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Investigation of tacking strategies using an America's Cup 45 catamaran simulator

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Abstract

The recent America's Cup has demonstrated the extreme performance capability of the AC45 and AC72 catamarans. The high cost and risk of catastrophic failure has imposed restrictions on the availability of these boats for training. As a consequence the use of simulators to allow shore-based training becomes an attractive option. The aim of this study is to use a recently developed AC45 tacking simulator to investigate the optimum tack sequence by conducting a parametric study of user control inputs based on previously recorded time histories. The study will provide a better understanding of the influence of the input parameters on the tack and allow improved shore-based training programmes to be developed.

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Keywords: Sailing Simulator; America's Cup; Real-time Simulation; Dynamic VPP

1. Introduction

The current America's Cup class catamarans, the AC45 and AC72, have highlighted the performance these boats can deliver under the correct conditions, but also the disastrous consequences when things go wrong. Interestingly, the design feature which gives these boats their high performance, the wing sail, is also their main drawback. The cost and complexity of preparing one of these boats to sail limits the time the crew can practice. The fixed nature of the wing, which can be seen in Figure 1, means they have a limited operating range of wind speeds and the cost of the wing sail has made the teams cautious in their use.

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In order to compete at high levels, a catamaran needs to tack in the most efficient manner. Tacking is a manoeuvre needed in sailing that allows the boat to change direction and to be able to sail against the wind (in upwind condition). Such a manoeuvre involves changing the heading through the wind as demonstrated in Figure 2. During a tack, the catamaran loses a large part of its forward speed due to immersion of the flying hull and the associated increase in drag, the aerodynamic forces opposing its forward motion and low momentum due to lightweight construction.

Table 1: AC45 boat particulars, (Ac 45 Official Website (2013))

Boat Length (m)	13.4
Boat Maximum Breadth (m)	6.77
Mast Height (m)	20
Boat Mass (kg)	1500

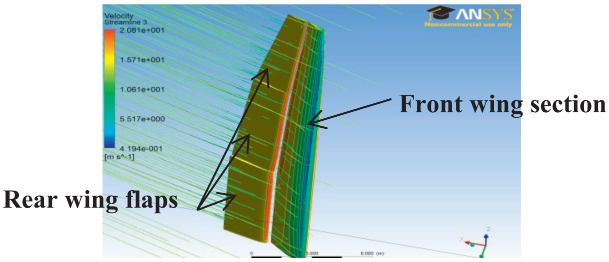

Figure 1: AC45 wing sail structure

The present project aims to investigate, through the use of a dynamic velocity prediction program (VPP), the possibilities of using a tacking simulator for training the helm and the main sheet trimmer. The focus was put on the smaller AC45 class boat as it has smaller crew and is a one-design class, thus making the simulator more versatile. Table 1 presents the catamaran main dimensions.

Sailing simulators have been used in previous applications for the analysis of tacking Masuyama et al. (1995), Verwerft and Keuning (2008), the starting manoeuvre Binns et al. (2008), match racing Roncin and Kobus (2004), handicap assessment Keuning et al. (2005), Philpott and Mason (2002), and evaluation of elite athletes Mooney et al. (2009). Most of the past work related to sailing simulators carried out at the University of Southampton has investigated the yacht-crew interaction and the possibility to improve the tactical steering and sail trim Scarponi et al. (2006), Spenkuch et al. (2008). The purpose of the current AC45 simulator has been to develop a hardware platform which would allow the helm and crew to practice a tacking manoeuvre under controlled conditions whilst providing detailed feedback on their performance Lidtke et al. (2013). This allowed a large number of time histories of tacks to be collected from both experienced and novice sailors. This paper presents the results of the analysis of this data, which was aimed at providing information as to what characterises an optimum tack of an AC catamaran and describing the important features of such a manoeuvre. Firstly, a brief description of the theoretical model used is given, which highlights the improvements made to the simulator since it was first presented. Methods of assessing the quality of a tack are then presented, followed by the outline of the approach undertaken to improve the baseline tack. The results are then presented and discussed.

Figure 2: Tack sequence of an AC45 showing the differences in heading and heel angle from the boat prior to tack (left figure), head to wind (centre) and when the boat fully recovered boat speed after the tack (right).

