20th Australasian Fluid Mechanics Conference
Perth, Australia
5-8 December 2016

Aerodynamic Interference of Yachts Sailing Upwind on Opposing Tacks

S. E. Norris[1] **and C. Durand**[2]

[1]Department of Mechanical Engineering
University of Auckland, Auckland 1142, New Zealand
[2]Ecole des Mines d'Albi-Carmaux, 81013 Albi, France

Abstract

When two sailing yachts pass each other on opposite tacks, the downwind (or leeward) yacht passes through the wake its upwind (or windward) counterpart. To date there has been no study that has quantified the changes in drive force associated with these manoeuvres, although it is of interest to the development of racing yacht tactics.

In this study a transient computational fluid dynamics model of yachts passing each other on opposite tacks is developed. Data is presented for a range of separation distances. Unexpectedly, it is found that the drive force on the windward yacht may be reduced by the encounter, while the leeward yacht experiences both and increase and decrease in drive force.

Introduction

During a yacht race the yachts will often sail closely to each other. Their close proximity will cause the sails on each yacht to interfere with the air flowing around the other yacht. For the second yacht this interaction can be either positive, increasing the drive force on the sails and changing the apparent wind direction in a beneficial direction, or negative where the reverse is true. Exploiting these interference effects is an important part of the tactics of yacht racing. Therefore it is desirable to be able to quantify the effects of the aerodynamic interference.

When sailing upwind a yacht will sail at an angle to the oncoming wind. The yachts may be on the same tack, as shown in Figure 1a, or on opposing tacks, shown in Figure 1b. The upwind yacht is to windward, while the downwind yacht is to leeward. If the yachts are positioned correctly the leeward yacht may be located in the wake of the windward yacht, and might be expected to be at a disadvantage. However, in addition to the wake, the upwash of a yacht's sails has an effect on other yachts, changing the direction of the apparent wind that they are sailing in.

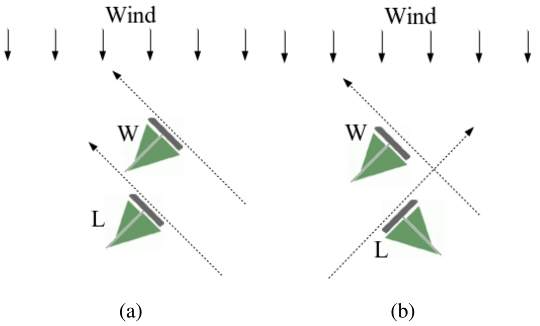


Figure 1: Yachts sailing upwind on (a) the same, and (b) opposing tacks, to (W) windward of (L) leeward of each other.

Most of the literature on yacht interference has been for yachts sailing on the same tack. The fact that the boats can be approximated as being stationary with respect to each other simplifies modelling the flow experimentally in a wind tunnel or numerically with CFD [2, 3, 4].

The only study to date to study yachts on opposing tacks is that of Spenkuch et al.[6], who modelled the yacht sails as lifting lines moving through a uniform potential flow. They present apparent wind data for a single case of yachts passing on opposite tacks. However, the forces on the yachts and effects of yacht separation are not presented.

In this study yachts sailing upwind are modelled using the RANS CFD code ANSYS CFX. The apparent motion between two yachts on opposite tacks is reproduced by having the yachts modelled in two separate meshes that move with respect to each other. The aerodynamic forces on the yachts sails are presented, and the effect of distance between the yachts is discussed.

Numerical Methodology

Yachts sailing on opposite tacks move with respect to each other. A means of modelling this relative motion without resorting to the expense of mesh deformation is shown in Figure 2. Each yacht is in its own mesh which slide sideways with respect to each other. Two non-sliding meshes are added at the inlet and outlet to simplify the definition of the inlet and outlet boundary conditions. In addition the whole assembly is in a frame of reference that moves to windward to match the velocity of the yachts resolved in that direction.

