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Station Keeping of Multi-Rotor UAVs in Windy Conditions

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ABSTRACT

Modern applications for UAVs require the craft to remain stationary while various tasks are completed. The potential usefulness of various octocopter designs with tilted rotors are investigated by studying the interaction between rotors and between the rotors and the wind.

1. Introduction

Multi-rotor Unmanned Aerial Vehicles (UAVs), also known as drones, were initially primarily used as mobile photography platforms, where holding a precise positioning was not crucial. However UAVs are increasingly used for applications such as foliage sampling, inspection of buildings or spraying of weeds. With such applications it is important that the UAV holds the same position, station keeping, while the task is completed. For such applications it is also important that movement due to disturbances, such as the turbulent wind, is kept to a minimum. While it is possible to station keep with conventional quadcopters, creating correction force requires pitching the whole craft forwards or sideways, which limits the response time and creates rotational disturbances which may also affect the task being undertaken. Research at the University of Auckland is currently considering two octocopter (eight rotors) designs, as depicted in Figure 1, which can generate forward or side forces without the need for pitching.

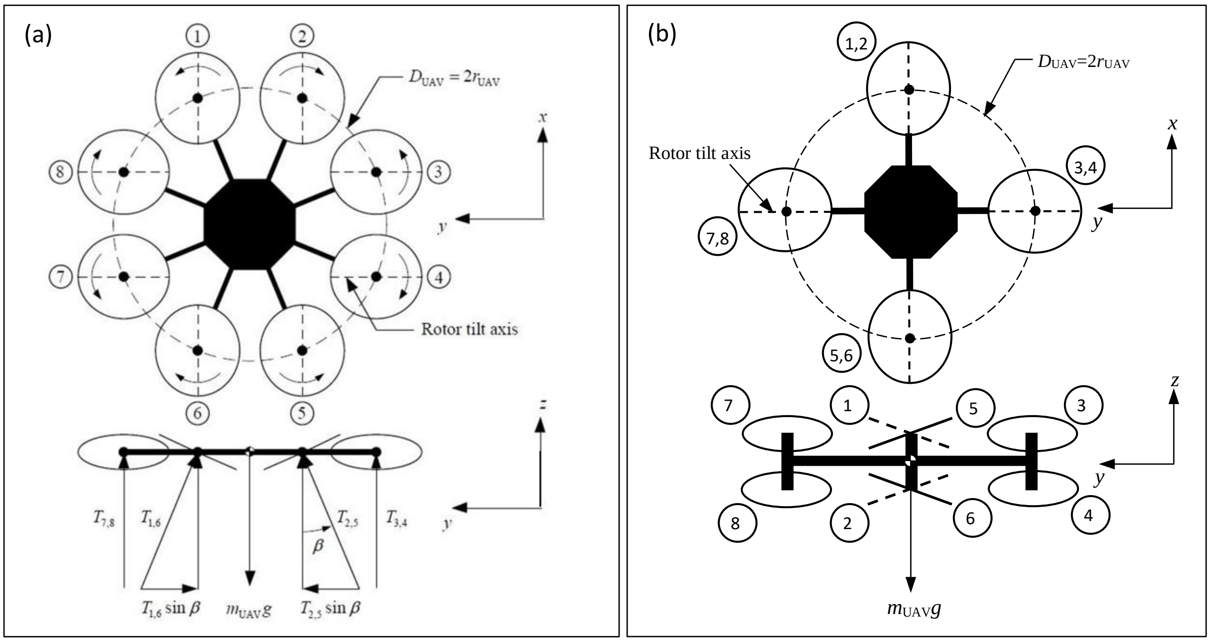

Fig. 1. Two octocopter designs: (a) A planar layout and (b) a layout with 4 coaxial pairs.

