

THE EFFECTS OF STAYSAILS ON YACHT PERFORMANCE

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Abstract. A staysail can be defined as any supplementary sail flown between the mast and primary genoa or spinnaker to enhance aerodynamic performance. Much of the time, huge expense and effort is put into improving the performance of the flying sails with little thought to staysail design and position. Wind tunnel experiments were carried out in the University of Auckland's Twisted Flow Wind Tunnel on a range of staysails operating under typical flying sails. Flow visualisation of interesting concepts was carried out. The analogy of the staysail as a turning vane that improves the flow over the other sails was investigated. Independent supports were used to determine the load contribution of the staysail to the overall loading of the sail combination. A range of clw heights of the staysail were investigated. A significant gain in driving force of around 10% on average and up to 17% has been demonstrated by correct selection and placement of staysails. Staysail area is not a key factor, with the smallest staysail testing giving one of the largest improvements. Masthead staysails and sailing triple-headed were both found to have a significant performance benefit over a conventional medium sized staysail.

NOMENCLATURE

AWA	Apparent wind angle
CF _X	Drive force coefficient
CF _Y	Side force coefficient
q ₁₀	Dynamic pressure at 10m height
SA	Sail Area
TWS	True wind speed

1. INTRODUCTION

A staysail can be defined as any supplementary sail flown between the mast and primary genoa or spinnaker to enhance aerodynamic performance. Staysails have been in use on sailing ships since the 16th century. In the high performance yachting sector they are commonly used in ocean-going classes such as the Open 60s and the Volvo Ocean 70s (VO70) and have more recently started making a more significant appearance in inshore events such as the America's Cup. Much of the time, huge expense and effort is put into improving the performance of the flying sails with little thought for staysail design and position. Some work has been carried out on evaluating their performance [1] although mainly under genoas at relatively tight angles where flow separation is not significant. Experimental and numerical studies are commonly performed without a staysail present even though it is accepted that it will be used at full scale for that particular sailing condition. This is in spite of the significant gains in performance that staysails can provide. The ability to substitute un-rated sails as staysails under certain rules, such as storm jibs, increases the potential benefits of staysails and makes it even more important to understand their effects.

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In order to investigate the effects of staysails, a number of wind tunnel tests were carried out at the Twisted Flow Wind Tunnel (TFWT) at the University of Auckland. Here a real-time velocity prediction program (RT-VPP) [2] was used to allow the model to heel to the correct angle for a certain sailing condition.

For the testing, a model of the proposed America's Cup 90; rule (AC90) class was used. However, the sails, combinations, attachment points, etc. that were investigated in this paper are not constrained to the AC90 rules – the model was simply used as a convenient test-bed. In particular, a number of staysail combinations more relevant to the VO70s and other offshore classes were looked at.

2. TEST SETUP

2.1. Model

The tests were carried out in the University of Auckland's Twisted Flow Wind Tunnel [3]. For all the tests, a model of the proposed AC90 at 1:17 scale was used. The model was equipped with remote controlled winches to trim the sails while the wind tunnel was running. The model was set up with hydrodynamic data allowing the RT-VPP to be used. This test method enables the rolling moment produced by the sails to be balanced by the righting moment produced by the keel and form stability. This is simulated in the wind tunnel by using an electric motor to adjust the heel angle dynamically. Consequently, accurate and efficient testing of a sail configuration through a range of simulated true wind speeds becomes possible; and this makes it

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straightforward for the trimmer to depower the sails correctly at the higher wind speeds.

A vertical velocity gradient was generated by adding roughness elements to the upstream section of the wind tunnel. The profile was such that it was an adequate simulation for both an AC90 and a VO70 sailing in about 12 knots true wind speed, and it was kept constant for all of the simulated wind speeds and angles. The horizontal twist angle was adjusted by twisting the wind tunnel's flexible vanes to the calculated values for the AC90 in 12 knots true wind speed and was corrected for each change in apparent wind angle in the wind tunnel.

The model was mounted in a cradle that was attached to a force balance underneath a turntable. Water was used to fill the gap in between the model and the floor to prevent pressure leakage under the hull.

2.2. Sails

The staysails were tested in combination with a conventional mainsail and two different generic flat and deep masthead asymmetric spinnakers, referred to as the A2 and A4 respectively. In total, eleven staysails of different shapes were tested in this investigation. The different staysails are listed in Table 1.

Table 1. Table of the different staysails.

Sail	Name	Properties
Small overlapping	S_{small}	Tack @ 52% J Foot length 75% J
Medium overlapping	S_{med}	Tack @ 71% J Foot length 82% J
Large overlapping	S_{lrg}	Tack @ 90% J Foot length 108% J
Masthead	S_{MH}	Masthead version of S_{med}
Small non-overlapping	$S_{small-NOL}$	Non-overlapping version of S_{small}
Medium non-overlapping	$S_{med-NOL}$	Non-overlapping version of S_{med}
Extreme high clew	S_{clew++}	High clew version of S_{med}
High clew	S_{clew+}	High clew version of S_{med}
Low clew	S_{clew-}	Low clew version of S_{med}
Extreme low clew	S_{clew--}	Low clew version of S_{med}
Modified small non-overlap	$S_{small-NOL-}$	Cut-down $S_{small-NOL}$ for improved sheeting

2.3. Tack positions

Many current rules do not prohibit tacking sails off the centre line. There is conceivably an advantage by tacking a staysail to the windward edge of the deck so that it acts as an extension to the mainsail to some degree. This was investigated in this research by altering the tack position. There were four tack positions to windward and three tack positions on the centerline. The locations of these tack positions are illustrated in Figure 1. The mast

location is just out of the photograph to the left and the forestay position is just out of the photograph to the right. The spinnakers were flown from the end of a bowsprit at approximately 150% J.

