

The hydrodynamic flow around the winged keel of Australia II yacht

B. Nugroho^{1*}, R. C. Chin², N. Moerke³ and P. Van Oossanen³

¹Department of Mechanical Engineering, The University of Melbourne, Melbourne, VIC, 3010, Australia

²School of Mechanical Engineering, The University of Adelaide, Adelaide, SA, 5005, Australia

³Van Oossanen Naval Architects B.V., Wageningen, Netherlands

*mailto: bagus.nugroho@unimelb.edu.au

Abstract

This paper presents computational fluid dynamics (CFD) of Reynolds-Averaged Navier Stokes (RANS) simulations to analyse the hydrodynamic flow around the ‘winged keel’ of the twelve-metre class *Australia II* yacht that won the 1983 America’s cup race. The simulations are designed to see the far field wake flow behind the keel at various Reynolds number under 0° leeway with 0° heel and when it is at a leeway angle of 4° with heel angle of 20° (replicating the actual sailing condition). Preliminary results indicate that the ‘winged keel’ generates strong high and low streamwise velocity variation in both the streamwise and spanwise locations. Some of these variations persist even up to 40 metres behind the yacht.

1 Introduction

One of the greatest achievements in the history of modern sport was the triumph of the twelve-metre class *Australia II* yacht in the 1983 America’s cup races, ending the longest winning streak (132 years) by the United States. With its radical design of upside-down winged keel (figure 1), the *Australia II* defeated *Liberty* convincingly 4-3 of the 7 races (van Oossanen 1985). The keel design’s main advantage was allowing the *Australia II* to sail at a much tighter angle against windward than her rivals (van Oossanen & Joubert 1986). The *Australia II*’s keel development itself was commissioned by the yacht designer Ben Lexcen in 1981 where most of the work took place in the Netherlands at Maritime Research Institute Netherlands (MARIN) and The National Aerospace Laboratory of the Netherlands (NLR). The keel development was guided by Peter van Oossanen (who led the towing tank experiments) and Joop Sloof (who led the computational simulation studies) (van Oossanen 1985, Ulbrich 2003). The dramatic outcome of the 1983 race shattered the general view that twelve-metre class yacht had reached its optimum design, and no significant advances were possible. Since then, there has been a significant increase in the amount of yacht research by many nations (at least six) and syndicates (around seven) inspired by the success of *Australia II*, leading to many engineering breakthroughs such as riblets for drag reduction mechanism, more complex keel and hull profile development, new design software, new mathematical model, etc. (Letcher *et al.* 1987).

For a sailing yacht, the keel holds essential roles, particularly when the yacht moves towards an upwind heading (or against windward): the first as a hydrofoil that generates the hydrodynamics side force to balance the aerodynamic forces from the sails and the second as a ballast to stabilise the hull against the heeling moment that is generated by the forces on the sails (van Oossanen & Joubert 1986; Letcher *et al.* 1987). With respect to the keel’s first role, when a yacht is at upwind heading, the wind on the sail has an aerodynamic force component at a right angle to the yacht’s heading (see figure 2a). According to van Oossanen & Joubert (1986) such transverse force can be five times greater than the forward thrust component. Therefore in order for a yacht to reach equilibrium, it requires to have an equal opposing force, which in this case is the hydrodynamic force on the hull, the rudder



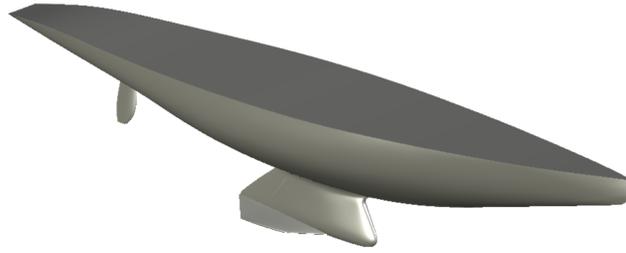


Figure 1. Hull and winged keel of Australia II.

