THE 14th CHESAPEAKE SAILING YACHT SYMPOSIUM
January 29-30 1999, Annapolis, Maryland USA

Use of CFD techniques in the preliminary design of upwind sails

Dr Patrick Couser, Formation Design Systems, Fremantle, Western Australia (and Australian Maritime Engineering Co-operative Research Centre, Perth Core, Curtin University of Technology, Perth, Western Australia)

Mr Norm Deane, Vice President of the International Mirror Class Association and Australian Manager/Coach for the International Mirror Class, Hobart, Tasmania, Australia

ABSTRACT

The results of the 1997 World Titles, held in Kingston, Canada, highlighted that there was considerable scope for improving the upwind performance of the International Mirror Class by making small adjustments, within the tolerances allowed by the class rule, to the sails and underwater foils. This paper describes some aspects of the Australian research and development programme in preparation for the 1999 World Titles to be held in South Africa in April.

Computational methods, based on the vortex lattice method, have been used to provide direction and guidance for the on-the-water testing and trialing programme. The use of these theoretical tools has enabled a far wider range of sail, centre board and rudder parameters to be investigated than would be possible using purely on-the-water testing.

The usefulness of well-understood computational and numerical methods in sail and foil design has been demonstrated; it has also been shown that these tools are within the reach of relatively small budget research and development programmes.

NOTATION

AME CRC	Australian Maritime Engineering Co-operative Research Centre
C_R	Drive force coefficient
C_S	Side force coefficient
C_L	Lift force coefficient
C_{Di}	Induced drag coefficient
C_D	Drag coefficient
C_F	Friction coefficient (ITTC 57)
b	Apparent wind angle
ldr	Lift to drag ratio
VPP	Velocity Prediction Program

INTRODUCTION

The work presented here builds on the results of the AME CRC’s Yacht Technology Research Programme. This programme involves the development of computational techniques for predicting yacht performance. Two of the principal tools which have been developed a the velocity prediction program (VPP) and a vortex lattice model which is used to compute sail forces. A review of the work being undertaken by the AME CRC's Yacht Technology Research Program is given by Couser (1997).

International Mirror Class

The International Mirror Class is a one-design dinghy with a crew of two. The overall length is 3.3m and, upwind, a total sail area of 6.5m^2 is carried. First introduced in 1963, the Mirror quickly became the most popular one-design class in the world. Since its introduction, nearly 70,000 Mirrors have been built around the world. In 1990 the Mirror dinghy became an international class recognised by the International Sailing Federation. The main dimensions of the Mirror dinghy are given in Table 1. The dinghy is shown sailing upwind in Figure 1.

Table 1: Principal particulars of the International Mirror Class dinghy:

P'mouth Y'dstk	1382 (1362 Single-handed)
Length over all	3.3m
Beam	1.4m
Draft	0.1m, centre board raised
Mast Height	4.9m, mast and gaff from deck
Mast Length	3.3m
Gaff Length	2.8m
Boom Length	2.3m
Sail Area	6.5m^2
Main	4.6m^2
Jib	1.9m^2
Spinnaker	4.4m^2
Rig	Gunter with optional spinnaker
Dinghy weight fully rigged	61.4kg
Normal crew	two; typical total crew weight 115kg

Figure 1: International Mirror Class dinghy.

Vortex lattice method

Computational methods for calculating the flow of the wind over a yacht's sails have been developed over many years. Amongst the pioneers in this field were Milgram (1968), Thrasher et al. (1979) and Register and Irey(1983). These methods are under continuous development and refinement, for example Fiddes (1996).

A computational method commonly used to predict the flow over sails is the vortex lattice method. This method is able to predict the flow of an ideal fluid over a number of lifting surfaces. It is relatively fast and suited to computing the flow over combinations of highly cambered, thin lifting surfaces, such as a sailing rig. The form of the method used in this investigation is based on the work of Greeley and Kerwin (1982) and Greeley et al. (1989). This code is under development at AME CRC under its Yacht Technology Research Program (Day and Couser 1998).

The current vortex lattice method is capable only of predicting the potential fluid flow over the sails; i.e. the effects of fluid viscosity are ignored. This is a reasonable approach for predicting upwind sail performance provided that separation is restricted to small areas in the vicinity of the mast. If the sails are operated near their maximum lift coefficient, it is possible that separation may occur from the leeward side of the sail. This will result in a much greater drag than that predicted by the potential flow model. Where significant separation does not occur the skin friction of the sails and the drag of the mast may be approximated by empirical equations and experimental data (Milgram 1978).

Although the predicted forces obtained by this method may not be precisely accurate in absolute terms, such computational techniques are very valuable for comparative studies and flow visualisation, since they may be carried out more cost effectively than wind tunnel tests and under more controlled conditions than on-the-water testing.

This paper presents the results of the numerical investigation and describes how this has focused the on-the-water testing programme. The results of numerical analysis and sailing trials are compared and contrasted. Areas for improvement in the numerical analysis are highlighted.

Previous work

This paper follows on directly from work carried out in early 1998 (Couser, 1998a). This study investigated the upwind performance of the International Mirror Class dinghy, with particular regard to the interaction between the jib and main sail and the effects of raking the mast aft. The latter point was of particular interest, since during the races of the 1997 World Titles, the British and Irish sailors had adopted this rig set-up in preference to a vertical mast and were able to dominate the racing, particularly in lighter winds. The results of this preliminary investigation confirmed that there were possible benefits in raking the mast aft in light winds. The raked mast appeared to provide two main benefits:

i) improved lift to drag ratio of the sails, particularly the main sail, and

ii) suggested an improved yaw moment balance and hence greater efficiency of the centre board and rudder. This second finding was rather speculative, and has been investigated in greater depth in the current paper.

The vortex lattice code used has been validated against wind tunnel data and calculations from other numerical methods (Couser, 1998b). The vortex lattice code was shown to produce satisfactory results within the inherent limitations of the vortex lattice method. Results from calculations of the flow over a high aspect ratio flat plate are consistent with those of linearised theory. Results for an IACC yacht rig were acceptable, however, induced drag was slightly under predicted when compared with the wind tunnel results and results from a three dimensional inviscid surface panel code.

Aim of current research

As has been briefly mentioned above, the aims of this current investigation were to:

- Investigate methods of improving the end-plate effect of the deck on the jib. Within the limitations of the class rule this can be best achieved by reducing the luff length of the jib, bringing the clew and foot closer to the deck; a jib built with the maximum allowable dimensions results in a clew some distance off the deck. This results in some loss of sail area but it was thought that this would be compensated by the increased end-plate effect.