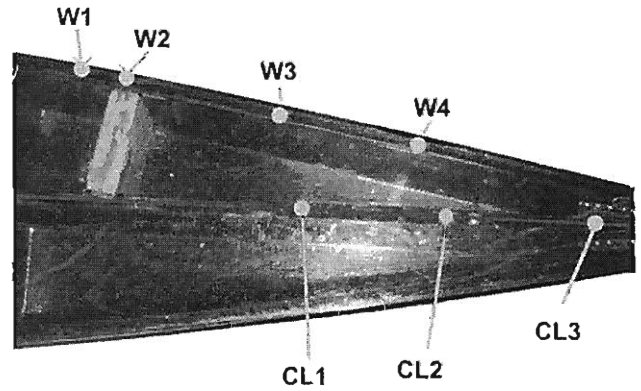


Figure 1. Tack positions on foredeck

2.4. Test procedure

Each staysail combination was tested beneath the A2 and the A4 where appropriate. The A2 was tested over a range of apparent wind angles (AWA) from 30° to 70°. The A4 was run from 40° to 90° AWA. At each angle, three true wind speeds (TWS) were chosen to give heel angles of approximately 0°, 10° and 20°.

The change in roll moment, and hence heel angle, between two different sail configurations has two main effects. The first is the aerodynamic change which is dealt with implicitly by the RT-VPP, as the yacht is heeled in the same manner in the wind tunnel as at full scale. The second is the change in hydrodynamic resistance with heel angle. The RT-VPP allows for this in its calculation of boat speed but, in order for this research to be independent of yacht type, the drive force is presented in all cases instead of the boat speed and so this change in hydrodynamic resistance is ignored. This approach is justifiable in this case as the addition of a staysail only makes a very small change to the heel angle, as will be shown in the following section. This means that the hydrodynamic resistance will not vary significantly between staysail configurations tested at the same condition, and that the drive force is a valid indicator of performance.

After optimising the trim for the best possible boat speed, the 3 forces and 3 moments were recorded and coefficients were deduced as:

$$C_{Force} = \frac{Force}{q_{10m} \cdot SA} \quad (1)$$

$$C_{Mom} = \frac{Mom}{q_{10m} \cdot SA^{3/2}} \quad (2)$$

where q_{10m} is the dynamic pressure at a 10m full scale height and SA is the sail area of the mainsail and spinnaker combination. None of the analysis in this paper takes into account the area of the staysail as, under most rules, the individual sail areas are rated but not the total area of sail carried at any one time. Hence, a staysail can effectively provide bonus boat speed. In the same way, no attempt has been made to equalise the areas of the different staysails tested.

The drive force coefficient was then interpolated over the range of wind speeds and wind angles to give a full performance surface for each sail set. These drive force surfaces are then suitable for input into other offline VPPs for subsequent use.

3. TEST RESULTS

3.1. Staysail size

The first set of tests looked at the effect of staysail size on performance. Three overlapping staysails were tested individually, the geometries of which are shown in Figure 2.

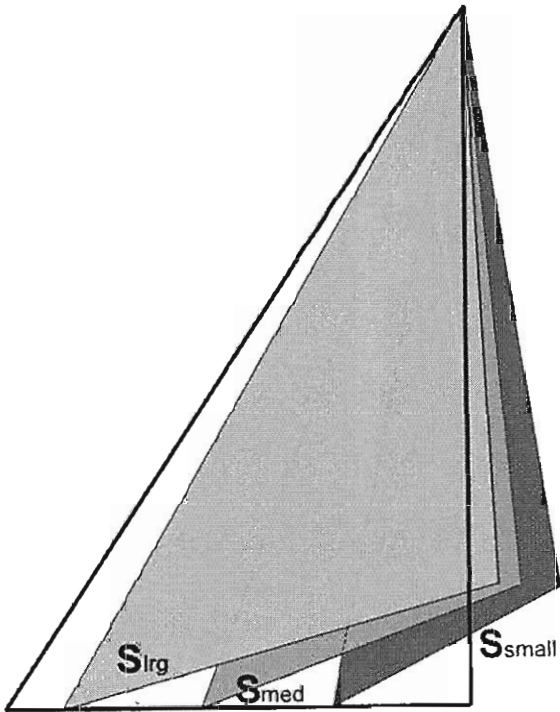


Figure 2. The range of staysail sizes in relation to the fore-triangle

In Figure 3 the performance plot of the sails is shown. It is a 3D surface of drive force coefficient (CF_x) against true wind speed (TWS) and apparent wind angle (AWA). For a particular AWA, the CF_x remains constant until the TWS increases enough to de-power the boat through heel and trim de-powering. Where there are multiple surfaces plotted, the surface that is visible (ie. highest) at a certain point is the combination that generates the best performance. Where the surface curves off and ends is

the point at which the yacht cannot de-power any further. This is a very useful way of presenting the large amount of data recorded and enables a comparison of different sail configurations. It can instantly show the conditions where cross-overs occur between different sails.

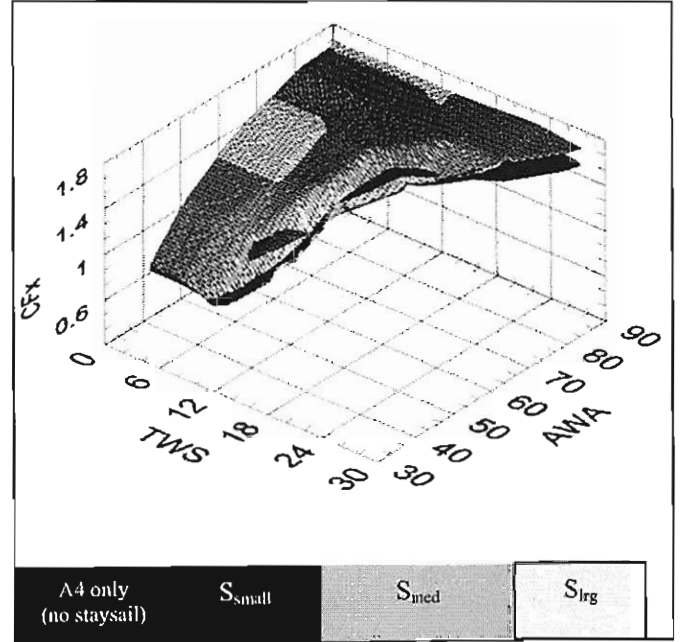


Figure 3. Surface plot over the three different staysails

It can be seen that the best staysail over most of the range tested is the medium sized overlapping staysail. The large staysail performs fairly well upright but has a significantly lower driving force when heeled and de-powering. In practice, the sheeting angle limits the trim of the small staysail at tighter angles.

