THE INTERACTION BETWEEN SAILING YACHTS IN FLEET AND MATCH RACING SITUATIONS

P.J. Richards, Yacht Research Unit, University of Auckland, New Zealand
N. Aubin, École Navale, France
D.J. Le Pelley, Yacht Research Unit, University of Auckland, New Zealand

SUMMARY
The interaction between yachts sailing upwind close hauled is investigated in the wind tunnel through measurement of the forces and moments on a balance mounted key boat which is experiencing interference from one or two opponent boats. For most of the tests the boats were set at an apparent wind angle of 25° and a heel angle of 25°. In addition the variation of forces and moments on the key boat, in isolation, were measured over a range of apparent wind angles and the drive to side force ratio is subsequently used as an indicator of the effective apparent wind angle when an interfering boat is present. The data from two boat testing was analysed to show that much of the reduction in drive force is due to changes in wind angle rather than wind pressure. These changes in angle and wind pressure are shown to be similar to those measured around an isolated yacht using two 3-component velocity measuring Cobra probes. With three boat interference there are too many possible position combinations to consider all of these and so tests focused on two starting line and two layline scenarios. The relative importance of each interfering yacht is investigated and the effects of separation on interference demonstrated.

1. INTRODUCTION AND BACKGROUND
In an earlier paper Richards et al. (2013) presented wind tunnel measurements of the interaction between two yachts when sailing upwind and downwind, with both symmetric and asymmetric spinnakers. The correct location of the negative interference and severe negative interference zones was presented for each sailing situation. In particular they pointed out that the popular understanding of interference, as encapsulated in documents such as “Racing Basics” by Mark Johnson (1995), doesn’t emphasise that the important wind vector is the apparent wind, relative to the yacht, which is calculated by the vector sum of the true wind and the reversed boat velocity. Although interference may be important during any leg of a race, it is often on the upwind legs where yachts are forced into closer proximity and hence this paper will focus on these upwind interactions. Initially two boat interference is studied in greater detail and then multiple boat interference is considered. Figure 1 shows an example of a two boat test, where the key boat, to the right, is mounted on the 6-component force balance, which sits below the black turntable, while the interfering yacht, with its white hull and sails, is moved to a variety of relative positions. For the current testing all yachts have been set up with 25° of heel and for most tests the apparent wind angle is 25°.

Figure 1 Two boat testing in the University of Auckland Twisted Flow Wind Tunnel
Marchaj (1982) provides a detailed discussion of situations similar to that shown in Figure 1, and points out that the key boat is in what is called the “safe leeward position” where it may experience both an increase in wind speed and a favourable change of local wind direction as a result of the windward yacht. In contrast he describes the position of the white yacht as the “hopeless position”, since almost any option will result in losses. He points out that “the turbulent wake behind the sail when close-hauled is deflected away from the line of the apparent wind toward the stern”. He also comments that the influence of the wind deflection and turbulence behind a yacht can be felt for up to ten boat lengths.

Marchaj also reproduces some quantitative wind tunnel data collected by M.S. Hooper using I-class yacht models. The apparent wind angle (AWA, the angle between the apparent wind and yacht velocity vectors) for both yachts was 40° and the yachts were heeled 15°. This AWA might typically occur when reaching, that is sailing approximately perpendicular to the true wind direction. The position of the “interfering” yacht was fixed while the “interfered with” yacht was moved about in relation to the fixed yacht. The data is presented as contours of the available drive force, component in the direction of motion, on the “interfered with” yacht as a percentage of the driving force which would be available in an undisturbed wind. The lowest percentages, down to 0-10%, were recorded along the line of the apparent wind downstream of the “interfering” yacht. Almost all downwind positions showed a loss of drive force which returned to nearly 100% one boat length either side of the centreline. Two regions of positive interference were identified. The strongest of these, with a gain of 20%, was located at the “safe leeward position” with the two models in-line across the apparent wind and with the “interfered with” yacht 0.6 boat lengths on the leeward side of the “interfering” yacht. The other region of positive interference (up to 5%) was half a boat length windward of the “interfering” model along the 60° direction (measured from the centreline of the interfering yacht).

