Aerodynamics of High-Performance Wing Sails

J. Otto Scherer[1]

Some of the primary requirements for the design of wing sails are discussed. In particular, the requirements for maximizing thrust when sailing to windward and tacking downwind are presented. The results of water channel tests on six sail section shapes are also presented. These test results include the data for the double-slotted flapped wing sail designed by David Hubbard for A. F. Di Mauro's IYRU "C" class catamaran *Patient Lady II*.

Introduction

The propulsion system is probably the single most neglected area of yacht design. The conventional triangular "soft" sails, while simple, practical, and traditional, are a long way from being aerodynamically desirable. The aerodynamic driving force of the sails is, of course, just as large and just as important as the hydrodynamic resistance of the hull. Yet designers will go to great lengths to fair hull lines and tank test hull shapes, while simply drawing a triangle on the plans to define the sails.

There is no question in my mind that the application of the wealth of available airfoil technology will yield enormous gains in yacht performance when applied to sail design. Recent years have seen the application of some of this technology in the form of wing sails on the IYRU "C" class catamarans. In this paper, I will review some of the aerodynamic requirements of yacht sails which have led to the development of the wing sails.

For purposes of discussion, we can divide sail requirements into three points of sailing:

- Upwind and close reaching.
- Reaching.
- Downwind and broad reaching.

Some of the requirements of upwind and downwind sailing will be discussed here. Reaching will be recognized as an intermediate condition with the sail design requirements falling between those of upwind and downwind sailing.

There are many criteria which can be used to judge the quality of a sail design. For our discussion of high-performance wing sails, the primary criterion will be to maximize the available driving force (thrust) for a given total sail area. Such a sail will maximize the speed of a racing yacht with a given measured sail area or minimize the size of the rig required for a cruising yacht.

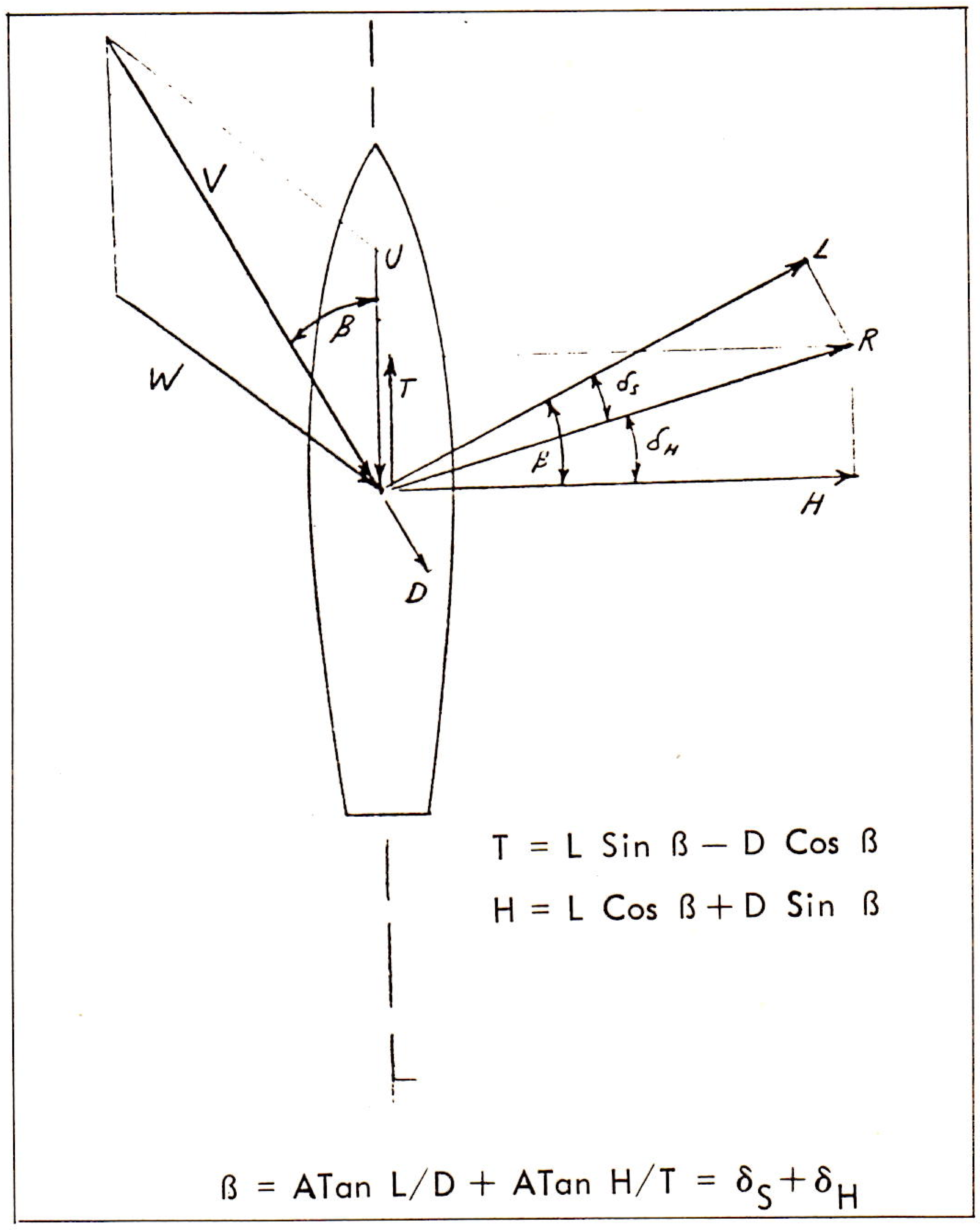

Fig. 1 Definition sketch of force and velocity vectors in upwind sailing

Upwind and close reaching

Aerodynamic requirements for sailing upwind and close reaching are basically the same. These points of sailing are characterized by having the apparent wind at a small angle to the course of the boat. This situation is shown on Fig. 1. The angle between the apparent wind and the course is denoted by β and may vary from about 25 deg for a fast, close winded boat to about 35 deg when close reaching. We might consider 30 deg as typical for this point of sailing.

