Atmospheric turbulence as seen by a moving object

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1 INTRODUCTION

Research at the University of Auckland has for many years included both wind tunnel and CFD studies of yacht sails, for example the recent study by Matich et al. [1] into unsteady loads on the sails of a TP52 yacht, Fig. 1(a). In recent years, research has also included the effects of turbulent winds on both multi-rotor drones and small fixed-wing Unmanned Aerial Vehicles (UAVs) such as Kahu, Fig. 1(b). Small fixed-wing UAVs tend to operate at low altitudes, under 500 m, and at low speeds, under 25 m/s. Hence, these craft are subjected to higher turbulence intensities than conventional aircraft and operate at lower Reynolds numbers, and so are more susceptible to stalling. With either wind tunnel or CFD modelling of unsteady loads on such craft, it is important to correctly model the turbulence as seen by the moving object. As a result, several important questions arise which will be addressed in subsequent sections.

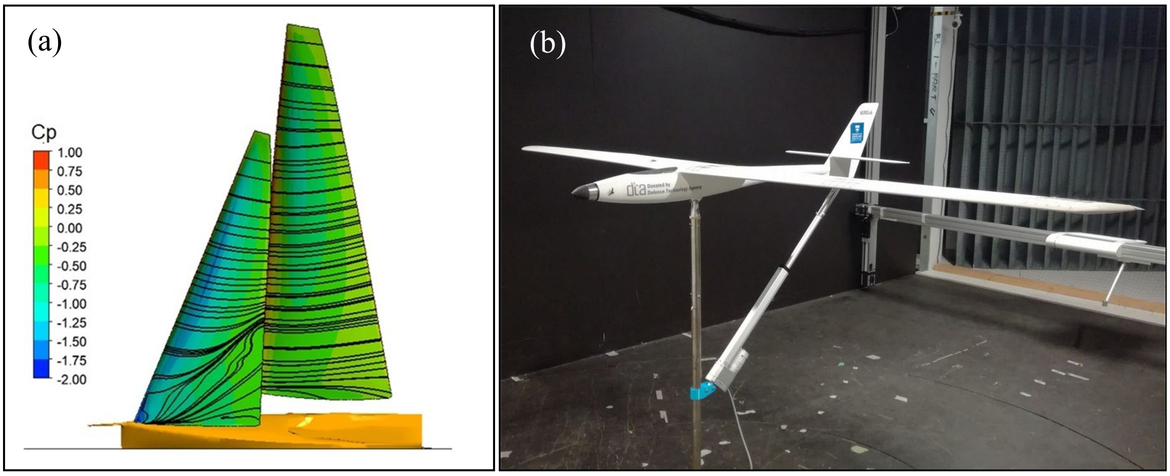

Fig. 1 (a) CFD modelling of a TP52 yacht and (b) Wind tunnel testing of Kahu fixed-wing UAV

2 WHICH COMPONENT OF TURBULENCE IS MOST IMPORTANT?

In many turbulence modelling situations, the default approach is to primarily consider the longitudinal turbulence intensity. However, with lifting surfaces this may not be the most important component. Consider a fixed wing UAV flying with a tail wind as depicted in Fig. 2(a). The turbulent fluctuations of the wind will be primarily determined by the mean windspeed and ground roughness, together with the altitude of flight. However, the UAV's airspeed, V_{Rel} relative to the air around it, will only depend on its trim and the power delivered by the propulsion system. The mean windspeed will not affect the airspeed but will change the ground speed, V_{UAV}. If it is initially assumed that the aircraft motion in response to unsteady loads is small, then relevant fluctuating velocities u', v', w' are those from the wind.