As expected, there was a significant change in the separation point on the leeward side of the mainsail when a staysail was added, as indicated by the telltales on the mainsail. There was a much smaller separation bubble at the leading edge with the staysail present because the position of reattachment occurred earlier on the mainsail.

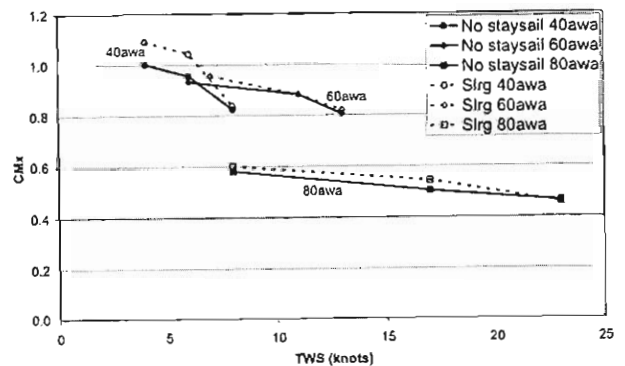


Figure 4. Comparison of roll moment with and without the large staysail

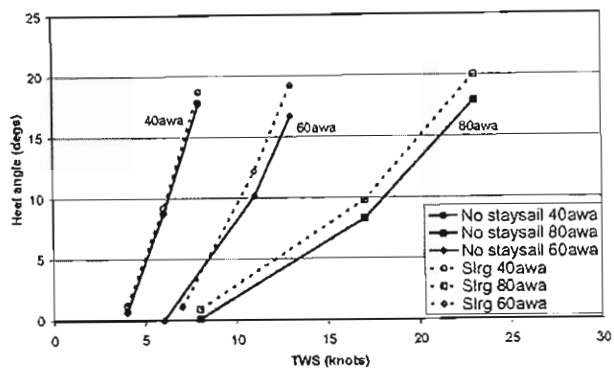


Figure 5. Comparison of heel angle with and without the large staysail

Figure 4 shows a comparison of the roll moment produced by the A4 with and without the large staysail present for 40°, 60° and 80° AWA. Figure 5 shows the corresponding differences in heel angle. It can be seen that, even though there is a significant difference in roll moment at 40°, this does not translate into a large difference in heel angle because of the shape of the righting moment curve. The largest increase in heel angle observed by adding a staysail to the AC90 was around 2.5° and in most cases was much less. The significance of this increased righting moment for other types of yacht will depend on the righting moment curve and hydrodynamic properties of the yacht, and the effects can be determined by running the RT-VPP in the wind tunnel in its full configuration.

3.2. Turning vanes

To investigate whether the staysail produces the additional driving force itself or whether it simply acts as a turning vane to improve the flow between the spinnaker and the mainsail, two different sized turning vanes were made. These vanes were made from bent sheets of aluminium. The camber was shaped to a circular arc and held constant over their length. They were fixed to the deck and held at a constant distance away from the mast using thin struts.

From the results plotted in Figure 6, it can be seen that the medium sized vane increases the drive force as much as the medium sized staysail does at 50° AWA. At other angles, there is less benefit or a even detrimental effect. This is because the vanes are fixed and will only work correctly for one particular angle. The small turning vane did not have such a pronounced peak but provided a significant improvement over the whole range down to 90° AWA (not shown). These two results mirror the trends of the respective staysails. However, it is still not possible from this test to say whether the staysails themselves produce a drive force or whether they simply improve the drive force of the mainsail and spinnaker.

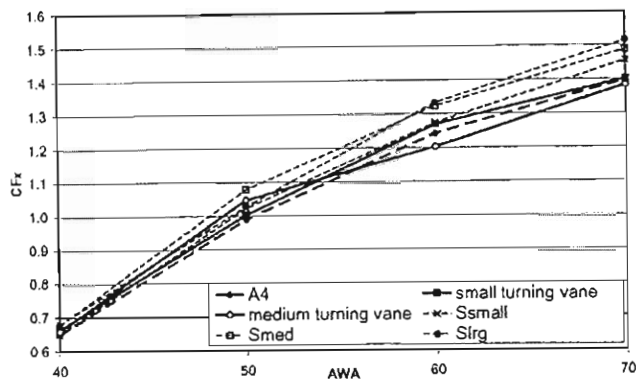


Figure 6 Small turning vane and large turning vane compared to the other staysails

3.3. Detachment rig

A detachment rig [5] was mounted to windward in order to investigate how much of the load the staysails were carrying themselves. The setup is shown in Figure 7.

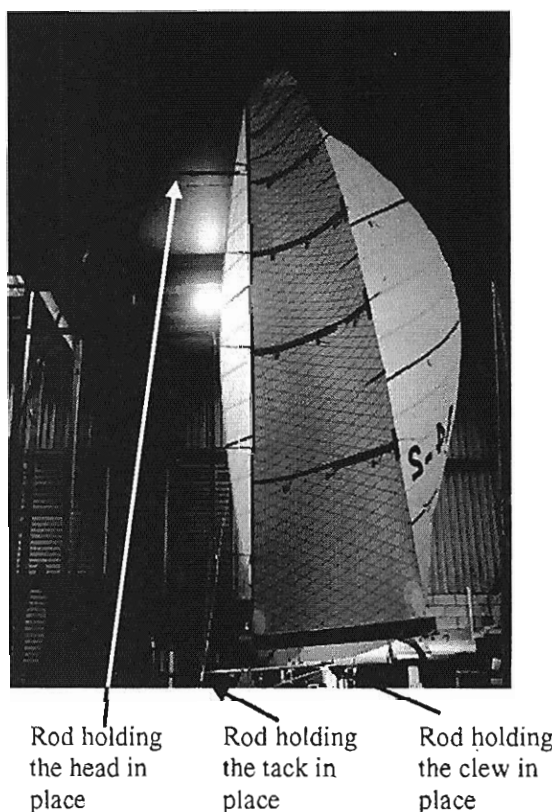


Figure 7 Detachment rig

This investigation used the small staysail S_{small} tacked to windward at position W3 and the medium sized staysail S_{med} tacked on the centreline. With the detachment rig present but not touching, the sails were trimmed and a measurement was taken. The wind tunnel was then kept running while the staysails were removed from the model and supported only by the detachment rig so that they were in exactly the same position, and another