It can be seen from Fig. 1 that the resultant force R, is nearly at right angles to the course so that there is only a small thrust force, T, compared with a rather large heeling force, H. The resultant, R is composed of an aerodynamic lift force, L, normal to the apparent wind and a drag force, D, in the direction of the apparent wind. It is convenient to express these forces in terms of coefficients, nondimensionalized with respect to the apparent wind velocity, V, and the sail area, S. Thus:

$C_R = R/\tfrac{1}{2}\rho V^2 S,$	resulting coefficient	(1)
$C_T = T/\tfrac{1}{2}\rho V^2 S,$	thrust coefficient	(2)
$C_H = H/\tfrac{1}{2}\rho V^2 S,$	heeling coefficient	(3)
$C_L = L/\tfrac{1}{2}\rho V^2 S,$	lift coefficient	(4)
$C_D = D/\tfrac{1}{2}\rho V^2 S,$	drag coefficient	(5)

The thrust and heeling force are related to the sail lift and drag by the expressions

$$C_T = C_L \sin\beta - C_D \cos\beta \tag{6}$$

[1] Head, Ship Propulsion and Research Division, Hydronautics, Inc., Laurel, Maryland.

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$$C_H = C_L \cos\beta + C_D \sin\beta \quad (7)$$

Upwind and close reaching, it is clearly desirable that the sail should develop the highest possible thrust up to wind speeds where stability or increased hull drag due to heeling force become important. Thereafter, the highest possible thrust will be obtained when the ratio of thrust to heeling force (C_T/C_H) or thrust to heeling moment $(C_T\sqrt{S}/C_M)$ is maximized. Heeling moment is simply the product of heeling force and the height of the center of effort:

$$C_M = \frac{M}{\frac{1}{2}\rho V^2 S\sqrt{S}} = \frac{Hh}{\frac{1}{2}\rho V^2 S\sqrt{S}} = C_H x \sqrt{A} \quad (8)$$

where

H = heeling force
h = height of center of effort
b = height of sail
$x = h/b$
A = aspect ratio = b^2/S
S = sail area

Thus, for any given sail geometry, C_M is proportional to C_H.

Inspection of equations (6) and (7) (or Fig. 1) indicates that reducing drag will both increase the available thrust and decrease the heeling force. The question then becomes: What type of sail geometry will provide the minimum drag, and thus maximum thrust, for a given lift coefficient, and what is the importance of increasing the available lift coefficient?

Drag comes from two sources: viscous or form drag caused by the skin friction and turbulence of the air flowing over the sail and its supporting structure, and induced drag which results from lost energy in the wake of the sail due to its finite span. These two types of drag are referred to as parasite drag, $C_{D(p)}$, and induced drag, $C_{D(i)}$, respectively:

$$C_D = C_{D_p} + C_{D_i} \quad (9)$$

Induced drag is a function of the vertical distribution of aerodynamic loading—not sail area. With constant wind velocity from top to bottom, the load distribution with least induced drag is in the form of a semi-ellipse as shown in Fig. 2*(a)*. For this case, the induced drag is expressed as

$$C_{D_i} = C_L^2/\pi A \quad (10)$$

where A is the aspect ratio:

$$A = b^2/S \quad (11)$$

Thus, equation (10) can be written:

$$C_{D_i} = C_L^2 S/\pi b^2 \quad (12)$$

from which it can be seen that the induced drag is proportional to lift coefficient squared and inversely proportional to the square of the luff length or span b.

