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Wind tunnel investigation of the interaction between two sailing yachts

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Abstract

The interference between two yachts sailing close-hauled upwind at 20° apparent and downwind under asymmetric spinnaker at 60° apparent is investigated in the wind tunnel by using two similar yacht models. The regions of positive and negative interference are determined and the sources of these effects investigated.

Introduction

With any form of yacht racing there will frequently be occasions when two or more yachts are sufficiently close to each other to cause some sort of interference. At times this can work to your advantage while at other times it is more a case of seeking to minimise your losses. In order to achieve either it is necessary to understand the areas of affected flow and the likely consequences of sailing in these flows.

The popular understanding of interference is encapsulated in documents such as “Racing Basics” by Mark Johnson [1] available on the University of Iowa website. In discussing the interference between yachts Johnson [1] comments “If you’re sailing in bad air created by other boats, you will go much slower that they will. Your mission, if you choose to accept, is to get to clear air. The first step in this process is determining the location of the bad air, relative to the boats around you.” He then goes on to use diagrams similar to figure 1, to discuss two effects: blanketing or the stopping of the air from reaching you, which is represented by the small, but intense, dark zone and backwinding, the lighter shaded area, where the wind is slightly reduced but more importantly the wind direction is changed by the air deflected off the leeward (L) yacht’s sails. This change in wind direction will either slow the windward (W) yacht or force it to tack away (turn to the right) or bear away (turn slightly left) and drop behind yacht L, in which case it will have to cross the turbulent wake and increase her losses. In yacht racing the yacht on starboard tack, with the wind approaching from its right, has right of way over yachts on port tack. One effective tactic for a yacht on port tack which is slightly ahead and approaching a yacht on starboard tack is to tack just before their paths would cross and position itself in the “lee-bow” position (L) depicted in figure 1. In this position it can find positive interference for itself while causing negative interference on the other yacht.

One slightly misleading aspect to figure 1 is that it isn’t clear whether the wind arrow represents the true wind, relative to a fixed point, or the apparent wind, relative to the yacht, which is calculated by the vector sum of the true wind and the reversed boat velocity. The angles tend to suggest that this represents the true wind and that the yachts are sailing “close-hauled” (as close to the wind direction as can be effectively handled) at a true wind angle of about 40°, which would be reasonable for a racing yacht sailing upwind. In which case the blanketing zone is in the wrong place since while the wake is carried downwind the movement of the yacht means that it also drops behind as the yacht moves forward. The blanketing zone should therefore be aligned with the apparent wind rather than the true wind.

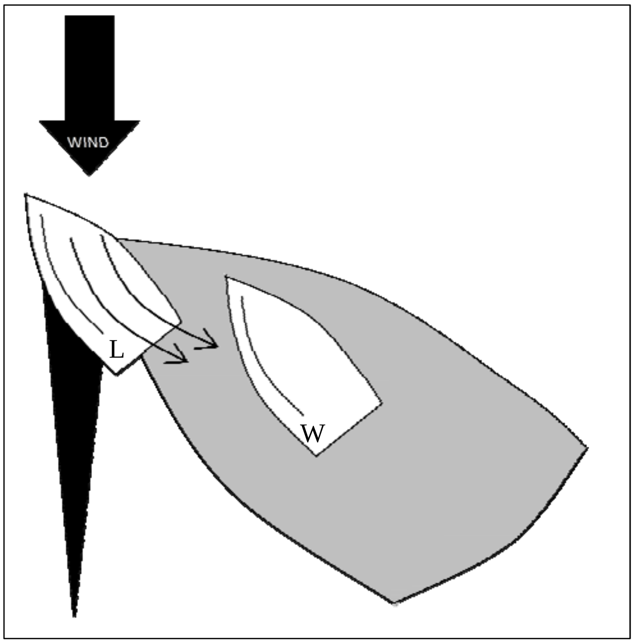

Figure 1. Interference zones as depicted by Johnson [1]

Marchaj [2] provides a detailed discussion of the situation shown in figure 1 and points out that yacht L 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 W. In contrast he describes the position of yacht W 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 toward the stern”, which would put the dark blanketing zone in figure 1 even further to the right. 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 [2] also reproduces some quantitative wind tunnel data collected by M.S. Hooper using J-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 [3] 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 [3] 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.