The planar arrangement, Figure 1(a), has eight rotors arranged in pairs, where each pair are tilted, by an angle β, towards each other. Rotor pairs 1,2 and 5,6 are tilted about longitudinal axes while the other two pairs are tilted about transverse axes. With this arrangement a forward, *x*-direction, force can be created by increasing the speed of rotors 4 and 7 while decreasing that of 3 and 8. In the same way a sideways, *y* direction, force can be created by increasing the speed of 2 and 5, while deceasing 1 and 6. The problem with the planar octocopter is that it is relatively large. An alternative arrangement, Figure 1(b), uses pairs of coaxial rotors, where essentially the even numbered rotors are placed below the odd numbered ones. Forward and side forces are created in the same manner as for the planar arrangement, however in this case there are interactions between the pairs of rotors. This paper will concentrate on the coaxial arrangement and will look at the forces generated under various conditions including the effects of wind.

2. Observations of a Conventional Quadcopter in a Wind Tunnel

A conventional quadcopter has been flown in the University of Auckland 7 m × 3.5 m wind tunnel, both with low turbulence flow and with grid generated turbulence. In the first set of tests, with smooth flow, the UAV was flown so that it stayed stationary with various wind speeds. The pitch angle α, as illustrated in Figure 2(a), was measured using an Inertial Measurement Unit (IMU) and the data recorded by an on-board data logger. The data was later analysed to give mean pitch angle as a function of wind speed, Figure 2(b), which was surprisingly linear with a polynomial curve fit only indicating a small quadratic term. If it is assumed that the thrust remains perpendicular to the rotor planes then equilibrium of forces relates the UAV weight ($m_{\mathrm{UAV}}g$= 15.2 N) to the drag force through

$$D = m_{\mathrm{UAV}}\, g \tan(\alpha) \tag{1}$$

Which, as can be seen in Figure 2(b), is also more linear than might be expected. The origin of the linear term can be partially explained through considering the advancing and retreating blades. For a blade element at radius *r*, of radial extent *dr,* the elemental drag contributions are approximately

$$dD_{\mathrm{Advancing}} \approx C_d\, 0.5 \rho (\omega r + W)^2 c dr \tag{2}$$

$$dD_{\mathrm{Retreating}} \approx C_d\, 0.5 \rho (\omega r - W)^2 c dr \tag{3}$$

$$dD_{\mathrm{Net}} = dD_{\mathrm{Advancing}} - dD_{\mathrm{Retreating}} \approx C_d\, 0.5 \rho 4 \omega r W c dr \tag{4}$$

where C_d is the elemental drag coefficient, ρ is air density, ω is the rotational speed of the rotor, *W* is the wind speed and *c* the local chord length. This interaction produces a net drag contribution which is proportional to wind speed. In these tests $\omega r_{\mathrm{Rotor}} \approx 60$ m/s>>*W*.

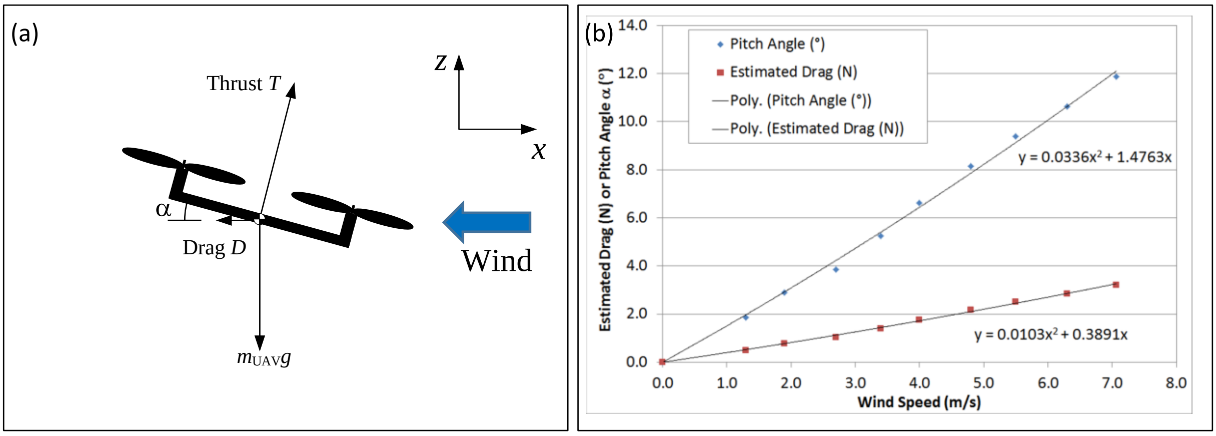

Fig. 2. (a) Quadcopter schematic and (b) the pitch α and drag *D* for various wind speeds