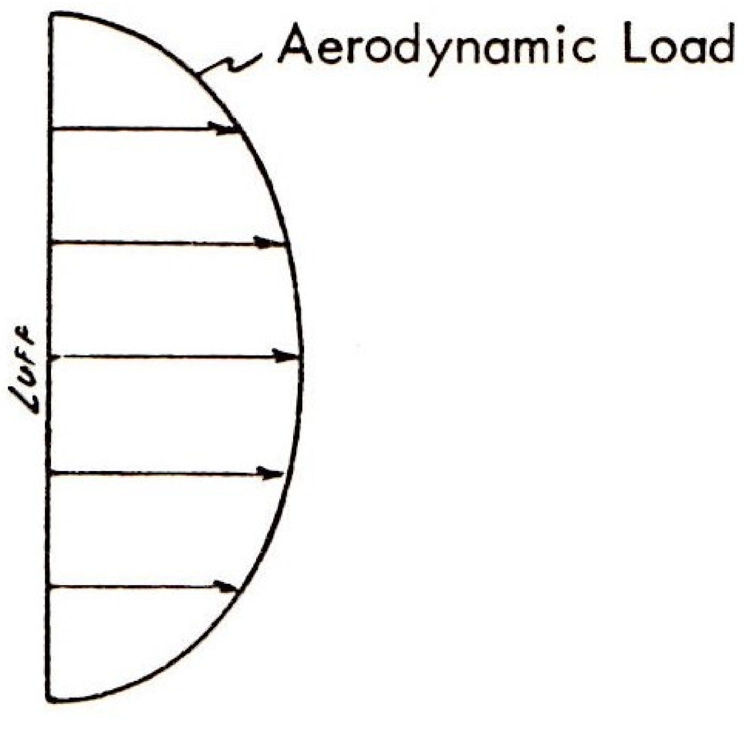

Fig. 2*(a)* Semi-elliptic load distribution

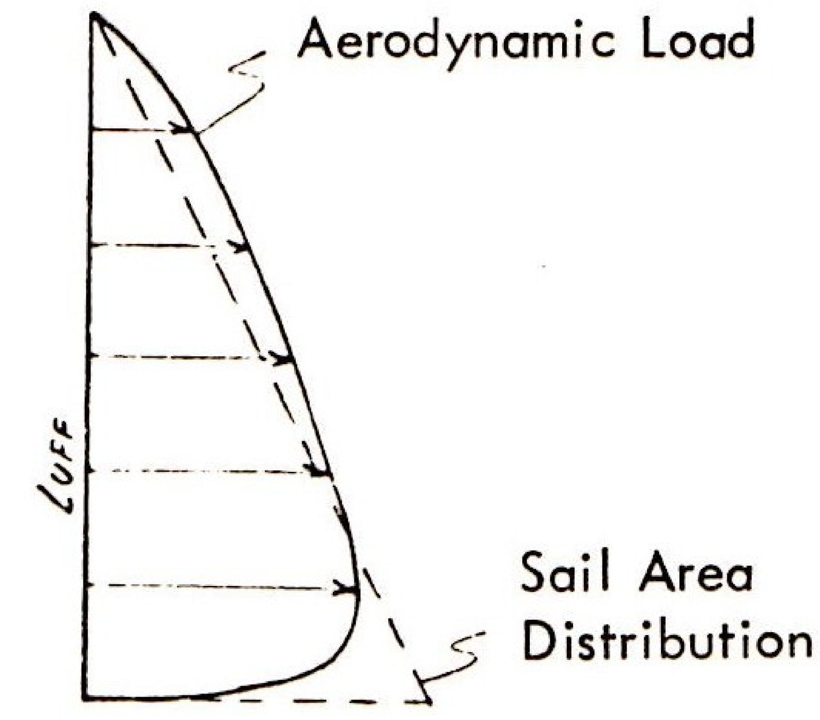

Fig. 2*(b)* Load distribution with triangular sail

The presence of the hull and water surface under the sail, plus the vertical velocity gradients above the water surface, tends to distort the optimum vertical distribution of loading away from the semi-elliptical shape. In principle, if the sail could be sealed to the hull along its foot, loading could be carried right down to the foot and the induced drag would be just cut in half. The sail could be said to have an effective aspect ratio AE of just twice its geometric aspect ratio.

In reality this benefit is difficult to achieve for two reasons. First, in practice it is difficult to obtain a really tight seal between the foot of the sail and the deck. Even a small gap of only a few percent of the sail height will eliminate much of the potential reduction in induced drag. Second, the reduced wind velocity over the surface of the water, plus the disturbed air flowing over the hull, will tend to diminish the benefit of sealing the foot of the sail to the deck. In addition, it is rarely possible to obtain the optimum vertical distribution of loading for the existing conditions of vertical wind gradient and gap under the foot.

It might be noted that it is a physical necessity that the vertical distribution of loading go to zero at the free ends of the sail, that is, the head and the foot if the foot is not perfectly sealed to the deck. The load distribution for a triangular sail might appear as shown in Fig. 2*(b)*.

In any case, the sail will produce the same induced drag as an equivalent wing operating in uniform flow with an optimum load distribution. The aspect ratio of this equivalent wing is called the "equivalent aspect ratio," AE, and may be either slightly greater or smaller than the geometric aspect ratio of the sail. Thus, equation (10) can be written more generally as:

$$C_{D_i} = C_L^2/\pi AE \quad (13)$$

Induced drag is of primary importance in upwind sailing and will actually limit the maximum obtainable thrust for most conventional sail configurations with effective aspect ratios between two and three. To understand this, it is in-

Nomenclature

A = aspect ratio = b^2/S
AE = effective aspect ratio
b = sail span (luff length)
c = sail chord
C_D = drag coefficient, equation (5)
C_H = heeling force coefficient, equations (3) and (7)
C_L = lift coefficient, equation (4)
C_M = heeling moment coefficient, equation (8)
C_R = resultant force coefficient, equation (1)
C_T = thrust coefficient, equations (2) and (6)
D = sail drag
H = heeling force
h = height of center of effort
L = sail lift
M = heeling moment
R = resultant sail force
S = sail area
T = thrust
U = boat speed
V = apparent wind speed
W = true wind speed
x = defined as h/b
β = angle between apparent wind and course
δ_h = hull drag angle = $a\tan(H/T)$
δ_s = sail drag angle = $a\tan(L/D)$
ρ = air mass density

drag ratio and the angle δ_h is similarly the arctangent of the hulls side force-resistance ratio. Thus:

$$\beta = ATAN\ (L/D) + ATAN\ (H/T) = \delta_s + \delta_h \quad (17)$$

This relationship is often referred to as the "course theorem." Stated in words, it says that the angle between the apparent wind and the boat's course is equal to the sum of the drag angles for the sail (δ_s) and hull (δ_h). This relationship is true for all points of sailing but holds its greatest significance for the case of upwind sailing. It points up the necessity of achieving high lift-drag ratios for the sail as well as the hull if a close-winded boat is to result.

Downwind sailing

Boats which sail straight downwind and depend on aerodynamic drag of the sails for thrust are limited to about half the speed of the wind. This is because, as the boat sails faster, the apparent wind over the sails is reduced. Since the driving force is reduced at a rate proportional to the square of the apparent wind speed and the hull resistance typically increases at a rate between the square and cube of the speed through the water, it becomes very difficult to obtain any significant gains sailing straight before the wind.

However, no theoretical limit to speed made good exists for boats which tack downwind, and indeed iceboats, with their very low resistance, can easily exceed the speed of the wind when tacking downwind. While the high-performance catamarans have not yet achieved a speed made good downwind which exceeds the wind speed, they do perform best when tacking downwind. Under such conditions the boat typically sails at about 45 deg from straight downwind and the apparent wind is just about abeam; that is, the angle β is about 90 deg. This condition is the same as broad reaching and is the one of concern in the design of wing sails.

Sailing downwind is conceptually much simpler than the upwind problem. Sail drag is of secondary importance as it acts normal to the course of the boat while the sail lift force, acting in the direction of required thrust, is of prime importance. Since an unstalled sail can produce more than twice the lift coefficient of a stalled sail, the downwind problem is basically one of designing a sail that will produce the highest possible lift coefficient before stall.

There are two considerations in achieving a high overall lift coefficient for a sail. The first is to provide a sail section shape which is capable of producing high lift coefficients. The second is to provide a sail planform and vertical load distribution such that this high lift coefficient can be achieved over the entire span.

High section lift coefficients with low form drag are achieved by the proper shape of the sail cross section. Lift coefficients are limited by the phenomenon of "stall." A foil stalls when the angle of attack becomes so high that the flow can no longer adhere to the low-pressure side and separates from the foil, leaving a turbulent wake and causing the lift produced by the low-pressure side to be destroyed. There are two types of stall: leading-edge stall and trailing-edge stall.