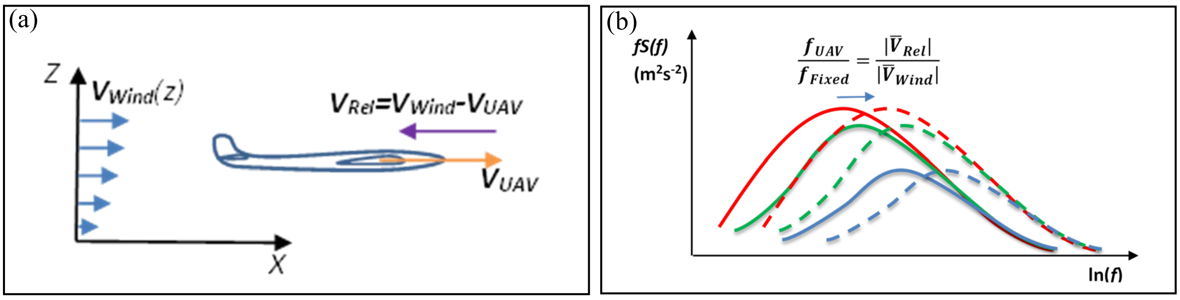

Fig. 2(a) Velocity vectors relevant to a fixed-wing UAV, and (b) Expected effect on turbulent spectra.

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Quasi-steady analysis of the unsteady loads on the UAV, assuming that the turbulence intensities are small and using small angle approximations, results in Eqs. 1 & 2 for the vertical (F'_z) and horizontal (F'_x) fluctuating forces.

$$F'_z = mg\left\{\frac{1}{C_L(\bar{\alpha})}\frac{dC_L}{d\alpha}\frac{w'}{|\bar{V}_{Rel}|} - 2\frac{u'}{|\bar{V}_{Rel}|}\right\} \approx mg\left\{10\frac{w'}{|\bar{V}_{Rel}|} - 2\frac{u'}{|\bar{V}_{Rel}|}\right\} \quad (1)$$

$$F'_x = mg\left\{\left(1 - 2k\frac{dC_L}{d\alpha}\right)\frac{w'}{|\bar{V}_{Rel}|} + 2C_D(\bar{\alpha})\frac{u'}{|\bar{V}_{Rel}|}\right\} \approx mg\left\{0.68\frac{w'}{|\bar{V}_{Rel}|} + 0.056\frac{u'}{|\bar{V}_{Rel}|}\right\} \quad (2)$$

To get an idea of the relative magnitudes, the numerical values given are for Kahu under cruise conditions where $C_L \approx 0.5$, $dC_L/d\alpha \approx 5$, $C_D = C_{D0} + kC_L^2$ with $C_{D0} \approx 0.02$ and $k \approx 0.032$. This suggests the greatest sensitivity is the vertical force responding to vertical turbulence. Even taking into consideration that near the ground the standard deviation of vertical turbulence might only be half that along wind, the vertical fluctuations would still contribute about 86% of the variance of vertical force. Perhaps more surprising is Eq. 2, which shows that the fluctuating horizontal force, while an order of magnitude smaller, is still dominated by vertical wind fluctuations. The conclusion from this analysis is that with lift generating structures it is more important to correctly model turbulence affecting the angle of attack than the along-wind.

3 HOW DOES MOVEMENT AFFECT TURBULENCE INTENSITIES AND SPECTRA?

If Eqs. 1 & 2 are manipulated to give the variances of the forces then these will be essentially functions of the turbulence intensities, such as $I_{w,UAV} = \sigma_w/|\bar{V}_{Rel}|$, when expressed in terms of the airspeed rather than the windspeed. Even with relatively low-speed fixed-wing UAVs the relative airspeed is normally higher than the windspeed: operations cease if the wind gets too high. Thus, the relevant turbulence intensity is lower than for a stationary anemometer. Nevertheless, these turbulence intensities become relatively high during take-off and landing since both the airspeed is lower and the UAV will be near the ground, where the turbulent fluctuations are usually higher.

As depicted in Fig. 2(b), it is suggested that the movement of the UAV does not alter the variances of the velocity fluctuations and so the area under the *fS(f)* curves remain the same, however the frequencies are all increased by the ratio of the airspeed to the windspeed. A simple analogy for this is to consider a car driving along a bumpy road. The size of the bumps, there distributions both in size and position are unaffected by the car's speed, but the frequency of the vibrations will certainly increase the faster it goes.

