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ScienceDirect
Procedia Engineering 2 (2010) 2511–2516
Procedia Engineering
www.elsevier.com/locate/procedia

8th Conference of the International Sports Engineering Association (ISEA)

Measurement of dynamic forces experienced by an asymmetric yacht during a gybe, for use within sail simulation software

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Received 31 January 2010; revised 7 March 2010; accepted 21 March 2010

Abstract

Assessing the relative performance and appropriate race tactics of competitive yacht designs led to the development of a fleet sail racing simulation tool - Robo-Race [1,2,3]. Dynamic wind tunnel tests of a scale model asymmetric spinnaker passing through a constant wind speed to determine heel and drive forces have been carried out. The results of this have been used to propose a new model that significantly improves the physical fidelity of the gybe manoeuvre within Robo-Race.

Gybe; Sailing Manoeuvres; Sail Simulation; Wind tunnel testing; Sail Dynamics; Robo-Race

1. Introduction

One of the key benefits of using sail simulation software for yacht performance prediction is that manoeuvres, such as tacks and gybes, are included in the analysis. This allows the performance of the boat to be assessed in terms of straight line speed and manoeuvrability. 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 Robo-Race simulator, previously developed within the department [1,2,3], allows both influence of the yacht design and tactical choices of the crew to model the behaviour of a fleet of yachts. It is designed to simulate fleet races with N yachts, where M yachts are controlled by the computer and N-M yachts controlled by a real sailor. In these simulated regattas sailors can race against other yachts crewed by an Artificial Intelligence decision making engine. This 'Navigator/Skipper' has been created using a combination of structured interviews and questionnaires designed to identify expertise level based on response. Different models for the yacht-crew interaction have been designed and implemented for the helmsman and the sail trimmers, 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.

Current aerodynamic force models for tacks and gybes are based on quasi static approximations of the lift and drag coefficients obtained from static wind tunnel testing. This sail force data is usually obtained at model scale by

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doi:10.1016/j.proeng.2010.04.024

trimming the sails to provide the maximum drive force for a given apparent wind angle (AWA), and therefore does not take account of the trimming style and sail dynamics involved in a manoeuvre. In order to obtain realistic tacking data, further static wind tunnel test have been conducted for yachts at very low apparent wind angles [4]. This research included investigations into the sheeting technique of backing the headsail or letting it flog. This data can give a good approximation of tacking forces due to the gradual way in which the sails are depowered and loaded up again. However, when a yacht with an asymmetric spinnaker gybes, both the mainsail and the spinnaker collapse as they change side and refill suddenly. As the current quasi static approximation assumes the sails remain filled and optimally trimmed throughout the gybe, the actual dynamic manoeuvre is likely to produce a significantly different force trace. There appears to be no publically available experimental force data available from a yacht gybe with which to improve the aerodynamic force model. The aim of this work was to carry out such tests and then apply the results to develop an improved aerodynamic model within the Robo-Race simulator. The experimental work was carried out as part of a student group design project within the Ship Science degree programme in Yacht and Small Craft.

2. Components of a gybe manoeuvre

A gybe manoeuvre is a sailing vessel changing tack by turning the stern of the yacht through the eye of the wind. The key stages of this procedure for an asymmetric yacht can be seen in Figure 1 and are described below:

1. The yacht starts off sailing on a broad reach (in this case on port tack) with both the mainsail and the spinnaker trimmed to provide maximum drive force.
2. As the boat bears away into the manoeuvre the spinnaker is eased out on the starboard side and sheeted in slightly on the port side. At the same time the mainsail is sheeted right in.
3. As the boat heads straight downwind the mainsail is gybed across the boat and eased out. The spinnaker starts to invert as it is sheeted in on the port side.
4. The spinnaker is over sheeted to encourage it to fill as the yacht starts to head back up onto the starboard tack.
5. The sails are adjusted to provide maximum drive force as the yacht returns to a broad reach.