Leading-edge stall occurs when the flow cannot adhere to the leading edge because of severe pressure gradients at the leading edge. This type of stall can be delayed by selecting the proper amount of camber and a good leading-edge shape.

Sail camber has probably received more attention than any other factor in sail design and therefore will not be discussed further here. However, a good leading edge is very important in both achieving high lift coefficients and low form drag. The conventional fixed mast provides a very poor leading edge. The turbulent wake shed from the lee side of such a mast leads to both high form drag and leading-edge stall at rather low lift coefficients. Even the thin leading edge of a jib is poor from the standpoint of early leading-edge stall and is very sensitive to small changes in angle of attack as would occur when sailing in a seaway.

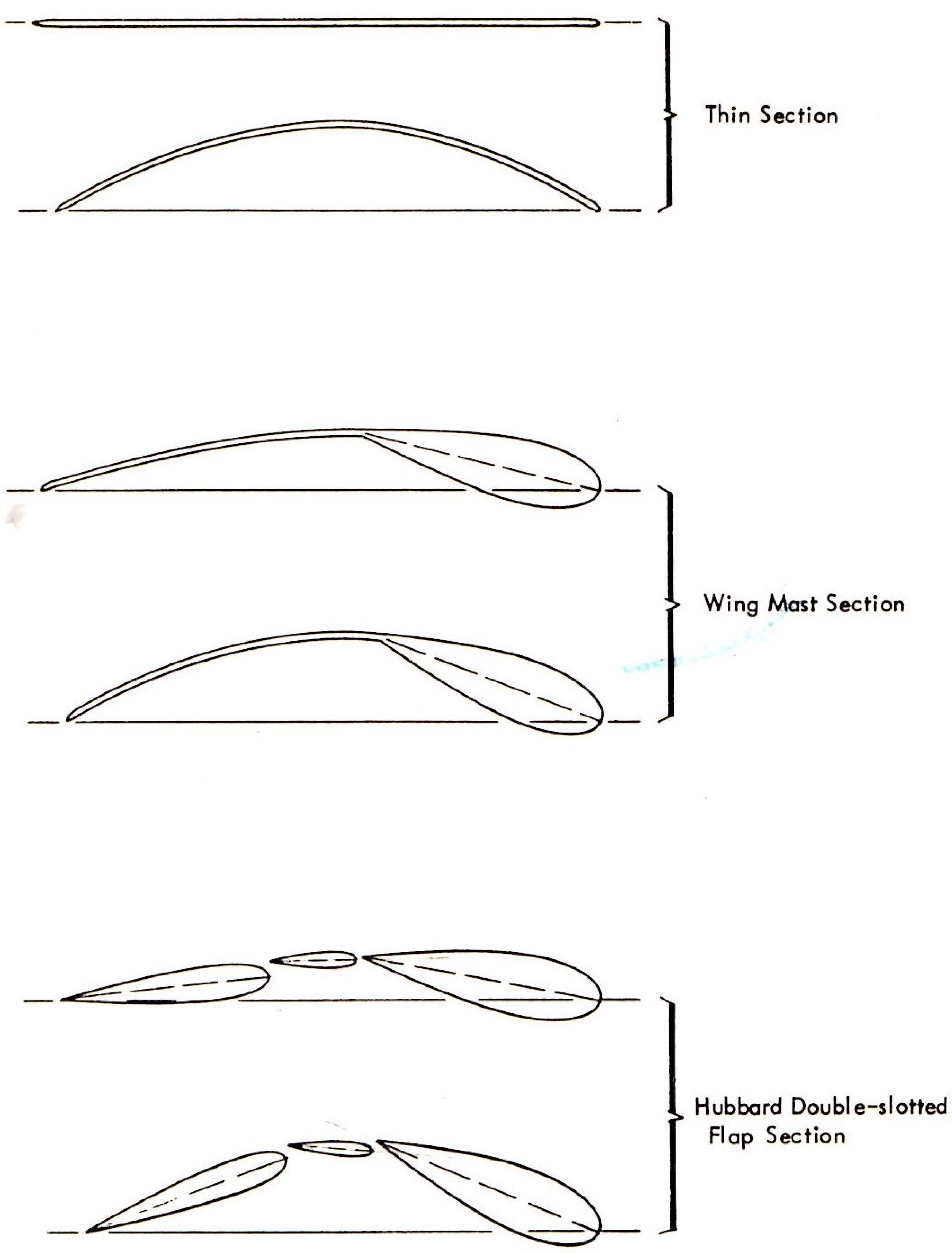

Fig. 5 Foil sections tested

Rotating, airfoil-shaped masts provide improvement. The large wing masts currently in vogue on the IYRU "C" class catamarans provide substantial improvement in leading-edge shape and have rendered the conventional mast nearly obsolete on these boats.

Trailing-edge stall is more difficult to deal with. This type of stall is caused by the inability of the low-energy air in the boundary layer to move from the low-pressure region near the mid-chord of the lee side to the higher pressure at the trailing edge. This form of stall usually limits the maximum lift coefficients of well-designed airfoils to values of two or less.

To achieve higher lift coefficients, some form of boundary-layer control is required to remove the low-energy air from the surface of the foil. The most common form of boundary-layer control is the slotted flap used on nearly all large modern aircraft.