- Investigate the effect of reducing jib foot length. The idea of this was to reduce the influence of the jib on the main. The main sail operates in the downwash of the jib and it was thought that by reducing the jib foot length, the performance of the main sail could be improved. Also the results of a previous analysis (Couser 1998a) indicated an adverse effect on the main arising from the vortex shed from the head of the jib.

- The effect on sail performance of changing the sail section shapes.

- Investigate the performance of the rudder and centre board. It was thought that the overall lift to drag ratio of the appendages could be improved by a more equal distribution of side force on the rudder and centre board.

SAIL ANALYSIS

Methodology

The principal aim of the numerical analysis was to provide guidance for the on-the-water testing. Despite the inaccuracies of the vortex lattice method (amongst others, all viscous forces and effects are ignored, and there are also a considerable number of assumptions), it was found to be a useful tool since a greater number of sail geometries could be tested and compared much more quickly than on the-water-testing. Such on-the-water testing is very time consuming and is itself susceptible to errors due to the relatively subjective nature of the testing. The results of both methods of experimentation were complementary and, in general found to give the same conclusions.

Table 2: Sailing conditions used for numerical analysis:

Boat speed	4.1 knots
True wind speed	12 knots
True wind angle	45°
Apparent wind speed	15.2 knots
Apparent wind angle	34°
Vertical wind gradient	constant
Air density	1.206 Kg/m^3
Heel angle	0°
Leeway angle	0°
Boom sheeting angle to CL	6°
Jib sheeting angle to CL	14°

Previous experience with the vortex lattice program over a number of years meant that issues such as panel density, wake length and convergence requirements were well-understood. In all cases each sail was modelled by 320 panels (20 spanwise and 16 chordwise), (Couser 1998a, 1998b, 1997; Day and Couser 1998). The sailing conditions were determined from experience and are summarised in Table 2. The flying section shapes and vertical twist profiles were measured from photographs taken of the sails looking up the mast whilst under sailing conditions. An example is shown in Figure 2.

Figure 2: Analysis of sail flying shape.

Sail geometries

The practical considerations of the International Mirror Class rule mean that manipulation of the plan shape of the jib is most likely to yield beneficial results; the plan shape of the main sail is usually kept at the maximum permissible dimensions. Two separate tests were conducted:

1. Investigate the effect of jib plan shape;

2. Examine the effect of jib and main sail section shape.

In order to examine the effects of sail plan shape changes, six different jib plan shapes were tested. The main sail plan shape was not altered since experience has shown that the most effective main sail planform corresponds to the maximum allowed by the class rules. The dimensions of the sail plan shapes are given in Table 3 and are plotted in Figure 3 and Figure 4.

A jib built to the maximum dimensions allowed by the class rules will have a clew some distance off the deck; typically 160mm; see Figure 4. The clew is most effectively brought down to the deck by reducing the luff length whilst keeping the tack position fixed and the leech and foot lengths at their maximum allowable values. Shortening the luff by 160mm places the clew and the foot of the jib virtually on the deck, at the cost of a small reduction in sail area.

Reducing the jib luff length will lead to a reduction in sail area and geometric aspect ratio (see Table 3); however, the improved end-plate effect, due to the clew and foot being closer to the deck, is likely to increase the effective jib aspect ratio leading to reduced downwash and induced drag. Hence the trade off is between reduced sail area and improved efficiency of the jib and main system.

Another effect which was of interest was the interaction of the jib tip vortex (from the head of the jib) on the main sail. It was thought that this was a detrimental effect and by reducing the jib luff length, the jib head was moved further from the main sail, enabling this hypothesis to be tested. The effect of reducing the luff length was assessed by testing the parent jib (Parent), two jibs with shorter luffs (V Short and Short), and a fourth jib with a longer luff (Tall).

In addition the effect of jib foot length was also of interest. Two further jibs were tested, the first (Narrow) had only the foot reduced compared with the parent, whilst the second (Tall, Narrow) had the shorter foot but the maximum luff length. The narrower jibs also had reduced sail area but increased geometric aspect ratio when compared with the parent. In all cases the jibs were tested rigged with the parent main sail.

Table 3: Main and jib plan shapes

Name	type	luff [m]	foot [m]	leech [m]	AR	AR diff.	Area diff.
Parent	main	4.052	2.135	4.520	3.4	—	—
Parent	jib	2.660	1.540	2.442	3.0	—	—
V Short	jib	2.500	1.540	2.442	2.7	-9%	-2.6%
Short	jib	2.580	1.540	2.442	2.8	-5%	-1.5%
Tall	jib	2.782	1.540	2.442	3.2	8%	1.0%
Narrow	jib	2.660	1.300	2.442	3.5	17 %	-14.4%
Tall, Narrow	jib	2.782	1.300	2.442	3.8	27 %	-13.9%

Note: In Table 3, AR is the geometric sail aspect ratio given by Height^2/Area.

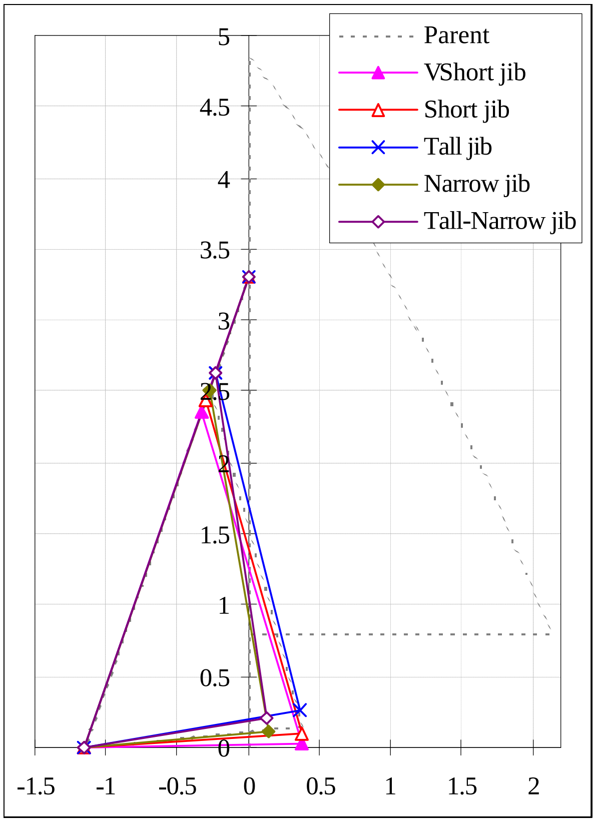

Figure 3: Main and jib plan shapes.

