properties, it was logical to first examine several shapes that other designers thought would be better. Two of these shapes plus the standard ellipse are shown in Figure 9. The pressure distributions for these shapes are plotted in Figure 10. Note that section "B" has forward sides that are slightly flatter than the ellipse. This causes the pressure distribution to be significantly different. It has a short region of almost constant pressure (a "roof-top" pressure). A transition trip device placed just before the beginning of this constant pressure area would probably be very effective in tripping the boundary layer to the turbulent state so that it would remain attached longer.

The "M" mast shape also has an area of approximately constant pressure. However, there is a pressure peak followed by a brief but steep pressure increase just before the constant pressure area. This sudden pressure increase would probably cause premature separation of the boundary layer well before the maximum-width point. Wind tunnel tests of such a shape might be very misleading if the effects of the genoa, the mainsail, and the Reynolds number are not simulated correctly.

From the above we see that the "B" section certainly has some of the desirable features discussed previously. It has a large suction-pressure area, and the pressure distribution is more favorable to the use of a boundary layer trip device. Sailing tests with the "B" section showed

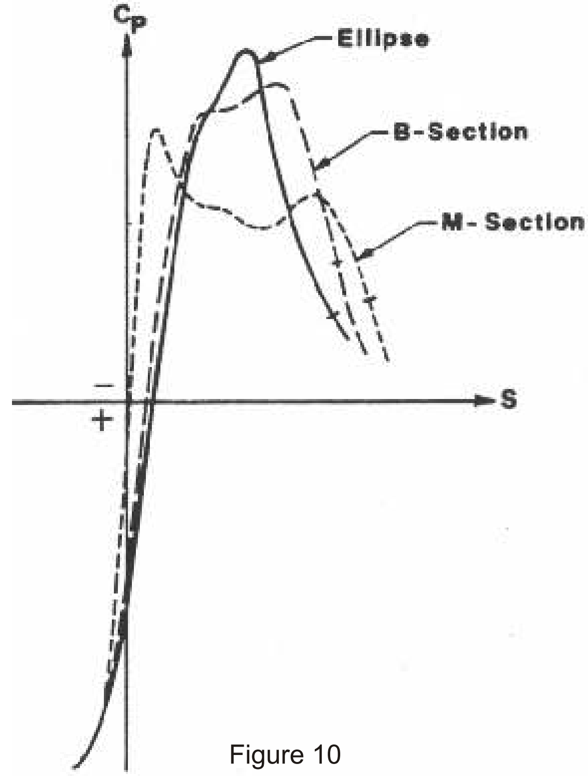

Figure 10

that it, indeed, was significantly better than the standard ellipse. Tests were also made without the unconventional V-shaped cutout on the aft side of the mast. In these tests the V cutout had no noticeable effect on the separation point on the mast. This is as one would expect since the shape of the forward half of the mast and the resulting pressure curve is the primary factor that determines the position and amount of lee-side separation. However, since the V-shaped cutout did cause excessive separation on the windward side of the mast it was deleted in the further tests of the "B" section. The "B" section with a modified back half was subsequently re-identified as the G-5 section.

Using this background information a number of other shapes were designed, analyzed and tested. A new shape eventually evolved from these tests that not only had higher suction pressures, but also had a pressure distribution curve that was very favorable to the use of a surface-mounted boundary layer trip device. This section was identified as the G-4 shape and was eventually used in the construction of the mast for *Courageous*. The *Courageous* mast shape is shown in Figure 11 along with the standard 12-Meter ellipse. The pressure distribution for each shape is shown in Figure 12.

The new G-4 section used on *Courageous* does not differ from the standard elliptical section by more than about ¼" at any point. The *Courageou*s section is characterized by a slightly blunted forward face. The forward-face corners (the knuckles) are followed by slightly flattened forward sides to the maximum-width point of the mast. The maximum-width point was also slightly further forward.