Upwind Wind Tunnel Study

The interference between two yachts has been investigated in the University of Auckland’s Twisted Flow Wind Tunnel. This 7m wide by 3.5m high low speed tunnel is equipped with vertical turning vanes which create a flow which changes direction with height. This feature replicates the combination of the true wind, which varies with height, with the boat motion which is the same for all heights. The result is flow which changes in both magnitude and direction with height. This twist in the flow is particularly significant when testing downwind sails such as the asymmetric spinnaker shown in figure 2.

Figure 2. The University of Auckland Twisted Flow Wind Tunnel.

Figure 3. The two models used in the upwind interference study.

For the upwind interference modelling two similar yachts (see figure 3), with a mast height h = 2.25 m, were set at an AWA of 20°, typical for sailing close-hauled, and a heel angle of 25°. One of the models was mounted on the six-component force balance, the key model, while the second was free to be moved around. The second model was located at various radii. At 1h a complete circle could be included but at other radii the constraints of the tunnel limited the angles that could be tested. The twisting vanes are not usually used for upwind testing and hence were moved aside. The velocity profile was nearly uniform except for a small boundary layer on the floor, about 300 mm high. Figure 4 shows the percentage change in drive force on the key model resulting from having the second interfering model in each location relative to that measured when the second model is removed.

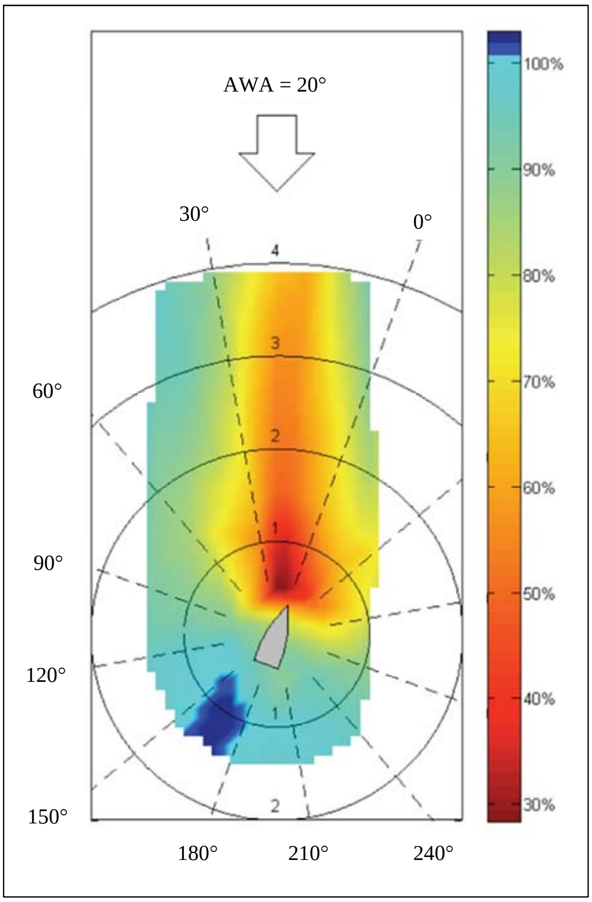

Figure 4. Changes in drive force on a close-hauled yacht when affected by a second yacht. The colours represent the percentage of the isolated yacht drive force which exists when a second similar yacht is located at each position. The radial co-ordinate is in multiples of mast height h.

Figure 4 shows that the negative interference line extends from the interfering yacht approximately along the apparent wind direction. However the centre of the negative band is a few degrees off the direct line showing that the wake has been deflected slightly by the lift generated on the sails as discussed by Marchaj [2]. Figure 5 shows a comparison of the wind tunnel data with Caponnetto's [3] vortex lattice modelling for a yacht separation of R =1h. Similar trends are observed with slightly higher drive force reductions recorded in the wind tunnel. In addition the region of positive interference, ratios over 1.0, is slightly smaller and as seen in figure 4 is located from directly astern to 30° windward of astern. This corresponds to when the key yacht is in the safe leeward position.