2. AC45 simulator

The current version of the simulator was developed during a Master of Engineering student project at the University of Southampton, as described in Lidtke et al. (2013). The equations of motions of a yacht are presented in Equations (1-4). These were first formulated by Masuyama et al. (1995), and define the relationship between the forces acting on the boat and its time response in surge, sway, roll and yaw. Numerical integration of these equations in time is performed using the 4th order Runge-Kutta method in order to yield the velocities and displacements.

Surge:
$$(m+m_x)\ddot{x} - (m+m_y\cos^2(\phi)+m_z\sin^2(\phi))\dot{y}\dot{\psi} = X_0 + X_H + X_{\dot{y}\dot{\psi}}\dot{y}\dot{\psi} + X_R + X_S \quad (1)$$

Sway:
$$(m+m_y\cos^2(\phi)+m_z\sin^2(\phi))\ddot{y} + (m+m_x)\dot{x}\dot{\phi} + 2(m_z-m_y)\sin(\phi)\cos(\phi)\dot{y}\dot{\phi} = Y_H + Y_{\dot{\phi}}\dot{\phi} + Y_{\dot{\psi}}\dot{\psi} + Y_R + Y_S \quad (2)$$

Roll:
$$(I_{xx}+J_{xx})\ddot{\phi} - [(I_{yy}+J_{yy})-(I_{zz}+J_{zz})]\sin(\phi)\cos(\phi)\dot{\psi}^2 = K_H + K_{\dot{\phi}}\dot{\phi} + K_R + K_S - mg\cdot GM\sin(\phi) \quad (3)$$

Yaw:
$$(I_{yy}+J_{xx})\sin^2(\phi)+(I_{zz}+J_{zz})\cos^2(\phi)\ddot{\psi} + 2[(I_{yy}+J_{yy})-(I_{zz}+J_{zz})]\sin(\phi)\cos(\phi)\dot{\psi} = N_H + N_{\dot{\psi}}\dot{\psi} + N_R + N_S \quad (4)$$

In the above, x, y, f and y denote boat displacements in the four degrees of freedom: surge, sway, roll and yaw, respectively, and the dot notation is used to express time derivatives; X and Y express forces acting on the boat along the longitudinal and transverse directions, respectively; K denotes the heeling moment and N the yawing moment about the centre of gravity; subscripts indicate the origin of the force: H for hull, R for rudder, S for sails and the coupling terms between the degrees of freedom; m is the mass of the boat, g is the acceleration due to gravity, GM is the metacentric height, I_{xx}, I_{yy} and I_{zz} are the moments of inertia in roll, pitch and yaw, respectively; m_x, m_y and m_z are the added masses in surge, sway and heave; J_{xx}, J_{yy} and J_{zz} denote the added moments of inertia about the principle axes of the boat.

The user interface with the simulator consists of a tiller to control the rudder angle; a sheet to control the wing sail angle; and a touchscreen for detailed control of the twist angle of the wing and settings for the jib and hydrofoils. The tiller and sheet controls use modified USB joysticks to interface with the computer. Figure 3 shows the simulator interface and two test participants tacking the AC45 catamaran. The entire framework is implemented in Matlab-Simulink® in order to provide a straightforward and seamless integration between the physical inputs, visual outputs and the numerical engine.

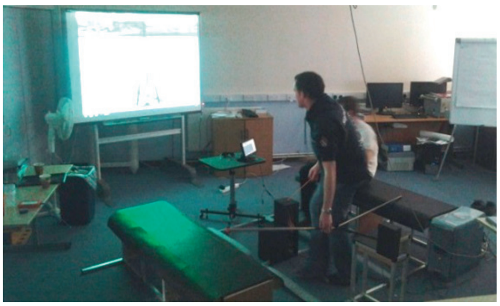
Figure 3: Simulator setup with the helmsman and crew executing a tack manoeuvre.

