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Real time simulation of tacking yachts: how best to counter the advantage of an upwind yacht

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Abstract

In this paper we introduce a new wake model (NWM) for sailing yachts capable of representing the complex wake flow. We implemented the NWM into the yacht fleet race simulator \textit{Robo-Race} \cite{1,2} and examined the effect of significant improvements in capturing the wind environment of a covered yacht on its performance and tactics. Various position options were investigated for maximising or minimising damaging effect of the leading or following yacht and were presented two case studies comparing the individual yacht performances.

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1. Introduction

The traditional way of quantifying the performance of a sailing yacht is carried out by assessing how fast a yacht will complete a course under prescribed wind conditions. The \textit{Robo-Race} simulator, which allows both influence of the yacht design and tactical choices of the crew, has been developed to capture the behaviour of a fleet of yachts \cite{1,2}. It is designed to simulate fleet races with \(N\) yachts, where \(M\) yachts are controlled by the computer and \((N-M)\) yachts are controlled by real sailors. In these simulated regattas sailors can race against other yachts crewed by an Artificial Intelligence (AI) decision making engine that has been created using a combination of structured interviews and questionnaires designed to identify expertise level based response. Different models for the yacht-crew interaction have been designed and implemented for the helmsman and the sail tailors, as well as a ‘routing engine’ which solves problems of a strategic and a tactical nature, such as collision avoidance and navigation in wind shifts.

As a yacht cannot sail directly against the wind, it has to move a zigzag course when sailing an upwind leg. The corresponding manoeuvre is called \textit{tacking}. Thereby, the vessels bow goes through the wind whereby the wind direction seen by the sails changes from one side to the other. Various authors investigated the phenomenon of

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tacking by applying mathematical models for finding the optimal tacking procedure [3, 4]. The mathematical model of tacking motions proposed by Masuyama is implemented in Robo-Race.

As part of a fleet race simulation it is important to be able to capture the yachts’ manoeuvres correctly as well as the interactions between them. The upwind sailing performance of a yacht is influenced by the presence of another yacht when the downwind yacht sails in the wind shadow of the upwind yacht. The upwind yacht is said to ‘blanket’ or ‘cover’ the downwind yacht. The blanketing effect caused by the upwind yacht’s sails has an effect on the flow propagating downwind reducing its magnitude and altering its direction. These perturbations generated by the upwind yacht have a great effect on the flow propagating downstream and are therefore an important tactical tool, especially in downwind match racing. Hence, the tactical decisions of both, the upwind and downwind yachts are made by maximising blanketing or minimising its damaging effects [5]. Existing models, such as the one developed by Philpott et al. [6], represent an empirical approach to the phenomenon of blanketing.

A superior and robust covering and blanketing model, developed by Spenkuch et al. [7], is currently implemented in Robo-Race [1, 2]. This new wake model (NWM) suitable for yacht fleet race simulations is based on lifting line theory whereby the wake of an upwind sailing yacht is represented as a single heeled horseshoe vortex and image system. It is believed that the implementation of this new covering and blanketing model into Robo-Race yield an important step forward in terms of enhancing the simulator’s reality which in turn supports the natural behaviour of the sailor [7].

The aim of this work has been to develop an approach that enhances the realism of the wind environment of the covered yacht on its performance and its tactics. The developed algorithm [7] is classified as a Lifting Line Method and used in this study. Dynamic yacht fleet race simulations are carried out with Robo-Race and used to conduct various tacking manoeuvre options focusing on maximising or minimising the damaging effect for the leading or following yacht. A series of case studies comparing yacht performances against opponents with known/unknown race behaviour styles are conducted aiming for a ‘best’ tacking strategy.

2. The wake model

The first part of the NWM describes the flow field calculation using the lifting line theory. This section is giving a brief overview of the model whereas a more detailed description of the new wake model can be found in [7].

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. In addition, the lifting line model has superimposed a viscous wake model due to the drag associated with the yacht and its sails. A synthesis of sail yacht wake representations based on detailed 3D Reynolds Averaged Navier-Stokes (RANS) Computational Fluid Dynamics (CFD) calculations with wind tunnel test results were used to capture the initial strength of the combined main-jib vortex system and its vertical height (see Figure 2) [8, 9].

Fig. 1. Nomenclature used for the lifting line model describing the vortex system of a sailing yacht, the wake flow field is represented by a series of line element vortices. For reasons of clarity, just the upper part of the vortex system is displayed [7].

Fig. 2. Vortex core development by showing the vorticity contour on surfaces downstream of the sail rig (varying local surface range) [8].
The objective of the lifting line approach is in capturing the flow interactions between multiple yachts. It is proposed that the use of an appropriate series of vortex line elements with varying vortex strength Γ along the elements can improve the representation of the modification to the local wind strength and direction due to the presence of multiple yachts (see Figure 1).