Caponnetto (1996) used a vortex lattice code to analyse the interference between two identical IACC yachts when sailing close-hauled with an AWA of 25°. The heel angle was 0°. In this study the “key boat” was fixed at the origin while a “second boat” has been positioned at various radii (R= 0.5, 1 and 2 mast heights (h)) for all angles around the “key boat”. At all three radii the lowest drive force and side force on the key boat occurred when the second boat was at an angle of 22° (measured from the bow in the same manner as the AWA) which is almost along the apparent wind line. At this angle the wake of the windward yacht crosses the key boat. With the second boat in this direction the ratio of the drive on the windward second boat to that on the leeward key boat is 4.8 for R=0.5h, 2.6 for R=1h and 2.0 for R=2h, which clearly shows the reduced interference as the yachts move apart. The results are also presented as the ratio of the drive force on the affected yacht to that for an isolated yacht sailing alone in free air. It is shown that when the yachts are moderately close to each other (R=1h) and the relative direction is 22° the ratio of 2.6 is produced by a 4% gain for the second boat and a 60% reduction in drive force for the key boat. The data shows that the key boat gets some positive interference if the second boat lies within a sector of ±60° of directly astern. Caponnetto (1996) points out the interesting observation that the drive force on the two interfering yachts is equal when the relative angle is 96° for all three separations considered. With this relative positioning two identical yachts could maintain the same speed and hence remain in the same orientation. However the data shows that in this case the drive force is 3% lower than an isolated yacht and so if they were both part of a fleet race then while they can match each other, they will be losing ground relative to other yachts.

While most studies to date have only considered two boat interactions, Spenkuch et al. (2008) have proposed a lifting line method for modelling covering and blanketing effects for yacht fleet race simulations. With this approach the wake of an upwind sailing yacht is represented as a single heeled horseshoe vortex (and image) system. At each time step changes in vortex strength are convected into the wake as a pair of vortex line elements. These subsequently move in accordance with the local wind, self-induced velocity and velocity induced by the presence of the wakes of other yachts. The lifting line approach was compared with CFD results and showed good agreement for single and two yacht setups. While the method is intended for use in fleet race situations, no CFD results are included for situations involving more than two yachts.

In Section 2 the important multiple yacht interference scenarios are discussed, while in Section 3 the wind tunnel modelling considerations are outline. Sections 4-6 deal with the results from 1, 2 and 3 boat testing.

2. FLEET AND MATCH RACING SCENARIOS

With either fleet or match races the course will typically take the form depicted in Figure 2 with the start line set up perpendicular to the true wind. The race will then consist of a number of windward and leeward legs. In this paper we will concentrate on interference between yachts during the upwind legs. With match racing the two yachts will often choose to be in close proximity to each other in order to avoid the chances of their opponent gaining a race winning advantage from being on the beneficial side of a wind shift. In fleet races it is almost impossible to cover all opponents and so interference effects tend to occur most frequently in situations such as:

1. At the starting line where all yachts are concentrated in a restricted area.
2. On occasions where a yacht on port tack encounters an opponent on starboard tack and is obliged to tack.
3. Along the lay lines leading up to the windward mark.

In such situations the most likely interactions are between two boats, then three boats and least often more than three boats, which probably only occurs near the starting line. Even if there are several yachts in close proximity, the fact that interference effects tend to weaken with distance means that each boat is only significantly affected by those boats close to it and so this study will only consider 2 and 3 boat interactions.
3. WIND TUNNEL SETUP

With wind tunnel testing of the interaction between yachts there are a number of factors which need to be considered and noted. These include:

- Since all models will be stationary, the situations modelled must represent two or more yachts moving with the same velocity vector. This means that the yachts must be on the same tack (port or starboard) and travelling at or near the same boat speed ($V_B$). Crossing situations cannot be accurately modelled.