In order to support this concept, Fig. 3 shows data from DNS modelling of flow between flat plates. The DNS data was calculated for the standard channel flow problem at a $Re_\tau = 3.95$. A finite volume solver was used within a domain periodic in the streamwise and spanwise direction, having dimensions 6.4 x 2 x 3.2. The problem is non-dimensional both in time and space. The conditions considered are a comparison between a stationary observer and others moving either at the centreplane flow speed ('Full'), or half that ('Half'), either 'With' or 'Against' the flow. Fig. 3(a) shows that as long as there is a significant relative velocity between the observer and the flow the variances of all three turbulent components hardly change. The exception is moving with the flow at the flow speed, which is impossible for a fixed-wing UAV but might be possible for a multi-rotor drone, where the *U* variance is lower. Fig. 3(b) shows that as expected most of the *W* spectra, perpendicular to the plates, have similar shape and area but shift in frequency in proportion to the relative airspeed. This is particularly clear on the high frequency end of the spectra where these cut the *fS(f)*= 0.05 line at non-dimensional frequencies of 6, 35, 67, 100 and 135 for relative speeds 0, 0.5, 1, 1.5 and 2 times the centreplane flow speed. Other spectra showed similar patterns.

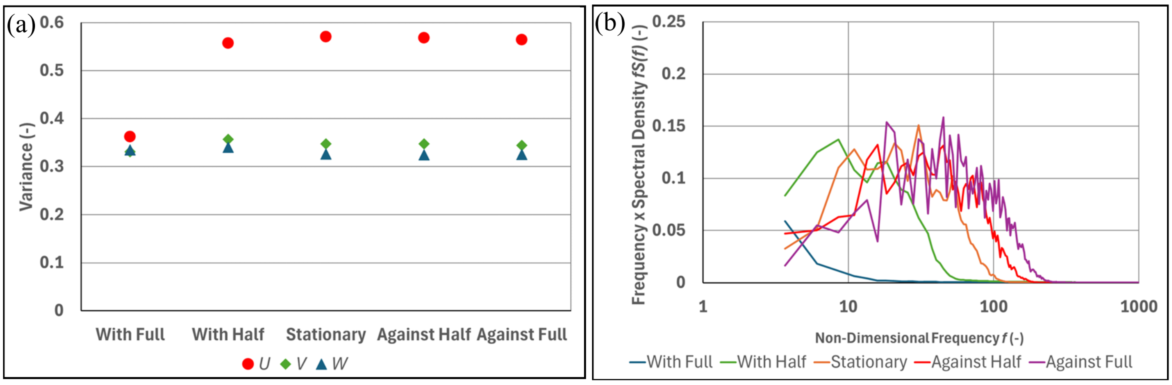

Fig. 3(a) DNS variances for a moving observer, and (b) The corresponding W spectra.

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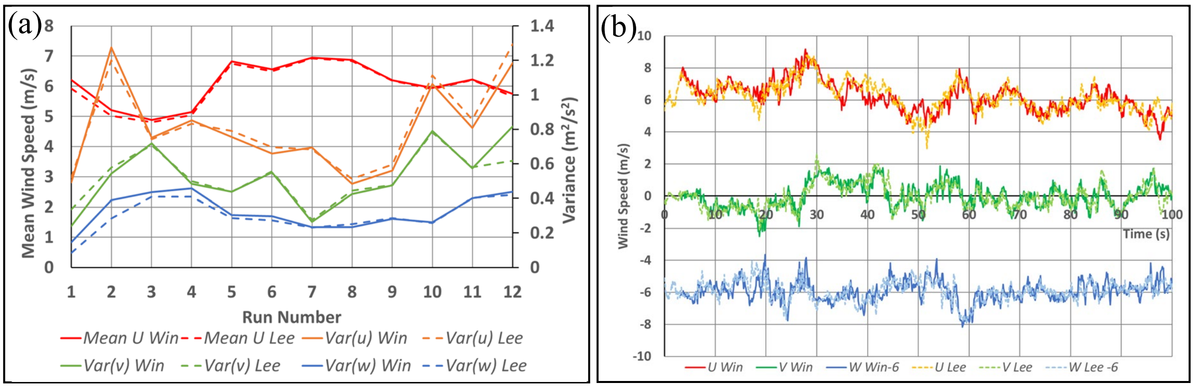

Fig. 4 (a) Mean windspeed and variances for 12 runs, (b) Time series for a separation of 20 m (Run 11), with the windward series delayed 3.2 s

4 HOW REALISTIC IS TAYLOR'S FROZEN TURBULENCE HYPOTHESIS?

One of the simplest approaches to understanding the effects of movement is to assume that Taylor's Frozen Turbulence Hypothesis applies, that is, turbulent eddies are carried past a point with a convective velocity in an essentially frozen state. In reality, the turbulent patterns are constantly changing, both through vortex stretching and the movement of eddies by other eddies, as well as by the mean wind.