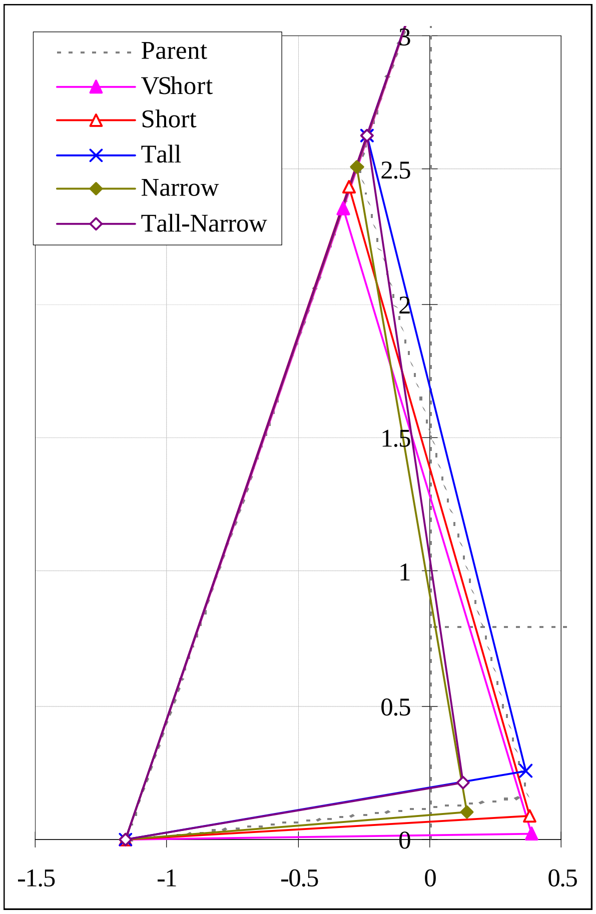

Figure 4: Jib plan shapes.

The effect of changes in the jib sections was investigated by testing the parent jib plan shape with three different section types (Parent, J1, J2). The sections of J1 had increased camber with the draught further forward, whilst J2 had sections with less camber and the draft further aft.

The jib section shape details are given in Table 4 and are plotted in Figure 5 to Figure 7. The linear dimensions: draft position; camber depth; and front and back depth, are expressed as percentages of the chord and the entrance and exit angles are in degrees with respect to the local chord (not including sail twist). The sail section shapes were measured at the 1/4, 1/2 and 3/4 span points of the sails.

In Figure 5 to Figure 10, the section camber distributions in percentage of local chord are plotted against percentage of local chord at the three vertical sections (1/4, 1/2 and 3/4 span) for the three jib and three main sail shapes tested.

Table 4: Jib section shapes

	Parent			J1			J2		
	1/4	1/2	3/4	1/4	1/2	3/4	1/4	1/2	3/4
Draft	39.7	41.2	48.5	37.8	40.2	44.9	40.9	46.1	53.3
Camber	12.8	12.6	12.1	14.3	15.3	14.1	10.6	10.5	9.4
Front	9.8	9.9	9.1	11.8	11.5	10.1	8.6	8.1	6.9
Back	8.2	9.1	8.9	9.3	10.0	10.0	7.1	7.4	7.5
Ent'nce	26.7	17.9	7.9	23.4	19.9	18.4	21.5	18.5	13.5
Exit	26.9	22.0	11.0	14.0	14.3	17.7	12.1	14.0	17.5

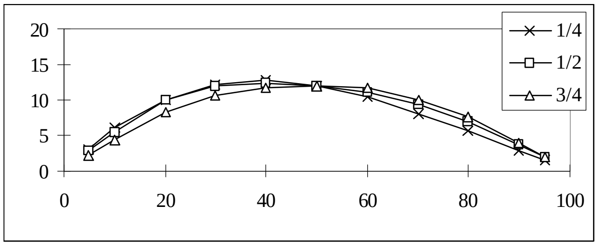

Figure 5: Jib section shape: parent.

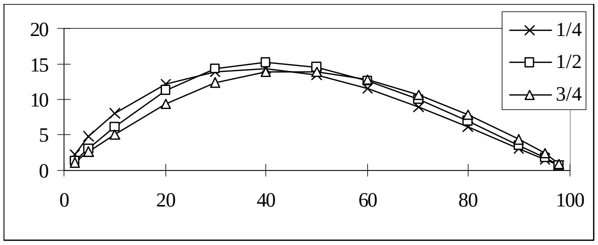

Figure 6: Jib section shape: J1.

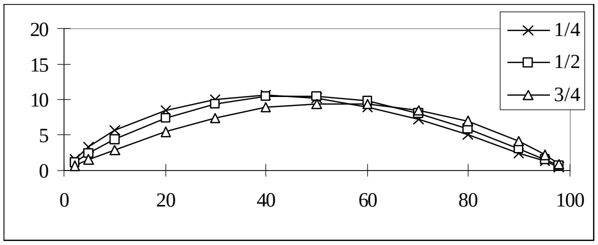

Figure 7: Jib section shape: J2.

The effect of main sail section shape was investigated by testing the parent main sail with three different sections with the parent jib. Both of the new main sails (M1 and M2) had the draught further forward and deeper camber than the parent. M1 had the deepest camber.

The main sail section details are given in Table 5 and are plotted in Figure 8 to Figure 10.

Table 5: Main section shapes

	Parent			M1			M2		
	1/4	1/2	3/4	1/4	1/2	3/4	1/4	1/2	3/4
Draft	42.1	46.3	46.7	39.0	43.5	42.1	33.0	39.9	43.0
Camber	11.9	13.3	12.9	13.9	16.1	14.2	12.8	15.0	14.3
Front	9.1	10.5	9.9	11.0	12.4	11.0	10.3	12.0	10.9
Back	8.6	9.1	8.8	9.7	11.5	9.9	8.4	10.6	9.7
Ent'nce	33.6	35.0	30.2	34.7	34.5	32.4	37.2	35.9	31.2
Exit	17.6	22.2	19.5	21.1	24.8	20.9	19.6	22.6	17.6

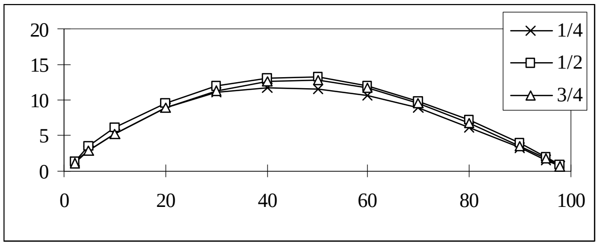

Figure 8: Main section shape: parent.