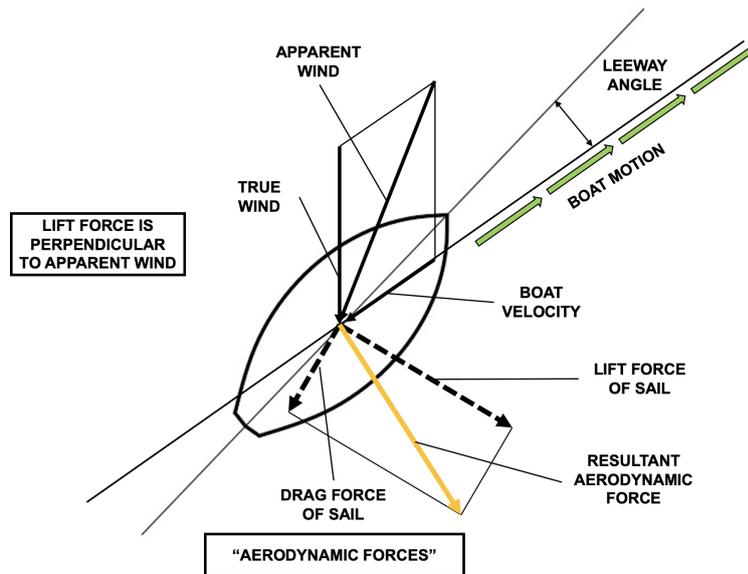
and, importantly the keel. The keel of a yacht can be described as a wing with a symmetric airfoil shape that can generate a hydrodynamic side force when the yacht experience an angle of incidence or leeway β relative to the direction of the yacht through water (see figure 2b). The airfoil shape needs to be symmetric because a yacht may provide leeway towards its port-side or star-board side. The balance between the aerodynamics and the hydrodynamics forces is illustrated in figure 3.

For a yacht under an upwind (against windward) sailing condition it is important to have a minimum amount of leeway angle to generate the required hydrodynamic side force because the drag of the hull increases with higher leeway angle (van Oossanen & Joubert 1986). Therefore one of the most important keel design problems is to design a keel that generates the required side force with a minimum drag (or resistance). If the keel is able to generate sufficient side force over a small leeway angle, there will also be less flow separation around the aft part of the hull resulting in lower drag. A critical component in designing a keel is its aspect ratio, readers are invited to refer to reports by van Oossanen (1985) and van Oossanen & Joubert (1986) for further explanations about yacht keel aspect ratio. Regarding yacht keel's second role, i.e as a ballast to stabilise the hull against the heeling moment that is generated by the forces on the sails, it is critical to also consider the shape and weight of the keel. The ballast on a typical yacht generally accounts about 70% – 80% of the yacht's total weight (Letcher *et al.* 1987). Due to its second role as a ballast, a typical keel will dictate yacht's centre of gravity. Therefore, a lower centre of gravity will result in a more stable yacht.

At the beginning of 1980's many yacht designers believed that keel design has reached its optimum possible planform, particularly with respect to the general shape (trapezium-type with a sweep-back angle) and taper ratio with value of 0.3 to 0.4 (van Oossanen & Joubert 1986). Such keel set ups are known to have less drag than a keel with no sweep-back angle and generates less wave (lower wave resistance). Various experiments indeed have shown that a sweep-back angle keel is desirable, however the reason of such results were only well understood in 1981. Studies by the NLR indicated that the reason is because the centre of the side force on the sweep-back angle keel is located further away from the water surface (further than no sweep-back angle keel). Further analysis by the *Australia II* design team indicate that an inverse taper or 'pside-down' keel would produce an even better performance than a traditional sweep-back angled keel (van Oossanen 1985). Such set-up would push the centre of the side force even further away from the water surface, resulting in lower wave resistance than the sweep-back angled keel. The 'upside-down' keel also provide a much lower centre of gravity, improving the yacht's stability.