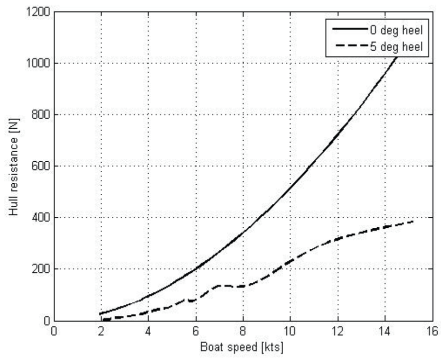

Figure 4: Hull resistance against boat speed for the upright condition (both hulls immersed) and 5 degree heel condition (1 hull immersed).

In order to solve the motion of the boat the forces acting on it, at any instance in time, need to be modelled accurately. This is done using a set of empirical relationships and regressed computational fluid dynamics (CFD) results. The adopted approach is based on a quasi-static analysis, thus neglecting the effects of unsteady fluid motion, but accounting for the velocities induced by the boat motions in the four degrees of freedom considered by Binns et al. (2002). One can immediately note by examining the governing equations that the rudder force and moment terms, denoted by subscript R, affect each degree of freedom (DoF). Equation (4), defining the yaw motion, is of key importance to the tack manoeuvre. It shows how the moment generated by the rudder (N_R) causes the boat to turn and how the other DoFs couple with the yaw motion, which emphasises the importance of capturing all the forces accurately to achieve a realistic motion simulation.

Several improvements have been made to the simulator since it was first developed and presented. Namely an improved hull resistance model was implemented, corrections to the rigid body and the added mass and the inertia were made, and more computationally-efficient Simulink code was developed. Figure 4 shows an example of the new hull resistance model and illustrates the resistance benefits of "flying" the windward hull. For instance, the drag may be reduced from 500 to 220 N at the speed of 10 knots.

3. Problem definition

Two critical issues are involved in the dynamics of a tacking sailboat: the speed loss as it goes head-to-wind and the time to complete the manoeuvre (in this case the time taken from initiating the tack until it has recovered at least 95% of its speed on the new course Verwerft and Keuning (2008)). From a helmsman's perspective, it is the latter that is of primary interest as during a race it is necessary to sail at the best Velocity Made Good (VMG), which allows the boat to always maintain the optimum speed with respect to the competitors. This is of utter importance in match racing (and therefore in an America's Cup regatta) as the speed of a tack influences the strategy choices taken against the challenger. Hence the helmsman needs to be able to tack in the most efficient way in different conditions. The speed recovery time will depend on the amount of speed lost during the tack, as this represents how much momentum has to be delivered back to the boat. The quality of a tack will therefore heavily rely on the rudder movements executed (i.e. the intensity of the motion and the angle at which it is set). It was therefore decided to investigate the influence of these parameters more closely.

The speed loss originates from several sources, such as increased windage drag in head-to-wind condition, rapid immersion of the windward hull and an associated hydrodynamic drag increase, and close to zero drive force from the sails. It is therefore beneficial to turn the boat around as fast as possible so as to minimise the period of time over which the sails are not producing any useful force. This does however impose a need for rapid and severe rudder motions, which will introduce additional drag to the system. More importantly, by putting the rudder "hard over" the helmsman risks stalling the rudder, which greatly increases the drag and reduces the performances of the rudder in terms of the ability to alter the course of the boat, all of which will make the boat less manoeuvrable Molland and Turnock (2007). This highlights the importance of achieving an appropriate balance in terms of handling the boat, with the optimum configuration being at the edge of the safe zone.

It was therefore decided to focus the investigation on exploring the optimum rudder action more closely. Past time histories from participants who took part in the initial training sessions were analysed and the best tack was selected as the baseline to be improved Lidtke et al. (2013). This data was compared with the telemetry from the America's Cup (AC45) boats, which provides wind speed and direction as well as boat position and speed over ground for each sailing venue, AC 45 Official Website 2013). The purpose of this study is to improve the best tack from the participant tests, looking at the rudder movements needed by the helm to achieve a tack as close as possible to that of a professional America's cup sailor. The rudder action record has three important features: the initial motion that turns the boat to windward, the significant counter motion just as the boat crosses the wind that takes away the rotational energy from the system, and a series of smaller motions that aim to stabilise the subsequent yacht course. As it may be argued that whatever happens after the boat has crossed the wind is a consequence of the first rudder movement. Its intensity, expressed as the rudder angle, and duration were chosen as the independent parameters of the study. A three-by-three matrix of rudder control parameters was then constructed around those of the baseline tack (Table 2). Simulations were then run using each set by first letting the boat sail steadily and allowing all transient forces to settle down. Then the tack was executed with prescribed initial rudder motion and appropriate secondary rudder movements so as to reach the desired boat heading at the end of the manoeuvre.