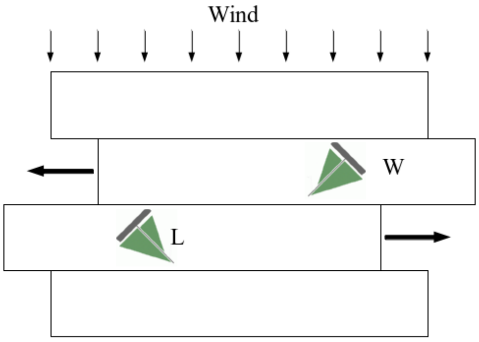


Figure 2: The arrangement used to model the relative motion between the (W) windward and (L) leeward yachts.

ANSYS CFX allows the use of sliding meshes such as these for the modelling of turbomachinery, with sliding and stationary domains modelling the rotor and stator stages of turbines and compressors. Unfortunately this require the use of a curved computational domain, to match the annular shape of the turbine. Therefore the model was made with a large radius of $\sim 210L_b$ as shown in Figure 3, where L_b is one boat length, to minimise the effects of having a curved, rotating frame of reference. The mesh was $20L_b$ long and $3L_b$ high, with the yachts located midway between the inlet and the exit. A uniform velocity was prescribed at the inlet and a constant pressure boundary condition was used at the outlet. The flow was periodic in the cross wind direction. The ground was modelled as a rough surface with a surface roughness of $z_0 = 0.25mm$. An unstructured tetrahedral mesh was used, and the flow was modelled with the ANSYS CFX 16.0 solver using the SST turbulence model, the Barth-Jesperson "High Resolution" differencing scheme for the momentum terms, and first order upwind for the turbulence scalars.

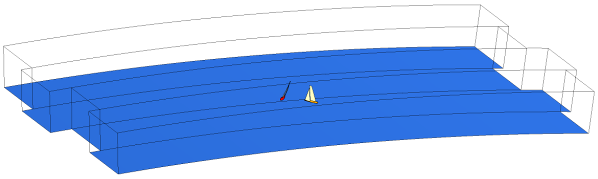


Figure 3: The curved geometry used for the computational model.

The modelled yachts were AC33s, which is a hypothetical monohull yacht that was proposed for the 33$^{\text{rd}}$ America's Cup contest. The sails were modelled as being infinitely thin surfaces on a mast that was $1.3L_b$ high. Excepting for the validation case the model yachts had hulls and were heeled 20° to leeward. The boats were sailing at an angle 40° to the true wind at boat speed 1.1 times the true wind speed, giving an apparent wind angle of 18°.

The forces on the sails were recorded through each run, and were resolved into the sideways and forwards (or drive) force on each yacht. The drive force was non-dimensionalised as a drive force ratio, DFR, which was the ratio of the instantaneous drive force to the drive force experienced by a single yacht sailing in free-air,

$$DFR = \frac{F}{F_{freeair}}. \tag{1}$$

The model was then use to simulate two yachts passing each other, for a range of boat separations, where the separation distance Δ is defined as the closest distance between the hulls of the yachts as they pass D non-dimensionalised with respect to the boat-length, L_b.

$$\Delta = \frac{D}{L_b} \tag{2}$$

The time t in the transient plots has been nondimensionalised with the boat-length and boat-speed U_b, and is zero at the time of the closest encounter between the yachts,

$$\tau = \frac{tU_b}{L_b} \tag{3}$$

It is instructive to know the apparent wind angle (AWA), which is the angle of attack of the sails in the moving reference frame of the yacht. This has been estimated by assuming that the lift to drag ratio is approximately constant for small changes in AWA. The change in direction of the force vector on the sails is then taken to indicate changes in the apparent wind angle.

Results and Discussion

The use of the sliding model was validated for a single yacht against the experimental pressure data of Fluck[1, 7]. So as to match the physical experiment, the sails shown in Figure 5 were modelled without a hull, upright in a uniform untwisted flow with a free slip lower boundary. They were modelled in a stationary domain at an apparent wind angle of 18°, and in a sliding frame at a true wind angle of 40° with the domain motion giving an apparent wind of 18°.