Despite the advantages of 'upside-down' keel, such shape would induce drag from the formation of vortex at the tip of the keel, particularly when the keel generates side force (when the yacht's leeway angle is non zero). According to Ulbrich (2003) such induced drag can be minimised by further increasing the keel's aspect ratio. Unfortunately, this method was not allowed due to the limit of maximum draft based on the 12-metre yacht competition rule. Hence the *Australia II*'s design team added a pair of winglets on the 'upside-down' keel, at both the port side and starboard side (see figure 1). The winglets themselves were based on the idea of Richard Whitcomb of NASA (The National Aeronautics and Space Administration) in 1974 (Whitcomb 1976). Further details about the design

(a)



(b)

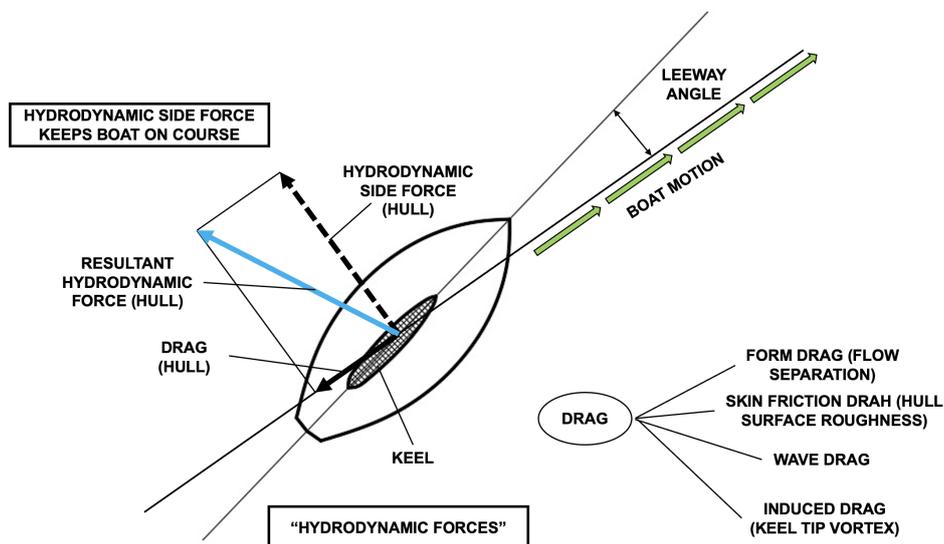


Figure 2. Aerodynamics and hydrodynamics forces acting on a Yacht when sailing upwind or against wind ward (image is redrawn from Ulbrich (2003))

and test process of the winglets on ‘upside-down’ keel (which later famously termed ‘winged keel’) can be found on the reports by van Oossanen (1985) and van Oossanen & Joubert (1986).

Since the famous victory of *Australia II* yacht in the 1983 America’s cup races there has not been many scientific reports that talk about the winged keel in detail. This is quite understandable as the 12 metre class was still competing in the America’s cup until late 1980’s and many research in the field were shrouded in secrecy to give yacht designer competitive edge. Despite the ending of 12 metre class usage in the America’s cup in the late 1980’s, this type of yacht is still compete in the 12 Metre World Championship. Therefore the authors believe that there are still venue to investigate the physics of 12 metre class yacht (particularly in term of winged keel). One avenue that is rarely visited or reported in literatures is the far field flow behind the keel. From the report by van Oossanen & Joubert (1986) it is known that the ‘Australia II’ winged keel generates strong vortices that can go at a relatively long distance downstream. Such vortices can disturb or influence other yachts behind

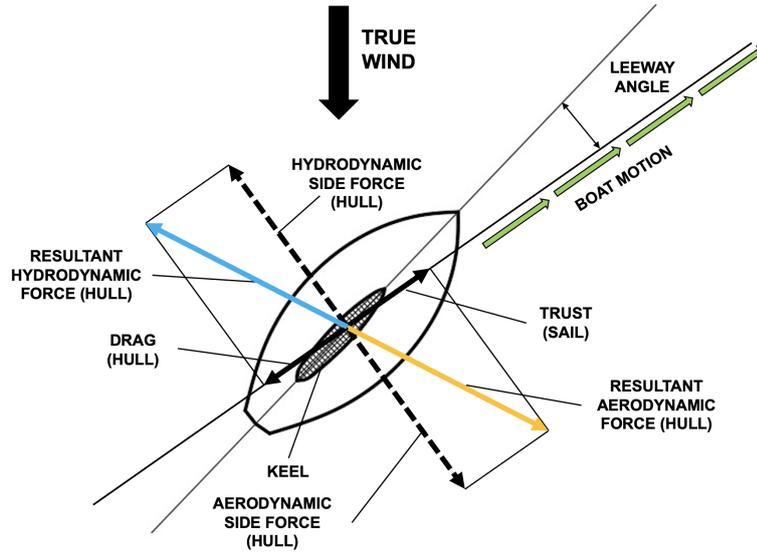


Figure 3. Balance between the aerodynamics and hydrodynamics forces (image is redrawn from Ulbrich (2003))