Further free flight tests were conducted with the tunnel narrowed to 3.5 m wide and a turbulence generating grid added. At the highest mean wind speed of 7 m/s, the turbulence intensity was 16-18% and the craft flew with a mean pitch around 13°. For each flight test the UAV was flown in manual 'stabilize' mode to its nominal hover position, before switching to the automatic 'position hold' flight mode. Analysis of the data collected showed that at this speed the positional standard deviations were: along wind ≈0.2 m, across wind and vertically ≈0.1 m. The standard deviation of pitch angles was around 7°, which indicates quite significant occasional excursions. It is hoped that the octocopter designs will both reduce the positional variation and minimise the pitching motions.

3. Coaxial Rotor Test Rig

A test rig, Figure 3, was designed so that the coaxial arrangement could be thoroughly investigated. Some of the important questions were: Would both the rotors still be able to produce vertical forces effectively? Could they produce significant horizontal forces? How would the wind affect the forces generated? The test rig consisted of two 280 mm diameter rotors, each with their own independently controlled brushless DC motor, mounted onto two JR3 force balances through which the forces generated by each rotor could be individually measured. Each motor and rotor assembly can be tilted at angles up to 20° if both assemblies are present, or to greater angles if one is removed. Figure 3(b) shows the 0° and 20° tilt situations.

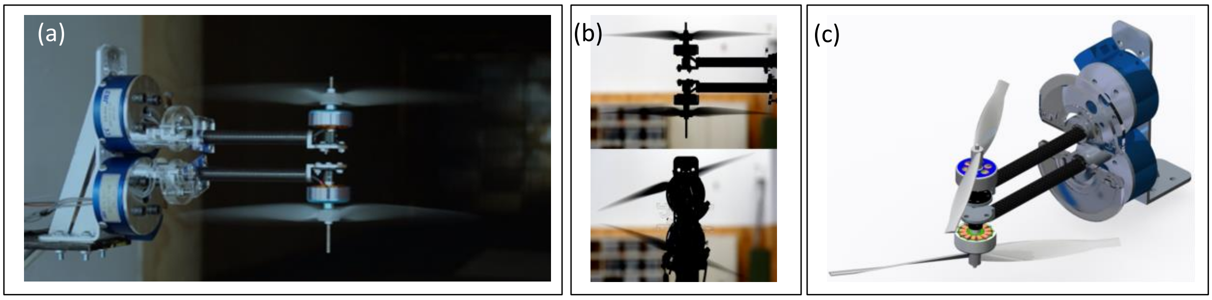

Fig. 3. (a) The coaxial rotor test rig, (b) two of the tilt angles used, upper image 0°, lower image 20°, and (c) a CAD model of the rig.

4. Single Rotor Tests

Initial testing was conducted with just a single rotor interacting with the wind, with both the rotational speed, ω, and wind speed, W, varied. With the rotor horizontal, Figure 4(a), the vertical force increased approximately in proportion to ω^2, but this was enhanced by a wind blowing across the rotor. With a wind speed of 10 m/s and rotational speed of 4000 rpm the vertical force was 27% larger than achieved in still air. On the other hand with zero rotation speed the horizontal force increased in proportion to W^2. However this increased further with rotational speed such that at 10 m/s, 4000 rpm it was double that with 10 m/s, 0 rpm. Although wind enhanced the thrust when the wind blew across the blade plane, the same was not true when the rotor was tilted 90° to face into the wind. In this case, Figure 4(b), the wind decreased the thrust and even made it negative at higher wind speeds. The speed at which the thrust becomes zero approximately equals the blade advance speed, see Figure 4(c), which is related to the pitch of the rotors, p, that in this case was 5.5" (140 mm). If the wind speed equals the blade advance speed given by

$$V_{\text{Blade advance}} = pn/60 = p\omega/(2\pi) \qquad (5)$$

where n is the rotational speed in rpm, the blade can effectively screw itself through the air without creating an angle of attack. As a result little or no thrust is created.