measurement was taken. This procedure was carried out for AWAs of 50°, 60° and 90° for both sails. This enabled the amount of force developed by the staysails to be isolated and examined.

The results shown in Figure 8 and Figure 9 show a similar trend for both staysails. At 50° AWA, all of the extra force produced is taken by the staysail itself and in the case of the medium staysail, it can be deduced that it actually reduces the amount of force produced directly by the mainsail and spinnaker. At 90° AWA however, almost half of the driving force increase is due to the flow improvement effects of the staysail on the other sails, which is shown by the staysail increasing the driving force even when detached from the model.

From these results it can be said that the staysail itself is mainly load carrying. This in turn suggests that a staysail works like a jib at tighter apparent wind angles whereas at deeper angles it also improves the flow in the gap between the mast and the spinnaker. The improvement seen over the mainsail then comes from sail interaction effects [6] where the suction peak of the mainsail gets lowered (because it is unloaded due to the cascade effect of the adjacent sails) and thereby the pressure gradient over the sail becomes smaller for a given mainsail setting.

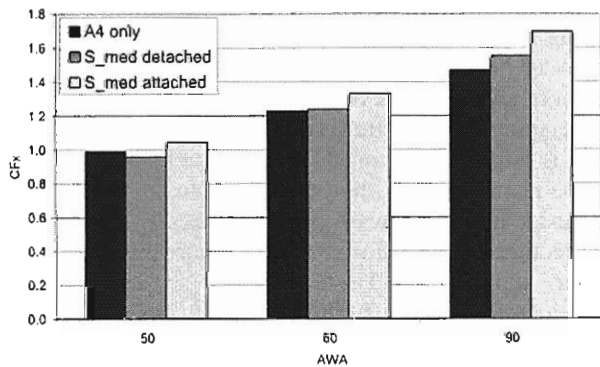


Figure 8. Detachment using medium staysail S_{med} tacked on centreline

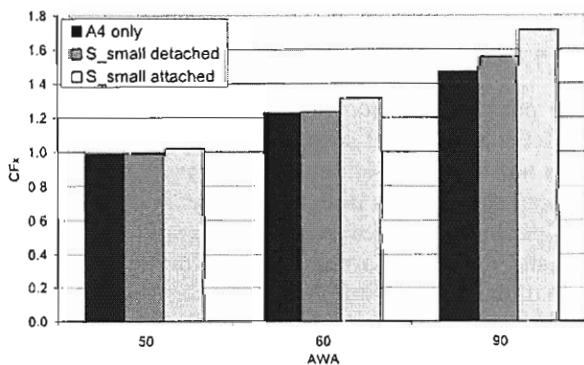


Figure 9. Detachment using small staysail S_{small} tacked at W3.

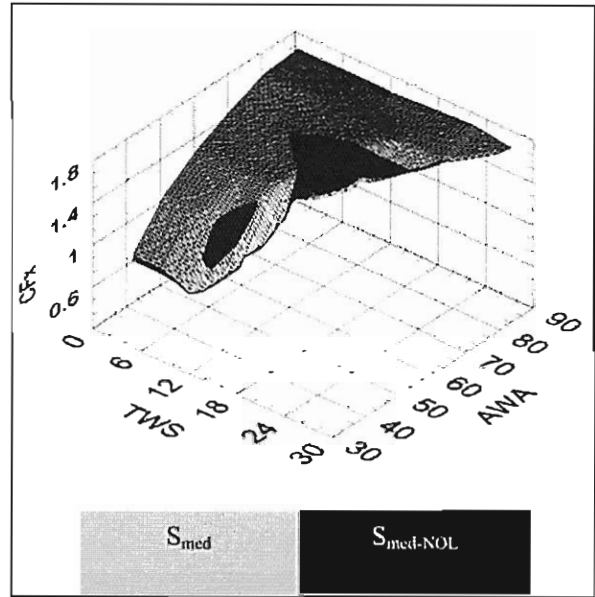


Figure 10 Comparison of medium sized overlapping and medium sized non-overlapping

3.4. Effects of overlap

Figure 10 shows the comparison of the medium sized staysail with and without overlap. The larger overlapping sail performs better at almost all conditions. The non-overlapping sail is only better at tighter angles when heeled because of the improved sheeting angle. The smaller sails also show a similar trend with overlap variation when deeper than 50° AWA and tacked on the centreline. At the tighter angles, it was possible to sheet the non-overlapping staysail inside the shrouds which extended its range considerably.

3.5. Tack position alteration

With the small non-overlapping staysail ($S_{small-NOL}$) tacked to windward it is possible to sheet it such that the leech of the sail touches the leading edge of the mast at tight apparent wind angles, creating an extended leading edge to the mainsail. Figure 11 shows the effects of varying tack position for the small non-overlapping staysail and its cut-down variant ($S_{small-NOL}$ and $S_{small-NOL-}$). These are the smallest staysails tested in this study yet they produce the largest increases in driving force at deep apparent wind angles, up to a 17% increase at 90° AWA. This is due to the sail's improved flow over the mainsail and through the slot. It was actually found to be beneficial to leave a small gap between the leech of the staysail and the mast, as the accelerated flow through this gap seemed to be the driver for re-attaching the flow on the leeward side of the mainsail.