4. Presentation and discussion of the results

Figure 5 compares the resulting tacks, showing the improvements with respect to the baseline. The preeminent tack can be seen to be the one with input a rudder action of 7 seconds and the maximum intensity in the rudder movement (i.e. 25 degrees). Analysis showed that if the rudder was put over too much at too high a rate, the response of the boat was slower and speed loss greater compared with other cases. This is a known problem for novice sailors who often set the rudder at its maximum angle, which leads to stall and the boat getting stuck head to wind.

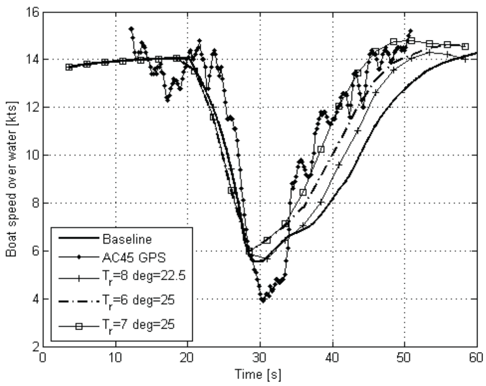

Figure 5: Speed comparison between the AC45 GPS tracking data and the best tacks with different rudder inputs.

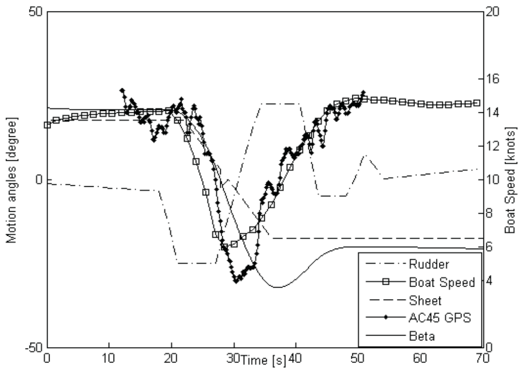

Figure 6: Boat motions for the tack with rudder action of 7 seconds and rudderangle of 25 degrees

It is important therefore, in order to perform a good tack, to balance the rudder angle and time needed to change its angle. In Figure 6 it is possible to see the boat motions and input data for the tack that more closely represents the motion performed by the AC45 professional athletes. One can clearly see the initial rudder action, the change of the boat heading towards the wind followed by a rapid speed loss with a flat minimum.

Table 2: Simulator input values to find the optimum tack.

Rudder Inputs	Rudder Action Duration (s)	Rudder Angle (deg)
1	6	20.0
2	7	22.5
3	8	25.0

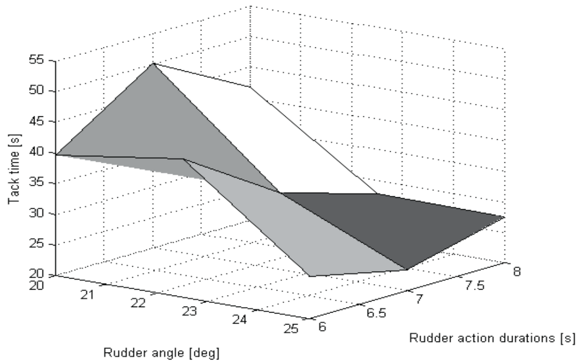

Figure 7: Speed recovery time as a function of rudder inputs.

The boat then slowly recovers its speed as the crew attempt to achieve the same apparent wind heading as the one the boat was following prior to the manoeuvre. It is clearly shown how the rudder input angle affects the boat apparent wind heading (*Beta*) and therefore the speed, which drops when the boat is head to wind (zero degrees). The heading is also influenced by the rudder counter action which balances the angle to be at 20 degrees when the boat sails straight.