Representative examples of the pressure coefficients on the sails are shown in Figure 4, which gives the pressure on the headsail on the four horizontal stripes shown in Figure 5 for which experimental pressures are available. Good agreement is found between the computed and experimental pressures, except at the luff (leading edge) where the CFD models predicts stagnation on the windward surface, and a small region of high suction on

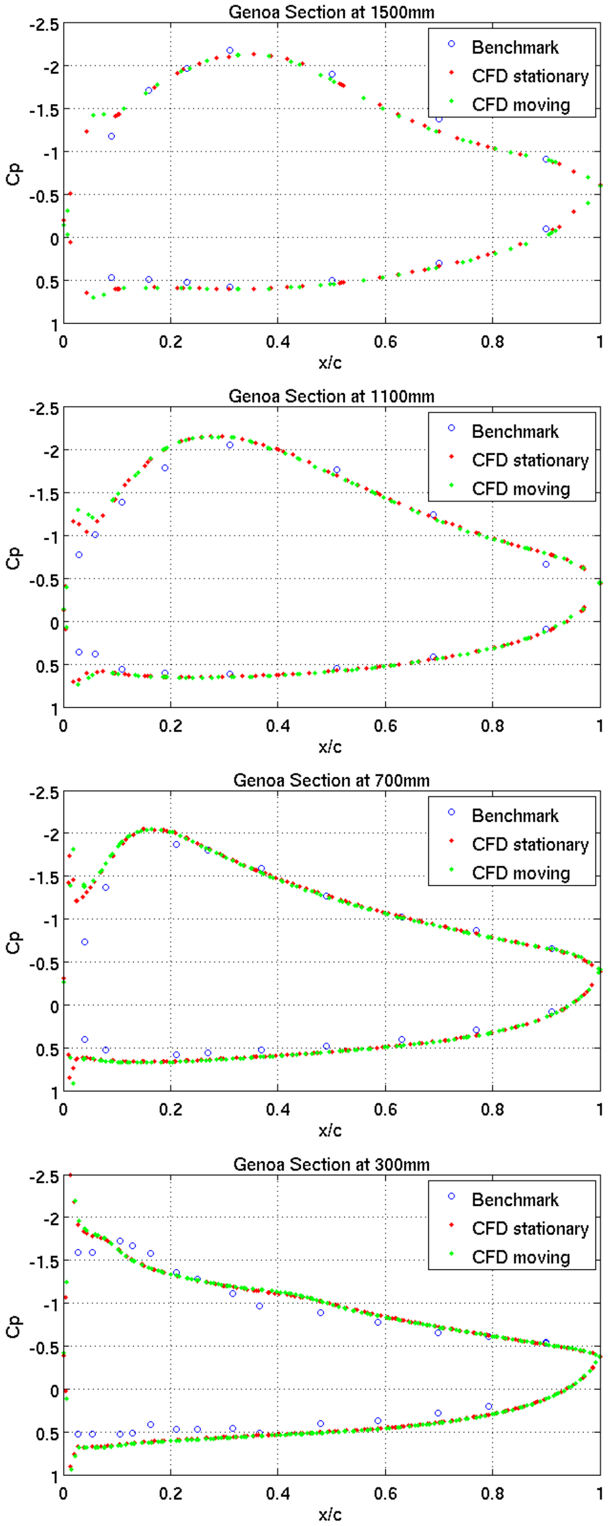


Figure 4: The pressure coefficients on the headsail calculated using a stationary and moving frame compared with benchmark experimental data of Fluck[1, 7].