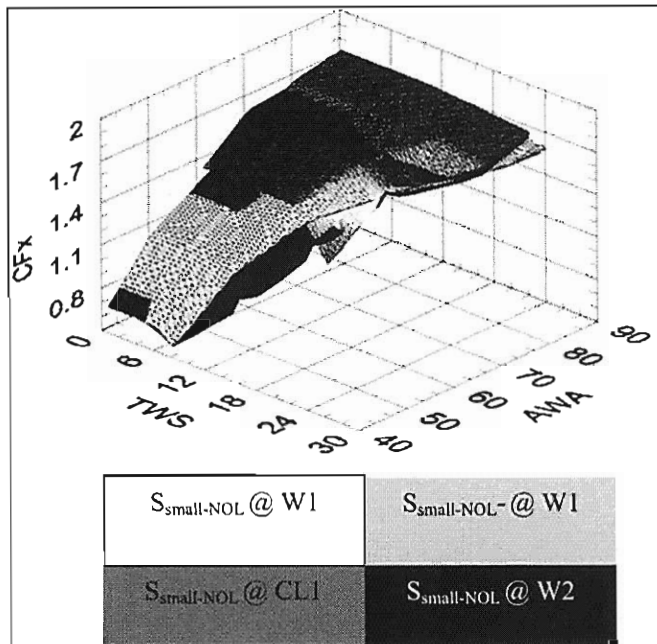


Figure 11 Effects of tack position of small non-overlapping staysail.

Figure 12 shows a similar trend for the small overlapping staysail tacked at different positions. The drive force is increased significantly at the deeper angles by tacking to windward. Part of the increase in driving force by tacking to windward is analogous to bringing the pole aft on a symmetrical spinnaker and thus changing the direction of the force vector. This makes these configurations more beneficial since they have a higher CF_x / CF_y ratio. This shift in direction is most pronounced at 90° AWA.

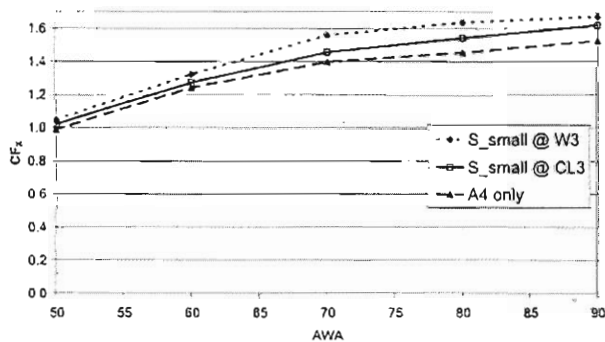


Figure 12 Effect of tacking the small overlapping staysail on the centreline and to windward.

3.6. Alteration of clew height

The range of clew heights investigated can be found in Table 2. The base sail was the medium overlapping sail and the leech was progressively lengthened for the low clew and shortened for the high clew sails respectively. No attempt was made to equalise the sail area.

Table 2. Range of clew heights for the different staysails as percentage of I measurement

Sail	Leech length in % of I
high clew S_{clew++}	79
S_{clew+}	83
S_{med}	87
S_{clew-}	90
Low clew S_{clew--}	93

This study showed a very clear trend with clew height, as shown in Figure 13. At the tighter angles with mainly attached flow, the larger sail with the lower clew performed better. At mid-range apparent wind angles, the lower clewed sails were best when upright, but the high clewed sails suddenly became much better past a heel angle of about 5-10°. At deeper angles, the high clewed sails were much better even when upright. This effect was mainly found to be due to the deck edge separation which occurred at very small angles of heel. The higher clewed sails interfered less with this separation bubble, as will be seen later in the flow visualisation results.

An important point here is the effect of heel angle on driving force. Previous research in downwind [3] and upwind testing [4] and independent commercial testing has confirmed that it is quite possible to increase the driving force when heeling slightly, although at large angles of heel the driving force will always reduce. At angles of around 70° AWA, the flow on the leeward side of the spinnaker is significantly separated and the drive force is largely determined by how much attached flow can be maintained. With a small heel angle, which does not result in a significant projected area reduction, the sail section of the spinnaker in the horizontal plane is longer and flatter. This reduction in curvature is analogous to sheeting further outboard, and results in a slightly larger area of attached flow and hence can result in a higher driving force. This is often negated by the flow separation from the deck edge interfering with the sail foot, but for high clewed sails, such as the staysails examined here or typical reaching sails, this effect is small.

3.7. Mast headed

In the preceding sections, all of the staysails discussed were set at a fractional hoist of about 7/8 of mast height. Whilst not currently permitted under most racing rules, a masthead staysail was designed. In theory, it will give a better performance because of the increased area, aspect ratio, and its ability to improve the flow over a greater length of the mainsail luff. When the masthead staysail is compared with the medium staysail S_{med} and the high-clewed staysail S_{clew++} as shown in Figure 14 it can be seen that the masthead sail has an overall better performance, especially at heeled conditions where it outperforms even the high-clewed sail.