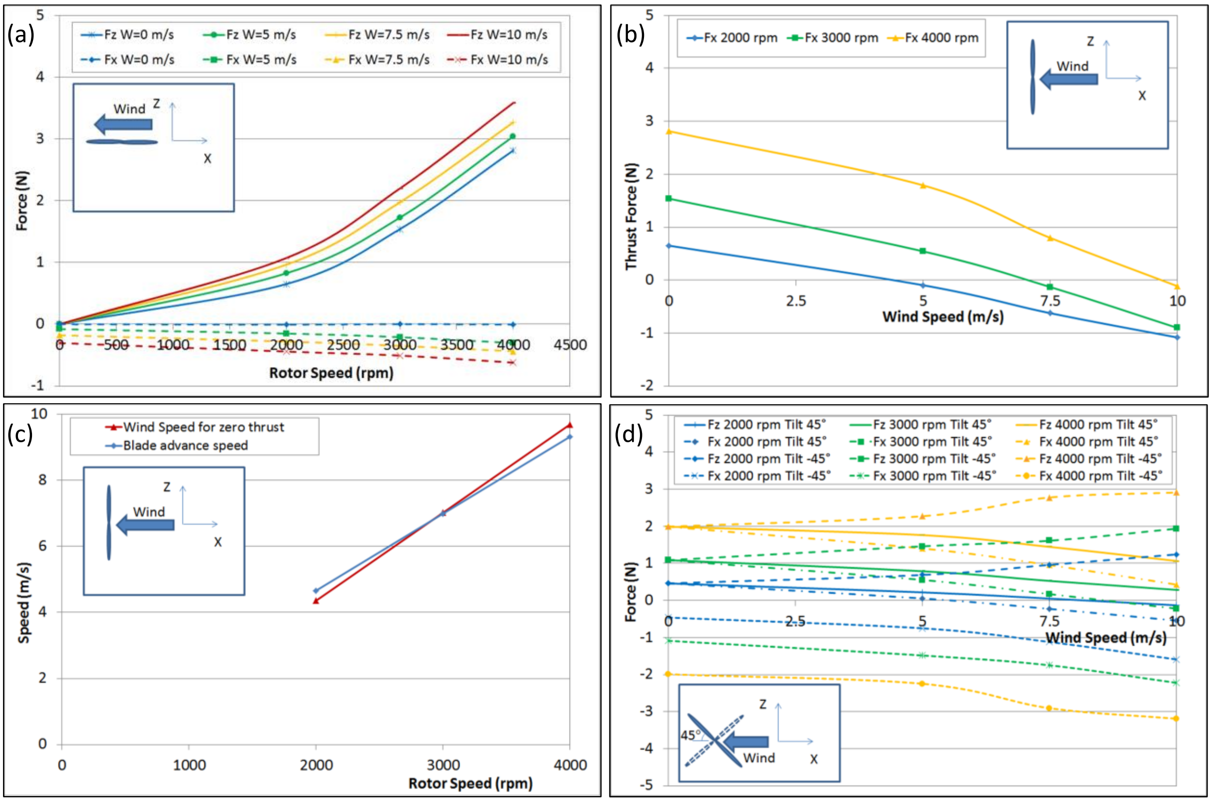

Fig. 4. Forces on a single rotor, (a) with wind blowing across the rotor, (b) with the rotor tilted 90° into the wind, (c) comparing the wind speed needed to reduce the thrust to zero and the blade plane velocity with no wind and (d) with the rotor tilted ±45°.

The final set of single rotor data, Figure 4(d), shows the effect of the wind on rotors tilted 45° either into or away from the wind. For the +45° case in still air the forward, *x* direction, force is equal to the vertical, *z*-direction, force. As the wind speed increases both force components decrease with the drive force, F_x, decreasing more rapidly than the vertical force. However this is not as rapid as occurred with the vertical rotor. In contrast if the rotor is tilted -45° away from the wind then the wind causes both components to increase in magnitude, which is good in terms of supporting the weight but is detrimental if the UAV is trying to move in the *x*-direction or to hold station in a wind.