- In reality the interactions between boats will mean that the forces on the various boats will be different and so one or more boats will slow down relative to the others. Fortunately the relative movements caused by these imbalances are quite slow with one yacht slowly pulling ahead of the other(s). This means that a passing manoeuvre can be considered to be a series of quasi-steady situations, where the yachts can be considered to be moving at almost the same speed, but with their relative positions changing.

- At the University of Auckland it is standard practice to carry out all testing on port tack. However, since all yachts are assumed to be symmetric, the results can be mirrored to represent starboard tack situations.

- Since the models are stationary the air movement generated by the wind tunnel represents the apparent wind (AWS), the vector sum of the true wind (TWS) and the reversed boat speed ($-V_B$) as illustrated in Figure 3.

- The University of Auckland wind tunnel is known as the “Twisted Flow Wind Tunnel”, but for the tests reported here the turning vanes, which create the twist, were not used. The twist in the apparent wind is created by the changes in the vector diagram with height, since the true wind speed increases with height whereas the boat speed remains constant. For off wind sailing conditions this twist can be significant but for the upwind conditions considered here the twist is at most a few degrees and hence can be ignored. This is fortunate since the vanes would interfere with many of the locations where we wish to place models.

![Figure 2 Classic fleet or match race course](image)
In Section 6 two of starting line scenarios will be considered. As noted in Section 2 the starting line may be considered to be perpendicular to the true wind, which means that it will not lie directly across the wind tunnel but instead will be angled slightly.

In many races the run to the starting line may be mistimed and so a yacht may have to shed speed in order to avoid crossing the starting line early. This means that the yachts on the starting line may in reality have a variety of forward speeds. However the ideal situation is that all yachts hit the starting line at full speed at exactly the right moment. It is this ideal situation which is modelled in the tests reported here.

In order to minimise changes in sail shape, semi-rigid fibreglass sails have been used on all models. These sails generally have a more realistic upwind shape and while some trimming can be carried out they tend to be much less sensitive to unintended trim changes.

Since the current investigation is concerned with general trends rather than a specific yacht in particular situations, the conditions chosen are intended to be generic. It has been assumed that the yacht will maximise its upwind velocity made good with a true wind angle (TWA) of 42° and that the yacht is then sailing at an apparent wind angle (AWA) of 25°. Simple analysis of the velocity triangle, shown in Figure 3, shows that these angles correspond to the condition when the boat speed is about 70% of the true wind speed. Most monohull displacement yachts can achieve boat speed to true wind speed (\(V_B/TWS\)) ratios higher than 0.7 at low wind speeds but will drop below this ratio as the wind speed strengthens. With the chosen angles the apparent wind speed (AWS) is 1.58 times the true wind speed and the starting line (assumed perpendicular to the true wind) is at an angle of 73° to the apparent wind (and hence the wind tunnel centreline). The heel angle was set to 25°. The yacht model used as the key boat had a mast height of \(h=2.2\text{m}\), sail area \(A=1.64\text{m}^2\) and hull length of \(L=1.5\text{m}\). The other models were very similar.

\[C_F = F / qA\quad \text{and}\quad C_M = M / qA^{1/2}\]

where \(q (=0.5\rho(AWS)^2)\) is the reference dynamic pressure based on the air density \(\rho\) and the Apparent Wind Speed, and \(A\) is the total sail area.

![Figure 3 Velocity Vector Diagram](image)
Figure 4 shows the variation of the primary force and moment coefficients with apparent wind angle. The sails were trimmed to maximise the drive force at AWA=25° and then remained in the same positions for other angles. Since the sails are made from fibreglass they retain their shape even when soft sails would distort due to back winding. As a result the data in Figure 4 is valid for the tests conducted but would be slightly different at low apparent wind angles with flexible sails.