it. For yacht race where the differences in distance between yachts at the front and the back are often only in a mere metres, it is an important aspect to consider.

This report will revisit the original ‘winged keel’ design of *Australia II* by conducting a Reynolds-Averaged Navier Stokes (RANS) simulation. The simulation’s aim to see the turbulent far field flow of the ‘winged keel’ at various Reynolds number under 0° leeway and 0° heel (i.e the yacht direction is steady and the hull is straight) and when it is at leeway angle of 4° with heel angle of 20° (similar set ups as that of Oossanen & Joubert (1986) and akin to the actual sailing condition).

2 Methodology

In this study, we conducted Reynolds-Averaged Navier Stokes (RANS) numerical simulations of the actual *Australia II* yacht using the fluid dynamics solver OpenFOAM. The turbulence model used is the $k - \omega - SST$ model. A multiphase solver (*interFoam*) using a volume of fluid (VOF) approach, within OpenFOAM is used to simulate both air and water phases. Here, we define α as the volume fraction of water, whereby $\alpha = 1$ is 100% water and $\alpha = 0$ is 100% air. The computational domain size is $120 \text{ m} \times 200 \text{ m} \times 220 \text{ m}$ in the x, y and z direction respectively (the computational domain size and resolution are illustrated in figure 4). The inlet boundary condition is set at fixed velocity for both phases (depending on the case of interest) and the outlet boundary condition adjusts the velocity for each phase to maintain the required mass flow rate. The top, bottom and side boundaries are set to freestream condition. The boundary condition of the yacht is set as no-slip wall. The number of grid points is approximately 23.6 million after a grid independence analysis. This yields a resolution of $y^+ \approx 2.8$ (using the inbuilt OpenFOAM function). A wall-function is applied in the yacht near-wall region. Note that with the current numerical setup, the simulation is unable to resolve wave breaking and air entrainment. The length L_A of the Australia II is approximately 17 m (distance between the bow and stern). The water densities of air ρ_a and water ρ_w are 1 kg/m^3 and 998.8 kg/m^3 respectively. The viscosities of air ν_a and water ν_w are $1.48\text{e-}5 \text{ m}^2/\text{s}$ and $1.09\text{e-}6 \text{ m}^2/\text{s}$ respectively. Three freestream velocities $U_\infty \approx 2.1 \text{ m/s}$, 3.1 m/s and 4.25 m/s are simulated, resulting in Reynolds numbers of $Re_L = U_\infty L_A / \nu_w \approx 2.4 \times 10^6$, 3.5×10^6 and 4.9×10^6 respectively.

In this study we are looking at the far field flow of the ‘winged keel’ at various velocities (4, 6 and