The analysed input data were assessed in a three dimensional plot, shown in Figure 7. This figure shows the time needed to recover 95% of the speed prior to the first rudder movement. It is clearly seen how the shortest time is achieved with rudder action duration of 7 seconds and the maximum rudder input, as previously stated. With the findings of this research it will be possible to develop training materials which will show to the crew the virtual environment of the course that the boat needs to follow in order to complete a tack in the most efficient manner. This will allow the users to train in a systematic way so as to improve their techniques and their boat speed.

5. Conclusion

It has been discovered that all of the best recorded time histories obtained during simulated training sessions were characterised by very similar features. This has led to the conclusion that, despite its complexity and multiple non-linearities, the tack manoeuvre of an AC45 boat has a relatively well defined optimum in terms of rudder and sheet action. The systematic variation of the baseline tack has clearly shown that the helmsman is forced to push the boat to the regions were the risk of stall is increasingly more prominent in order to achieve optimum performance.

This further confirms the potential of the use of sailing simulation for crew training and indicates an interesting path for future research. Overall, the approach undertaken could easily be applied to a set of telemetry data obtained for a particular team over a range of sailing conditions. This could provide a set of benchmark manoeuvres and guidelines which could be used to increase their tacking performance and indicate the areas where further improvement is required. It is believed that the simulator may be particularly useful to the Youth America's Cup teams as they have a limited number of days of training in the boats and relatively less experience with the AC boats than the professional sailors. The combination of the two factors implies that their training on shore with the use of a simulator could significantly reduce the risks the crew are exposed to and increase their performance.

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References

AC 45 Official Website. http://www.americascup.com/about/boats Accessed [28/03/2013]

Binns, J. R., Bethwaite, F. and Saunders, N., 2002. Development of More Realsitic Sailing Simulator, in International Conference on High Performance Yacht Design.

Binns, J. R., Hochkirch, K., De Bord, F. and Burns, I. A., 2008. The Development and Use of Sailing Simulation for Iacc Starting Manoeuvre Training, in 3rd High Performance Yacht Design Conference.

Keuning, J. A., Vermeulen, K. J. and de Ridder, E. J., 2005. A Generic Mathematical Model for the Maneuvering and Tacking of a Sailing Yacht, in The 17th Chesapeake Sailing Yacht Symposium.

Lidtke, A. K., Marimon Giovannetti, L., Breschan, L. M., Sampson, A., Vitti, M. and Taunton, D. J., 2013. Development of an America's Cup 45 Tacking Simulator, in The Third International Conference on Innovation in High Performance Sailing Yachts (INNOV'SAIL).

Lidtke, A. K., Marimon Giovannetti, L., Breshan, L., Sampson, A., Vitti, M. and Taunton, D. J., 2013. Development of an America's Cup 45 Tacking Simulator, in INNOV'SAIL 3rd Internation Conference on Innovation in High Performance Sailing Yachts.

Masuyama, Y., Fukasawa, T. and Sasagawa, H., 1995. Tacking Simulation of Sailing Yachts–Numerical Integration of Equations of Motion and Application of Neural Network Technique, in The 12th Chesapeake Sailing Yacht Symposium.

Molland, A. F. and Turnock, S. R., 2007. Marine Rudders and Control Surfaces : Principles, Data, Design and Applications. Elsevier/Butterworth-Heinemann, Amsterdam ; London

Mooney, J., Saunders, N., Habgood, M. and Binns, J. R., 2009. Multiple Applications of Sailing Simulation, in SimTecT.

Philpott, A. and Mason, A., 2002. Advances in Optimization in Yacht Performance Analysis, in The 1st High Performance Yacht Design Conference.

Roncin, K. and Kobus, J.-M., 2004. Dynamic Simulation of Two Sailing Boats in Match Racing, in Sports Engineering.

Scarponi, M., Shenoi, R., Turnock, S. and Conti, P., 2006. Interactions between Yacht-Crew Systems and Racing Scenarios Combining Behavioral Models with Vpps, in 19th International HISWA Symposium on Yacht Design and Yacht Construction

Verwerft, B. and Keuning, J. A., 2008. The Modification and Application of a Time Dependent Performance Prediction Model on the Dynamic Behaviour of a Sailing Yacht, in Proceeding of the 20th international hiswa symposium on yacht design and yacht construction.