For a particular trim the forces and moments on the yacht can be assumed to be a function of the effective apparent wind angle and the effective dynamic pressure. As a result the interaction between yachts can be considered to be a mixture of these two effects. Since the drive force reduces to zero more rapidly than the side force, the ratio of these forces can be used as an indicator of the effective apparent wind angle. The forces individually cannot be used for this purpose since they are modified by both changes in wind direction and strength. By using the drive/side force ratio the influence of the wind strength is removed and the results can then be used to indicate the effective apparent wind angle. In order to do this the apparent wind angle has been plotted against the drive/side force ratio and a polynomial fitted to this curve as shown in Figure 5. Once the effective apparent wind angle has been determined a corresponding side force coefficient can be obtained from the polynomial fitted to the curve in Figure 4. The measured side force can then be divided by the side force coefficient and the sail area in order to give an estimate of the effective wind dynamic pressure. In this way it is possible to differentiate between reductions in drive force caused by a change in wind direction from that caused by a reduction of wind pressure.
4.2 Modified Flow Field

For the second single boat test two Cobra probes were mounted on a stand at heights of \( z = h/3 \) and \( z = 2h/3 \). These probes can measure the three components of the wind speed vector at moderate frequencies. For this test the model yacht was positioned well upstream in the wind tunnel and the probe stand moved in a regular grid around the model. Care was taken to make sure that the probe had the same alignment at all locations. There was a region close to the hull and below the heeled sails where the probes could not be positioned, this is indicated in Figure 6 by the blanked-out area around the hull.

The data collected has been processed to give contour maps of the changes in the local apparent wind angle, the percentage strength of the wind dynamic pressure (\( q \), based on the total wind speed at each point) and the local flow elevation angle, all relative to the values measured without the model present. The results, shown in Figure 6a & b, show that upstream of the yacht the flow is deflected slightly such that a yacht in that location would experience a small increase in the apparent wind angle, whereas downstream the changes in effective apparent wind angle are much larger and extend over a greater area. At the lower level the flow deflections are highest immediately downstream of the yacht and the centreline of the affected zone seems to lie between the upstream apparent wind direction (straight down the page) and the yacht’s centreline. At the higher level the deflection angles are somewhat smaller, more localised and reach their maximum value some distance downstream. The most affected zone is also more aligned with the upstream apparent wind. Figures 6c & d both show a region of increase dynamic pressure on the windward side of the yacht. This can be associated with the circulation created around the sails. In addition at the lower level there is a clear wake region with reduced dynamic pressure, which at this level coincides with the greatest changes in local apparent wind angle. The elevation angles in Figures 6e & f indicate an upward flow on the windward side of the yacht and a downward flow on the leeward side. The strong vertical flows in Figure 6f indicate the presence of the tip vortex shed from the head of the sails and carried downstream by the apparent wind. It may be noted that the change from upward to downward flow is a roughly the same location as the largest changes in AWA in Figure 6b.

![Figure 6](image-url)

Figure 6 Changes in local wind direction, strength and elevation angle at \( z = h/3 \) and \( 2h/3 \)

(Continued on next page)
Figure 6 Changes in local wind direction, strength and elevation angle at $z=h/3$ and $2h/3$
Figure 7 Reductions in a) Drive force, b) Side Force and d) Effective Dynamic pressure and c) changes in apparent wind angle for another yacht located at each point, when experiencing interference from the yacht shown.
5. **TWO YACHT TESTING**