5. Interacting Coaxial Rotors

Some of the effects observed with a single rotor are also apparent in the interaction of two rotors. For example, as depicted in Figure 5(a), the downward flow created by the top rotor decreases the vertical force on the lower rotor so that it consistently 75-80% of that of the top rotor. In all the results in Figure 5 the two rotors were set to the same speed and tilted to the same angle, but in opposite directions. Analysis of the top rotor vertical force showed that it was almost equal to that of a single rotor, which means the lower rotor has little effect on the one above. With both rotors the vertical force reduced slightly as the tilt angle increased, whereas the horizontal force on each rotor increased significantly as the thrust was directed more in that direction. Summing the two sets of forces together to give the net forces, Figure 5(c), shows that the resultant is almost vertical which means that the horizontal force on the bottom rotor almost matches that on the top rotor, even though its vertical component is lower. This can be attributed to the flow created by the top rotor which has a component parallel to the bottom rotor blade plane and hence generates a side component in that direction. This additional component is clear in the angle of the resultant forces relative to vertical, as presented in Figure 5(d). The top rotor resultant is almost perpendicular to the blade plane whereas that for the bottom rotor is angled up to 4° beyond normal.

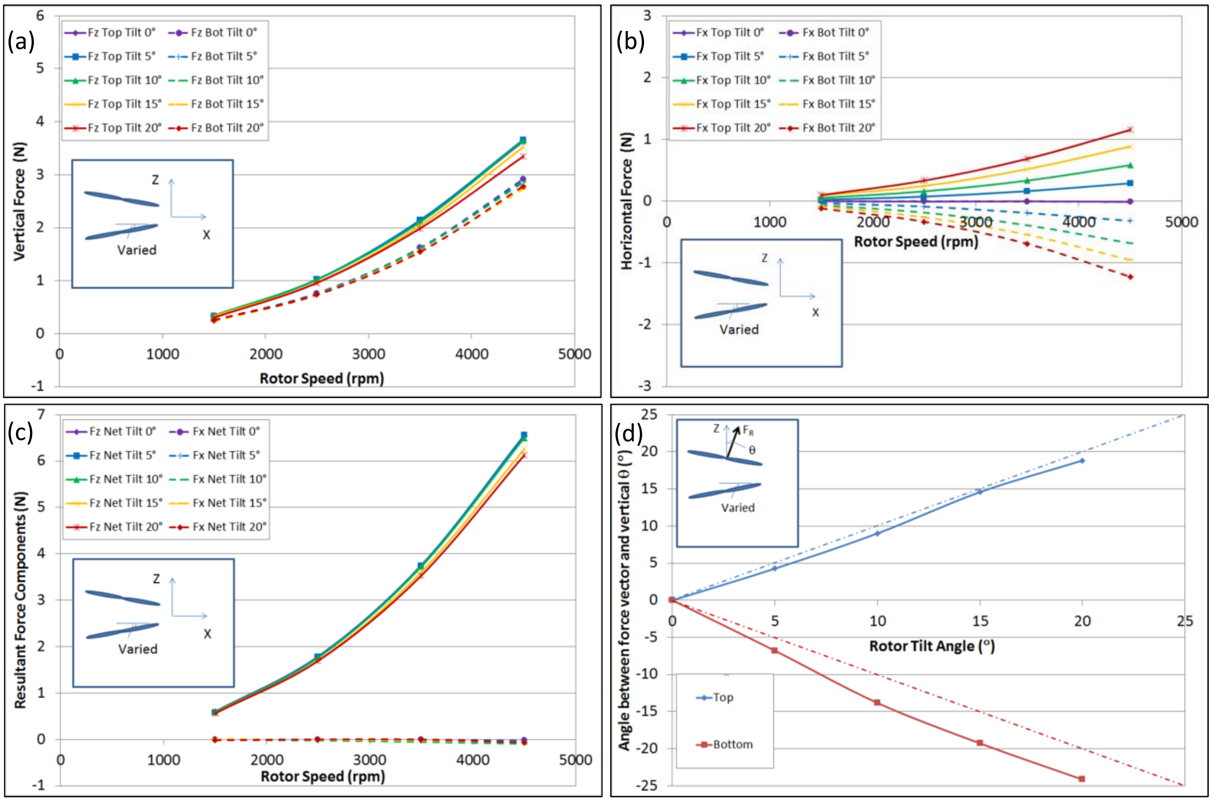

Fig. 5. The interaction of two tilted coaxial rotors when rotating at the same speed: (a) Vertical and (b) Horizontal forces for various tilt angles, (c) Net forces for the two rotors combined and (d) the angle between the resultant force vector on each rotor and vertical.