In the spring of 1973, A. F. Di Mauro sponsored a series of tests at Hydronautics, Incorporated to determine the feasibility of using a double-slotted flap to achieve high lift coefficients on a new wing sail for his "C" class catamaran *Patient Lady II.* This very ingenious wing was designed by David Hubbard. It consists of three panels: a leading-edge panel of 45 percent of the chord which serves as the mast, a 15-percent chord central panel, and a 40-percent trailing-edge panel. The after two panels are hinged on a four-bar linkage from the leading panel so that it can be cambered to sail on either tack. This section was tested in the Hydronautics

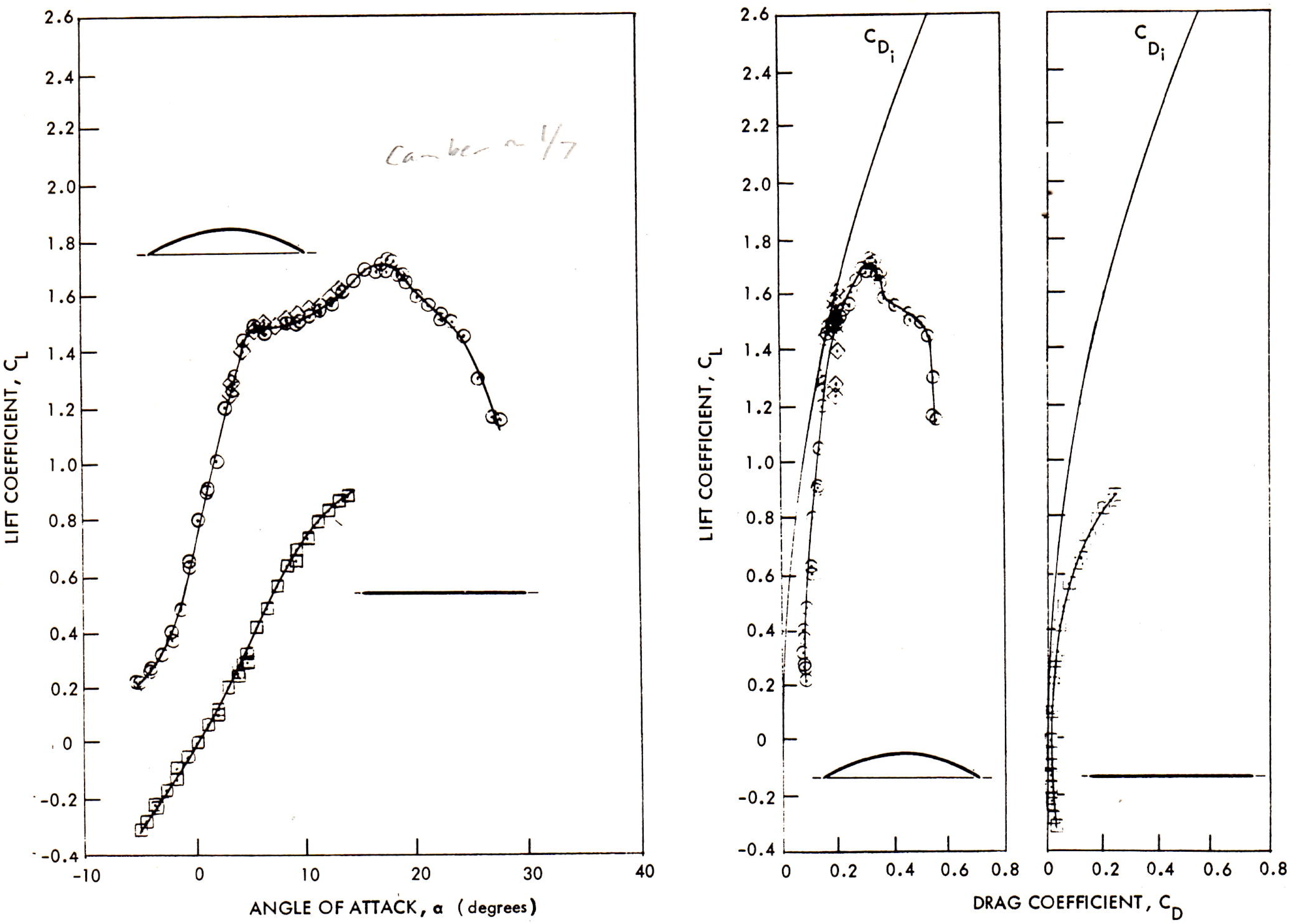

Fig. 6 Variation of lift coefficient with angle of attack and lift coefficient versus drag coefficient for thin section

high-speed water channel in both a high-camber and low-camber configuration. For comparison, high- and low-cambered models of a conventional wing mast and a thin section similar to a jib were also tested. Sections of the six models are shown in Fig. 5.

The models have a 6-in. cord and a 15-in. span, giving them an aspect ratio of only 2.5. The results of these tests are presented on Figs. 6 through 8. These results have been corrected for tunnel boundary effects and converted to an aspect ratio of 4, the aspect ratio of the full scale rig.

Each figure presents lift coefficient, C_L, as a function of angle of attack, α, and lift coefficient, C_L, versus drag coefficient, C_D, for each foil type. The drag coefficient plots also contain a reference induced drag line for aspect ratio 4 as given by equation (13). In principle, the parasite drag is the difference between this reference induced drag line and the measured drag data. However, it will be noted that in Figs. 6 and 7 the measured drag is actually less than the theoretical induced drag. It is believed that this is caused by the aspect ratio correction procedure so that, in reality, these data actually represent an aspect ratio of slightly greater than 4. However, this does not detract from the relative comparison of the foil types.

The unusual behavior of the highly cambered thin section (Fig. 6) is of interest. This behavior is the result of separation occurring on both the pressure and suction side at the same time—an indication of excessive camber for a section with such a thin leading edge.

However, of greatest interest are the results of the Hubbard slotted section which exhibited a maximum lift coefficient of 2.4. This is a very high value compared with 1.9 for the wing mast and 1.7 for the thin section. Even more encouraging is the fact that the parasite drag is not greater than that of the wing mast in the low-camber configuration. This means that this section will provide improved downwind sailing with no penalty to upwind performance. As a result, this section has been adopted for the new wing sail on *Patient Lady II.*

In order to achieve a high overall lift coefficient for the entire sail, the entire sail should be uniformly loaded. Referring to Fig. 2*(b)*, it can be seen that for a triangular sail the top portion tends to be overloaded while the foot can never be fully loaded.

