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WIND TUNNEL AND CFD MODELLING OF PRESSURES ON DOWNWIND SAILS

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1 INTRODUCTION

In order to gain further understanding of the flows around downwind sails, pressure tapped spinnaker and mainsail models have been tested in the University of Auckland Twisted Flow Wind Tunnel. The sails are constructed from two thin fibreglass layers with the pressure tubes passing between these two layers and exiting from the foot of each sail as shown in Fig. (1) below. Complimentary computational modelling has also been carried out using the Fluent CFD code. This work is an extension of work previously carried out by the authors [1].

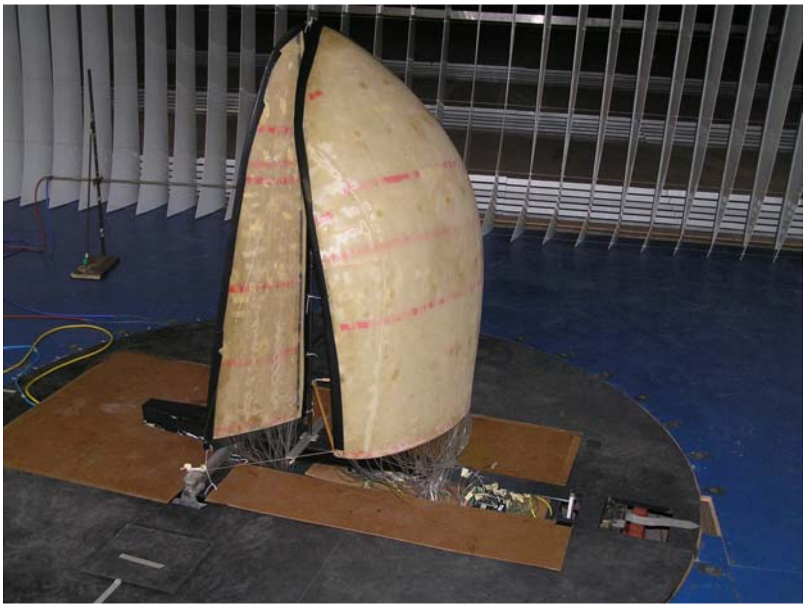

Figure 1: The wind-tunnel model

2 EXPERIMENTAL AND CFD METHODS

$1/25^{th}$ scale models of generic IACC main and symmetric spinnaker sails have been modelled in the wind tunnel by constructing these from two thin fibreglass layers. The spinnaker had 48 pressure taps on each surface and the mainsail 30 taps on each surface, which were arranged as seven rows of taps across each sail, as illustrated in Fig. (3). The target velocity and twist profiles were based on an IACC yacht sailing at a true wind angle of 160° at a speed of 10.5 kts (5.25 m/s) in a true wind of 14 kts (7 m/s) at a reference height of 10m, which corresponds to a reference apparent wind angle of 120°. A true roughness length of 0.25 mm was estimated to be appropriate for these conditions. The relative position of the sails was monitored by measuring the angle of the boom (along the foot of the mainsail) and the spinnaker pole (from the mast to the windward lower corner of the spinnaker) to the hull centreline. In order to support the fibreglass sails two spinnaker poles were used but the angle to the windward pole was monitored since this is the only one that would exist with a cloth sail. In addition to the pressure measurements, the total forces on the model was measured by a six component force balance located below the floor of the tunnel. Separate windage measurements were made on the model hull and rig, without any sails, and deducted from the total forces. Force estimates for each individual sail were calculated by assigning a contributory area vector to each tap and then summing the components. The total force obtained by pressure integration was compared to the balance total force, less windage.

The computational modelling made use of the Fluent CFD code in a manner very similar to that described in Ref. [1]. The Realizable k-ε turbulence model was used. The boundary conditions were set to give a twisted velocity profile, similar to that in the Twisted Flow Wind Tunnel.

3 RESULTS AND DISCUSSION

Fig. (2) shows the effect of varying the boom angle when the spinnaker pole is at 40° and the reference apparent wind direction is 120°. Also shown in Fig. (2) are the total forces measured by the force balance (dotted lines). It can be observed that the forces estimated by pressure integration are similar to the directly measured forces and that both sets show similar trends as the boom angle is varied. The slight differences are due to a variety of errors.