The blunt forward-face and corner knuckles helped give high velocities and high suction pressures over the

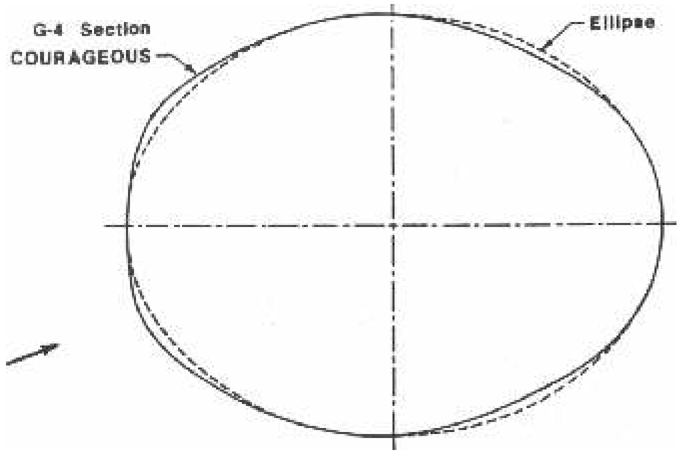

Figure 11

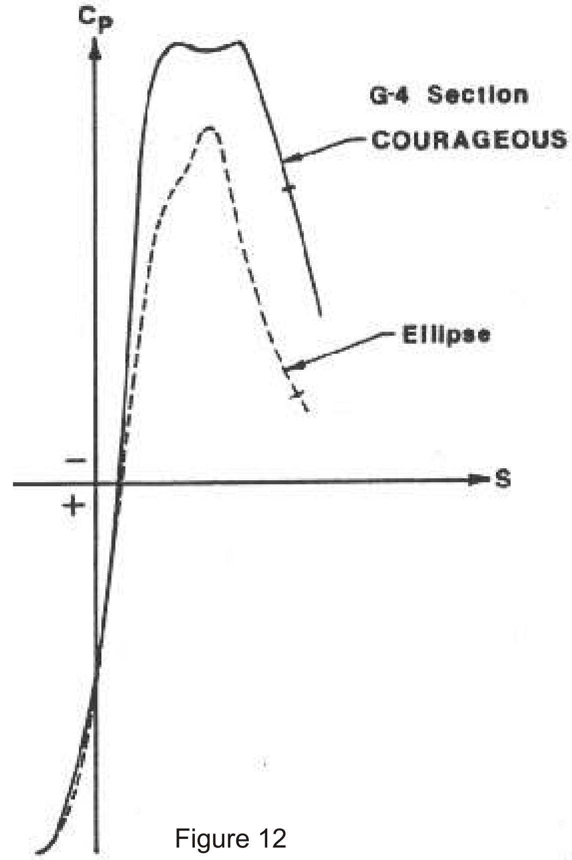

Figure 12

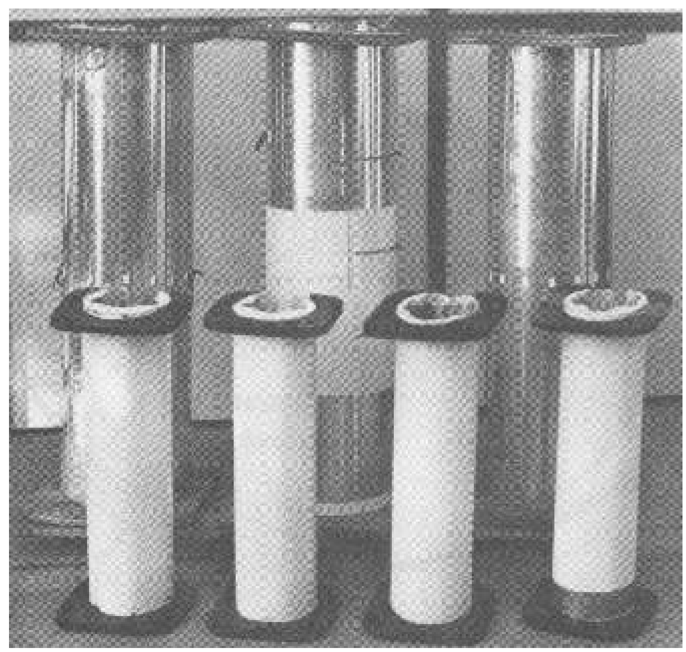

Figure 13

forward part of the mast. The slightly flattened forward sides were shaped to help maintain the constant pressure "roof-top" region, and to move the final pressure peak as far aft on the section as possible.