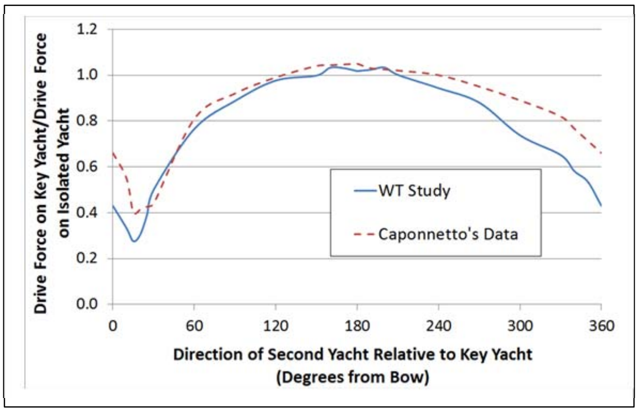

Figure 5. Comparison of the wind tunnel drive force ratio with Caponnetto's [3] vortex lattice modelling for yacht separation R = 1h.

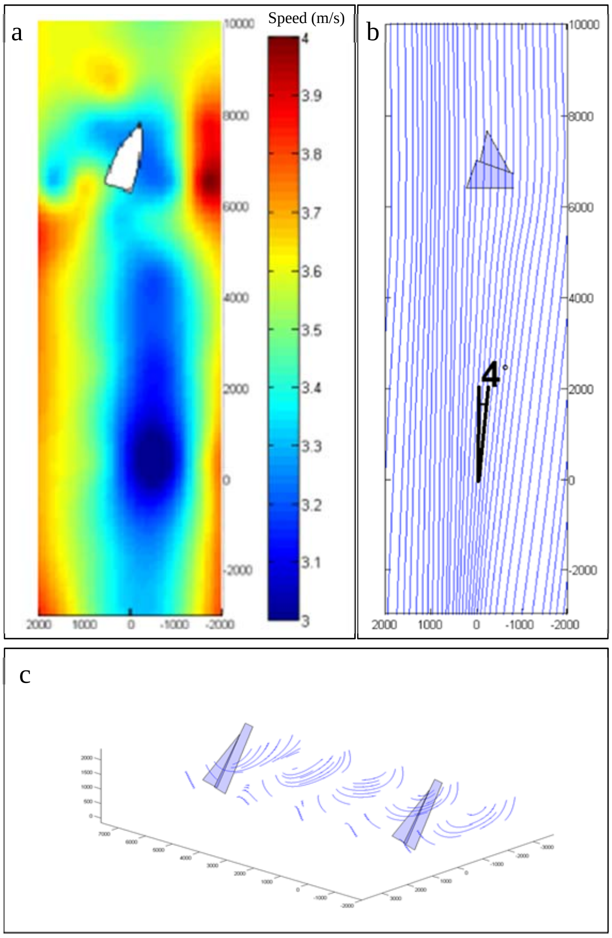

Figure 6. Cobra probe velocity measurements: (a) Mean wind speed at 1/3 mast height, (b) streamlines at mid-height and (c) streamlines on various transverse vertical sections with two yachts. Distances in mm.

In order to more fully understand the flow field cobra probe (Turbulent Flow Instrumentation- Series 100) measurements were made at 1/3rd and 2/3rd mast heights. This was carried out with both one yacht in a windward position and with two yachts on the centreline of the tunnel about 3 mast heights apart. Figure 6a shows the changes in wind speed at 1/3rd mast height with just the upstream yacht, the region of low speed flow is clearly visible. The velocity data has been interpolated to give the streamlines at mid-mast height in figure 6b and for the case of both yachts on various vertical slices in figure 6c. These show that the downstream yacht would experience not only a weaker flow but one that is effectively 4° further away from the true wind direction. Figure 6c confirms that this change in wind direction is associated with the strong vortex which is shed from the head of the upstream yacht. The CFD modelling of Spenkuch et al. [4] of a similar situation also shows the influence of the masthead vortex and the consequential effect on the force generated by the downstream yacht.

The data used in figure 4 can be reinterpreted to give the regions of influence of a yacht, this is shown in figure 7. The contours of this graph represent the percentage of the isolated drive force that a yacht would experience at that position. The symbols are measured data while the lines have been constructed from these and curve fits along various radii where it has been assumed that at large radii the curve asymptotes to unity. The apparent wind is vertically down the graph. It can be seen that the major negative influence is primarily downwind of the yacht while there is a small positive interference region ahead of the bow. This data, when transformed to the starboard tack situation, suggests that figure 1 should be more like that shown in figure 8.