The second part of the NWM describes the viscosity model. To represent the viscous effect of the flow passing the yacht, a plane and self-preserved wake depending on the freestream velocity \( U_0 \) and the shape of the circular obstacle is used. Tennekes introduced an approach combining the velocity deficit \( \Delta U_{Viscous} \) in a self-preserved viscous wake at any Point \( P(x_P, y_P) \), where \( \Theta \) describes the momentum thickness

\[
\Delta U_{Viscous} = -1.579 \left( \frac{\Theta}{x_P} \right)^{\frac{3}{2}} \exp \left[ -\ln 2 \left( \frac{y_P}{0.252 (x_P/\Theta)} \right)^{\frac{3}{2}} \right]
\]

By combining the lifting line model with the viscous wake yields the new wake model. Considering the physical flow features, the actual position of Point \( P \) in space has to be determined relative to the horseshoe vortex system which represents the yacht’s wake. The corresponding searching procedure determines whether the point is in the far-field or within the viscous affected vortex core zone stretched by the spheres around the vortex elements and the cylinder around them. In considering the whole horseshoe vortex and image system of \( M \) yachts with all nodes of each yacht shed of at \( m \) time steps the induced velocity \( \dot{Q} \) at a point located in the far-field is calculated by, where \( B=bottom, E=elements, H=horizontal, I=image, R=real, T=top, V=vertical \)

\[
\dot{Q} = \sum_{j=1}^{M} \left( \sum_{n=1}^{m} \dot{Q}_{RVE} + \sum_{n=1}^{m} \dot{Q}_{HEB} + \sum_{n=1}^{m} \dot{Q}_{HET} + \sum_{n=1}^{m} \dot{Q}_{RVE} \right)
\]

Equation (2) is also used to create the self-relaxing/dynamic moving wake by calculating the induced velocity \( \dot{Q}_{Vortex} \) of each individual vortex system node due to the nodes mutual influence and multiplying it with the time step \( \Delta t \). In addition, taking into account the induced velocity \( \dot{Q}_{Vachts} \) due to the presence of other yachts, the viscous effect of an upwind yacht, and the nodes displacement due to the local wind speed. Therefore, the total displacement \( \dot{D}_{N_i, total} \) of a wake’s node \( N_i \) at a time step is described by Equation 3. Consequently, the updated apparent wind velocity \( U_{AW} \) seen by a yacht at any point of the flow field can be expressed by using Equation 4.

\[
\Delta \dot{D}_{N_i, total} = \left( \dot{Q}_{Vortex} + \dot{Q}_{Vachts} + \dot{Q}_{Wind} \right) \Delta t \quad (3)
\]

\[
\dot{U}_{AW} = \dot{U}_{Viscous} + \dot{Q}_{Vachts} + \dot{Q}_{Vortex} + \dot{Q}_{Wind} \quad (4)
\]

3. The implementation

The interaction of yachts is an important tactical tool in regattas and particularly in match races such as the America’s Cup. Therefore, the yacht interaction model based on Philpott et al. [6] was replaced in Robo-Race by the lifting line approach as phenomenon of covering and blanketing has to be presented well in an advanced sailing simulator. Considering two yachts where the upwind yacht is sailing ahead of the downwind yacht. The upwind yacht creates a wake of disturbed turbulent flow affecting the incident flow of its opponent downstream. This interrelationship is expressed in the structure of Figure 3 showing the interaction of three yachts within a race. Furthermore, the principles of the data flow within Robo-Race are shown replicating the physical and practical features of yacht interaction.

Figure 3 describes an agent-block in Simulink® that controls the sailing yacht Yacht A in Robo-Race and the corresponding data flow. Considering Yacht A operating in a race with two opponents, Yacht B and Yacht C, the agent block needs Yacht A’s state (own state) and the aerodynamic values as an input to solve the differential equations within the block. Furthermore, the input Marks is needed for the navigator to aim towards it whereas a PID-controller controls the rudder angle and the sail settings [1]. For the wake calculation the state and the wake data of the opponents are needed as well as the weather conditions and the aerodynamic values. The disturbed flow is
considered as a function of the generated sail lift which is directly related to the vortex circulation, of the shed height, of the vortex decay rate within the wake, and of the relative position of the yachts to each other [7].

It can be seen that the block uses the state and wake information of the opponents and the weather data (Wind) as inputs so that the complex and dynamically changing sailing environment is described. The outputs correspond to the state and wake information of Yacht-A which is forwarded to the other yacht agents. A schematic diagram of how apparent wind angle (AWA), true wind angle (TWA), and true wind speed (TWS) are calculated within the agent-block is given in Figure 4.

Fig. 3. Vortex Principle of yacht interaction and data flow within Robo-Race for 3 yachts.

