Wind measurement from a moving yacht

P.J Richards, A. Larsson, D.J. Le Pelley
Yacht Research Unit, University of Auckland, New Zealand

Introduction

The mean motion of the wind relative to a moving yacht is well understood and is simply a matter of vector addition. This process does have some complexity since while the boat speed is the same for all heights, the true wind speed will increase with height and so the vector sum at the head of the mast will be different from that at the foot of the sails. As a result the apparent (relative) wind at the head tends to be faster and approach the yacht from a lower apparent wind angle (measured from the bow). This twist in the flow is most marked when sailing downwind and is the reason why the University of Auckland Yacht Research Unit has a Twisted Flow Wind Tunnel [1]. Hence if the likely boat speed, for a particular true wind speed, is known then it is possible to calculate the mean wind speed and twist profiles that need to be modelled in the wind tunnel. However it is less obvious what the appropriate turbulence levels are. It can be argued that if the wind is horizontally homogeneous then the statistics of the measured wind, at some particular height, will be independent of the measuring position. Hence the range and distribution of fluctuations should be the same whether observed by a stationary or moving anemometer. Further if the anemometer moves into the true wind then the apparent mean wind speed will increase, the standard deviation of fluctuations would be similar and the apparent turbulence intensity decrease. On the other hand if the anemometer moves downwind then the apparent wind speed decreases and the turbulence intensity increase. It is however doubtful that this concept would hold true if the anemometer was to move downwind at exactly the mean wind speed.

In order to investigate the characteristics of the wind as seen by a moving yacht, the Yacht Research Unit mounted two ultrasonic anemometers and two 3-component accelerometers on a Farr 727 yacht as illustrated in Figure 1. The intention was to measure the fluctuating wind and at the same time monitor the motion of the anemometers as this was expected to modify the observed wind speeds. The results presented are from one day's sailing on the Waitemata Harbour in Auckland.

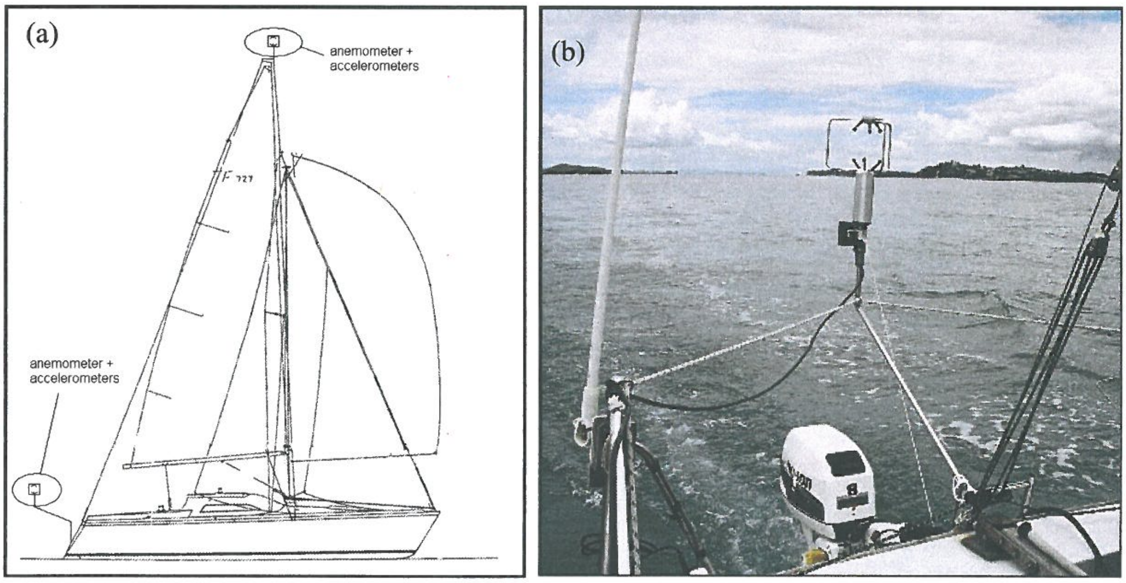

Figure 1. (a) The locations for the anemometers on the yacht and (b) photograph of the lower (stern) anemometer. The black box projecting to the left from the base of the anemometer contains the 3-axis accelerometers.