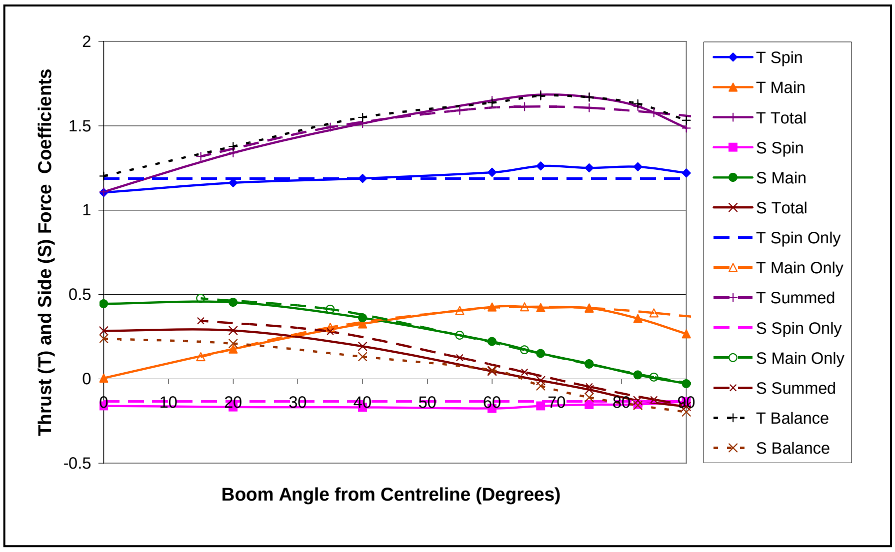

Figure 2: The effects of varying boom angle when the spinnaker pole is at 40° and the apparent wind angle 120°. Thrust and side forces on each sail as calculated by pressure integration from tests with the two sails together (solid lines) and independently (dashed lines). Also shown are the balance measured total forces (dotted lines).

Both sets of results show that the total thrust force is maximized when the boom angle is about 65°-75° and that the total side force at this point is small. The individual sail forces show that the spinnaker provides about 75% of the thrust force, but it is the drop off of the thrust force provided by the mainsail at angles above 75° that clearly affects the overall maximum. Fig. (3) shows the measured pressures on both sails at three boom angles. While the pressure distributions are similar at boom angles of 60° and 75°, there is a clear difference at 90° where the suction pressures on the leeward side of the mainsail are significantly reduced. This is caused by the mainsail getting close to the spinnaker and hence the positive pressures on the windward side of the spinnaker affects the suction pressures on the mainsail.

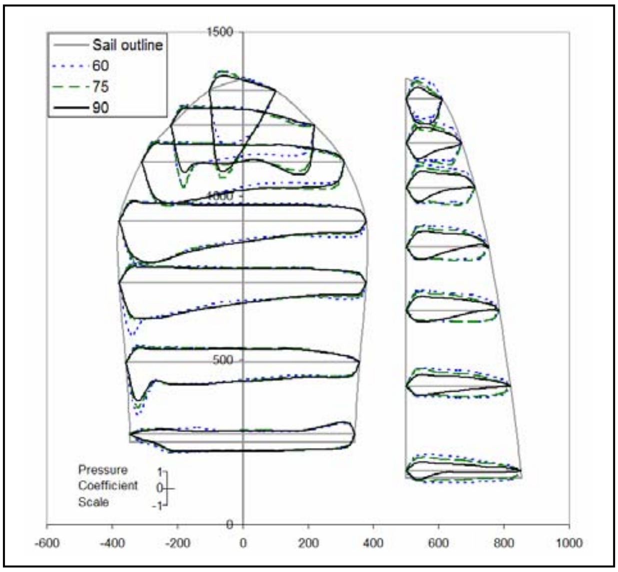

Figure 3: Pressures on the mainsail and spinnaker for three boom angles (60, 75 and 90°). The spinnaker pole was at 40° and the apparent wind angle 120°.

Also included in Fig. (2) are the forces obtained by pressure integration from test series where each of the sails was tested on its own (dashed lines). These forces have also been combined to give a summed total force which shows what force might be obtained if there was no sail interaction. The results show that for boom angles less than 75° the forces on the mainsail are not significantly modified by the presence of the spinnaker but at higher angles the thrust force is reduced as discussed above. However it does appear that the mainsail influences the spinnaker pressures over a broader range of angles, with the thrust force from the spinnaker increased by the presence of the mainsail for all boom angles greater than 40°. As a result the maximum thrust force for the two sails together is greater than the sum of the thrust forces the two individual sail could generate on their own.

Fig. (4) and (5) shows the results from a series of tests where the boom was at 75° and the spinnaker pole angle varied. These show that the highest thrust force is obtained with the pole angle around 40°. At lower pole angles the proximity of the spinnaker reduces the suction on the leeward side of the main and the suction on the leeward side of the spinnaker become very uniform, which indicates that the flow is separated. On the other hand with the pole further aft, higher angles, the pressures near the windward leading edge (luff) of the spinnaker change sign. In practice this leads to the luff curling under and partially collapsing. At intermediate angles there are strong suctions pressures over much of the leeward side of the spinnaker leading to the high thrust forces. Fig. (5b) shows the pressures at 3 heights on each sail predicted by the CFD modelling. In general a very similar set of results is obtained. It is intended that the CFD modelling will be used to investigate the changes in the flow which lead to these pressure distributions.