Fig. 4. Schematic Diagram showing the data flow starting at the dynamically changing wind environment dictating the acting forces which influences together with the opponents the NWM and hence the new updated wind conditions seen by the yacht.

4. Test cases

The effect of the position of a following yacht sitting behind the leading yacht on an upwind leg is investigated in this section. Therefore two upwind yacht fleet simulations with the new wake model (NWM) were conducted and two different wake plots were analysed.

Fig. 5. Wake flow, velocity deficit measured relative to the undisturbed wind flow seen by the yacht. The yacht sailed at an apparent wind speed of 7 m/s and was located at x=0, y=0.

Fig. 6. Wake flow, deflection angle [°] measured relative to the undisturbed wind flow seen by the yacht. The yacht sailed at an apparent wind speed of 7 m/s and was located at x=0, y=0.

Two ACC yachts (yacht length, YL = 24 m) race on an upwind leg where the following two sailing situations were considered. First, the following yacht, Yacht B, is sailed parallel to the leading yacht, Yacht A, which changes course and covered Yacht B which in turn reacts to the new situation. Second, the following yacht, Yacht B, sailed
parallel and in the wake of the leading yacht, Yacht A, which bore away putting Yacht B closer to its wake centre. This attack was not answered with a counter attack by Yacht B which remained in Yacht A’s wake. The wind speed was kept at a constant value of 3.93 m/s with wind direction from north to south. To demonstrate the improvement of the NWM, the tracks of the yachts on the course and important data influencing the yachts’ performance, such as true wind speed (TWS) components are displayed. The computer controlled yachts were run with a PID-controller on the sail settings and the rudder always aiming for an apparent wind angle of 22°.

Figure 5 and 6 show the wake contour of a sailing yacht sailing upwind at an apparent wind speed (AWS) of 7 m/s. The yacht is located at x=0, y=0. Figure 5 displays the loss in AWS downstream relative to the AWS seen by the yacht whereas Figure 6 shows the change in wind angle within the yacht’s wake. The shape of the affected flow area can be simplified as an acute triangle. The biggest changes in velocity deficit and flow angles occurred in the yacht’s close proximity where velocity drops of more than 60% and flow angle changes of more than 8° could be observed. Significant changes in the flow characteristic could be observed up to 6 YL downstream in longitudinal yacht direction whereas the affected cross section width was around one YL wide.

Within a match or a fleet race sailors try to avoid going into an opponent’s wake but often race situations force the sailor to do so. The contour plots of Figures 5 and 6 provide a helpful tool for sailors making a decision about the location where to sit behind a yacht and areas which should be strictly avoided. Using these contour plots, the described yacht races were set up and the effect of the position of a following yacht in the opponent’s wake on TWS and the resultant consequences are shown in Figures 7 to 10.
Figures 7 and 8 display the tracks of Yacht A and Yacht B on its upwind leg. The position of the two yachts at various times are shown whereas the Yacht A’s wake was added to illustrate the relative position of Yacht B to Yacht A’s wake. In Figure 7, Yacht A and Yacht B started inline where Yacht B was sailing in clear air behind Yacht A. After the start, Yacht A bore away and came up. This manoeuvre was answered by Yacht B which always tried to have clear wind in her sails by avoiding Yacht A’s wake. She succeeded as the distance between the yachts stayed almost the same. The clear wind of Yacht B can be seen in Figure 9 where almost no difference in TWS of the yachts can be determined after having answered Yacht A’s manoeuvre.

Another race situation occurred in Figure 8 where Yacht B started its race on the left side of Yacht A’s wake centre. By not answering Yacht A’s manoeuvre correctly Yacht B was forced to go through Yacht A’s wake which synonymous with a massive TWS loss (see Figure 10).

5. Conclusions

A robust covering and blanketing model for yacht fleet race simulations based on lifting line theory is presented in this paper. This new model is capable of representing a complex wake field of a yacht as a series of vortex elements and captures the main features of the flow to a sufficient level of fidelity. The lifting line elements move in accordance with the local wind, self-induced velocity and velocity induced by the presence of the wakes of other yachts. Furthermore the superposition of the lifting line model and a viscous wake model to calculate the velocity deficit yield important improvements compared to the previous implemented blanketing model of Philpott et al. By implementing this new covering and blanketing model into the sailing simulator Robo-Race, it is believed that an important step has been made to enhance the reality of the simulator which in turn supports the sailor in his/her natural sailing behaviour when controlling an ACC-yacht in Robo-Race. The detailed analysis of a yacht’s wake using contour plots offered the opportunity to determine yacht positions of the following yacht to counter the advantage of an upwind yacht. Two upwind race situations with two yachts were successfully conducted within a match race simulation using the yacht fleet race simulator Robo-Race. In future, sailing sessions with real sailors will be carried out to assess the improvements of Robo-Race in realism and performance through sailor’s feedback.

References