In a manner similar to the Cobra probe measurements, two boat testing has been conducted with one model mounted on the balance and the second model moved around it. The forces measured have then been processed in order to calculate the percentage of the isolated drive force and side force that occurs with interference. In order to relate these measurements with the flow field measurements the contour maps in Figures 7a & b show the percentage of the isolated values that are felt by another yacht at each location if it is affected by the one shown. This means that the yacht shown at point 0.0 is the interfering yacht. The results show that a yacht in the lee bow position experiences a slight increase in both the drive and side force. However if the yacht is in the wake of the interfering yacht then the drive force is reduced significantly and the side force to a lesser extent. The data has been analysed using the polynomials discussed in section 4.1 to determine whether the reductions indicate a change in wind direction or a reduction in wind strength. The results in Figures 7c & d show patterns similar to those in Figure 6, though since the forces on the model are an integral of the flows at all heights the indicated changes in apparent wind angle are less severe than measured at z=h/3, as seen in Figure 6a. It is worth noting that in the region where the drive force is reduced to a level between 20-30% of the isolated value (a 70-80% reduction), the indicated dynamic pressure reduction is in the 80-90% range (a 10-20% reduction). It therefore follows that most of the reduction is due to the adverse changes in wind direction.

6. **THREE YACHT TESTING**

With more than two yachts interacting there are a huge number of possible combinations of relative positions and so it is almost impossible to consider all of these. As a consequence we will concentrate on two situations where multiple yachts are most likely to be in close proximity, namely the starting line and the layline. For each of these we will consider two slightly different scenarios and seek some guidelines on maximising relative gains, or at least minimising losses.

6.1 **Starting line scenario 1 – Key boat between two opponents**

In a fleet race situation it is inevitable that all of the yachts will try to be as close as possible to the starting line as the race begins and hence this places a constraint on their relative positions, which makes the number of possible combinations manageable. As stated earlier we will consider the ideal, if somewhat unrealistic, situation where all the yachts reach the line at the same time and at full speed. For most of the yachts this means that there will be one yacht to windward and another to leeward. In some cases the gap between neighbouring yachts may be quite small, while at other times these may be larger. Some of the obvious questions that arise for a skipper as he/she approaches a starting line might be:

- If he has a choice between a narrow gap and a wider gap, which one does he head for?
- If there is space should she keep close to the windward or the leeward neighbour?

In order to test this situation three yacht models were set up on the starting line, the central yacht was the key boat mounted on the force balance, while the others were moved along the starting line as illustrated in Figure 8. For each position of the leeward yacht, the windward yacht was moved to a range of positions, making a 2D array of position combinations. In addition tests were conducted with only the windward yacht, representing a situation where the leeward boat is far away, and with only the leeward boat. The photograph in Figure 9 shows the three models in one of the close proximity situations. It may be observed that the wind tunnel start line, the white line under the bows of the models, isn’t directly across the tunnel but, as discussed in Section 3, is at an angle of 73° to the tunnel centreline, so that it is effectively perpendicular to the true wind direction, while the tunnel centreline represents the apparent wind direction. Also visible in Figure 9 are the wooden frames used to support the two interfering models and for the windward boat there are also weights to stop the model from tipping over. Although these may cause some disturbance to the flow it was reasoned that their relatively small size and the fact that they are near ground level would mean that any disturbance would be negligible.

![Figure 8 Starting line scenario 1, a yacht between two others.](image-url)
Figure 9 *Three boat interference testing in the wind tunnel.*

Figure 10 shows the results from this three boat study in terms of the “Drive force interference factor” which is defined as

\[
\text{Drive Force Interference Factor} = \frac{\text{Drive force}}{\text{Drive force on an isolated yacht}}
\]

Including this definition, values over 1.0 indicate beneficial interference whereas values below 1.0 are detrimental to the performance of the central key boat. Included in the figure are two sets of two-boat data. The only curve which goes above 1.0 is for the no leeward boat (LB) case, where the windward boat (white hull in Figure 9) may cause both a beneficial change in wind direction and a slight increase in wind dynamic pressure. These beneficial effects are seen to be most significant when the two boats are close to each other. The other set of two boat data is that with no windward boat (“No WB”) which is displayed as the unconnected larger symbols down the right hand side of the graph. It can be clearly seen that the detrimental effects of the leeward boat are far more significant, with reductions to levels as low as 40% of the isolated drive force. While this negative interference also decreases with separation it is still having a marked effect when the yachts are 0.86h apart.