4. Mast Section Testing

The testing of various mast-section shapes was mentioned several times in the earlier parts of this paper. But, just how do you go about testing a new mast-section shape? The first idea suggested was to use a wind tunnel. However, the complicated interaction between the genoa and mainsail and the separation behind the mast make accurate and meaningful wind tunnel testing very difficult and expensive. Wind tunnel tests can often be just as misleading as tank tests. Water channel tests have similar problems. The one remaining approach was to conduct actual sailing tests of the new mast shapes. Since it was impractical to test a full mast, a test technique was devised in which the test section shapes were wrapped around an existing boat's mast and the airflow and separation observed and photographed under actual sailing conditions. With this technique it was possible to test two or three sections at the same time so that direct comparisons could be made of the airflow about the various test shapes. Some of the sections tested are shown in the photo in Figure 13.

In these tests the airflow patterns were visualized by using short pieces of ribbon attached to the mast and mainsail. Both the windward and lee sides were observed as the boat sailed in different wind and sea conditions, and the position of separation on the mast and the point of flow reattachment on the mainsail noted. On some of the tests the flow was visualized with the aid of a stream of soap bubbles generated in front of the mast. To accomplish this a small compressor on deck was used to force air through a special nozzle that generated the bubbles. With the nozzle attached to a long pole it was possible to move the bubble stream about in front of the mast. Pressure and velocity fields around the mast test-sections were also measured approximately by the use of a hand-held pitot tube attached to a sensitive pressure gauge.

When one shape was found to have less flow separation when compared directly with the conventional elliptical shape it was then subjected to further analytical studies to find out why. As an example, some shapes were found to be more tolerant of the movement of the boat through choppy water than others. This could not have been detected in a wind tunnel test.

Some of the sections were modified and tested with slightly different shapes a number of times. Most of these tests were made at about 60% of the 12-Meter full size mast using the author's Ranger 23, *Kittiwake*. These tests narrowed the choice down to two shapes, the G-4 and G-5 sections. These two shapes were then tested along with the standard elliptical section at full-scale conditions on the Ericson 46 *Bright Star*. These tests were arranged by Bill Ficker. In these tests both the G-4 and G-5 sections showed better airflow (less separation) than on the standard elliptical section, with the G-4 section being the best of the two new designs. On the basis of these tests, the G-4 section was selected for use in the construction of the new mast for *Courageous*. This was somewhat unusual since two masts had already been constructed for *Courageous* using the standard elliptical shape. However, the airflow improvements with the new G-4 shape seemed to justify the construction of a third mast.

One basic assumption made throughout this work was that it was important that the boundary layer be tripped from the laminar state to the turbulent condition before the final peak-suction pressure point was reached. This was because the turbulent boundary layer is better able to withstand the sudden pressure increase that always occurs right after the final peak-suction pressure point. This tripping of the boundary layer can usually be achieved by a properly shaped and positioned surface transition strip device. However, each mast shape requires a slightly different transition strip position. Without this it would be difficult to accurately compare the potential performance of different mast shapes.