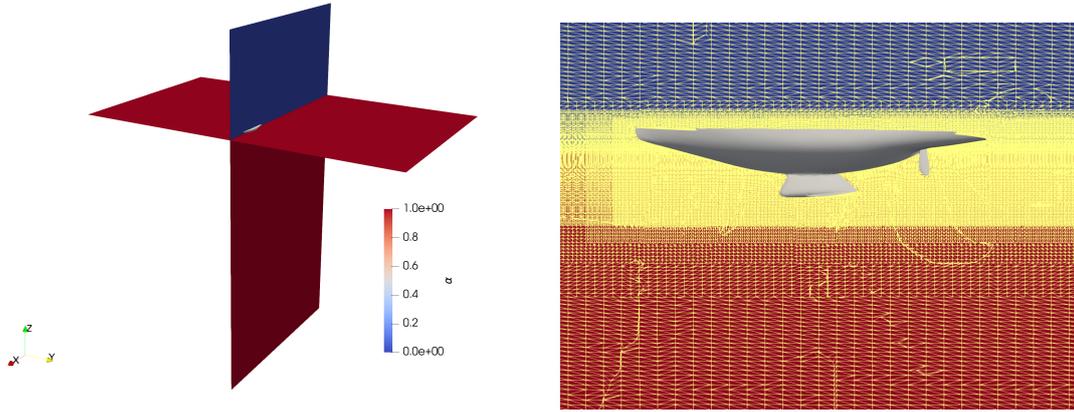


Figure 4. Left: computational domain size. Right: mesh resolution in the vicinity of the yacht.

Case	knots	U_x (m/s)	nautical miles per hour	Reynolds number ($\times 10^6$)	leeway($^\circ$)	heel($^\circ$)
C1	4	2.1	4.6	2.4	0	0
C2	6	3.1	6.9	3.5	0	0
C3	8.25	4.2	9.5	4.9	0	0
L3	8.25	4.2	9.5	4.9	4	20

Table 1. Summary of numerical parameters.

8.25 knots) under 0° leeway and 0° heel condition. At the highest velocity, we also vary the leeway and the heel angle to 4° and 20° respectively to simulate an actual sailing condition and to match the experiment of Oossanen & Joubert (1986). A summary of the computational parameters (including the velocity and its associated Reynolds number) are shown in table 1.

3 Results

3.1 Flow around ‘winged keel’ at 0° leeway and 0° heel condition at various velocities

In this section we set the yacht at a 0° leeway and 0° heel, or in other words the yacht is at a balanced situation (does not experience any rolling) and assumed to move with the wind exactly behind it (or against the wind). In a real yacht it is not possible for a yacht to move straight against the wind head on (at 0°) because the sail would not be able to provide lift. This set up is conducted to act as a baseline reference only. Figure 5 (left) shows the streamwise velocity from case C3 (at a velocity of 8.25 knots), the image indicates a long streak of slow speed flow emitted from the rear of the winged keel due to the wake formation. Note that the velocity U_x is negative due to the x -axis orientation used in the computational domain (see figure 4). Note that the reference position of $x = 0$ m is based on the meeting point between the ship bow and the water and air. The slow speed flow seems to persist over a long region (beyond 40 metres downstream of the keel). Such slow speed flow is generated by the winged keel’s trailing edge in the form of clockwise and anticlockwise vortices that were observed on the wind tunnel experiment by Oossanen & Joubert (1986). Figure 5 (right) shows the volume fraction of air and water. On average, there is no noticeable air entrainment from the atmosphere at the bow of the yacht nor in the wake region of the yacht.

The influence of keel on the far field flow behind the yacht are shown in figure 6 at various locations behind the yacht, namely -20 m, -40 m, -60 m and -80 m (see image 5 (left) for the location’s illustration). The various colours inside the plots indicate different velocities, black : 4 knots, blue : 6 knots, and red : 8.25 knots (case C1-C3). The plots indicate that for all velocities, the velocity profiles behave in a similar manner. At $x = -20$ m downstream of the yacht’s bow the flow behind the keel

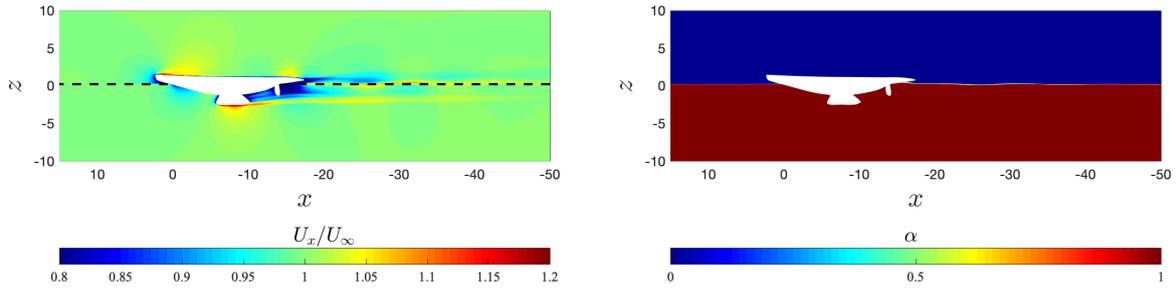


Figure 5. Left: Streamwise velocity for Case C3. Right: Volume fraction (α) of water for Case C3.