![Drive force interference due to yachts on either side.](image)

(Note: Larger symbols on the right-hand side indicate no windward boat and the upper line is the no leeward boat data)
The three-boat data in Figure 10 is arranged so that each line represents a particular leeward boat position while the horizontal position of the symbols indicates the simultaneous windward boat position. It shows that to a certain extent the effects from the windward and leeward boats are additive. For example if the leeward boat is at 0.86h, then bringing the windward boat close to the key boat partially improves the situation. However if the leeward boat is close to the key boat then the windward boat seems to have no beneficial effect, and possibly makes the situation slightly worse. Detailed analysis of the drive and side force data for this scenario shows that the vast majority of the effects are caused by changes in wind direction and that changes in wind strength never cause more than a 15% reduction in drive force.

The overall picture that emerges from this test is that a skipper should maximise their separation from a leeward boat. If there is a choice between a wide and a narrow gap then head for the wide gap and err towards the windward end of that gap. Some advantage may be gained by getting close to a windward boat but there are dangers with this strategy, since while there are gains to be had in the lee bow position, if you are slightly early and have to shed speed as you approach the starting line then your relative position can rapidly change from one of advantage to severe disadvantage as you drop back into the wake of the windward yacht.

6.2 Starting line scenario 2 – Key boat beside two opponents

In the previous section it was shown that while a windward yacht can offer weak assistance, a leeward yacht can have a marked detrimental effect. Since on a starting line there will often be multiple yachts on each side of any boat, the question arises as to whether the yacht beyond the immediate neighbour has any significant influence? This has been investigated by placing the two interfering yachts either to windward or to leeward. A variety of positions for the nearest yacht were used, and with each of these a range of positions for the further away yacht tested, including removing the second yacht completely. The single interfering boat results are represented by the larger unconnected symbols in Figure 12.
The results in Figure 12 show a difference in influence for the second windward boat in comparison with a second leeward boat. With the windward boats the second boat doesn’t appear to enhance the beneficial effect given by the single windward boat, and in fact appears to weaken the effect. In contrast a second leeward boat enhances the detrimental effect with all distance combinations. It isn’t clear but there is a suggestion that there may be an optimal distance for the second leeward boat in terms of their combined effect. One possible explanation for this is that if the second boat is too close it adversely affects the one in the middle, so that it then has less effect on the key boat. It would be interesting to see if a third leeward opponent would enhance these adverse effects further, however the space in the wind tunnel and the availability of similar models meant that it was not possible to extend this study to more than two leeward yachts.

We therefore conclude that a second windward yacht has little influence and can be ignored, however a second leeward boat enhances the adverse effects and should be avoided if possible. The indications from an interference point of view are that the leeward end of the starting line is to be preferred, however factors such as the true wind not being quite perpendicular to the line, anticipated wind shifts etc. may negate this advantage.

### 6.3 Layline scenario 1 – Key boat between two opponents

The other upwind situation where yachts are frequently in close proximity is on the layline leading to the windward mark. In the wind tunnel the simulation is carried out for yachts rounding clockwise and leaving the mark to the starboard side. For this scenario the situation considered is one where the key boat is between two opponents, with each boat trailing the one in front of it by 1.5 boat lengths. The question considered is simply “whether there is an advantage to be gained by erring to windward or leeward of the line being taken by the other two boats”. Obviously a skipper would not choose to be on the leeward side if this resulted in not reaching the mark on the current tack as the two additional tacks required would mean a significant loss overall. For these tests the two opponent boats were always in line with each other and were moved along equal advantage lines which are perpendicular to the true wind and therefore angled in the same way as the starting line in the wind tunnel. The resulting situations are therefore equivalent to the key boat moving windward or leeward of the line taken by the leading and trailing yachts, as illustrated in Figure 13.