However, it would be too time consuming to determine the best transition strip position for every section being tested. This problem was solved when it was discovered that a properly positioned halyard would cause turbulent flow to exist over the mast. This process is illustrated in Figure 14. The halyard is positioned off of the surface of the mast at the stagnation point. A highly disturbed wake forms behind the halyard. This wake splashes on the mast surface and causes the boundary layer to be turbulent almost from its beginning. In most of the sailing tests a wood dowel was used in place of a halyard. The dowel was inserted into holes in the mast section clamping blocks at the top and bottom of each section. The position of the dowel was adjusted to obtain the maximum effectiveness out of each test section. The importance of obtaining the turbulent boundary layer over the mast section could be vividly illustrated by suddenly removing the dowel and watching the instant increase in the separation region on the mast and mainsail.

This halyard boundary-layer tripping technique can obviously be used on any boat if small fittings are spaced up the mast to keep two halyards properly positioned (one on either side). There is also some evidence that the lee side halyard in such an arrangement will also help in delaying the lee side separation.

The use of the above tripping technique also had one other side benefit. Since it was not going to be possible to use the dowel on the actual 12-Meter mast, a surface mounted strip would have to be developed. However, the dowel positioned off of the mast at the stagnation point was able to trip the boundary layer on all of the sections tested, including the standard elliptical section. This had

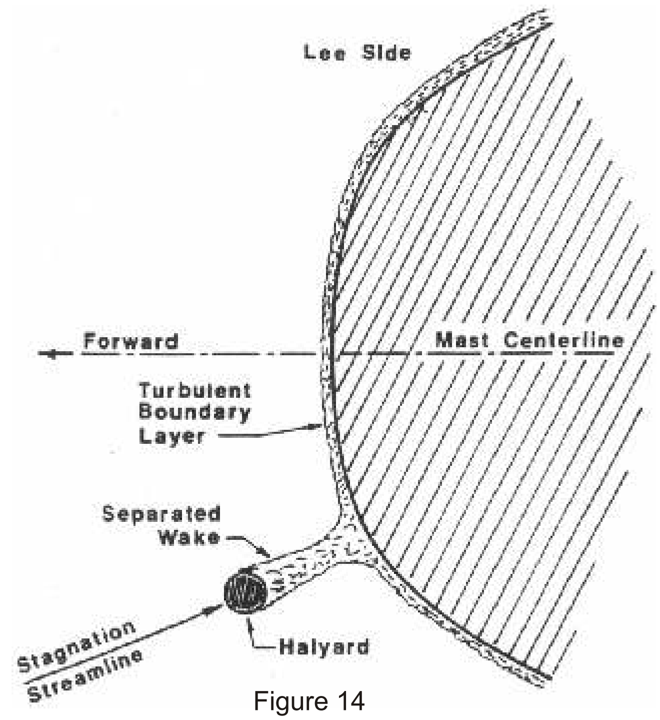

Figure 14

the effect of giving the elliptical section somewhat of an unfair advantage over the other sections in the sailing tests (since it would be one of the more difficult sections to trip with a surface mounted device). This was one way of assuring that any new improved mast section was, indeed, better than the elliptical section would be on the actual boat.

The final phase of this work was the design of a surface mounted transition strip device to do the same job that had been accomplished with the stagnation point halyard or dowel in the sailing tests. Based on wind-tunnel testing experience, there were several types of devices that could accomplish this:

(1) Sand-grain roughness
(2) Spherical-ball roughnesses
(3) Vortex generators
(4) Surface mounted wires
(5) Triangular three-dimensional roughness strips

Approaches 1 and 2 were not considered because of the difficulty of installation and maintenance. Approach 3 was also discarded because of the installation problem. Although approach 4 has been demonstrated to work on masts, it is a two-dimensional type of roughness and is not as effective as properly designed three-dimensional roughness. Approach 5, the strip of three-dimensional triangular elements, did not have any of these problems and would be very effective. The problem, however, was in the manufacturing of the strips. This was quite adequately solved by Bud Gardiner. The final transition devices were molded plastic strips which could be easily glued to the mast.