Varying the wind tunnel speed throughout an experiment is not possible, therefore a range of apparent wind angles over which the AWS remains relatively constant needed to be determined. Using data from a Velocity Prediction Program WinDesign [5] for a 90ft asymmetric yacht it was determined that AWA's greater than 130 degrees matched this criteria, providing a 100 degree AWA range that could be modelled in a wind tunnel. It was considered that this was sufficient to capture the 'dynamic' component of the gybe, where the sails are not necessarily trimmed to provide maximum drive force but are adjusted due to gybing technique.

3. Experimental procedure

Model scale tests of a 90ft America's Cup Yacht, were conducted within the low-speed section of The University of Southampton's 7x5 wind tunnel. A scale factor of 21.1 was used providing a down wind sail area of 2.4 m^2, approximately 16% of the wind tunnel cross-sectional area. This produces forces of a suitable magnitude to be accurately measured whilst still allowing blockage corrections to be applied. The dynamometer and acquisition software was set up and calibrated in the same manner as for static sail testing described in detail in [6].

To accurately model the sail dynamics it was important to keep the same wind speed to sail cloth weight ratio as the full scale yacht. As it is impractical to scale the sail material, both full scale sail cloth and apparent wind speed were used. This differs from standard static testing procedure where the wind tunnel speed is often increased above the model scale AWS to provide suitable force magnitudes. It was therefore decided to use an AWS of 3.2 ms^{-1}, which corresponds to a true wind speed (TWS) of 20 knots, so as to maximize the measured forces.

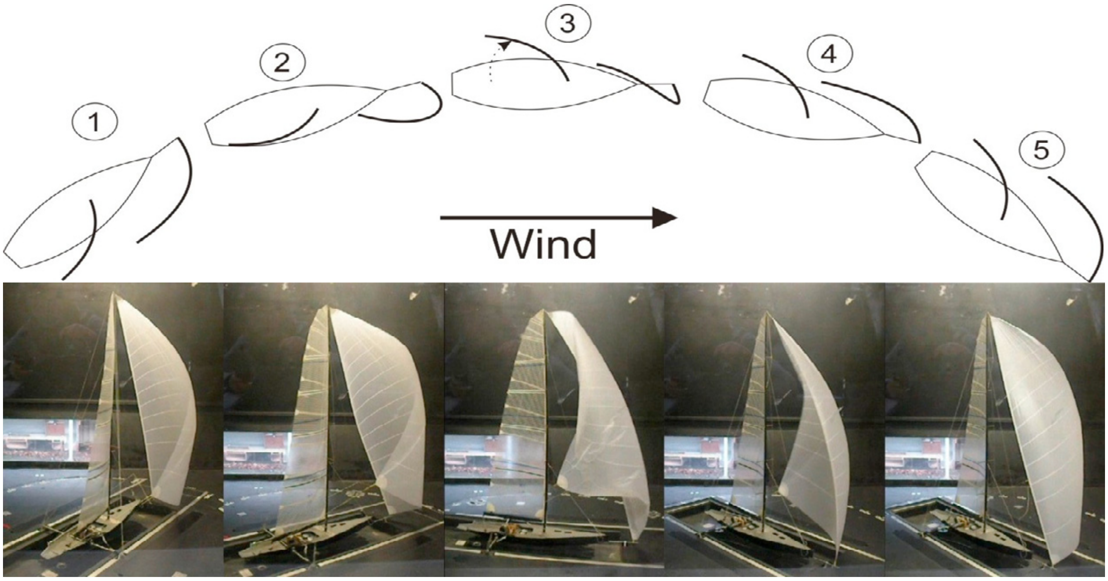

Figure 1 - Stages of an asymmetric yacht gybe (above), pictures of the corresponding stages of model scale yacht gybe performed in the wind tunnel (below).