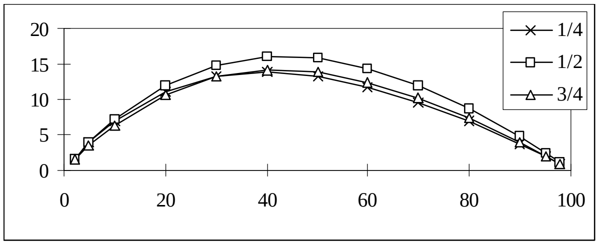

Figure 9: Main section shape: M1.

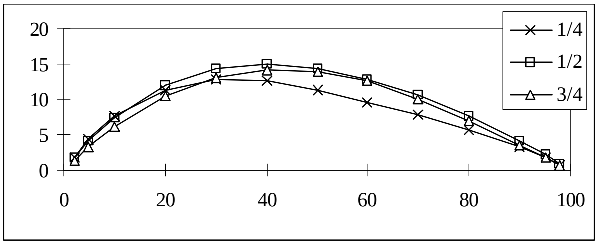

Figure 10: Main section shape: M2.

These new sail section shapes were based on sails which had proved successful at the 1997 world titles and other regattas. In all cases the sails tested represented sails which could be physically built using the sail cloths allowed by the class rule. The main aim of these tests was to determine if the vortex lattice code was sufficiently accurate to correctly predict the effects of changing the sail section shapes.

During sailing the camber and draught of the sails are continuously manipulated by the crew to suit the prevailing conditions. It was not certain whether the vortex lattice code would be able to correctly categorise the different sails since the optimum for a given set of sea and wind conditions often depend on factors which the vortex lattice method cannot model — for example in rough sea conditions, when the dinghy and rig are moving considerably due to wave action, sail sections with deeper camber are favoured, whilst in flat water the sails are flattened.

An example of a typical panel layout used for the vortex lattice model is given in Figure 11. It should be noted that due to limitations in the program, the foot of the sails had to be horizontal. The vertical position of the foot of the sail was calculated by averaging the height of the tack and clew of the sail. This had some implications when considering the end-plate effect of the deck. The end-plate is most effective near the leading edge of the foot, since this is where the greatest pressure differential is generated. Raising the foot of the sail in this area, to produce a horizontal foot for the vortex lattice model, will tend to under predict the benefit of the end-plate.

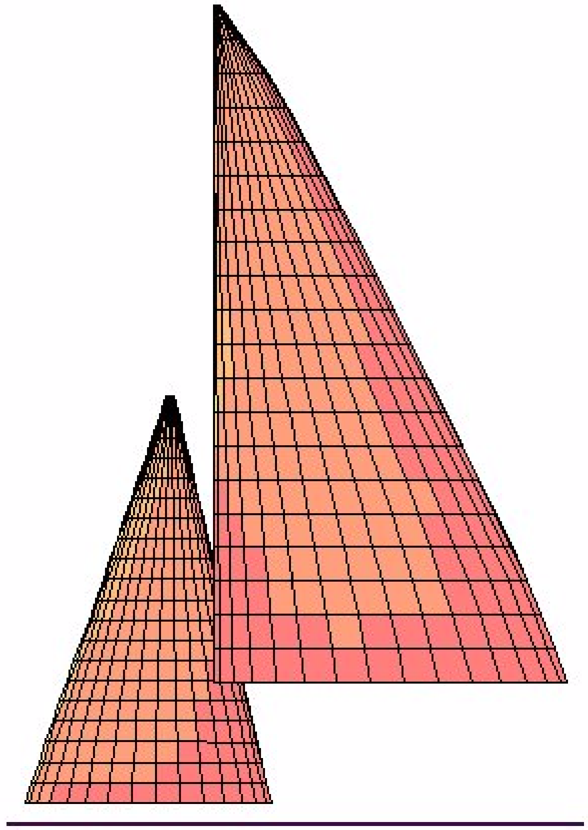

Figure 11: Typical vortex lattice panel layout.

Results from computational models

It has been found that the vortex lattice code used for the calculations is useful for comparing the relative changes in magnitude of the sail force and moment coefficients when compared to a base or parent condition. The results have been broken down into two main groups: effect of changes in jib platform and effect of changes of jib and mainsail sections (camber and draught). Attention is focused on the forces and moments of primary importance; for the International Mirror Class, this is the drive force, the side force, and to a lesser extent the heeling moment. These forces will determine the speed of the dinghy. This will be primarily dependent on the drive force. However, too great a side force may result in a large leeway angle and/or greater induced drag from the underwater appendages. Also in all but the strongest winds, the heeling moment should not be a limiting factor since the crew are normally able to provide adequate righting moment.

The effect of jib plan shape on drive force (for the upwind sailing condition described in Table 2) is presented in Figure 12. The values are the percentage increase in drive force compared with the parent. Figures are given for the change in drive generated by the main sail, jib and complete rig (in all cases both sails were tested together).

The results of the numerical analysis showed that the reduced luff length is beneficial. For the two jibs of reduced luff length (V Short and Short) the drive force generated by both the main sail and the jib are increased. The tall jib shows a small improvement in the drive generated by the jib, but the drive of the main and the total rig is reduced. These changes are probably due to changes in effective jib aspect ratio offset against changes in jib sail area. The V Short and Short jibs have slightly reduced sail area but benefit since the gap under the foot of the jib is reduced. This is particularly effective for the V Short jib, which is virtually sealed at the deck.

The benefits of reducing the gap under the foot is that the effective aspect ratio of the sail is increased and the induced drag is reduced. Also the downwash created behind the sail is reduced and this is why the performance of the main sail is also improved. The reduction in gap may also improve the spanwise loading on the jib, resulting in reduced induced drag and improving the lift to drag ratio of the sail.