The detailed flow pattern off of the thin triangular strip of elements is illustrated in Figure 15. The sides of each triangle generate small vortexes that introduce a continuous stream of disturbances into the laminar boundary layer. The three-dimensional nature of these

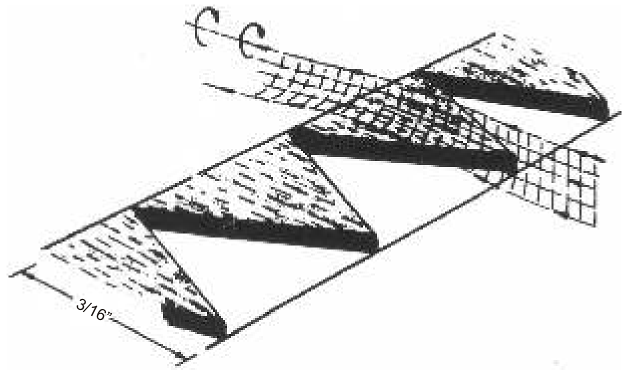

Figure 15

disturbances and their very close spacing ensure the maximum effectiveness of the strip over a wide speed range.

The next step was to determine the optimum position for the strips on the *Courageous* mast section. Small tufts were glued to the G-4 test section to give a visualization of the amount of flow separation on the aft lee side of the mast. The transition strip was glued to the mast section and the separation observed. The position of the strip was changed several times until a position was found that gave the maximum effectiveness (least separation) for the widest wind angle range. The idea was to position the transition strip on the forward flat face of the mast as close to the knuckle as possible without the strip itself inducing separation.

The effectiveness of the strip was also verified by the use of a special paint applied to the section. Ammonia gas was pumped out through holes in the front center of the mast and the different concentration of gas in the laminar and turbulent regions caused the paint to change color from yellow to blue. A thin-film gauge was also used to check for the presence of turbulent flow. The gauge was positioned behind the transition strip and the output signal amplified and converted to an audio signal. The type of sound produced indicated the type of flow present (laminar, turbulent, or separated).

5. Mast Construction

To better hold the mast to the desired design shape, the mast sections were formed from flat plates and welded in the Southern California area under the guidance of Bud Gardiner. Robert Chubb did the numerical lofting work necessary in making the templates used in forming and welding the sections to the desired shape. The three 30-foot mast tubes were then shipped to the East Coast where Hood Yacht Systems assembled and completed the outfitting of the mast. The new mast was not ready for the first set of trial races but went into the boat just before the July observation trials. However, the transition strips on the lower two-thirds of the mast were removed when it was found that the threads in the genoa were being damaged by the sharp front edges of the strips during tacking maneuvers. New transition strips were manufactured and reinstalled on the mast just before *Courageous*' four-race win streak in the final trials against *Intrepid* (only this time with the sharp edges of the strips sanded down so as not to damage the genoa).

6. Application on Other Boats

After viewing the material presented here on the *Courageous* mast, it is quite logical to ask how this new 12-Meter mast shape might work on an ocean racing yacht. However, when considering this it should be remembered that the 12-Meter mast is closely controlled by the 12-Meter rule. As a result, the mast has a rather fat shape with a major-to-minor dimension ratio of only about 1.24. Moreover, the mast on an ocean racer is not constrained by any such rule. As an example, the main-mast on the 79' *Kialoa III* has a major-to-minor dimension ratio of 1.41.

The general effect of a longer ellipse is that the shape of the pressure distribution is more rounded at the peak suction-pressure point. The boundary layer might, therefore, stay attached a little past the peak-suction point before it separates. For the same width dimension, the longer ellipse would seem to be the better mast section as far as the aerodynamic properties are concerned. However in the sailing tests, it was interesting to note that a properly designed 12-Meter mast section sometimes had better lee side flow on the mainsail than a much smaller elliptical mast section with a higher fineness ratio.