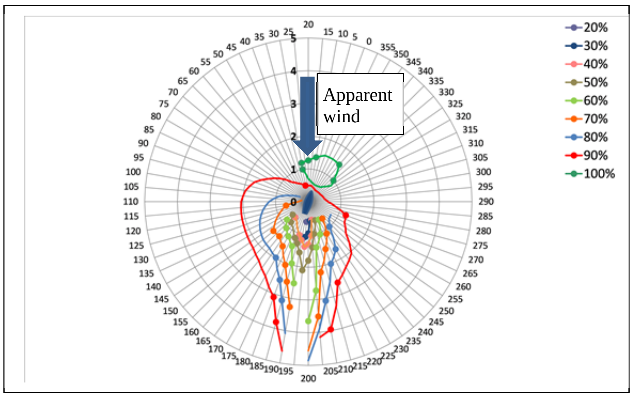

Figure 7. The region of influence of a yacht sailing close-hauled.

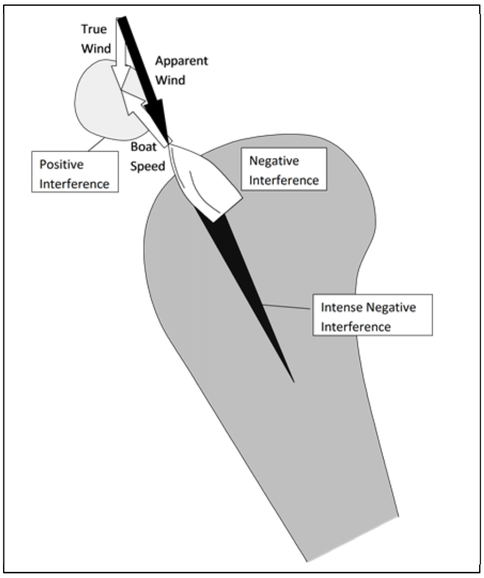

Figure 8. A revised version of figure 1 based on the wind tunnel data.

Downwind Wind Tunnel Study

A similar study of the interference of yachts when sailing downwind has been conducted. Two yacht models, similar to the one in figure 2, were set at an AWA of 60° and were heeled 7.5°. Each 2.25m high yacht was equipped with a mainsail and A3 asymmetric spinnaker and these were trimmed for maximum drive force at 60° AWA in isolation, but were not retrimmed at other times. Due to the space required for the study the twisting vanes could not be used and the velocity profile almost uniform.

Figure 9a shows that the region of negative interference is once again approximately downstream of the interfering yacht but is deflected slightly more away from the apparent wind direction towards the stern. In this situation the deviation from the apparent wind direction is around 9°, whereas it was near 5° in figure 7. There is a suggestion of a positive interference region ahead of the interfering yacht but this isn't well defined. The sources of the negative interference are quite clear in figures 9b-d. In figure 9b the region of reduced wind speed is similar to that of the reduced drive force but less intense. However it should be noted that the force is roughly proportional to the square of the wind speed and is also affected by the wind direction, which as shown in figure 9d, is adversely changed by over 30° in some areas.