Instrumentation

Two Young Model 81000 3-axis ultrasonic anemometers were sampled at 10 samples per second and the data recorded on a laptop computer. One of these was attached to the head of the mast and the other on a purpose built bracket at the stern of the yacht. The results have been processed so that the velocity components are considered positive if the yacht is sailing upwind on a port tack (that is with the wind approaching the yacht from the bow (u component) and from the port (left) side (v component)). The vertical velocity component (w) is positive if it is up he mast. It should be noted that the axes are attached to the yacht and heel and pitch with the yacht. Since it was recognised that the anemometers would be moving around it was necessary to monitor this motion. Attached to each of the anemometers was a box containing three Analog Devices model ADXL105 accelerometers which were sampled at 100 samples per second and the data recorded on a second laptop. These were arranged so that they sensed the anemometer motion in the same directions that the anemometer resolved its components. A hand held GPS unit was used to monitor the approximate speed and direction of sailing but was not integrated into the data logging system at that time.

Raw Velocity Data

While the raw data obtained from the anemometers contains contributions from the wind and from the movement of the yacht it does represent the wind as seen by the sails which are also non-stationary. Figure 2 shows typical results from one upwind and one downwind run. During most of the upwind run the apparent wind speed at the head of the mast is about 7.1 m/s and approaches the yacht from an apparent wind angle of 37°, while the mean wind speed sensed by the anemometer at the stern gave a mean speed of 6.5 m/s and an apparent wind angle of 34°. The boat speed was estimated to be about 2.4 m/s on a 20° heading which suggests the true wind was blowing at 5.2 m/s from 325° at the masthead. During the first 30s of the downwind run the mean velocity at the masthead was 2.8 m/s with an apparent wind direction around 170°, while that at the stern was only 1.9 m/s from about 165°. During the downwind run the boat speed was about 1.4 m/s on a heading of 140°, which suggests a wind speed of 4.2 m/s from a bearing of 330°. Note that while the true wind speed is 20% lower than during the earlier upwind run the apparent wind is only about 40% of the upwind value.

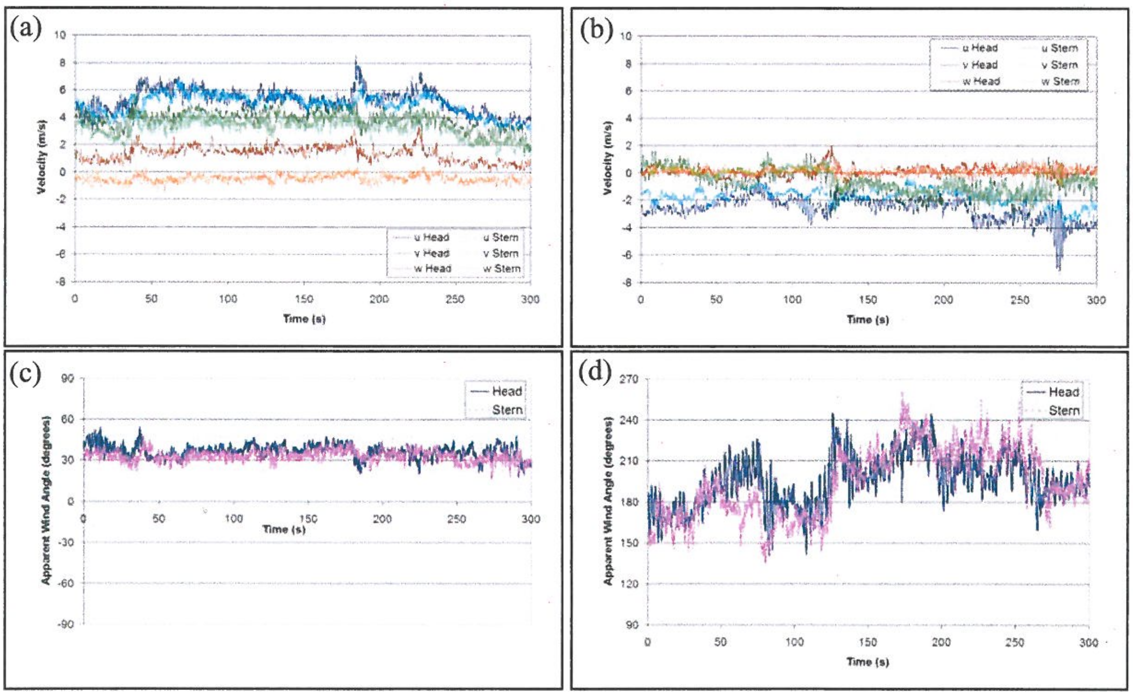

Figure 2. Raw velocity measurements for (a) an upwind and (b) downwind run and the corresponding apparent wind angles, (c) upwind and (d) downwind.