While Figure 5 has the same rotational speed for both rotors, Figure 6 illustrates the effect of non-equal speeds on the net forces with 10° and 20° tilt angles. For each set of data one rotor's speeds is held constant at either 2000 rpm or 4000 rpm, while the other rotor's speed is varied between these limits. For Figure 6(a) the top rotor speed is fixed, while it is the bottom rotor speed for Figure 6(b). In both figures the vertical forces can be seen to reflect the two rotational speeds with the highest value occurring when both are at 4000 rpm and the lowest when both are 2000 rpm. It may be noted that a higher vertical force occurs when the top rotor is 2000 rpm and bottom 4000 rpm, compare to the case when these are swapped. This occurs because the top rotor has a more adverse effect on the bottom rotor. Increasing the tilt angle from 10° to 20° only slightly reduces the net vertical forces whereas it almost doubles the net side forces. In both Figure 6(a) & (b) the horizontal force is near zero if the speeds are equal, but increases almost linearly with any difference in speed. With a 2000/4000 rpm combination, the horizontal force is about 25% of the vertical.

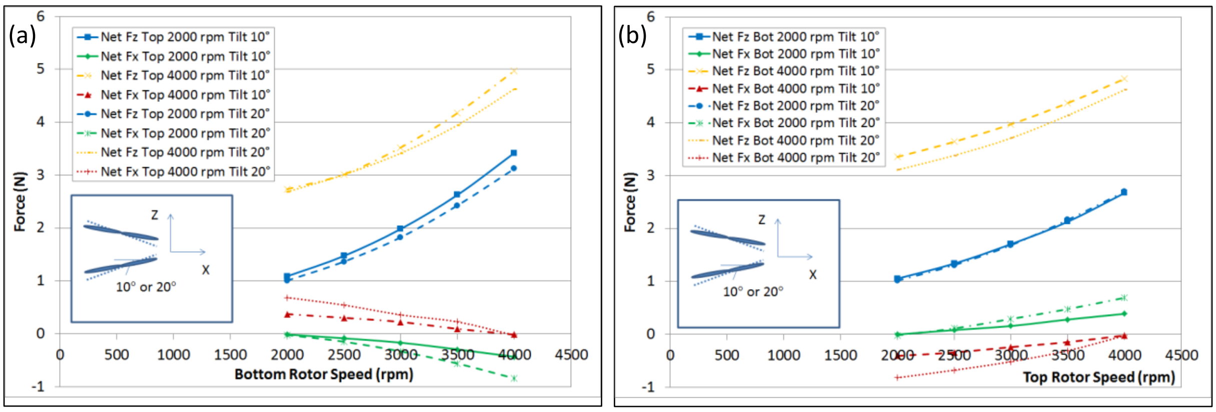

Fig. 6. Resultant forces when the speed of one rotor is held constant and the other varied. (a) Fixed top rotor speeds of 2000 rpm or 4000 rpm and (b) fixed bottom rotor speeds.