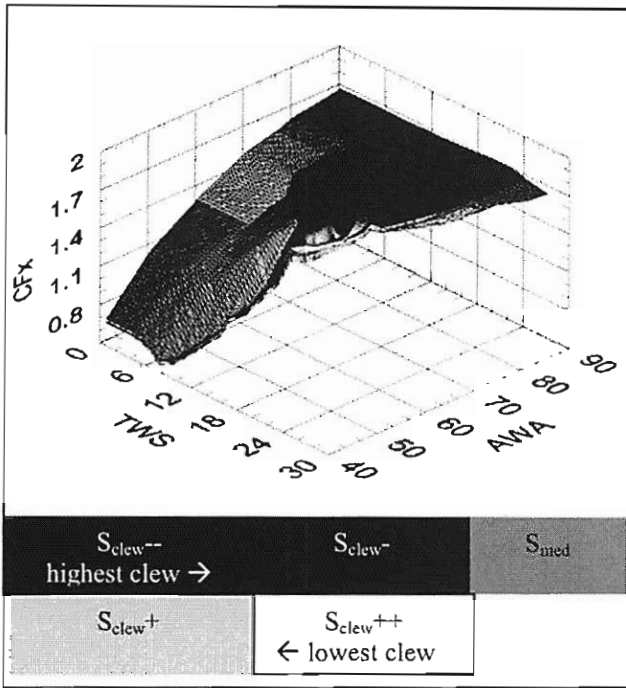


Figure 13. Comparison of different clew heights

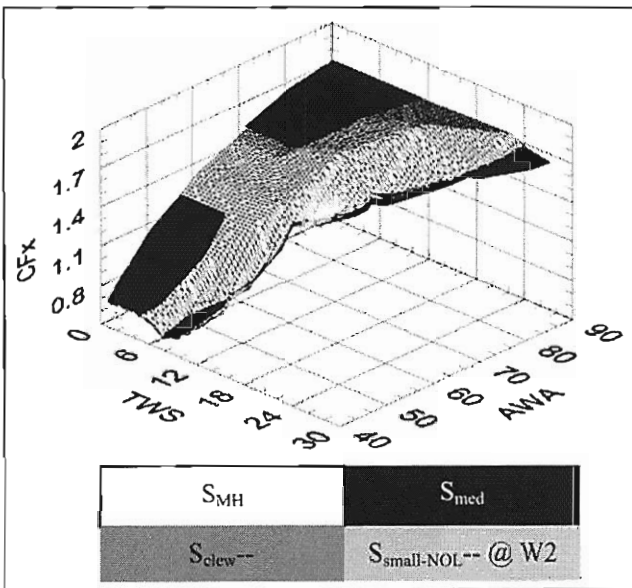


Figure 14. Comparison of masthead staysail with competing staysails

3.8. Tighter angles

To test the effects of sailing tighter than 40° AWA, the deep A4 was replaced with the flatter, smaller A2. In Figure 15 it can be seen that the best staysail at tighter angles is the small non-overlapping staysail tacked at W3, while the medium sized overlapping staysail S_{med} actually decreased the driving force compared to the A2 alone at 50° AWA. This is likely due to the significant change in flow direction caused by the staysail which interferes with the oncoming flow to the spinnaker, thereby reducing its effectiveness and lift.

At 70° AWA, with a larger slot between A2 and mainsail, the medium sized overlapping staysail performed better.

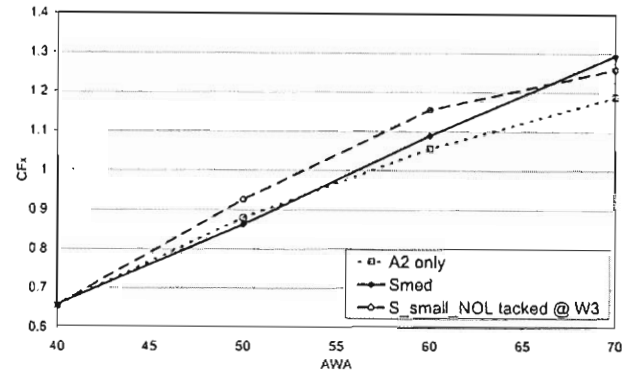


Figure 15. Comparison of staysails with the A2.

When looking at the surface plot in Figure 16, which shows the staysails under the A2, it can be seen that the small non-overlapping staysail tacked at W3 and the high-clew staysail are the best at higher true wind speeds.

The conditions where the staysail does not provide a positive effect can be seen from this plot, and it should be noted that this is not purely an apparent wind angle limitation but also a wind speed condition. As the yacht heels, the section of the sail normal to the flow direction becomes flatter and longer which has the effect of delaying separation. Also, the flow through the slot exits much higher up where there is less constriction, allowing the staysail to produce a performance gain. Thus when upright, the staysail may only be carried as tight as 40° AWA but when heeled there is still a beneficial effect to around 35° AWA for this geometry.

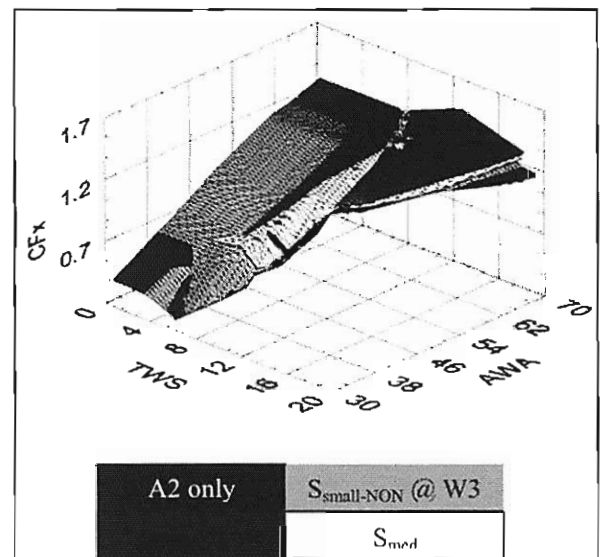


Figure 16 Comparison of different staysails under the A2

3.9. Triple-headed

A common technique in offshore races such as the Volvo Around the World Race is to use two staysails inside deep running sails. The smaller of these is often a storm jib, which in the current version of the Volvo rule is “un-carded” and must be carried anyway. The triple-headed configuration tested here consists of the small overlapping staysail tacked at W3 and the large overlapping staysail on the centreline. A photograph from leeward can be seen in Figure 17.