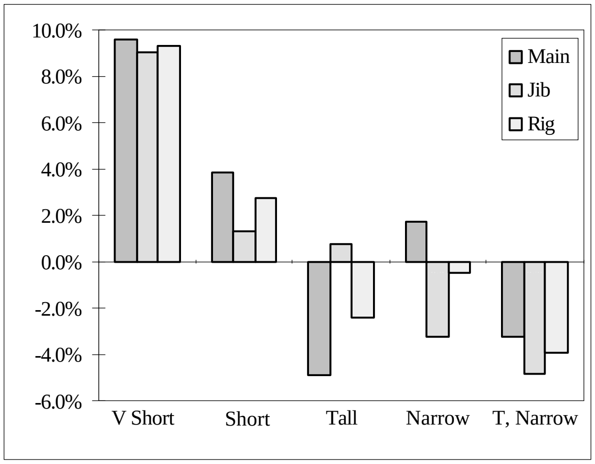

Figure 12: Effect of jib plan shape on drive force.

The lift to drag ratio is particularly important for upwind performance. It may be shown that the drive coefficient, C_R, is given by Equation (1), where C_L is the lift coefficient.

$$C_R = C_L\left(\sin b - \frac{\cos b}{ldr}\right) \qquad (1)$$

Hence at small apparent wind angles, *b*, it is important that the lift to induced drag ratio, *ldr*, be as large as possible for the drive coefficient to be maximised.

The effect of plan shape on lift to induced drag ratio is shown in Figure 13. Here it may be seen that all the jibs show an improvement over the parent. The improvement in the shorter jibs is due to reducing the gap under the jib, thus increasing the effective aspect ratio, whilst the improvements of the taller and narrower jibs are due to increases in the geometric aspect ratio. However, the large increases in lift to induced drag ratio of the Narrow and Tall, Narrow jib are not realised in terms of improvements in the drive force because of the reduction in area associated with these jibs (see Figure 14).

The lift to induced drag ratio of the main sail is also affected by changes in the jib plan shape. The improvement is most for the V Short jib; the Tall jib has a detrimental effect on the main sail. This is thought to be due to the tip vortex generated at the head of the jib. It appears that moving the head of the jib away from the main is beneficial. The improvement in main sail performance behind the Narrow jib is probably due to the increase in geometric aspect ratio reducing the downwash behind the jib. In the case of the Tall, Narrow jib, this is offset by detrimental interference from the jib tip vortex.

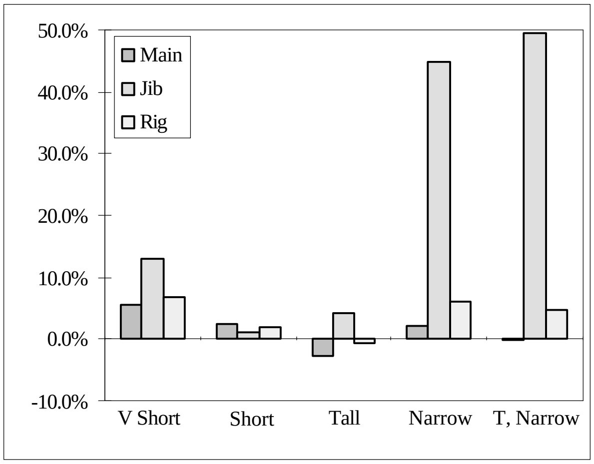

Figure 13: Effect of jib plan shape on lift to induced drag ratio.

The shorter jibs show small reductions in area, and the tall jib a slight increase, however the jibs with the shorter foot lengths have significantly reduced sail area (Figure 14). It is for this reason that these sails do not produce increased drive despite significant increases in lift to induced drag ratio.

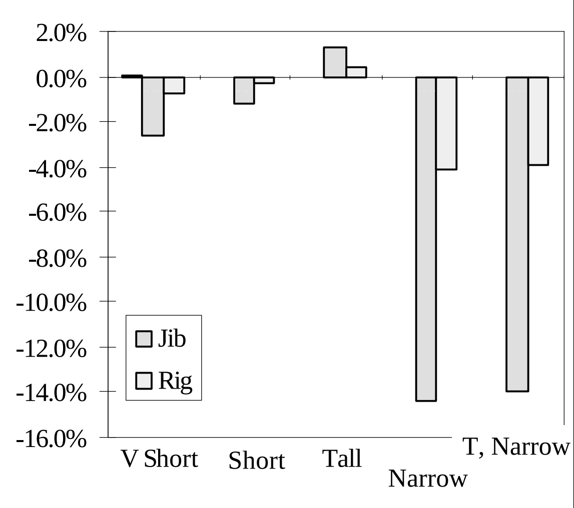

Figure 14: Effect of jib plan shape on sail area.

The changes in side force generated by the different sail combinations is shown in Figure 15. The increase in side force for the two shorter jibs is primarily due to the greater lift force generated by these sails resulting from reduction of the gap under the foot of the jib. The Tall jib shows a slight reduction in side force mainly due to the reduced forces on the main sail experienced with this jib, whilst the relatively large reduction in side force for the Narrow jibs is due to the reduction in sail area (and reduced main sail forces for the Tall Narrow combination).

The increases in side force for the shorter jibs would require greater side force to be generated by the centre board, rudder and hull. This would lead to some increase in induced drag, but it is likely that this would be more than offset by the increase in drive force obtained with these jibs.

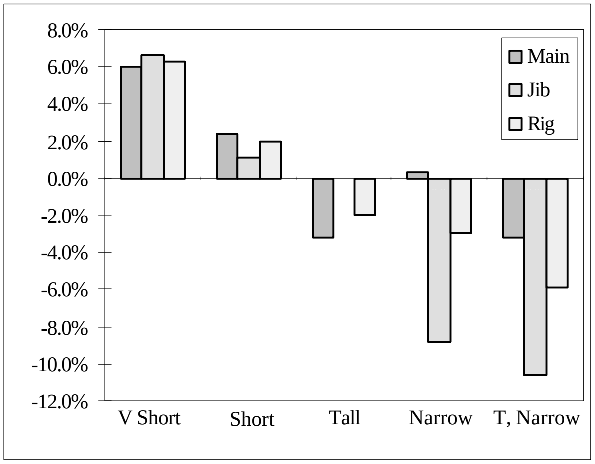

Figure 15: Effect of jib plan shape on side force.

The heeling moments of the total rigs are largely unaffected by the changes in jib plan shape. In any case the small increases for the two shorter jibs should be easily accommodated by the crew without loss of performance.

