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The Effect of Sail Loading Distributions on Sailboat Performance

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1 INTRODUCTION

The performance of a sailing vessel is affected by a large number of parameters, some which are controllable, and others which are not. This paper discusses the effects on the applied forces on the vessel produced by varying some geometric sail parameters. These variations have been applied to a C-Class catamaran to determine their effect on the performance of a particular vessel. This type of boat has been chosen because the hydrodynamic equations may be formulated rather readily, see, for example Yeh (1965) and Bradfield (1968). Also sufficient information exists (Martin (1976) and Bradfield (1976)) from race comparisons to distinguish some effects of the variation of parameters. Induced drag is shown to have a major effect on the boat's performance particularly at low wind speeds; the aerodynamic drag or "windage" of the hull and crew, and of the sail planform also influence the speed.

2 NOTATION

AR	aspect ratio (height^2/area)
C_d	section drag coefficient
C_L	lift coefficient
C_H	hydrodynamic sideforce coefficient
D	aerodynamic drag force
e_b	centreboard efficiency factor
H	hydrodynamic sideforce
L	aerodynamic lift force
L_{WL}	load waterline length
R	hydrodynamic resistance
S_A	sail area
S_W	wetted surface area
T_A	total aerodynamic force
T_W	total hydrodynamic force
V_A	relative or apparent wind speed
V_S	boat speed
V_T	true or absolute wind speed
Δ	displacement (tonnes)
β_A	angle between apparent wind vector and boat velocity vector
γ	angle between true wind vector and boat velocity vector
ε	'drag angle', $\varepsilon_A = \tan^{-1}\frac{C_D}{C_L}$, $\varepsilon = \tan^{-1}\frac{R}{H}$
λ	leeway angle
ρ_A	density of air
ρ_ω	density of water.

3 INDUCED DRAG

The equations of motion applied to the steady motion of a vessel through the water lead to the following relationships (Bradfield (1968), Apperley (1974))