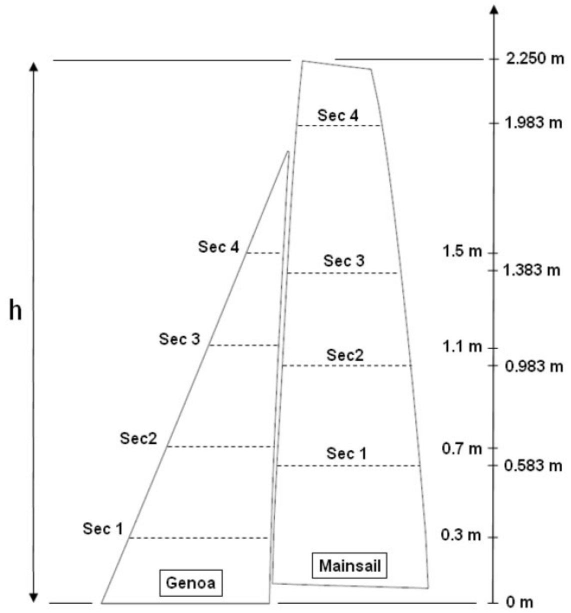


Figure 5: The locations of the pressure taps for the experiments of Fluck[1, 7].

the leeward surface. The stationary and moving reference frame solutions are in good agreement with each other, confirming the suitability of using the sliding frame model.

The model was then use to simulate two yachts passing each other for a range of boat separations Δ. For these calculations the yachts were heeled and a hull was added to the model. The magnitude of the velocity on a plane at $1/8$ mast height for boats crossing at a separation of $\Delta = 0.35$ is shown in Figure 6, which clearly shows the wake behind each yacht's sails. A region of accelerated flow is seen on the leeward surface of the sails, and slowed flow is seen to windward.

The time history of the drive force ratio on the yachts as the pass each other is shown in Figure 7a for a yacht separation of $\Delta = 0.35$. At $\tau = -6$ the yachts are well separated and the forces on them are the same as for sailing in clear air. For times greater than $\tau \approx -2$ the yachts start to interact and the forces on the sails change from their clear air values. At $\tau = 0$ the leeward boat passes directly downwind of the leeward yacht, and the interaction continues until $\tau \approx 2$ by which time the yachts are well separated.

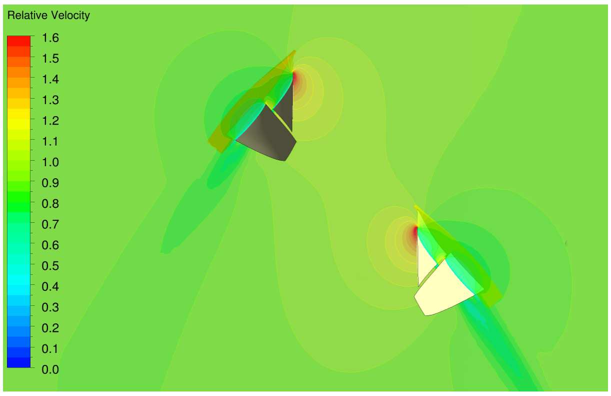


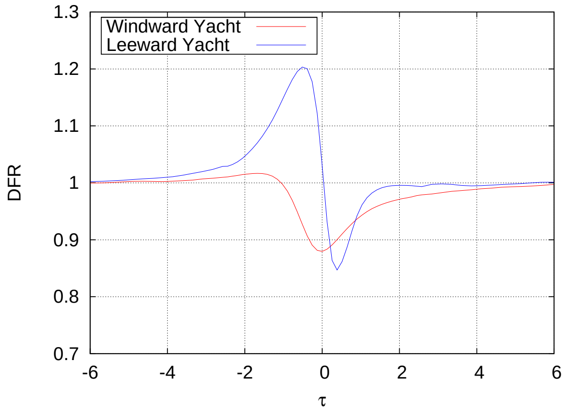
Figure 6: Two yachts passing with a separation of $\Delta = 0.35$ at $\tau = -1.3$. Contours of relative wind velocity U/U_T at $1/8$ mast height. The true wind runs from top to bottom.

It is interesting to see that the windward yacht is affected by the leeward yacht, and there is a drop in its drive force at $\tau = 0$. In order to understand the reason for this the apparent wind angle has been plotted in Figure 8a. It can be seen that the upwash from the leeward yacht decreases the AWA on the windward yacht (known as a "header" by sailors), decreasing the drive force. This would be countered in practice by steering the yacht at an angle further away from the wind.