As a result, the top will stall before the bottom and thus prevent the achievement of a high average lift coefficient for

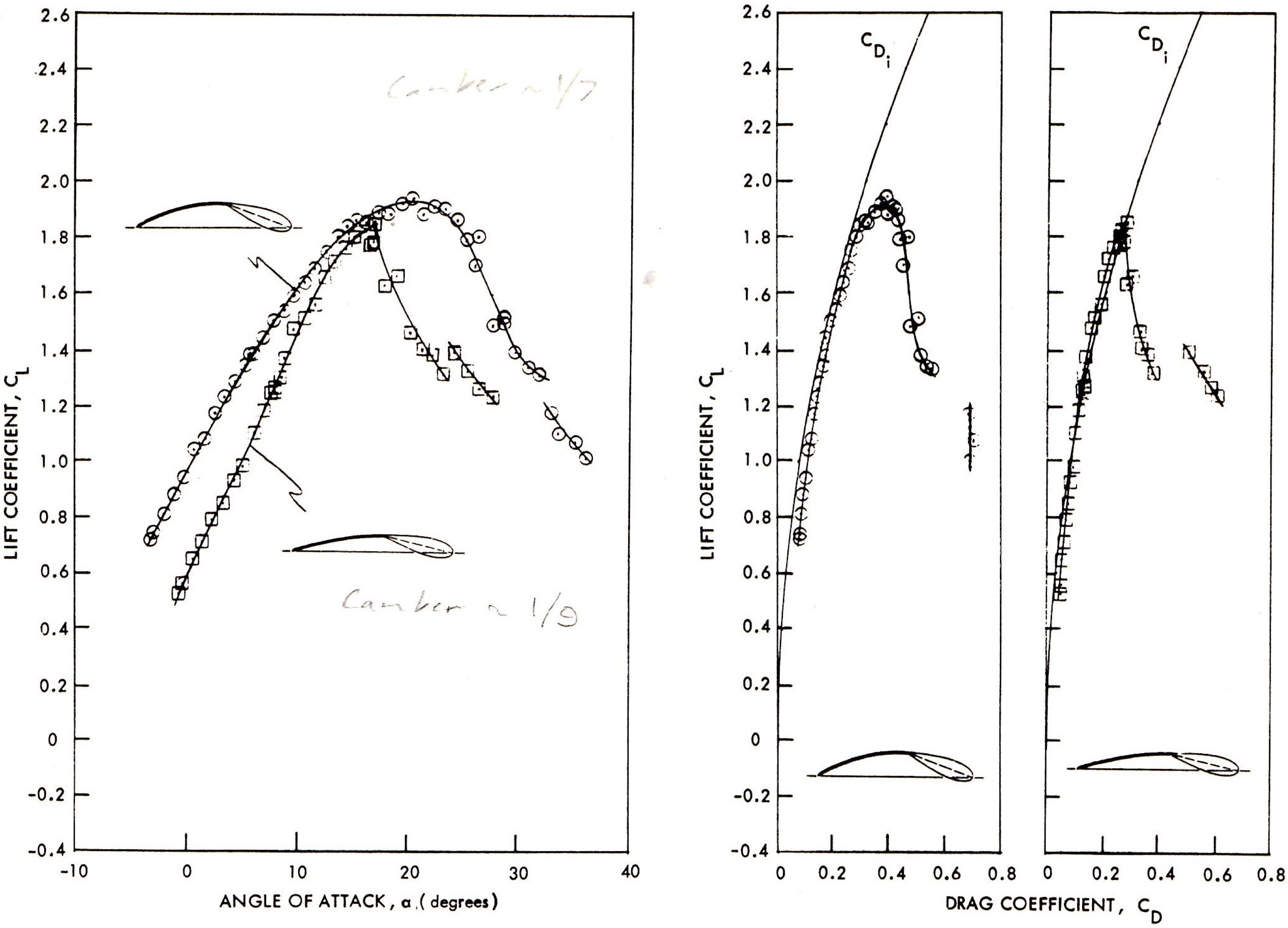

Fig. 7 Variation of lift coefficient with angle of attack and lift coefficient versus drag coefficient for conventional wing mast section

the entire sail. Obviously, it is desirable to distribute the sail area in a more or less elliptical fashion so that it tends to match the load distribution. This will not only provide a reduction in induced drag, but higher overall lift coefficients.

The roach which can be supported with full-length battens does a great deal to improve sail area distribution in the upper portion of the sail. The wide chord of a wing mast further helps to provide a good distribution of sail area. However, the foot remains a problem unless it is sealed against the deck or cut back to a rather small chord.

The control of sail twist is also an important factor in obtaining high overall lift coefficients. The presence of a vertical gradient in wind velocity over the water surface results in a twist to the apparent wind approaching the sail. Sailing upwind this twist is very small, while on a board reach or tacking downwind the twist in apparent wind may be 20 to 30 deg or more between the top and bottom of the mast for a fast boat. The reason for this can be seen by comparing Figs. 9*(a)* and 9*(b)*.

When sailing to windward, Figure 9*(a)*, the wind generated by the speed of the boat makes an angle of only 45 deg with the true wind. When combined with the true wind, only a small angular twist in the apparent wind occurs even for a fairly large difference in true wind speed between the top and bottom of the mast.

However, when broad reaching as in Fig. 9*(b)*, the wind generated by the boat's speed makes an angle of about 135 deg with the true wind. The geometry works out to cause a very large twist in apparent wind direction between the top and bottom of the sail.

Therefore, to operate efficiently over a wide range of courses, the sail must be capable of operating with both small and large amounts of twist while still maintaining good cross-sectional shape along the entire span. In the case of the double-slotted flap section on *Patient Lady II,* this has been accomplished by dividing the flaps into three sections so that the bottom flaps can be set at higher angles of attack than the upper flaps, thereby effectively creating a twist when sailing downwind.