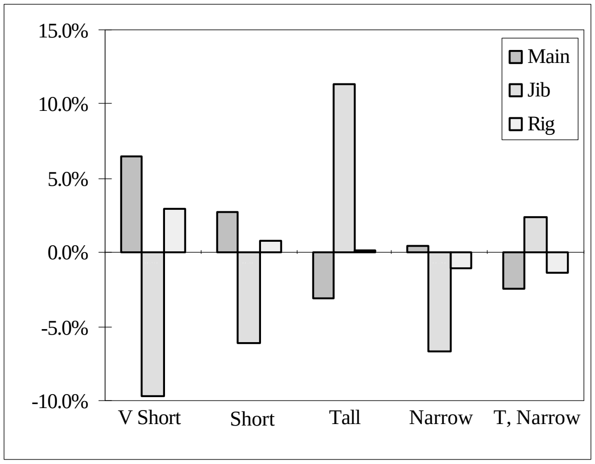

Figure 16: Effect of jib plan shape on heel moment.

Although the centre of effort of the jib moved a little for the different plan shapes, movement of the overall centre of effort of the rig was negligible.

Overall, the results indicate that the shorter luff jibs (V Short and Short) have the potential of offering increased performance over the parent jib. This is primarily due to the increase in drive force obtained with these sails.

It is interesting to note the marked increase in main sail drive force with the V Short and Short jibs rigged. It is thought that this is mainly due to reduced downwash from the jib. (This is achieved since the gap under the jib foot is reduced and hence the effective aspect ratio of the sail is substantially increased.) Also it appears that there is benefit in moving the jib head further from the main sail. For fractional rigs there is the likelihood that the tip vortex from the jib head will have a detrimental effect on the performance of the main sail.

The effect of changing the sail section shapes on drive force, heel force and heel moment are shown in Figure 17, Figure 18 and Figure 19 respectively. In all cases, the parent jib and main sail planforms were used with the different sail section shapes under investigation.

The differences are relatively small and appear to be dependent primarily on section camber. This is as might be expected for an inviscid flow model such as the vortex lattice method. With this method it is not possible to determine whether separation will occur; separation is possibly more likely for the sections with greater camber.

Both Main 1 and Jib 1 have deeper camber but similar draught position as their respective parents. This gives greater forces for these sails. The greater camber in Main 1 also has the beneficial effect of increasing the upwash on the jib, making the jib more effective. By contrast the better performing Jib 1 has a detrimental effect on the main probably due to increased downwash. The finer sections of Jib 2 appear to have no benefit; the even greater detrimental effect on the main is perhaps a little surprising. Main 2 has a slightly greater section camber than the parent but the draught is significantly further forwards. This has a detrimental effect on the main sail drive, though the improvement in jib performance compensates for this somewhat. Similar findings are reported by Larsson and Eliasson 1994, page 141. Here the results of wind tunnel tests are presented which show that, for upwind sailing, the optimum draft position is approximately 50% of the chord.

The results for side force and heeling moment follow the trends observed for the drive force.

Changes in the overall longitudinal centre of effort of the sails, due to the different section shapes, were negligible.

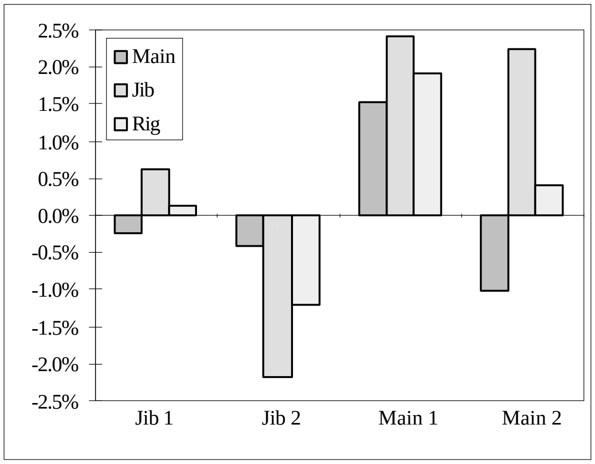

Figure 17: Effect of section shape on drive force.

Figure 18: Effect of section shape on side force.

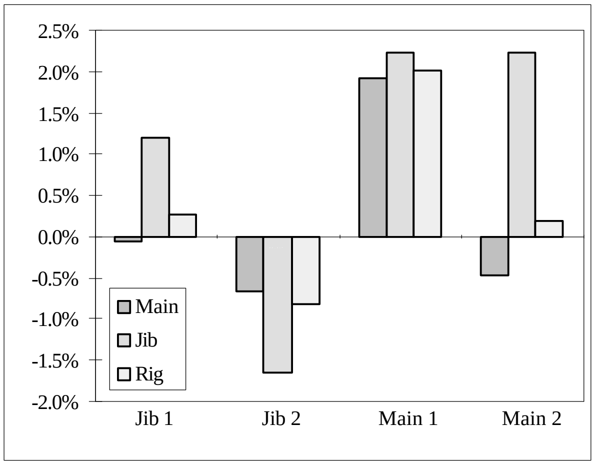

Figure 19: Effect of section shape on heel moment.

To summarise, for the wind speed and sailing condition tested, see Table 2, the computational analysis was useful in differentiating between the different jib planforms under investigation.

The V Short jib was found to provide the best drive force and showed a small improvement in lift to induced drag ratio compared with the parent. These effects have been attributed to the gap under the foot of the sail being reduced sufficiently to produce a substantial increase in effective aspect ratio.

The two narrower jibs showed large increases in lift to induced drag ratio, but suffered in terms of drive force due to the significant reduction in sail area.

The results of the investigation into the effects of sail section shape were less conclusive. This was because of the lack of viscous model. To make judgements on the best sail section shape, the effects of separation and stall need to be accounted for. As might be expected from a potential flow model, sections with deeper camber were found to produce higher forces. In practice these sails may suffer from greater separation and increased viscous drag.

Results from on-the-water trialing

Results from on-the-water trialing, in light to moderate winds, seem to confirm the findings of the vortex lattice modelling. To date only the two shorter jibs have been tested.

The changes in flow under the foot of the jibs were confirmed by flow visualisation using wool tufts.

The Short jib proved beneficial, particularly for pointing ability. Reducing the luff length further did not seem to provide additional benefit, however this may have been caused by the sail sections becoming distorted in the bottom of the sail as it was cut down. It is planned to build and test a new V Short jib.

It is possible that the full benefit of the V Short jib, predicted by the vortex lattice code, will not be realised in practice. This is because of the dinghy and rig geometry; the neglect of the viscous drag component (friction and profile drag); and the disturbed flow onto the foot of the jib near the deck resulting in a loss of the lift produced from a portion of the sail very close to the deck.