One might also ask about taking the *Courageous* shape and just stretching the fore and aft dimensions to give a section with a higher fineness ratio. The results of attempting to do this are shown in Figures 16 and 17. And

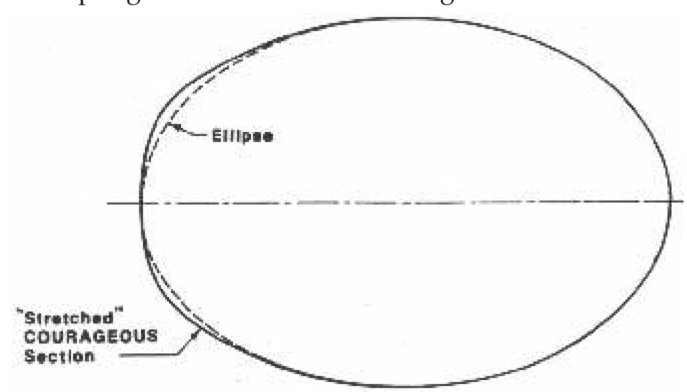

Figure 16

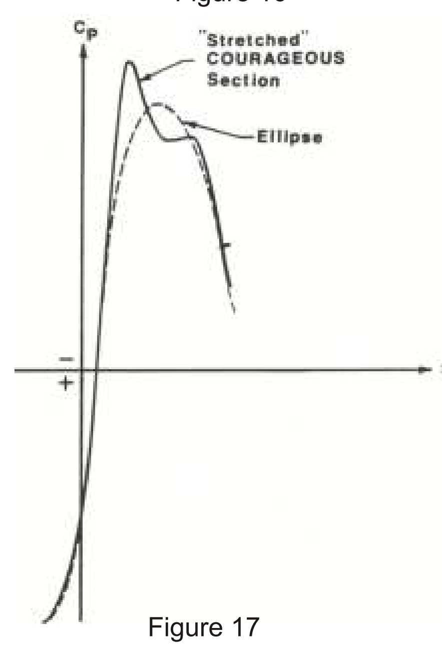

Figure 17

as the pressure plot in Figure 17 shows, the results are disastrous. The “Stretched” *Courageous* mast has a premature peak velocity near the forward knuckle on the mast, followed by a steep pressure increase. The boundary layer would separate at this point and the “Stretched” *Courageous* mast shape would have worse performance than the simple elliptical section.

Obviously, the job of designing a “better” mast section is no easy task. And as indicated above, misguided attempts can very easily end up with a mast that would not be as good as a simple ellipse.

A number of additional analytical and experimental studies have been conducted to determine how the mast shape should be altered to give better performance on the higher fineness-ratio ocean racer type of masts. However, these results are not available for publication at this time.

7. Conclusions

The results presented in this paper indicate that the mast must be considered from the proper viewpoint; that is, as the leading edge of the mainsail airfoil (with an imbedded separated region on the lee side) and under the influence of the flow generated by the jib-mainsail airfoil combination. The problem of calculating the flow around the mast is a rather difficult one. Although the results presented in this paper are only approximate in nature, it is felt that proper trends between shapes are reasonably accurate. Moreover, this is somewhat substantiated by the fact that when the pressure distribution indicated that a shape should be bad, it usually turned out to be so in the sailing tests.

The results of the studies described in this paper seem to indicate that the mast is not quite the villain that it was previously thought to be. Although it does cause separated flow to exist over a portion of the mainsail, its position as the leading edge of the mainsail airfoil also causes a part of the surface of the mast to contribute a significant amount of forward thrust. This helps compensate for the drag-casing effects of the mast. The leading edge thrust is increased (and the drag contribution reduced) if the mast is rotated to windward as is done on some catamarans.

However, even with the studies described here, the understanding of the mast-mainsail problem is still in a rather uncertain status. The ideas and interpretations presented in this paper are based on the results obtained by the author to date. Obviously, much more work is required to completely verify (or possibly refute) these ideas and interpretations. This paper is, therefore, presented with the hope that other researchers will pursue this interesting subject further in order to expand our understanding of these fascinating technical aspects of our sailing sport.

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