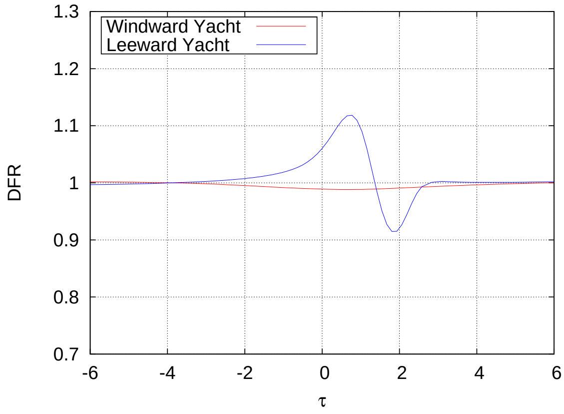
The variation in force on the leeward yacht are greater than its windward counterpart. Initially, between $\tau = -2$ and $\tau = 0$ there is an increase in the drive force, due to the upwash from the windward yacht increasing the AWA (a "lift" in nautical terminology), and the yacht sailing in the high velocity region to leeward of the windward yacht. However, between $\tau = 0$ to $\tau = 1$ there is a drop in the drive force as the yacht passes through the low velocity wake of the windward yacht.

Figures 7b and 8b show similar time histories of the drive force ratio and apparent wind angle for a case with larger separation of $\Delta = 4.0$. The leeward yacht now has negligible effect on the windward yacht. However the leeward yacht still experiences the effects of the windward yacht, with an increase and decrease in force as before, although the changes in force have decreased with increasing separation. They are also delayed in time by $d\tau \approx 1.5$.

The effect of separation distance on the magnitude of the variation in drive force ratio is shown in Figure 9. The leeward yacht gets a maximum increase in drive force ratio of 20% for small separations, which decreases with increasing separation.

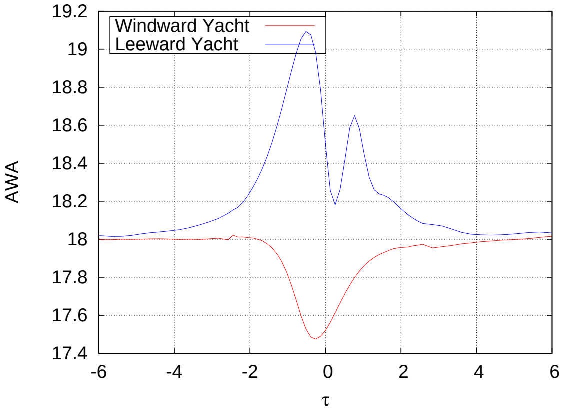


(a) $\Delta = 0.35$

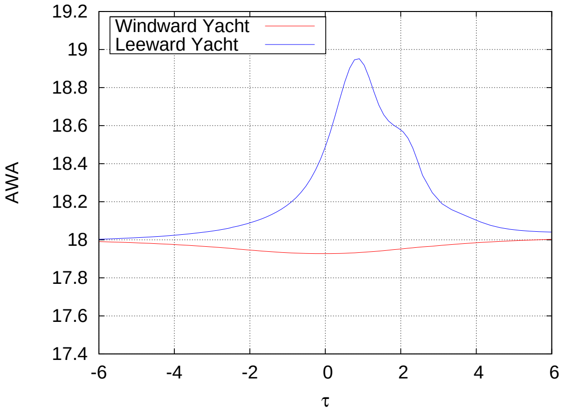


(b) $\Delta = 4.0$

Figure 7: Time history of the drive force ratio on the windward and leeward yachts, for separations of $\Delta = 0.35$ and $\Delta = 4.0$.



(a) $\Delta = 0.35$



(b) $\Delta = 4.0$

Figure 8: Time history of the apparent wind angle on the windward and leeward yachts, for separations of $\Delta = 0.35$ and $\Delta = 4.0$.