Summary

The future of sail development holds great promise if we

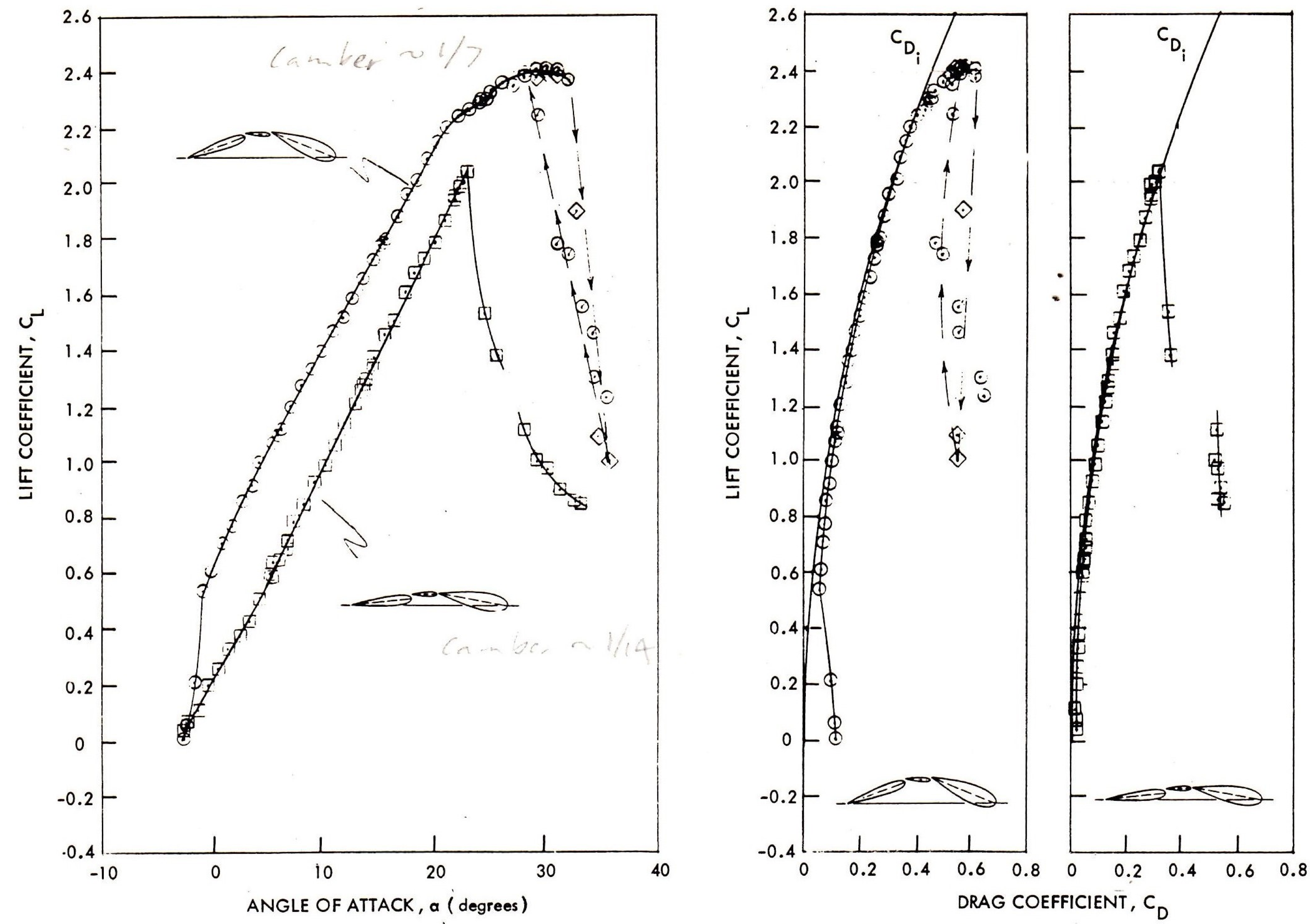

Fig. 8 Variation of lift coefficient with angle of attack and lift coefficient versus drag coefficient for Hubbard double-slotted flap section