Due to the high downwind boat speeds of large asymmetric yachts, the optimum velocity made good (VMG) is achieved at unusually small apparent wind angles (AWA). This means that the bearing away and heading up phases of the gybe are increased in length and the sails remain optimally trimmed for much of this process. Another implication for fast asymmetric yachts is that the apparent wind speed (AWS) changes significantly throughout the gybe as the vessel travels directly away from the wind. To simplify the experiment the mainsail remained fixed, in a sheeted in position, whilst the spinnaker was manually adjusted to accurately model the trimming technique used while racing. During each gybe the turntable was rotated at a constant rate while the drive force (Df), heel force (Hf) and AWA were recorded with respect to time. A series of photographs showing this experimental procedure can be seen in Figure 1. Multiple tests of the gybe manoeuvre were conducted to achieve a smooth and repeatable experiment.

4. Results

The individual drive and heel force traces obtained from six separate gybes can be seen in Figure 2. The mean values obtained from these six sets of data are also displayed, along with the three dynamic stages of the gybe. One of the most striking differences between these results and similar static wind tunnel test data is the relative magnitude of the heel force compared to the drive force. When sailing at large AWA the heel force is usually small compared to the drive force, due to the sails being eased out in their optimally trimmed position. In a real gybe the mainsail starts off eased out, it is then sheeted in to encourage it to gybe and then eased back out again. However in this experiment the mainsail remained sheeted in at all times. Over sheeting the mainsail increases the heel force generated, meaning that much larger heel forces were generated at the beginning and end of the gybe than would be expected in reality. To eliminate this issue the mainsail would have to be actively controlled, to replicate how it would be trimmed in practice.

As the yacht bears away and the spinnaker is eased out (stage 2), the drive force is initially maintained due to the sail still being correctly trimmed for the AWA. As the spinnaker is eased out further the drive force gradually decreases until the sail collapses. The heel force is predominantly generated by the over sheeted main sail and therefore reduces linearly as the yacht turns, bringing the sail more in line with the wind. In stage 3 it can be seen that the spinnaker remains collapsed but continues to flap as it is brought round the forestay causing the unsteady fluctuations in the individual drive force plots. The mainsail does not gybe until an AWA of approximately 195 deg, indicated by the heel force becoming negative. Again this differs from a real gybe where the crew usually force the mainsail across when the AWA is approximately 180 degrees. In stage 4 the spinnaker suddenly fills again on the new tack, causing the drive force to rapidly increase, meanwhile the heel force linearly increases in the opposite direction as the mainsail is turned into the wind.

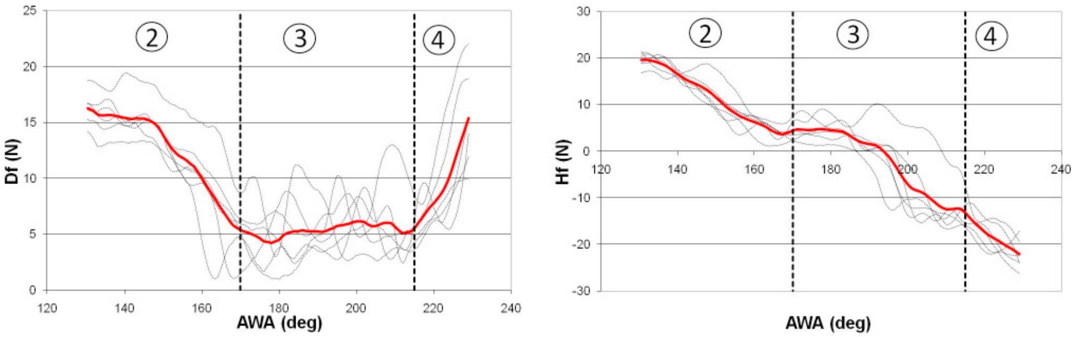

Figure 2 – Variation of Drive and Heel force (Df and Hf) throughout a gybe, with individual runs represented as dotted lines and their average as a solid red line.