To investigate how quickly turbulent patterns change, two Young 8100 ultrasonic anemometers were mounted on 6.5 m high masts and positioned on a flat coastal location in line with the mean wind. Two 300 s records were recorded at 10 samples per second for 6 separation distances of 1, 2, 3, 5, 10 and 20 m. Fig. 4(a) shows the mean wind speed and the three variance recorded at the windward and leeward mast. While there were changes in the conditions over the twelve records, it is clear that on each occasion the two anemometers detected similar conditions. Fig. 4(b) shows the first 100 s of three time series (with the *W* series displaced -6 m/s for clarity) for run 11, with the anemometers 20 m apart. The time series of the windward anemometer is delayed 3.2 s since this gave the highest correlation for all 3 series. It is clear that all the pairs of series are closely related, particularly for fluctuations lasting several seconds, but there are also noticeable changes, most obvious for short duration fluctuations.

Correlation analysis for time delay of all runs showed almost identical delays for each of the three components and these were generally close to that expected, $\tau = \Delta x/\bar{U}$, as shown in Fig. 5(a). Fig. 5(b) shows the peak correlation coefficient as a function of separation distance. As might be expected these are near unity for short separations and decrease steadily with increased distance. It may be noted that the vertical correlations decrease at a higher rate than the other two components. This is probably due to the lower levels of low frequency contribution in the vertical spectra, as seen in Fig. 6(a).

Although there are significant changes in the high frequency variations in the time series, Fig. 6(a) shows that even with a 20 m separation the upwind and downwind spectra are very similar across the whole frequency range. This suggests that while the details of the turbulence are evolving the statistical characteristics remain unchanged. Fig. 6(b) shows the coherence of the *U* time series for frquencies <0.5 Hz. Insufficent data was collected for accurate analysis but this shows a clear pattern of decreasing coherance both with frequency and separation. Similar patterns were observed with the other components.