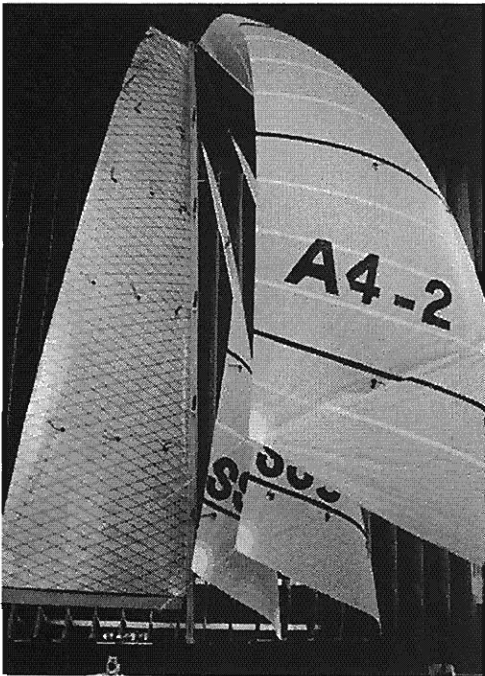


Figure 17 The AC90 yacht with a triple headed configuration.

In Figure 18 a comparison between the previous best (small non-overlapping staysail tacked at W2) and the triple-headed configuration is shown. It can clearly be seen that the triple-headed has the overall highest drive force for almost all conditions deeper than 60° AWA. The rolling moment was also slightly larger but this was taken into account by the dynamic heeling and therefore this configuration still probably produces a better boat speed. It is interesting to note that the two overall best configurations for deep angles have the smallest and largest sail areas of all of the configurations tested, with the common theme being the small staysail tacked close in on the windward rail.

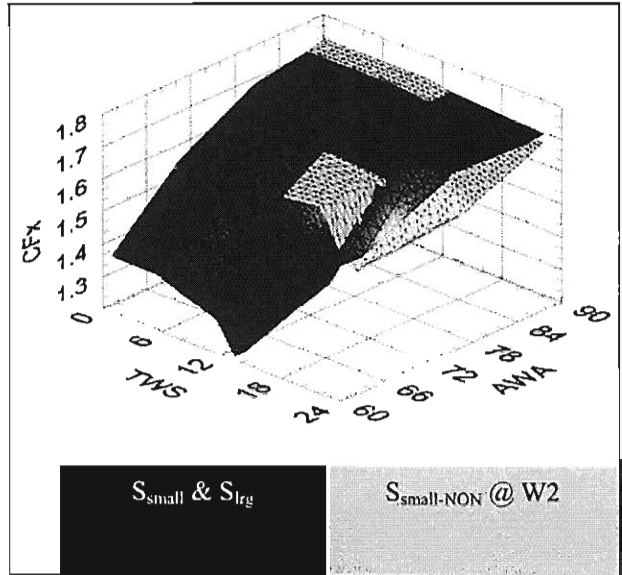
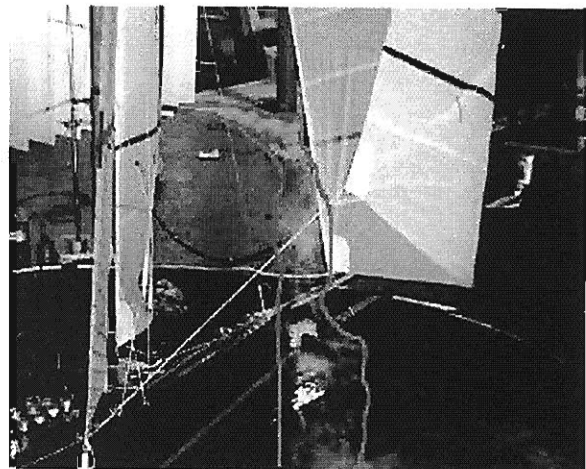
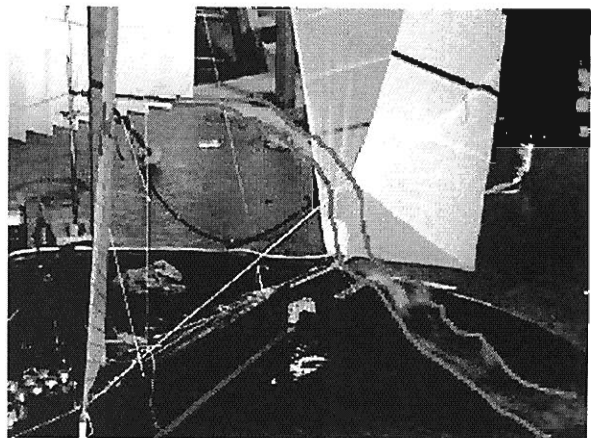


Figure 18 Comparison of triple headed and the small non-overlapping staysail tacked at W2.



A.



B.

Figure 19. A- Small non-overlapping at W2 at 90° AWA. B- A4 only at 90° AWA.

3.10. Flow visualisation

To get a better understanding of how the flow was affected by the staysail, an attempt to visualise the flow using smoke was carried out. Initially, the configuration of the A4 and the small non-overlapping staysail tacked at W2 was used at 90° AWA, since this was the single staysail configuration that produced the largest increase in drive force. With the staysail present and not present there were clear differences in flow behaviour. It can be seen clearly from Figure 19(B) that the flow without any staysail present goes straight over the hull and then down under the spinnaker, staying largely normal to the boat centreline. When the staysail is present (Figure 19(A)), the flow is turned much more in the horizontal plane and exits further aft, closer to the clew of the spinnaker. This confirms the turning vane effect of the staysail and improved flow through the slot.

There was also an attempt made to visualise the different behaviour of the flow when the clew height was altered (Figure 20). For this investigation, the high-clew and the low-clew staysails were used at 60° AWA as this condition produced the largest change in driving force. As the model heeled over, the interference of the low clew with the deck separation bubble could clearly be seen. With the high-clew staysail, the flow over the deck could exit cleanly beneath the foot of the staysail which can be seen in Figure 20.