APPENDAGE ANALYSIS

Methodology

The International Mirror Class rule allows for some variation in size and position of the appendages. General practice is to keep the centre board and rudder as deep as is allowed by the class rule. However it is possible to vary the chord of each by approximately 7% and 10% respectively and the longitudinal position of each by approximately 40mm. The vortex lattice code was used to predict the forces generated by the appendages at different leeway angles. Nine test cases were used, corresponding to three different combinations of maximum and minimum allowable centre board and rudder sizes at three different longitudinal positions.

The appendages were modelled as flat plates of the appropriate span and chord, this was a fair representation of the mirror dinghy's appendages which are constructed from plywood sheets with some fairing allowed near the leading and trailing edges. A mirror image was imposed in the free surface, thus providing a perfect end-plate. This would be near to reality for the centre board, which is underneath the hull, but an overestimate of the rudder end-plate since the rudder is hung on the transom and is open to the free surface.

The rudder and centre board were aligned with the hull centre line whilst the leeway angle was varied from 0.0° to 7.5°; the rudder angle was kept constant at 0.0°. The boat speed of 4.1m/s, which was used for the sail analysis, was also used for the appendage analysis.

Results from computational models

It was slightly surprising to find that the differences between all the different combinations tested were virtually negligible. It is unclear exactly why the differences between the different appendage arrangements were so small. The results for lift to drag ratio (including friction drag based on ITTC 57) are given in Figure 20, and Figure 21 shows the variation of side force with leeway angle. The results for all the configurations tested are plotted in these diagrams. As may be seen, there was virtually no difference in either lift to drag ratio or side force for all the cases tested. This is perhaps a little surprising considering that the change in total appendage area was around 4% and a similar change in side force might be expected. The lift to drag ratio of the configurations with greatest centre board and rudder separation were marginally better than those where the separation was less; also it was marginally more beneficial to have a large rudder and small centre board, both these effects would tend to distribute the side force more evenly between the two appendages, this in turn, would lead to improved lift to drag ratio for the appendage system. However, the predicted differences were less than 1% and are of dubious significance.

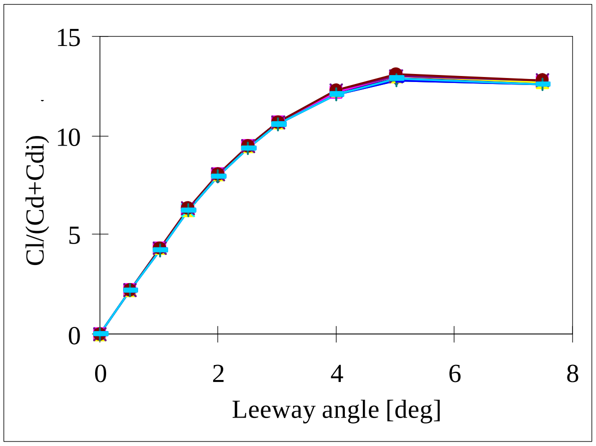

Figure 20: Effect of appendage geometry on lift to drag ratio.

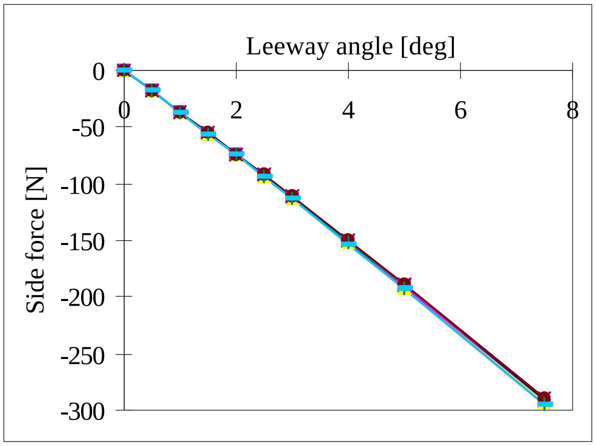

Figure 21: Effect of appendage geometry on side force.

However, what became apparent from the tests was that there is an optimum angle of attack (leeway angle) at which the appendages operate at their highest lift to drag ratio. In this context it has been assumed that the optimum angle of attack is the angle at which the appendages operate at maximum lift to drag ratio. This could be verified by VPP analysis. The optimum angle of attack for the rudder and centre board is shown in detail in Figure 22.

What is also apparent is that the optimum angles for centre board and rudder are different. Figure 22 indicates that an angle of approximately 5° is required for the centre board to be at its optimum angle of attack, and that the rudder would require around 7.5° This shows that the centre board produces something of the order of 3° of downwash at the rudder. Thus for both centre board and rudder to be operating at their maximum lift to drag ratios, the dinghy should be sailed at a leeway angle of approximately 5° with approximately 3° of weather helm. The weather helm is to be expected since the rudder operates in the downwash of the centre board and in order for it to have the optimum effective angle of attack some weather helm must be applied. The values presented above should be considered whilst bearing in mind the limitations of the analysis; these are likely to be describing the trends accurately but the absolute magnitudes may be incorrect. Larsson and Eliasson 1994, page 157 indicate that, as a rule of thumb, 5° may be assumed to be optimum.

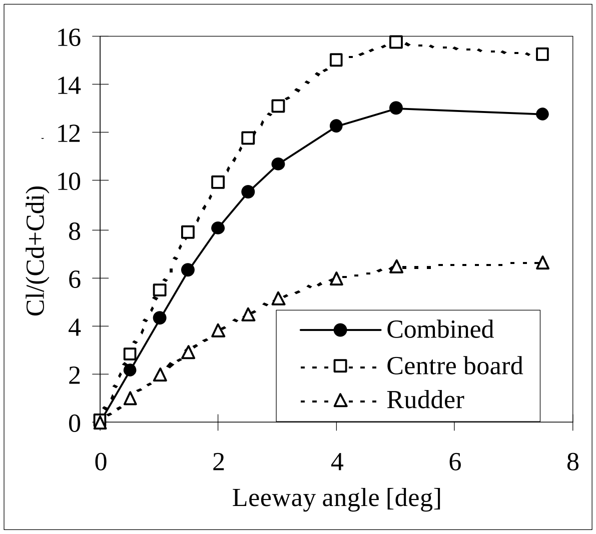

Figure 22: Variation of lift to drag ratio with angle of attack for centre board and rudder.