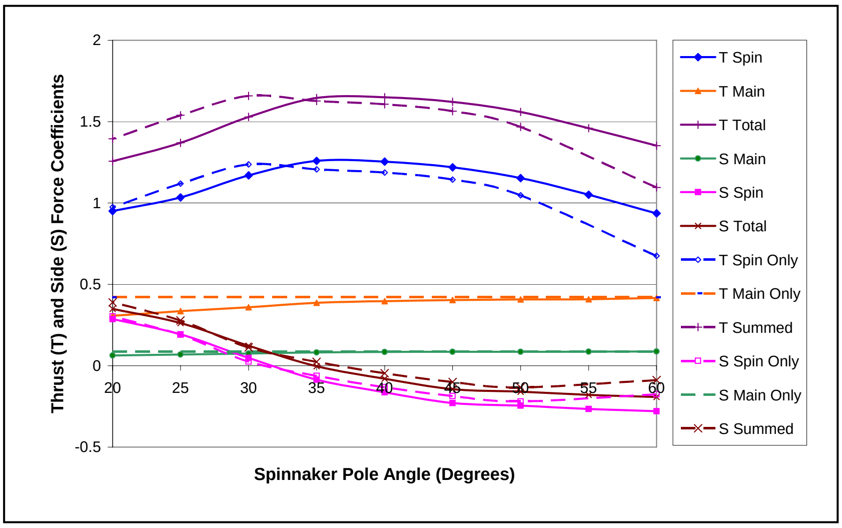

Figure 4: The effects of varying spinnaker angle when the boom is at 75° and the apparent wind angle 120°. Thrust and side forces on each sail as calculated by pressure integration from tests with the two sails together (solid lines) and independently (dashed lines).

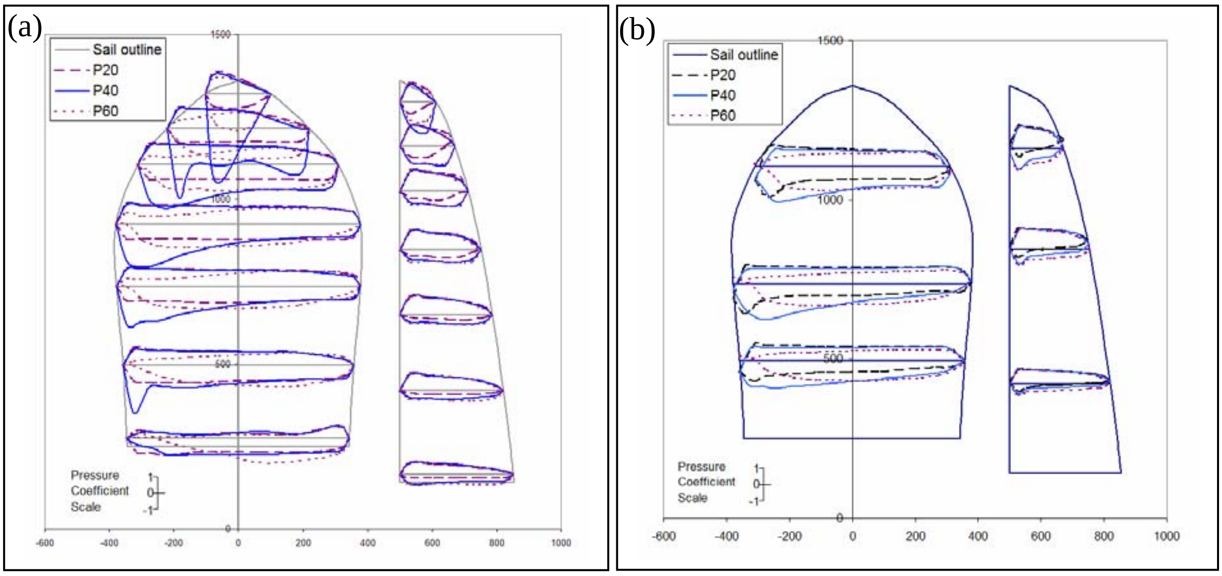

Figure 5: Pressures on the mainsail and spinnaker for three spinnaker pole angles (20, 40 and 60°) obtain from (a) wind tunnel testing and (b) CFD modelling. The boom was at 75° and the apparent wind angle 120°.

4 CONCLUSIONS

- Both wind tunnel and computational modelling have been successfully used to investigate the pressure distributions around downwind sails
- These tests have provided fresh insight into sail interaction.

5 REFERENCES

[1] W. LASHER, P.J. RICHARDS, Validation of RANS simulations for spinnaker force coefficients in an atmospheric boundary layer. *Journal of Ship Research*, 51(1), 22-38, 2007