4. OPTIMUM STAYSAIL CONFIGURATION

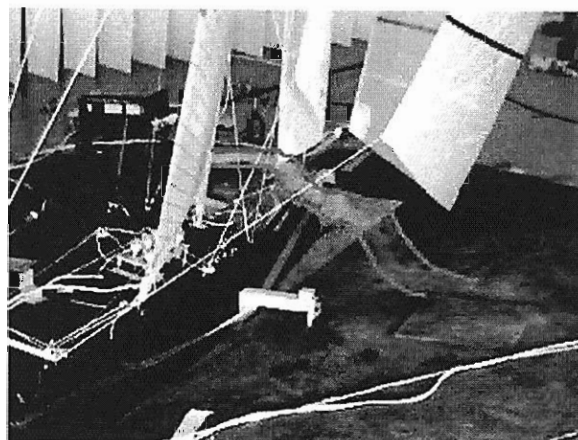
The results from the tests presented here can be used to select a suitable staysail configuration.

If only one staysail is to be carried, the medium sized overlapping staysail with a high clew would be the most suitable ($S_{clew^{++}}$). Whilst not the best performer in all tests, it has the most consistent performance over the whole range and has significant performance advantages when sailing at heel angles of more than 5°. It also performs very well at the tighter wind angles and under the flatter A2. For a canting keel yacht such as a VO70, where the yacht can be kept more upright, the S_{med} might be more suitable.

However, a further advantage could be gained by also carrying a small non-overlapping staysail ($S_{small-NOL}$) with pad eyes positioned both on centerline and on the windward rail for the tack. When used alone and upright, this gives a bigger driving force at deep angles than the conventional $S_{clew^{++}}$ or S_{med} . Although this was not a combination tested, it is expected that this sail flown with the $S_{clew^{++}}$ or S_{med} would give performance benefits similar to the triple-headed configuration tested here.

These observations fit well with current practice. The IACC boats from the 32nd America's Cup carried staysails similar in form to the S_{med} from angles as tight as 50° AWA right through to the deeper angles. It should be noted, however, that the work carried out here is only

valid for boats with a fixed bowsprit. At angles deeper than about 80° AWA, a spinnaker pole can be squared well back from the forestay which changes the geometry of the slot between the mainsail and spinnaker significantly.



A.



B.

Figure 20. A- high clew with 20 degrees of heel at 60° AWA. B- low clew with 20 degrees of heel at 60° AWA.

Figure 21 shows the gain in driving force coefficient for the upright condition using the best combination of $S_{clew^{++}}$ and $S_{small-NOL}$ at various tack positions. Over the entire sailing condition surface, there is an average gain in driving force of around 10% with peak gains of around 17%.

Figure 22 shows the increase in heel angle of the AC90 for the best staysail configuration compared with the A4 only. The differences are small compared with the driving force increases.

5. CONCLUSIONS

This paper has presented a comprehensive series of tests carried out at the University of Auckland's Twisted Flow Wind Tunnel on the ability of staysails to improve a yacht's performance. The staysails have been shown to

work both by generating force themselves and also by modifying the flow between the mainsail and headsail.

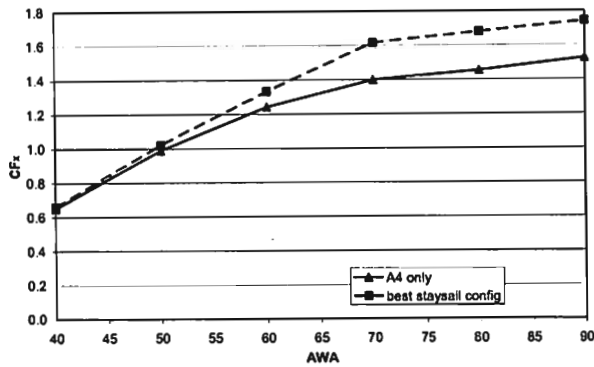


Figure 21. Drive force comparison of best staysail combination with A4 only

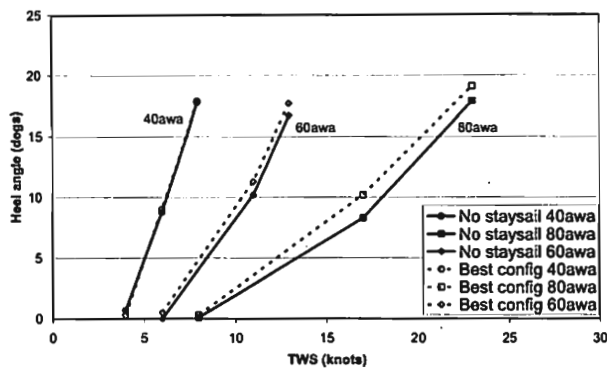


Figure 22. Heel angle variation of AC90 for best staysail combination compared with A4 only

The staysail sizing study suggests that the medium staysail was near the optimum area when the tack is constrained to centerline, with improved visual mainsail flow compared with the other staysails.

The effects of overlap showed that there is a significant area effect of two similar staysails, but that a non-overlapping sail is required for the correct sheeting angle when at tight wind angles or tacked to windward.

The tests looking at tack position showed that there is a very large potential gain in performance by tacking the staysail out to the windward rail and sheeting the leech close to, but not touching, the mast. The optimum tack position found in these tests was W2 but this will depend quite strongly on the geometry of the staysail and yacht being used.

The clew height tests confirmed that a high clew is more efficient than a low clew for the majority of realistic sailing conditions. Only a small heel angle of around 5-10° is required to produce a separation bubble over the deck. This tends to reduce the force produced by the staysail if it interferes with much of the sail foot.

Conversely, a higher clew can result in a larger driving force when heeled than when the yacht is upright.

A significant gain in driving force of around 10% on average and up to 17% has been demonstrated by correct selection and placement of staysails. Staysail area is not a key factor, with the smallest staysail tested giving one of the largest improvements.

Masthead staysails and sailing triple-headed were both found to have a significant performance benefit over a conventional medium staysail. Masthead staysails are not allowed by many rules and would require furling before gibing, but could theoretically be of use in longer distance offshore races. Triple-headed combinations can offer significant performance benefits if suitable sails are available for use.

The testing was carried out using an AC90 design as a base. The results are expected to vary with different yacht designs, in particular with the geometry of the foretriangle, although the trends presented here will likely remain the same.

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