Results from on-the-water trialing

Results from on the water trials seem to indicate that the "standard" International Mirror Class set-up has insufficient weather helm. This means that the rudder is producing little, or even worse, negative side force which in turn results in the centre board being overloaded and excessive induced drag being generated from both centre board and rudder.

During trials, both moving the centre board forward in the slot and raking the mast aft have been found to be beneficial. Both of these actions would have increased the weather helm and the side force generated by the rudder.

Trials were conducted where the rudder angle was measured. It was found that about 2° of weather helm was optimum in a moderate breeze. Unfortunately it was not possible to accurately determine the leeway angle, although around 4°–5° seems reasonable.

A slightly narrower centre board was found to be beneficial in light airs, a small amount of sailing in stronger winds did not reveal any disadvantages with the narrower centre board. Reducing the area of the centre board would reduce the weather helm (since the centre of lateral resistance is moved aft). However, provided that the dinghy was being sailed with around 4°–5° of weather helm this would not be detrimental to rudder performance. The results of the appendage analysis indicated that a very small benefit, in terms of appendage lift to drag ratio, may be achieved by reducing the centre board chord. It is possible that the numerical analysis is under predicting this change.

CONCLUSIONS

The findings of this research are summarised below. Most of these findings are based on the results of the numerical investigation using the vortex lattice code, and in general, these findings have been confirmed by on-the-water testing.

A shorter jib luff length was found to be beneficial. The shorter luff length brought the clew of the jib closer to the deck, which reduced the gap under the foot of the jib significantly. This increased the effective aspect ratio of the jib, reducing induced drag and reducing the downwash on the main; this in turn made the main sail more efficient. It was also felt that there was less detrimental interference, with the main sail, from the tip vortex shed from the head of the jib. The jib tip vortex was thought to reduce the performance of the main sail. With the shorter jib luff length, the head of the sail was moved further from the luff of the main sail.

The results of the investigation into the effect of section shape were inconclusive. This was mainly due to the lack of a viscous model. As might be expected from an ideal flow model, the deeper sections were found to produce greater forces. However, with the lack of a high accuracy, viscous model it was not possible to determine whether these deeper sections would have any adverse characteristics due to viscous drag and/or separation.

Another possible area for improvement of the sails' performance would be to reduce the induced drag by improving the spanwise loading. The spanwise loading can be most effectively adjusted by altering the vertical twist distribution and camber of the sail; care must be taken to ensure that near theoretical optimum shapes are practical to build and also trim and adjust whilst sailing.

The results of the appendage analysis indicate that to make effective use of the rudder, the dinghy should be sailed with around 3° of weather helm and a leeway angle of approximately 4°–5°. These values were in broad agreement with the findings from on-the-water testing. Care must be taken not to have too much weather helm since the rudder is open to the free surface and may ventilate. However, as is well known by sailors, lee helm should be avoided.

There was no discernible difference in the performance of the different centre board and rudder options tested.

It has been demonstrated that the vortex lattice method is an effective tool for the analysis of sails and appendages. However, a suitable method for including viscous effects would be useful.

The analysis of yacht performance by investigating the performance of the individual systems – sails, hull, appendages – separately can only be taken so far. A full analysis can only be made using a VPP. This allows the complex interactions and necessary force / moment balances between the sails, hull and appendages to be made and for the yacht to be "sailed" round a race course and the times for different design alternatives compared.

Use of a VPP requires model testing for hull and appendages performance, and wind tunnel testing for sail performance. However, the vortex lattice method may be useful to estimate sail and appendage performance, and especially to predict the effect of small changes once base data have been obtained.

The major benefit of using a potential flow model such as the vortex lattice method over a viscous flow model, is the speed and ease with which the computations may be carried out.

In the context of this paper, the vortex lattice method has been useful in selecting sail planforms and the results from the computational analysis have been supported by findings from on-the-water trials.

However, it was felt that the vortex lattice code was not sufficiently accurate to predict the effects of changes in sail section shape since effects such as separation and stall could not be modelled. For detailed analysis of this kind, a Navier Stokes model would be useful, however the additional cost in terms of computer power and time would be manifold.

ACKNOWLEDGEMENTS

The authors would also like to thank Steve Walker for assistance with the design and construction of the sails and the skippers and crews who assisted with the on-the-water trailing.

The authors wish to acknowledge the assistance of Curtin University of Technology and AME CRC Yacht Technology Group in providing access to the vortex lattice code used in this research.

REFERENCES

Couser, P., "Computational methods for investigating sail forces – A case study," Proc. Yacht Vision '98, Auckland, New Zealand. January, 1998a.

Couser, P., "Validation of SVL vortex lattice code," AME CRC Internal report. June, 1998b.

Couser, P., "Prediction of aerodynamic sail forces for upwind yacht velocity prediction programs," Proc. 1st Australian Sailing Science Conference, Hobart, Tasmania, Australia. November, 1997.

Day, S. and Couser, P. "The AMESVL sail aerodynamics programs - philosophy, usage and coding developments," AME CRC Internal Report No. IR 98/9, 1998

Fiddes, S.P. and Gaydon, J.H., "A new vortex lattice method for calculating the flow past yacht sails," Journal of Wind Engineering and Industrial Aerodynamics. 63 pp35-60, 1996.

Greeley, D.S., and Kerwin, J.E., "Numerical methods for propeller design and analysis in steady flow," Trans. Society of Naval Architects and Marine Engineers. 90, pp415-453, 1982.

Greeley, D.S., Kirkman, K.L., Drew, A.L. and Cross-Whiter, J., "Scientific sail shape design," Proc. SNAME 9th Chesapeake Sailing Yacht Symposium. Annapolis, Maryland, U.S.A., 1989.

Larsson, L. and Eliasson, R.E., "Principles of Yacht Design", McGraw and Hill, Int. Marine, ISBN 0-07-036492-3, 1994

Milgram, J.H., "Effects of masts on the aerodynamics of sail sections," Marine Technology. 15, 1, pp35-42. January, 1978.

Milgram, J.H., "The analytical design of yacht sails," Trans. Society of Naval Architects and Marine Engineers. 76, pp118-160, 1968.

Register, D.S. and Irey, R.K., "Analysis of steady flow over interacting sails," Proc. SNAME 6th Chesapeake Sailing Yacht Symposium. Annapolis, Maryland, U.S.A., 1983.

Thrasher, D.F., Mook, D.T. and Nayfeh, A.H., “A computer based method for analysing the flow over sails,” Proc. SNAME 4th Chesapeake Sailing Yacht Symposium. Annapolis, Maryland, USA., 1979.