It can be observed that the apparent wind direction is much more variable on the downwind run, this partially occurs because maintaining a consistent apparent wind angle is necessarily more difficult when sailing downwind and partially because small changes in transverse velocity (across the yacht) cause large changes in the apparent wind angle. There are also much larger differences between the masthead and stern measurements both in terms of magnitude and direction. However the differences in the upwind case are smaller than might be expected. It is thought that the stern anemometer readings are being affected by the flow from the mainsail. In particular it may be noted that while the yacht is heeled to leeward, thus creating a flow up the mast, this is only apparent in the masthead results. The stern anemometer indicates a downward flow that is probably being caused by the trailing vortex that is shed from the foot of the sail.

The Effects of Yacht Motion

Close examination of Figure 2 shows that the velocities measured included significant periodic velocity fluctuations. These appear to be dominated by fore and aft fluctuations with periods around 1.5-2s and transverse variations with a slightly longer period of around 3s. The largest burst of these is apparent in Figure 2(b) at a time of around 275s. It is thought that this was caused by the passage of the wake from a ferry. In order to determine the movement of the anemometers the measured accelerations were integrated and then aligned in time by using a correlation method. The output from the accelerometers is also influenced by gravity and so the differences between masthead and stern values were used to estimate the angular velocities of the yacht. This was then used to correct for the pitching and heeling of the yacht. Figure 3 shows a comparison between the masthead anemometer velocities, high-pass filtered at 0.2Hz, and the integrated accelerations. Correlation coefficients as high as 0.9 were obtained in cases where there was significant motion. Much lower correlations were obtained for the anemometer at the stern due to there being much less motion. From these and other runs there appeared to be more pitching motion when sailing upwind and more heeling (rolling) when sailing downwind. It can be seen that the motions have typical amplitudes between 0.5 m/s and 1 m/s, but at one time the fore and aft motion reached ±3 m/s. These motions are larger than likely turbulent fluctuations.

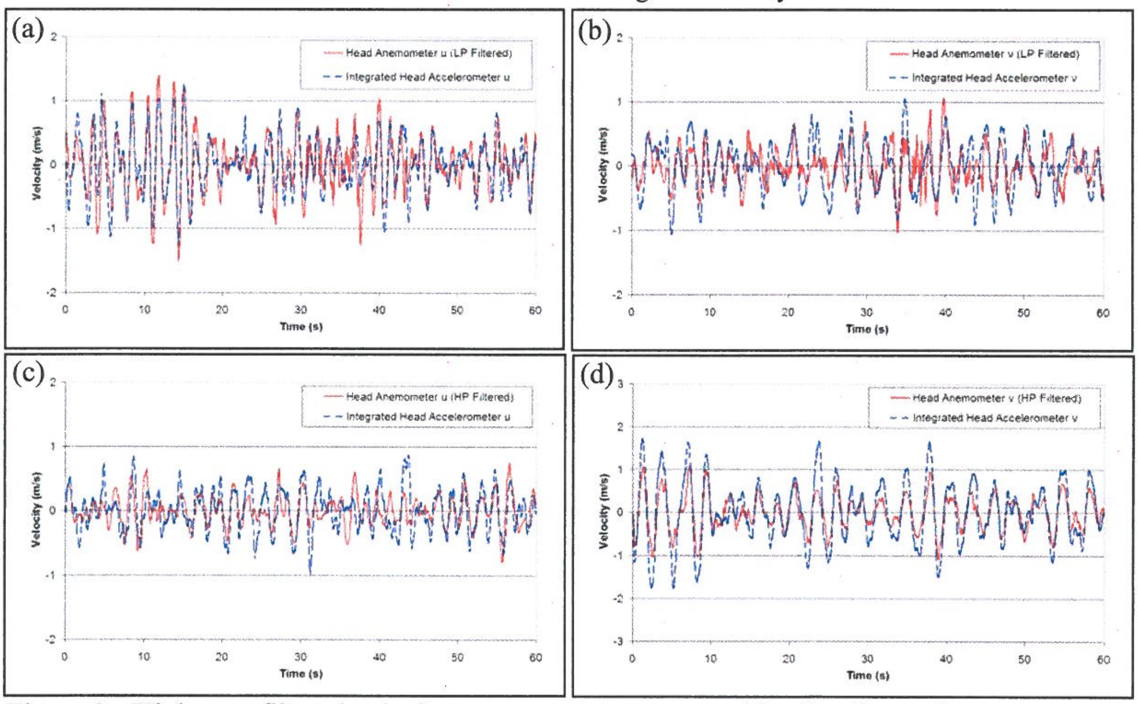

Figure 3. High pass filtered velocity components as measured by the ultrasonic anemometers at the masthead in comparison with the integrated accelerometer measurements. (a) u component upwind, (b) v component upwind, (c) u component downwind and (d) v component downwind.