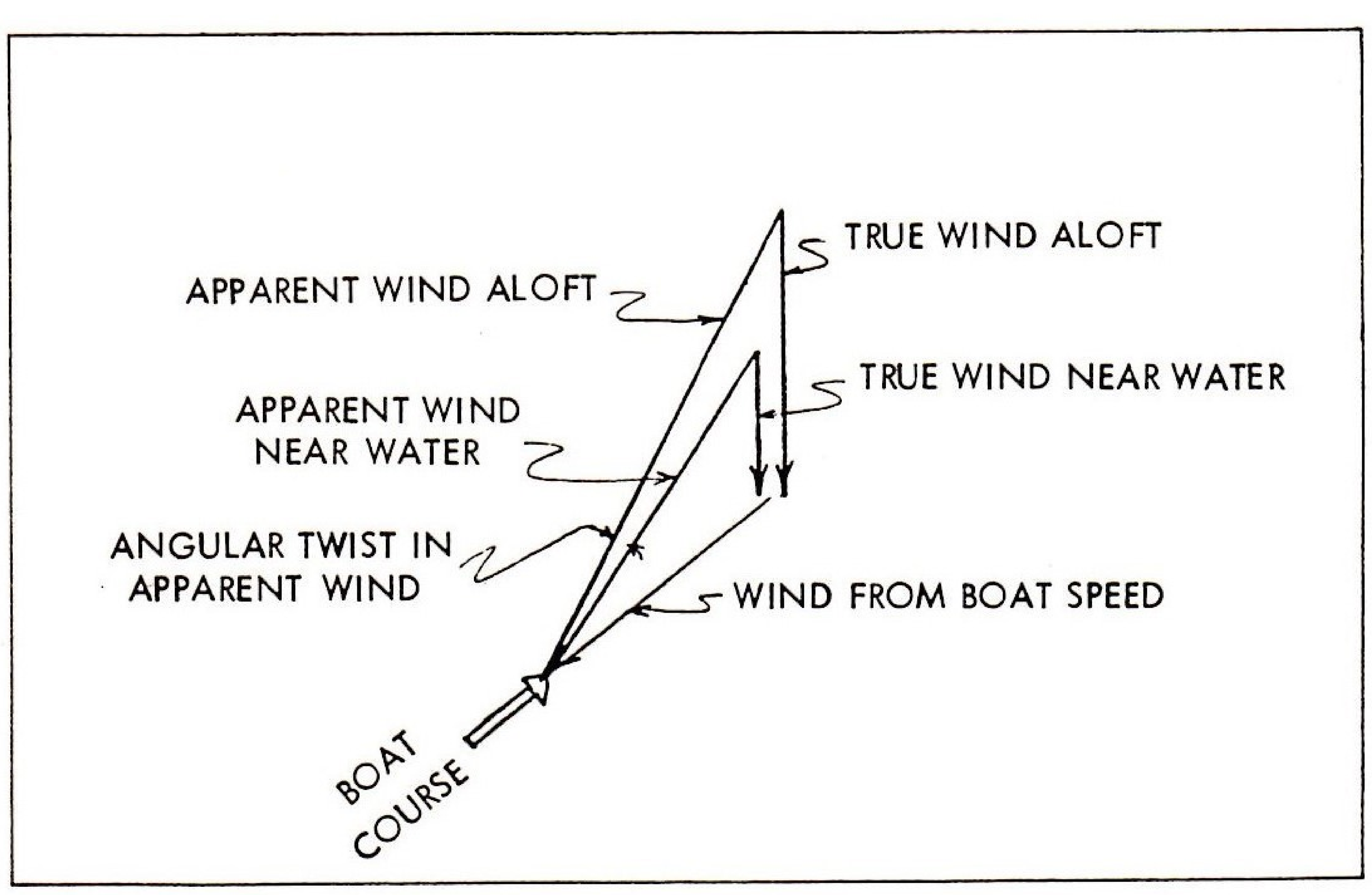

Fig. 9(a) Velocity diagram showing twist in apparent wind when going to windward

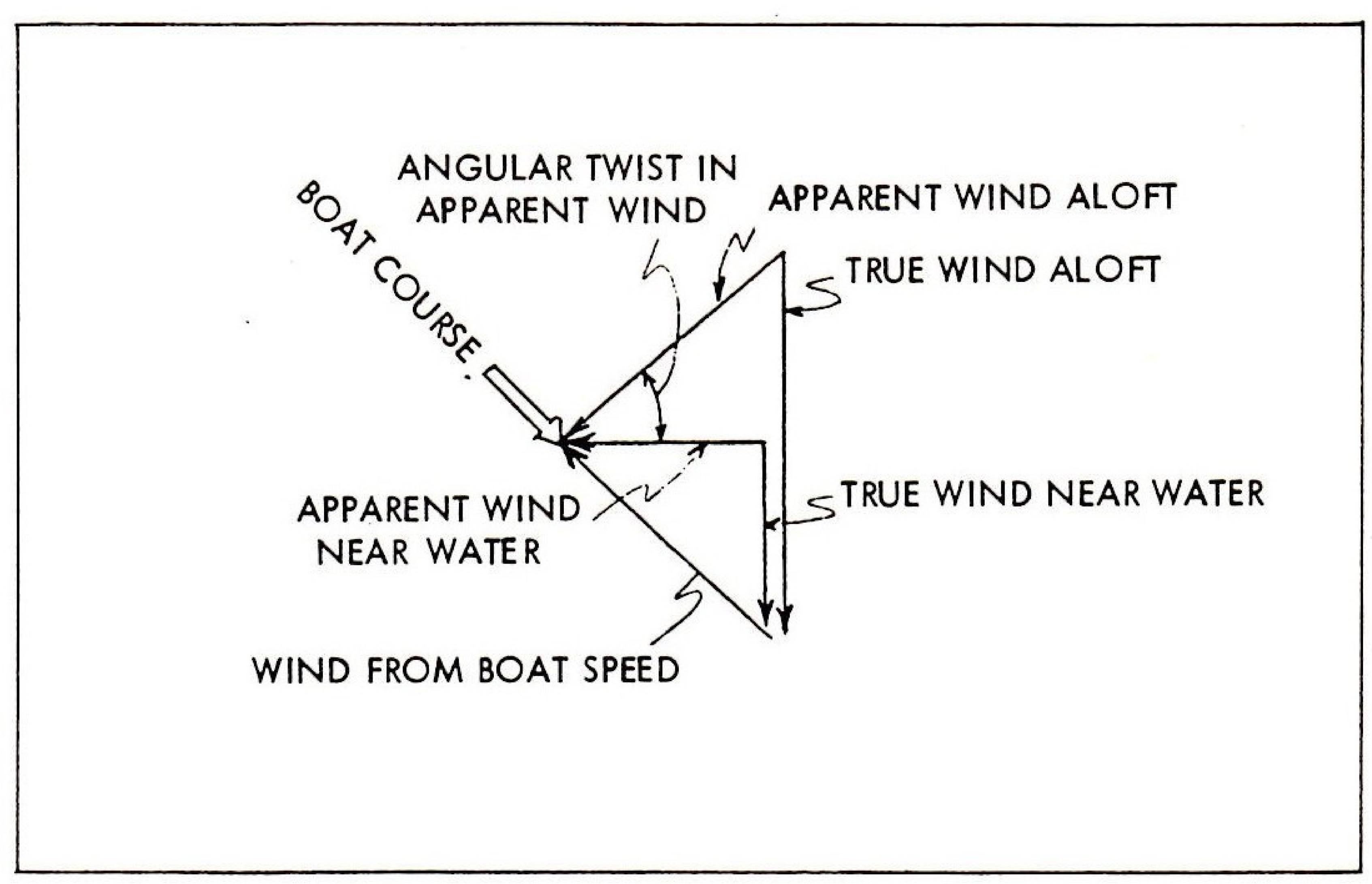

Fig. 9(b) Velocity diagram showing twist in apparent wind when broad reaching

can advance from the old soft-cloth sails and fixed masts. The technology already exists for major improvements in sail design and performance. The adoption of aerodynamically clean wing sails will eventually improve boat performance as well as lead to smaller, more manageable rigs.

It appears that the major requirement to improved upwind sailing is the reduction of induced drag, while for downwind sailing the most important problem is to achieve high lift coefficients. Substantial room for improvement still exists in both cases.

Acknowledgment

The author wishes to express his sincere appreciation to Messrs. A. F. Di Mauro, owner, and David Hubbard, designer of *Patient Lady II* for permission to publish the experimental data from their sail tests. This is an especially welcome addition to the available yacht sail data. Their willingness to make these data available for use by potential competitors stands in marked contrast to the general secrecy found among the designers and owners of highly competitive development boats.