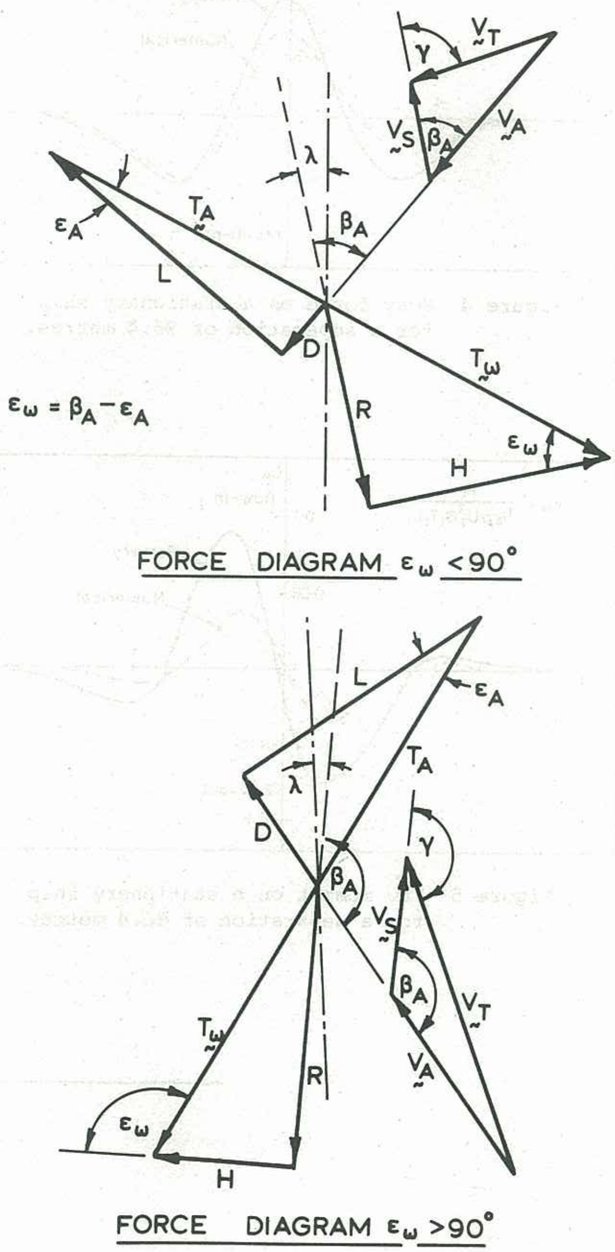

Figure 1 Definition of Parameters

$$\frac{V_S}{V_A} = \left[\tfrac{1}{2}\frac{\rho_A}{\rho_\omega} \cdot \frac{C_{TA}}{KC_S} \cdot \frac{S_A}{S_W} \left(\sin\varepsilon_\omega + \sqrt{\sin^2\varepsilon_\omega - 4\frac{S_W}{S_i} \cdot \frac{KC_S}{e_b \pi AR}\cos^2\varepsilon_\omega}\right)\right]^{\frac{1}{2}} \tag{1}$$

and

$$\frac{V_S}{V_T} = \frac{1}{\sqrt{(V_A/V_S)^2 + \cos^2\gamma - 1} - \cos\gamma} \tag{2}$$

These terms are defined in the glossary and in Figure 1.

A computer programme has been used to study the effect of the parameters in these governing equations. The sail section used in the calculations is the one described by Apperley (1974). Figures 2 and 3 indicate the variations in boat speed caused by changes in the induced drag component at different aspect ratios, the induced drag being calculated from the usual expression

$$C_{Di} = \frac{C_L^{\,2}}{\pi . AR} \tag{3}$$

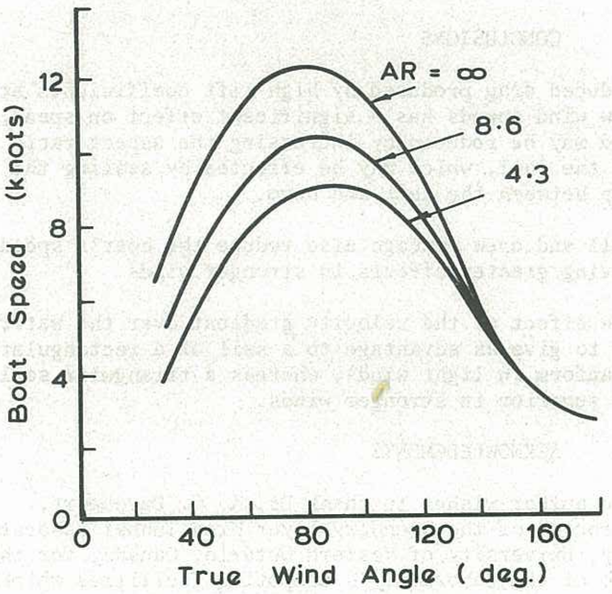

Figure 2 Effect of Induced Drag at V_T = 5 knots

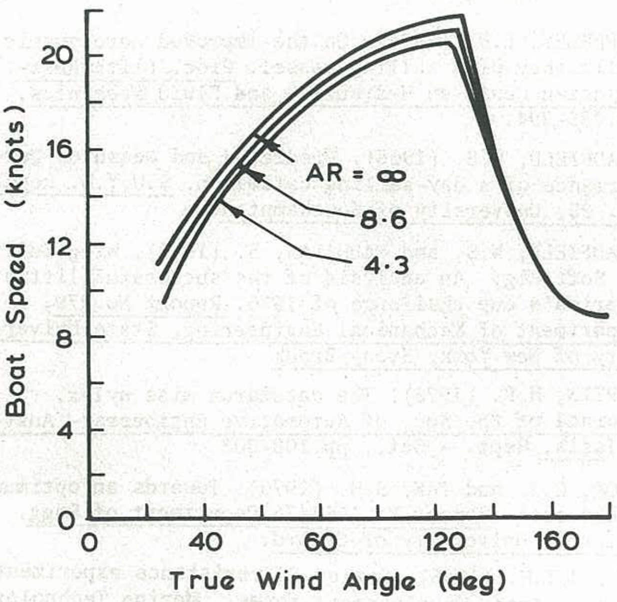

Figure 3 Effect of Induced Drag at V_T = 15 knots

An aspect ratio of 4.3 is the value for the sail with the usual gap between the boom and the deck, the second curve AR = 8.6 shows that by sealing this gap an increase in speed of some 12% may be obtained at a wind angle $\gamma = 90^o$ at V_T = 5 knots. The remaining curve is for a two-dimensional sail, showing the maximum effect of induced drag. Figure 3 indicates that at higher wind speeds the effect of induced drag is much less, as the overturning moment limits the force that may be applied to the vessel and consequently the lift coefficients are lower.