is still highly unstable. There is strong variation in the normalised mean velocity ($U/U_\infty \approx -0.9$ to ≈ 1.1) at the keel's depth that is caused by the vortices that arise from the winged keel's trailing edge. At $x = -40$ m downstream of the yacht's bow the flow's mean velocity variation starts to diminish significantly. Interestingly however, although the mean velocity variation diminishes, there are still artefacts of it even at $x = -80$ m downstream of the yacht's bow.

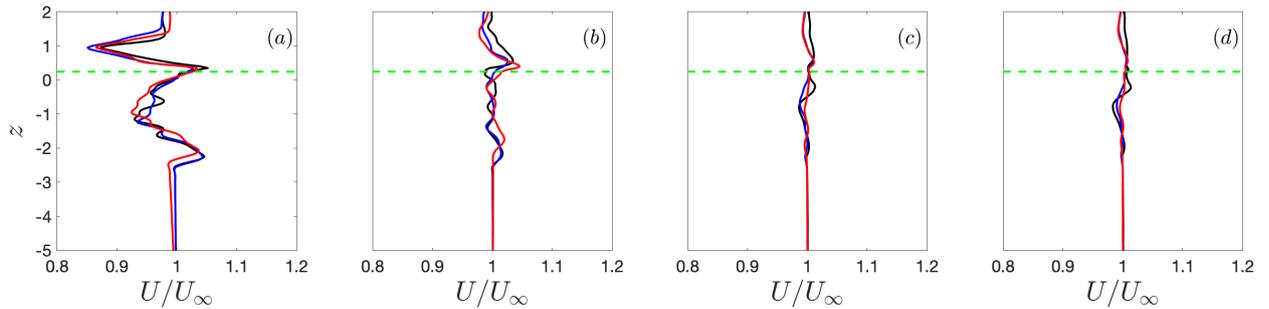


Figure 6. Streamwise velocity profiles at various downstream locations for all cases along $y = 0$. (a) $x = -20$ m, (b) $x = -40$ m, (c) $x = -60$ m and (d) $x = -80$ m. The black lines represent 4 knots, blue indicates 6 knots, and red is 8.25 knots.

Figure 7 shows the far field flow behind the yacht's keel from a different perspective, viewed from above at the depth of 2.4m below waterline. The coloured lines indicate different velocities, refer to the image for the velocity details. The streamwise velocity profiles for the 4 knots and 6 knots behave almost similar as each other, there is a strong high velocity ($U/U_\infty > 1$) at the centre of the keel (at $y = 0$ m) at the downstream location of 20m. For the 4 knots case the high speed flow at $y = 0$ seems to diminish as we go further downstream. For the 6 knots case, however, the high speed flow seems to persist even at $x = -80$ m downstream. Another interesting feature of the 4 knots and 6 knots cases is the twin slow speed flow at $y \approx \pm 1$ m, which may come from the end points of the winged keel (both at starboard and port side). The two slow speed peaks for the 4 knots and 6 knots can be observed even at $x = -80$ m downstream.

Although both of the 4 knots and 6 knots mean velocity profiles behave almost similar at $z = -2.4$ m, the 8.25 knots case have a different mean velocity pattern, particularly at the downstream location of $x = -20$ m and -40 m. At these two locations, the flow has a tendency to have a low speed pattern ($U/U_\infty < 1$) over a wide spanwise area. At the downstream location of $x = -20$ m the mean velocity at the keel's centre location (at $y = 0$ m) is slightly higher than the port side and the starboard side (at