Spectral Analysis

Since the motion of the masthead anemometer was so large it has been difficult to estimate the true wind fluctuations by subtracting the integrated accelerometer motion from the measured relative velocities. Although the resulting time series is believable at times any errors between the motion and the corresponding velocity sensed by the anemometer leaves a significant trace which was almost certainly not part of the true wind. Figure 4 shows spectral densities for the measured relative wind, the motion velocities as determined from the accelerometers and the estimated true wind obtained by taking the difference. With both components it is clear that at frequencies between 0.2 and 1.0 Hz the anemometer spectra are significantly elevated as a result of the motion. While the spectra for the series created by subtraction shows less of this and is more realistic it still contains errors. This is apparent in the fact that at times the "difference" spectra are above the anemometer spectra, while it is expected that the apparent wind spectra should always be above the true wind spectra. In spite of the limitations of the reconstructed true wind series it is suggested that these may still indicate differences that result from the various sailing situations. Direct comparison of the various components has little meaning since, as discussed in relation to Figure 2, these make quite different contributions to the total apparent wind depending on the sailing conditions.

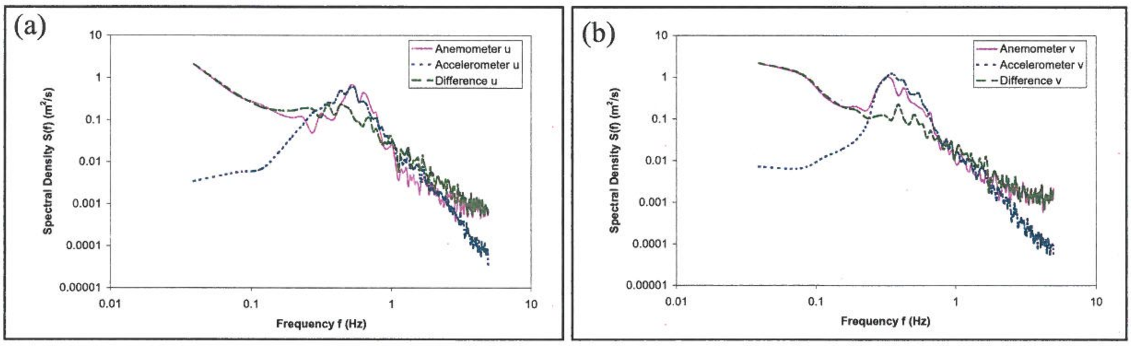

Figure 4. Masthead spectra from the downwind run: (a) u component and (b) v component.

In the wind tunnel it is the resultant apparent wind that is modelled and so the various components were resolved in order to create a time series for the direction aligned with the resultant mean apparent wind. Spectral analysis of these time series yielded the result shown in Figure 5. This preliminary result suggests that the longitudinal spectrum is independent of the sailing situation. However the corresponding turbulence intensity was only 8% when sailing upwind and double this when sailing downwind.

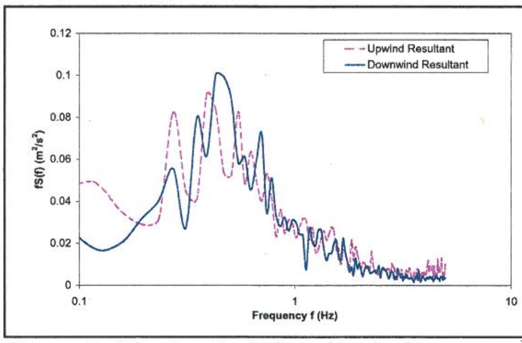

Figure 5. Masthead wind spectra in the mean wind direction for an upwind and downwind run.

Conclusions

Anemometer and accelerometer measurements on a moving yacht have demonstrated the high level of movement of the masthead. This motion has complicated the reconstruction of the true wind as observed by a moving yacht. Preliminary spectral analysis has suggested that the true turbulence spectra are independent of the sailing situation although the turbulence intensities are affected by the changes in the mean apparent wind speed.

References

1. Flay, R.G.J., (1996) A twisted flow wind tunnel for testing yacht sails, *Journal of Wind Engineering and Industrial Aerodynamics*, Vol. 63, pp 171-182.