The direct force traces provide a useful insight into how the forces vary throughout a gybe. To allow this data to be compared with static results blockage corrections need to be applied. Initially the raw force data Df and Hf was transformed and non-dimensionalised into lift and drag coefficients (C_L and C_D), using the AWS and the model sail area. Then a standard Maskell wake blockage correction was applied to take account of the increase in force magnitude due to the tunnel constraining the flow. This correction process is described in detail in [7]. Finally the lift and drag coefficients were converted back to drive and heel force coefficients (Cx and Cy) to allow easy comparison with Robo-Race. This converted data can be seen in Figure 3.

5. Implementation in Robo-Race

The Robo-Race tool is written using Matlab-Simulink®. At each time step (typically 0.1 sec) the force generated by each sail is evaluated based on the AWS, AWA and tabulated force coefficients. In order to enable it to perform a dynamic gybe, it was necessary to compare the coefficient data measured in the wind tunnel to the existing quasi-static data in Robo-Race. Figure 3 displays the drive and heel force coefficients over the apparent wind angle of a gybe. Although their magnitudes, at the beginning and end of the gybe vary this is primarily because in the experiment the over trimmed mainsail does not produce the additional drive force usually found but increased heel force instead. It was concluded that the variation in experimental drive force was mainly due to the spinnaker alone. It is believed that the real life dynamic heel force would be more closely represented by the quasi static approximation currently used in Robo-Race. As a result only the drive force data for an Asymmetric spinnaker was modified in Robo-Race to represent the trends measured in the wind tunnel.

To modify the data in Robo-Race a relationship had to be developed to represent the experimental data. The wind tunnel data was normalised to match the Robo-Race data at the beginning of the gybe. The ratio between the drive force of the normalised wind tunnel data and the quasi static data used in Robo-Race was then calculated. This ratio was then used by Robo-Race as a thrust correction factor to modify the calculation of drive force, to match the trends determined from wind tunnel testing. By incorporating this, Robo-Race could determine the dynamic drive force experienced when gybing for apparent wind angles within the range 130 to 230 degrees. The Thrust Factor is set to 1 when not gybing, when outside this apparent wind angle range or when a gybe has not been initiated or is complete.

To see what impact this modification had on a yacht within Robo-Race, a simulation of a yacht gybing with just an asymmetric spinnaker was completed both with and without the Thrust Correction Factor. Figure 4 compares the aerodynamic drive force generated in both cases with experimental data. It can clearly be seen that the drive force calculated with a Thrust Correction Factor agrees much more closely with the wind tunnel data. However it should be noted that unlike the experimental testing the apparent wind speed (AWS) in Robo-Race varies throughout the gybe. This is the reason why the drive force increases coming out of the gybe, where the AWS has increased due to the vessel slowing down.

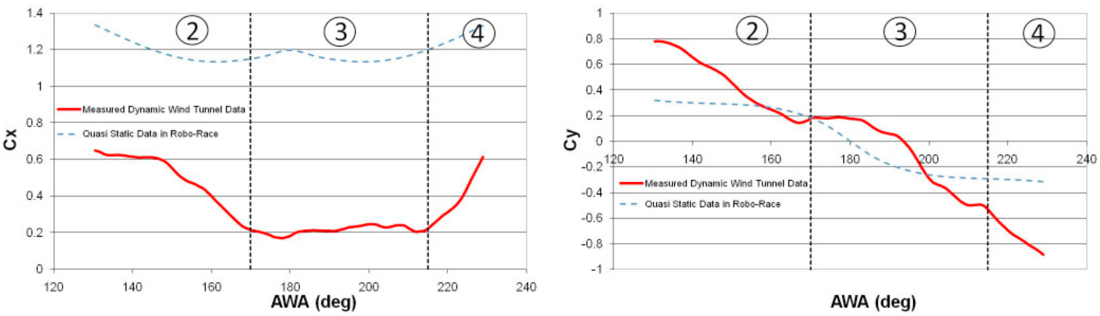

Figure 3- Non-dimensional drive and heel force coefficients (Cx and Cy) for the wind tunnel data, with wake blockage corrections applied, and the quasi static force coefficients used by Robo-Race.