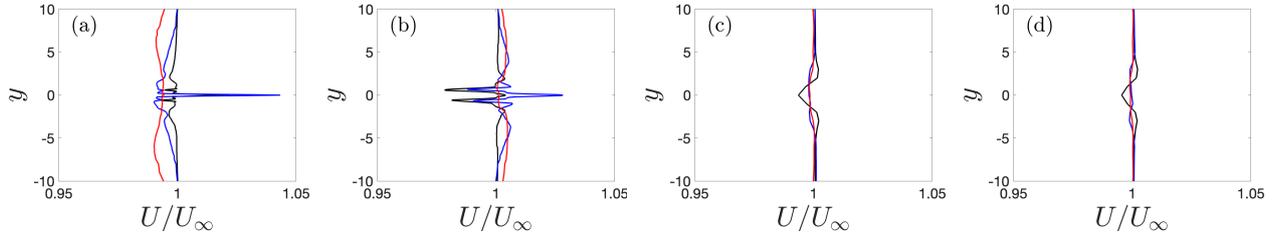


Figure 7. Streamwise velocity contours at 2.4m below waterline (or $z = -2.4\text{m}$) at different locations downstream for (a) $x = -20\text{ m}$, (b) $x = -40\text{ m}$, (c) $x = -60\text{ m}$ and (d) $x = -80\text{ m}$. The black lines represent 4 knots, blue indicates 6 knots, and red is 8.25 knots.

$y \approx \pm 7\text{ m}$). However, at the downstream location of $x = -40\text{ m}$ the situation is reversed, here the mean velocity at the keel's centre location is higher than the port side and the starboard side. Interestingly however, at the downstream location of $x = -60\text{ m}$ and -80 m , for the 8.25 knots case the streamwise velocity behave almost similar as the 4 knots and 6 knots cases. These conditions indicate that in a yacht race, when a winged keel yacht is leading at a velocity of $\approx 8.25\text{ knots}$, care must be taken by the other pursuing yachts because the wake from the winged keel yacht may influence them even when they are not directly behind it.

3.2 Comparison between ‘winged keel’ at 4° leeway and 20° heel, and the 0° leeway and 0° heel condition at a similar velocity

Figure 8 shows the general simulation comparison between the yacht at 4° leeway with 20° heel (L3), and the 0° leeway with 0° heel (C3) condition at a similar velocity. As previously mentioned, for the C3 case, the yacht does not experience any rolling and it moves straight against or with the wind. For the L3 case, one could see that the yacht body is rolled towards the starboard side (or $-y$ location) at 20° , hence there are more wetted area on the starboard side than the port side of the yacht. The flow behind the yacht is also not symmetric because of the 4° leeway towards the portside (or $+y$ location). This situation set up is close to what the yacht would experience in a real upwind sailing direction and based on the experiment of van Oossanen & Joubert (1986).

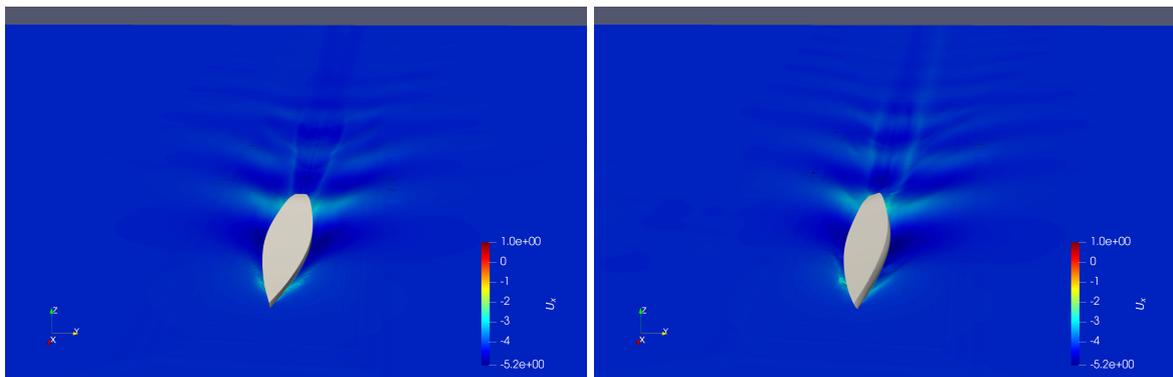


Figure 8. Left: Case C3. Right: Case L3.