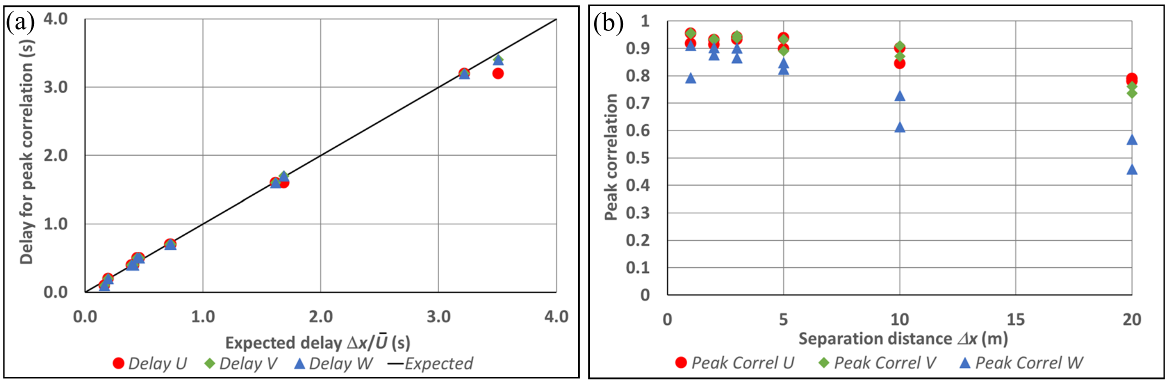

Fig. 5(a)Time delay for peak correlation and (b) peak correlation coefficient

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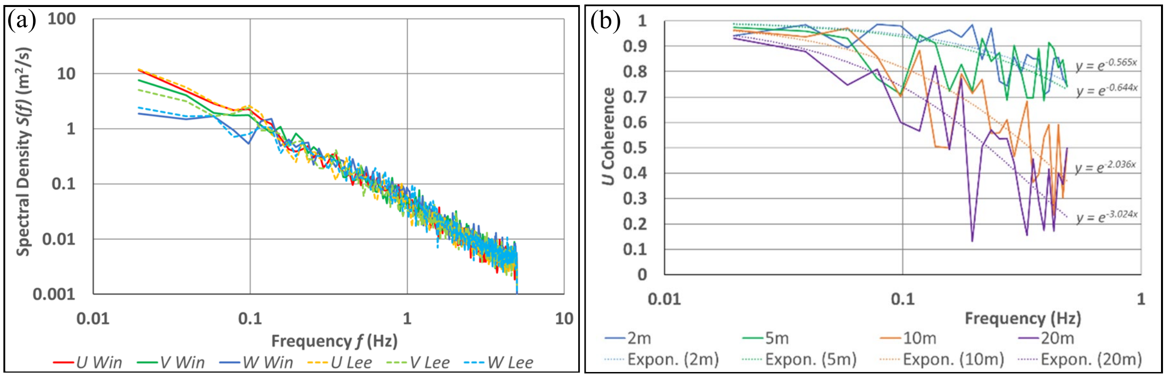

Fig. 6(a) Spectral density comparisons with Δx=20 m. (b) U coherence for selected Δx and f<0.5 Hz.

5. HOW DOES THE CRAFT'S DYNAMIC RESPONSE CHANGE THE SITUATION?

The discussion so far has assumed the craft does not respond to the fluctuating loads, but of course it will. A simple passive 1D model for a UAV responding to vertical wind fluctuations of the form $w'/|V_{Rel}|=A_{Wind}\sin(\omega t)$ shows that the craft will move vertically in response to the wind such that the angle of attack amplitude seen by the wing, A_{UAV}, is given by

$$\frac{|A_{UAV}|}{|A_{Wind}|}=\frac{\omega/\omega_0}{\sqrt{1+(\omega/\omega_0)^2}} \qquad \text{with} \qquad \omega_0=\frac{g\frac{dC_L}{d\alpha}}{C_L(\bar{\alpha})\bar{V}_{Rel}} \tag{3}$$

For Kahu at cruise speed $\omega_0\approx 5.4$ rad/s. Fluctuations lasting much longer than 1 s are responded to by the UAV moving, which results in a reduced angle of attack amplitude. Therefore, when modelling in the wind tunnel the wind spectrum needs to be reduced by a high pass filter of this form.

6. IS THE DIRECTION OF MOVEMENT RELATIVE TO THE WIND IMPORTANT?

With a yacht sailing upwind, the wing is almost vertical and so it is fluctuations in wind direction which change the angle of attack. Flay and Jackson [2] argue that if direction fluctuations are sufficiently slow the crew will respond and act as a high-pass filter, similar to the UAV passive response. Matich et al. [1] recently modelled a TP52 yacht sailing with the true wind direction varying with a 10s period. In this case the yacht movement and wind are not in the same direction, see Fig. 7(a), but the observed period of the force variations was under 7s, roughly in proportion to the ratio of apparent (relative) to true wind speed.

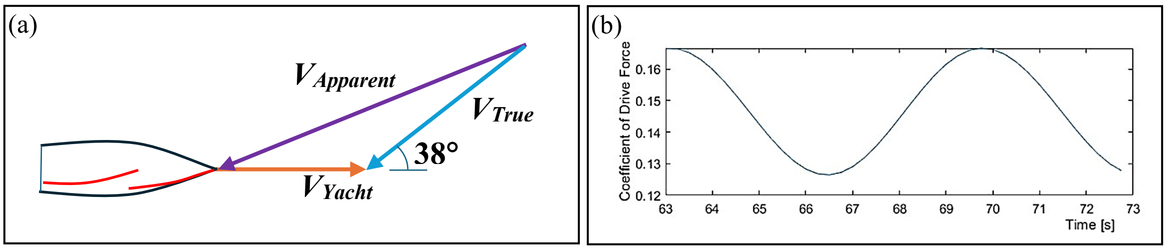

Fig. 7(a) Wind vectors for a yacht. (b) Drive force when the true wind direction varies, period =10s.

7. CONCLUSIONS

When modelling turbulent winds impacting a moving object which has lifting surfaces, it is most important to correctly model the velocity component which alters the angle of attack. Initially it may be assumed that the movement does not change the standard deviation of wind fluctuations but the turbulence intensity should be reduced in proportion to the ratio of airspeed to windspeed, and the frequencies of the spectra increased by this ratio. The dynamic response of the craft may result in high-pass filtering of the turbulence. The direction of movement of the craft relative to the wind is not thought to be significant.

REFERENCES

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