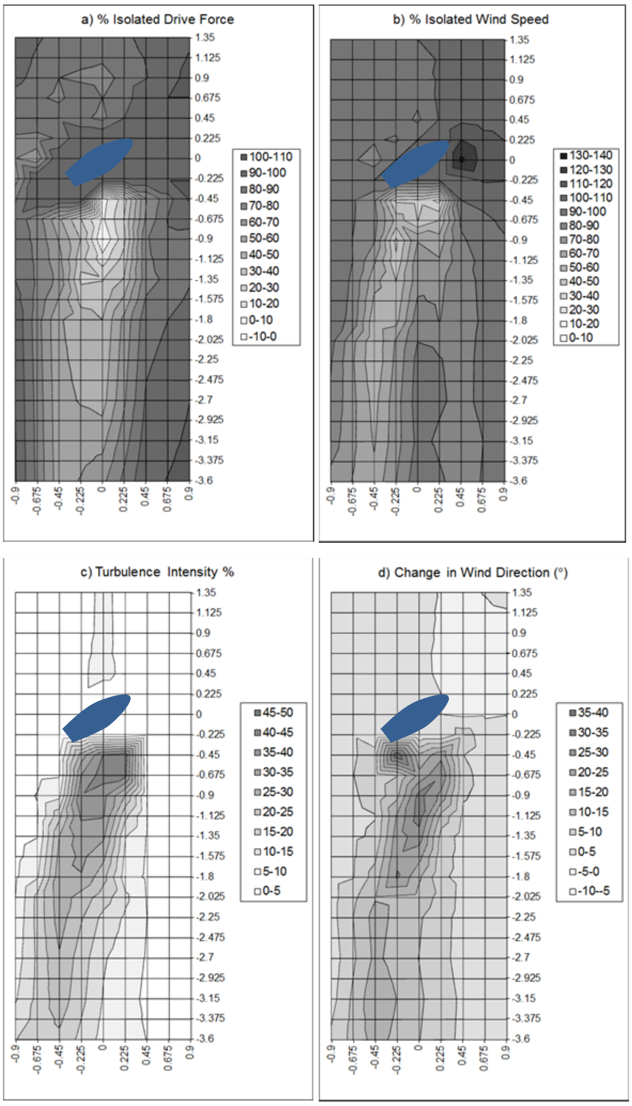

Figure 9. Downwind interference data a) percentage of the isolated drive force on a second yacht at the position shown, b) percentage of the isolated wind speed, c) turbulence intensity and d) change in wind direction (positive values are less favourable). All velocity related values are at 1/3rd mast height and all distances in multiples of mast height.

Figure 9c shows that the wake is also very turbulent with turbulence intensities over 40% in some areas. This may not directly affect the drive force but it would make it extremely difficult to keep the spinnaker correctly trimmed and may even cause occasional partial collapse of the sail.

Figure 10 is the downwind equivalent of figure 8. The particular situation depicted is based on a true wind angle of 145° on starboard gybe and an apparent wind angle of 60°. This means that the apparent wind vector is at 85° to the true wind and so the main affected region lies across the true wind rather than in-line with it. In the past some yacht race animations have incorrectly shown the "dirty air" zone for downwind sailing more in-line with the true wind. This may possibly be traced to data such as that reported by Marchaj [2] who shows results based on work carried out by Eiffel, who investigated the interference of two flat plates. Such data may be relevant for sailing straight downwind (AWA = 180°) with the apparent and true wind directions aligned and the yacht driven by the drag force. However yachts can usually achieve a better velocity made good, which is the yacht's velocity component in the true wind direction, by sailing at lower true wind angles. With modern racing yachts the speed that can be achieved usually means that the AWA is always less than 90°, even when sailing downwind, and so it is the lift that provides the drive, which determines the character of the wake and makes it more like the upwind situation.

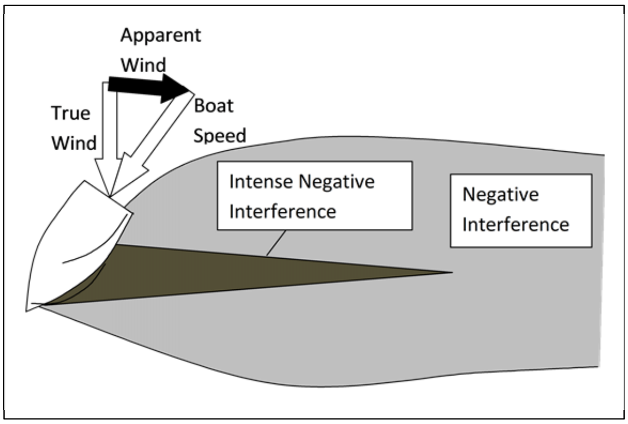

Figure 10. A simple schematic diagram for interference when sailing downwind.

Conclusions

A wind tunnel study of the interaction between two yachts sailing both upwind and downwind has been conducted. The results show that in both cases the drive force on a downstream yacht is significantly reduced in a region either side of a line slightly aft of the apparent wind direction. With upwind sailing a small positive interference region was found in the lee bow position.

References

[1] Johnson, M. Racing basics, available on-line at www.uiowa.edu/~sail/skills/racing_basics/index1.shtml

[2] Marchaj, C.A., Sail theory and practice, *Dodd Mead & Company, NY*, 1982.

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

[4] Spenkuch, T., Turnock, S., Scarponi, M., & Shenoi, A., Lifting line method for modelling covering and blanketing effects for yacht fleet race simulations, *Proceedings 3rd High Performance Yacht Design Conference, Auckland, NZ, 1-4 December 2008.*