Figure 9 shows the the far field flow behind the yacht's keel for the C3 (0° leeway and 0° heel) and L3 (4° leeway and 20° heel) cases viewed from above at the depth of 2.4m below waterline (both yachts are sailing at 8.25 knots). The mean velocity indicates that at $x = -20\text{ m}$ downstream, the L3 cases experience higher streamwise velocity than the C3 case between spanwise location of $y = -3\text{ m}$ to $y = 10\text{ m}$ (port side), the opposite situation happens at the spanwise location of $y = -3\text{ m}$ to $y = -10\text{ m}$ (starboard side). At -40 m downstream, the starboard ($y < 0\text{ m}$) side of the L3 case seems to be dominated by low speed streamwise velocity (much lower than the C3 case). At $x = -40\text{ m}$ and

-80 m downstream there are not much differences in the streamwise velocity in the spanwise locations for both C3 and L3 cases.

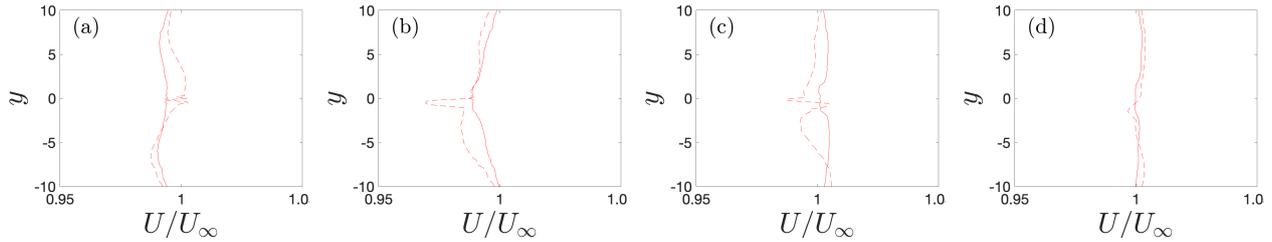


Figure 9. Streamwise velocity contours at 2.4m below waterline at different locations downstream for (a) $x = -20$ m, (b) $x = -40$ m, (c) $x = -60$ m and (d) $x = -80$ m. Red line represents case C3 and red dash line is for case L3.

4 Conclusions

Numerical simulations of the twelve metre class yacht *Australia II* that won the 1983 America's cup races was conducted to investigate the mean far field flow behind its winged keel. Two major cases were investigated, the first is at various Reynolds number under 0° leeway and 0° heel (cases C1–C3) and the second is when the yacht is at a leeway angle of 4° and a heel angle of 20° (case L3). For the first case, the results indicate that velocities at 4 knots and 6 knots behave in almost the same manner where there are velocity variations near and around the winged keel at water depth $z = -2.4$ m, however there are not much variations in the spanwise direction. For the second case we compare the yacht at 4° leeway with 20° heel (L3), and the 0° leeway with 0° heel (C3) condition at the same velocity. The results indicate that the L3 case causes the starboard side to experience lower velocity than the port side when it is compared to the C3 case at downstream distances of -20 m and -40 m. However, there are not much differences between C3 and L3 cases beyond the distance of -40 m downstream.

Acknowledgements

This work was supported with supercomputing resources provided by the Phoenix HPC service at the University of Adelaide.

References

- Letcher, J. S., Marshall, J. K., Oliver, J. C., & Salvesen, N. 1987. Stars & stripes, *Scientific American*, **257(2)** 34–41.
- Ulbrich, N. 2003. Australia II or Secrets of the Upside-Down Winged Keel Design, *41st Aerospace Sciences Meeting and Exhibit*, **39**.
- van Oossanen, P. 1985. The development of the 12 meter class yacht Australia II, *In SNAME 7th Chesapeake Sailing Yacht Symposium*, 81–101.
- van Oossanen, P. & Joubert, P. N. 1985. The development of the winged keel for twelve-metre yachts, *Journal of Fluid Mechanics*, **173** 55–71.
- Whitcomb, R. T. 1973. A design approach and selected wind tunnel results at high subsonic speeds for wing-tip mounted winglets, *NASA Tech. Note*, **D-88260**.