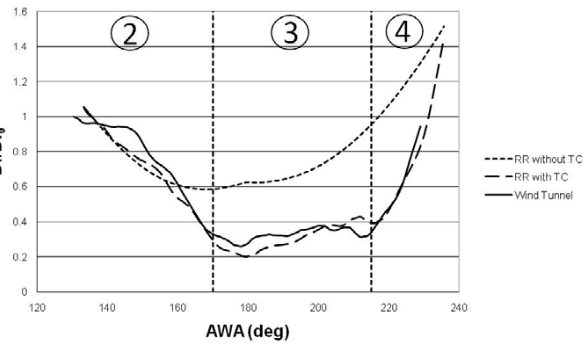

Figure 4 – Drive force Df, non-dimensionalsised by the initial drive force Df_0 at 130 AWA, recorded from a Robo-Race simulation with and without the Thrust Correction (TC) applied, plotted alongside the corrected wind tunnel data.

In Figure 5 the impact of this reduction in drive force on the vessels speed, and hence position, can clearly be seen. As you would expect the momentum of the yacht ensures there is little difference going into the gybe between the two simulations. This momentum also delays the point where the minimum surge speed occurs until the yacht has almost completed the manoeuvre. The use of the thrust correction factor results in a loss of ground of approximately 5m after 40 seconds.

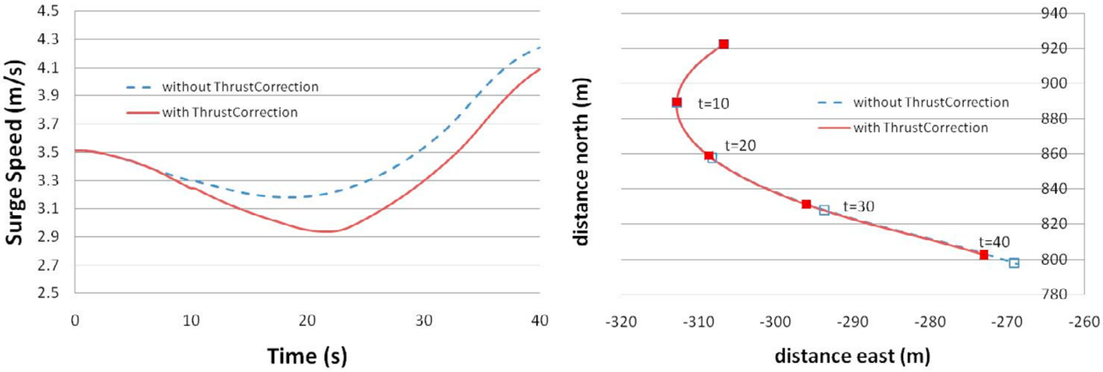

Figure 5 - The impact of Thrust Correction on vessel surge speed, and track, with respect to time (t) in seconds. The simulation was performed in a northerly wind of 5 m/s.

6. Conclusion

Multiple gybes of an asymmetric yacht have been successfully completed in a wind tunnel, providing repeatable dynamic force data. This identifies significant differences in the forces assumed by the quasi-static approximation, mainly the large reduction and steep increase of drive force when the asymmetric spinnaker gybes. Due to unrealistic mainsail trimming a larger heel force was measured compared to that expected in a real gybe situation. It is believed the quasi static heel force data provides a better representation of a real life gybe.

A relationship was developed to modify the existing quasi static drive force data in Robo-Race. This relationship was applied as a thrust correction factor to account for the dynamic effects when simulating a gybe. This resulted in the dynamic drive force recorded in Robo-Race to follow the trends determined from the experimental data. The impact of the dynamic force model was identified as a reduction of boat speed throughout the gybe. With regard to the wind tunnel test procedure future tests will aim to allow the mainsail to be gybed realistically in the wind tunnel.

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