4 HULL AND CREW DRAG

Apperley (1974) shows the lift and drag coefficients produced by the hulls and crew on a C-Class catamaran with the crew in their normal sailing positions. Introducing these coefficients into the equations enables the effect of these force components to be considered. Figure 4 shows that again, as with the induced drag, the maximum effect on speed occurs when reaching, at $\gamma = 90^o$, but in this case the effect is some 7% change in speed. At higher wind velocities the change in speed will be greater because of the effect of this fixed drag component on the smaller lift force. At V_T = 15 knots the speed change is 11%.

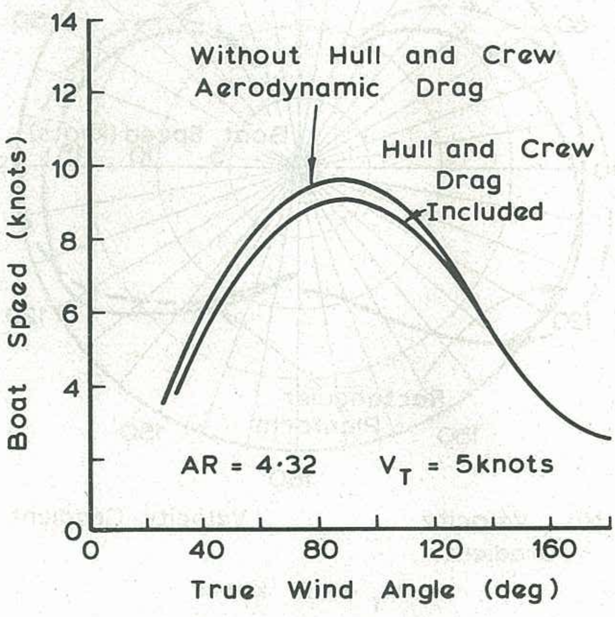

Figure 4 Effect of Aerodynamic Drag of Hull and Crew

5 VELOCITY GRADIENT AND PLANFORM

The existence of a vertical velocity gradient near the water surface is generally recognised, although its exact nature and its effect on a sailboat are not well defined. It is certain that the type of gradient will vary with atmospheric conditions and conditions of the fetch. Apperley (1974) discusses the effect on the angle of attack of a gradient of the form $V/V_{Tm} = (y/y_m)^{\alpha}$ where V is the velocity at height y above the water and y_m is the mast height. The major effect of such a gradient is to produce a change in the angle of incidence of the approaching wind flow requiring "twist" or wash-out of the sail for constant angle of attack and optimum driving force at low wind speeds.

Wood (1976) has shown that at higher wind speeds where overturning is a limiting factor, reverse incidence of the upper sail area would be beneficial in increasing the driving force.

The existence of a velocity gradient will influence the planform of the sail chosen. Those parts of the sail high above the water will produce larger forces than equal areas lower down. At higher wind speeds the angle of attack of the upper sail will have to be reduced to reduce the capsizing moment, and under these conditions larger sail areas closer to the water will be more suitable.

Figure 5 shows the effect of sail planform on the performance of a C-Class catamaran both with and without a velocity gradient at a wind speed V_T = 15 knots. The sail shapes used have equal areas, are of equal height (span), one being rectangular in shape and the second triangular. The reversal of sail incidence, as suggested by Wood, has not been considered in the determination of the results shown in Figure 5. For the case of uniform wind velocity (no gradient) the triangular sail is superior to the rectangular one, because of the reduced moment arm, to $\gamma = 130^o$, where stability is no longer critical and the two planforms produce equal forces.