![Figure 13 Layline scenario 1, key boat between two opponents.](image)

The three boat drive force data is shown in Figure 14 along with data interpolated from the two boat testing for the situations where there is either one boat ahead or one boat behind. It is clear that the one ahead and one behind case is dominated by the presence of the leading yacht. In fact the drive force reductions with three boats are more severe than measured with just the boat ahead. From the two boat testing with only the boat behind one might expect some relief to be provided but this doesn’t appear to be the case, instead things seem to be worse. It is possible that having three models in a line across the tunnel is deflecting the whole flow to the side in a manner that is not necessarily totally realistic. Although as noted by Marchaj (1982) “A particularly bad position is one behind a number of yachts sailing on a close-hauled course. The helmsman of a following yacht will find himself facing a strongly deflected wind …”. So it may be that the combined group is enhancing the detrimental effects on the key boat.

In terms of strategy it can be concluded that with either one boat ahead or with one ahead and one behind it is better to err to windward of the direct layline. This would mean sailing a little further on the opposite tack before manoeuvring onto the lay line and thereby suffering something of a loss, but would then increase the drive force once the tack was completed. In addition since the major cause of the losses is a change in effective wind direction then sailing at a slightly higher true wind angle after the tack should increase the drive force and maintain speed, while the fact that the yacht is slightly beyond the layline will mean that the mark can still be reached while on this lower course.
6.4 Layline scenario 2 – Key boat ahead of two opponents

Figure 14 shows that there is a slight increase in drive force that can be gained from having an opponent behind. On occasions it may be possible to get onto a layline with two boats close behind you, as illustrated in Figure 15. The questions which then arise are:

- Do the two boats offer more assistance than the single boat behind?
- Is there an optimal position relative to those boats in term of maximising drive force?

The particular situation tested assumed that the two opponents were 1.5 boat lengths behind the key boat and that they were in a position of equal advantage relative to each other. The two boats had one half-beam separation between the two hulls.

The drive force interference results shown in Figure 16 show that the fractional increase in drive force is only of the same order as that to be gained from a single opponent. It also shows that the gain will be maximised by being on the leeward side of the central axis between the pair of opponents, either by being directly ahead of the more leeward opponent or slightly leeward of that line provided the mark can still be reached by taking that line.
7. CONCLUSIONS

The interaction between yachts sailing upwind close hauled has been investigated through wind tunnel measurement of the forces and moments on a balance mounted key boat which is experiencing interference from one or two opponent boats. The variation of forces and moments on the key boat, in isolation, were also measured over a range of apparent wind angles and the drive to side force ratio used as an indicator of the effective apparent wind angle when an interfering boat is present. The data from two boat testing shows that much of the reduction in drive force is due to changes in wind angle rather than wind pressure. These changes in angle and wind pressure are similar to those directly measured around an isolated yacht using Cobra probes. With three boat interference there are too many possible position combinations to consider all of these and so tests focused on two starting line and two layline scenarios. It has been shown that on a starting line with one opponent to windward and one opponent to leeward the interference is dominated by the adverse effects of the leeward boat. If the leeward boat is sufficiently remote then the windward boat can offer some relief. However if the two opponent boats are to windward then the small increase in drive force primarily depends on the proximity of the nearest of the two. With two boats to leeward the second boat enhances the adverse effects of the nearer boat. Two layline scenarios have also been considered and it was found that the most significant interference occurs if there is a yacht immediately ahead, in which case drive force losses can be minimised by erring to windward.

REFERENCES

Caponnetto, M., The aerodynamic interference between two boats sailing close-hauled, International Shipbuilding Progress, 44(439), 241-256, 1996


Figure 16 Drive force interference for the key boat on the layline with two opponents behind.