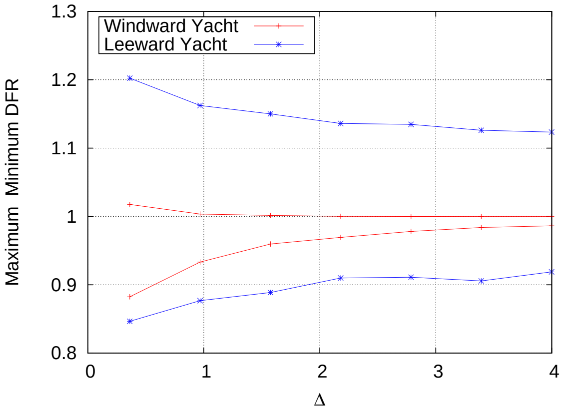


Figure 9: Variation of maximum and minimum drive force ratio with separation distance.

Interestingly the windward yacht experiences a very small increase of 2% at low Δ, but this rapidly goes to zero by $\Delta = 1$. The reduction in the drive force decreases quite rapidly for the windward yacht, but that for the leeward yacht decreases much more slowly.

The results shown here are quite surprising, for it would be reasonable to assume that the windward yacht would be unaffected in the passing manoeuvre described here, while experience shows that the leeward yacht can be adversely affected by passing through the wake of the yacht to windward. However, when considering the integral of the drive forces on the windward yacht shown in Figure 7, the increase in the drive force as the two yachts approach each other is greater than the decrease when it passes through the wake of the windward yacht, so it experiences a net increase in drive force. This hold true for separation distances up to four boat-lengths, which was the maximum separation distance studied. Moreover, for small separation distances the windward yacht can be adversely affected with a net decrease in the total drive force, although this reduction in drive force rapidly decreases with boat separation.

One possible reason for the unexpected improved performance of the leeward yacht can be found by examination of Figure 6. The decrease in the velocity in the wakes is not large, and might be affected by due to poor mesh resolution or the unprototypical aerodynamically clean nature of the CFD, which is lacking mast and rigging. A larger wake, with a greater decrease in wind velocity, would be expected to reduce the drive force in the leeward yacht.

Conclusions

Yacht passing each other on opposite tacks has been modelled and the forces on sails have been presented for the first time. The windward yacht has a slight decrease in the drive force for small separation distances, but as separation increases this becomes negligible. The leeward yacht experiences an increase in the drive force as it approaches the windward yacht, which is followed by decreased force.

The variation in force is due to changes in apparent wind direction due to upwash from the other yacht, and the leeward yacht having to sail through the low speed wake of the windward yacht.

The results do not agree with experience, and it is suggested that a poor prediction of the wake may lead to overestimates of the leeward yachts performance.

References

[1] Fluck, M., *Extended Lifting Line Theory applied to two interacting Yacht Sails*, Masters Thesis, Technological University of Munich, Germany, 2010.

[2] Marchaj, C.A., *Sailing Theory and Practice*, Dodd, Mead and Company, 1962.

[3] Richards, P.J., Le Pelley, D., Jowett, D., Little, J. and Detlefsen, O., Wind tunnel investigation of the interaction between two sailing yachts, *The 18^{th} Australasian Fluid Mechanics Conference*, Launceston, Australia, 2012.

[4] Richards, P.J., Le Pelley, D., Jowett, D., Little, J. and Detlefsen, O., A wind tunnel study of the interaction between two sailing yachts, *The 21^{st} Chesapeake Sailing Yacht Symposium*, Annapolis, Maryland, USA, 2013.

[5] Richards, P.J. and Norris, S.E., Appropriate boundary conditions for a pressure driven boundary layer, *J. Wind. Eng. Industrial Aero.*, **142**, 2015, 43–52.

[6] Spenkuch, T., Turnock, S.R., Scarponi, M. and Shenoi, R.A., Modelling multiple yacht sailing interactions between upwind sailing yachts, *J. Mar. Sci. Technol.*, **16**, 2011, 115–128.

[7] Viola, I.M., Pilate, J. and Flay, R.G.J., Upwind sail aerodynamics: a pressure distribution database for the validation of numerical codes, *Intl. J. Small Craft. Tech.*, **153**, 2011, 47–58.