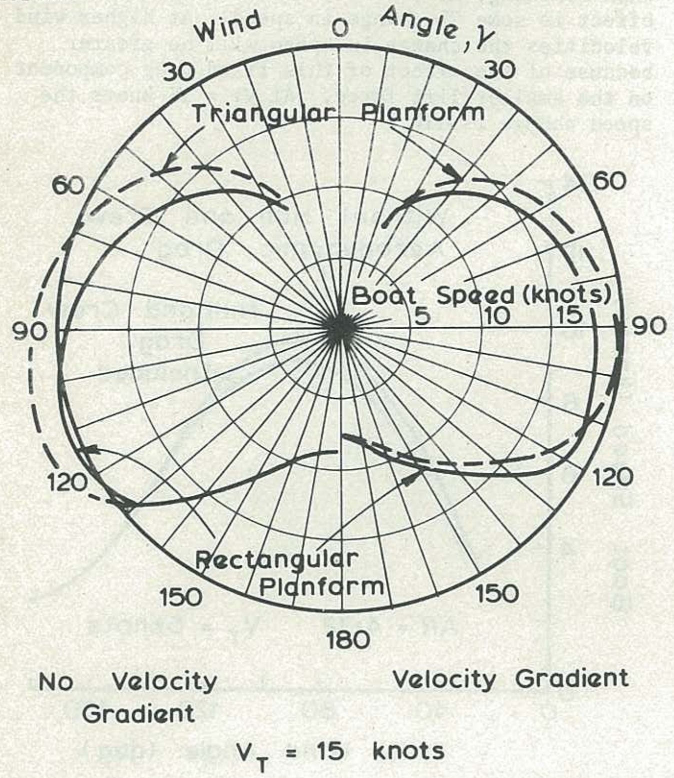

Figure 5 Speed Variations Due to Sail Planform

With a velocity gradient, the triangular sail shape is superior to $\gamma = 115^o$, where again stability is no longer critical and here the rectangular sail, with a larger area exposed to the higher wind speeds, is dominant. At lower wind speeds, where the overturning moment produced is sufficiently small, the rectangular sail is superior for all wind directions.

6 SPEED - MOMENT RELATIONSHIP

In Figure 6 the variation of capsizing moment and speed with wind angle, γ, is shown. The capsizing moment here has been calculated using the total aerodynamic force T_A, rather than the heeling component, H, as most catamarans have stability curves which are relatively insensitive to direction, in fact diagonal capsizes are common. Figure 6 shows that the maximum capsizing moment occurs at $\gamma \approx 65^o$, whereas maximum speed is at $\gamma \approx 85^o$. Thus it can be seen that when sailing near maximum speed, "bearing away" in gusts is desirable as this will reduce the capsizing moment rapidly, whereas "rounding up"

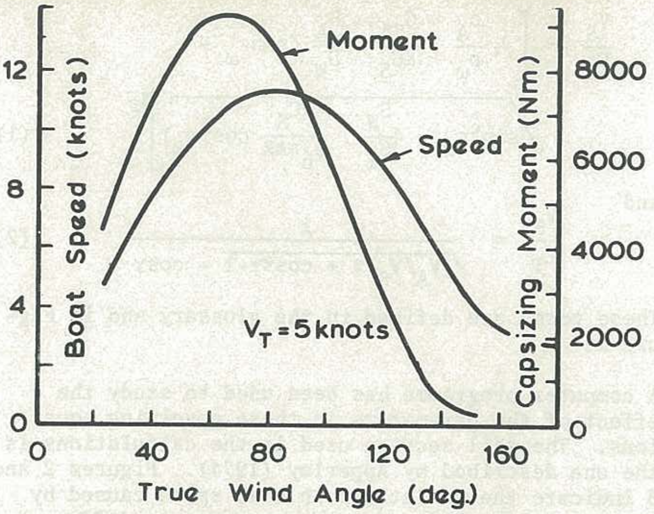

Figure 6 Variation of Speed and Capsizing Moment with Wind Angle

will increase the moment and probably cause a capsize.

7 CONCLUSIONS

Induced drag produced by high lift coefficients at low wind speeds has a significant effect on speed, and may be reduced by increasing the aspect ratio of the sail, which may be effected by sealing the gap between the deck and boom.

Hull and crew windage also reduce the boat's speed, having greater effects in stronger winds.

The effect of the velocity gradient over the water is to give an advantage to a sail of a rectangular planform in light winds, whereas a triangular sail is superior in stronger winds.

8 ACKNOWLEDGMENTS

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