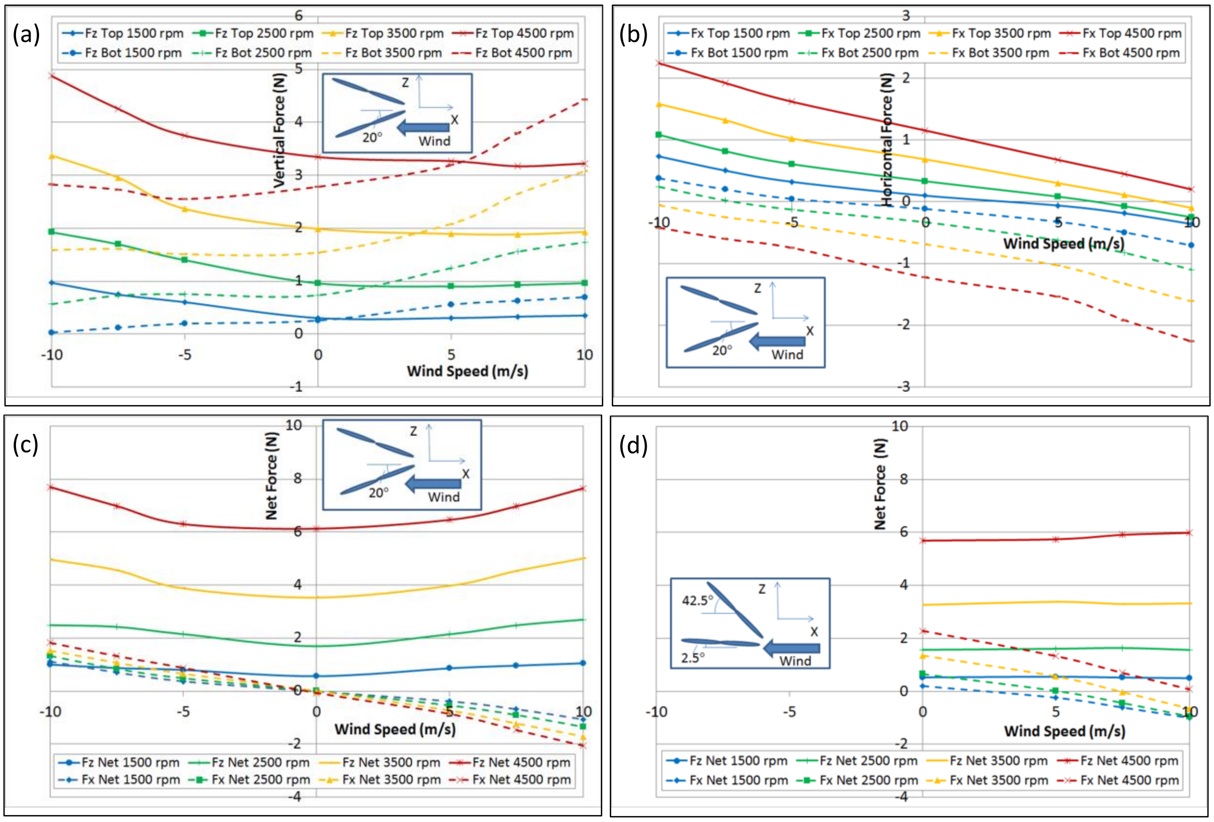

Fig. 7. Interaction between coaxial rotors and the wind: (a) vertical and (b) horizontal forces; (c) net forces on the UAV when level and (d) when the UAV is pitched into the wind 22.5°

5. Interaction between Coaxial Rotors and the Wind

The final set of tests investigated the interaction between rotors tilted 20° and the wind. The data presented in Figure 7(a)-(c) is for the case where the UAV is level and so the tilt angles are equal and opposite. Under this condition the wind decreases the vertical and horizontal components when there is a component of the wind from the upstream side of the rotor but increases both components if coming from the downstream side. This means positive wind, from the right, decreases the forces on the top rotor and increases them on the bottom rotor. The net effect, Figure 7(c), is the vertical force increases slightly with wind from either direction while a side force results in the downwind direction. This side force must be counteracted and while this could be achieved by changing the rotational speeds of the rotors, in practice counteracting the mean wind speed is likely to be achieved by pitching the whole craft into the wind. Figure 7(d) shows the net forces when the craft is pitched 22.5° into the wind. In this case the vertical force is relatively unaffected by the wind while a drive force is created which can be used to accelerate the craft forwards up to a certain wind strength. In practice a combination of mean rotor speeds, differential rotor speeds and pitch angle will be used to hold the craft in position and react to unsteady loads.

5. Conclusions

The forces created by a pair of coaxial rotors under various conditions has been studied. The results show that interaction with the wind can reduce the thrust when the wind has a component from the upwind side, while a component across the blade plane can enhance the thrust but also creates a side force proportional to the wind speed. By using tilted rotors and unequal rotational speeds it is possible to create side forces of the order of 25% of the vertical force. It is believed that the use of octocopter designs incorporating tilted rotors has the potential to improve their station keeping performance. Further research is planned which will consider other aspects of this problem.