Quadcopter Propulsion and Propeller Aerodynamics

A quadcopter is propelled by 4 propellers, where the thrust produced by the propellers is dependent on their speed or rpm which is controlled by the BLDC motors spinning them. This rpm can be related with the quadcopter's input voltage as shown in Figure 1 with the following formula: RPM = Input Voltage x Motor KV. In my scenario with a 6S LiPo battery (22.2V) and 1750KV motors, each motor runs at 38850 rpm.

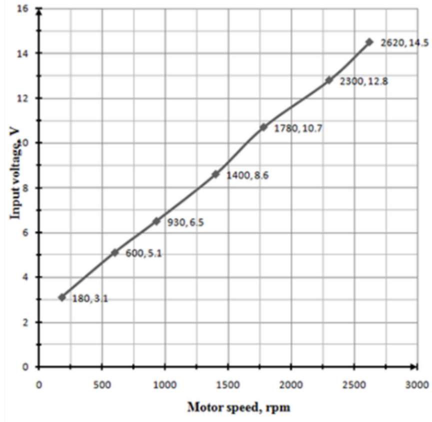

Figure 1: A graph showing the relationship between motor speed and input voltage

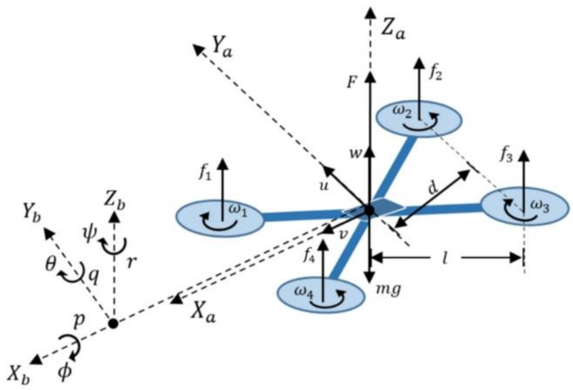

Figure 2: Free body diagram for quadcopter

As shown in Figure 2, when ideal conditions are assumed with no air resistance, the only force opposing the propellers' thrust downwards is the quadcopter's weight. Considering Newton's 2nd Law of Motion, the total thrust produced by these propellers must therefore be greater than the total weight of the quadcopter for acceleration. In my case, the total mass was measured to be 0.65kg giving a weight of 6.38N. As a result, the thrust produced by each propeller must be 1.595N.

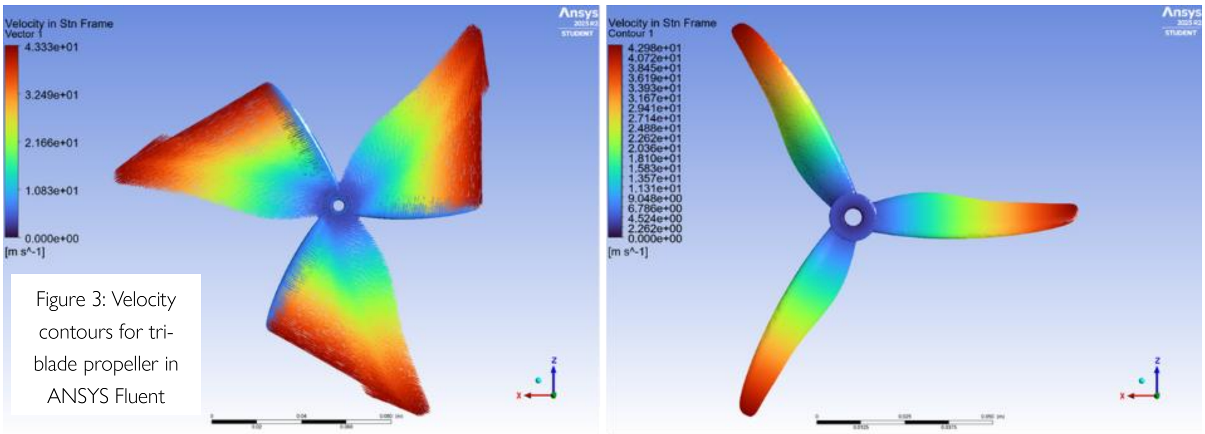

Figure 3: Velocity contours for tri-blade propeller in ANSYS Fluent

To test this, I conducted a CFD experiment on tri-blade propellers, varying the pitch and number of blades to design an optimal propeller which gave a minimum thrust of 1.595N (shown above). However, an issue I faced particularly at lower altitudes during take-off and landing, was significant vertical instability – more specifically at a height of approximately 10-15cm above the ground. My initial thoughts were that the quadcopter was experiencing ground effect and a turbulent flow field as a result. However, I decided to investigate this in some more detail.

Firstly, lift is generated by a pressure differential across the upper and lower surfaces of the propeller blades. A by-product of this differential is wingtip vortices where the high-pressure air curls around the edge of the wing to the low-pressure surface, as shown in Figure 4. This spiral induces downwash (a component of velocity acting downwards) that causes the thrust vector to shift backwards slightly, reducing the angle of attack and causing induced drag. After conducting a CFD experiment, I found that this was concurrent with my results. Particularly in Figures 3 and 5, we can see that the stationary frame velocity is greatest at the tips as well as a significant pressure difference between the upper and lower surfaces.

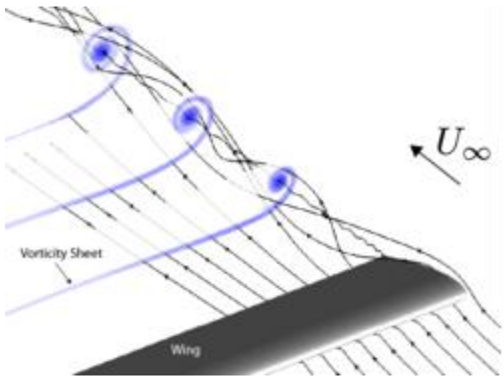

Figure 4: Diagram showing wingtip vortex formation

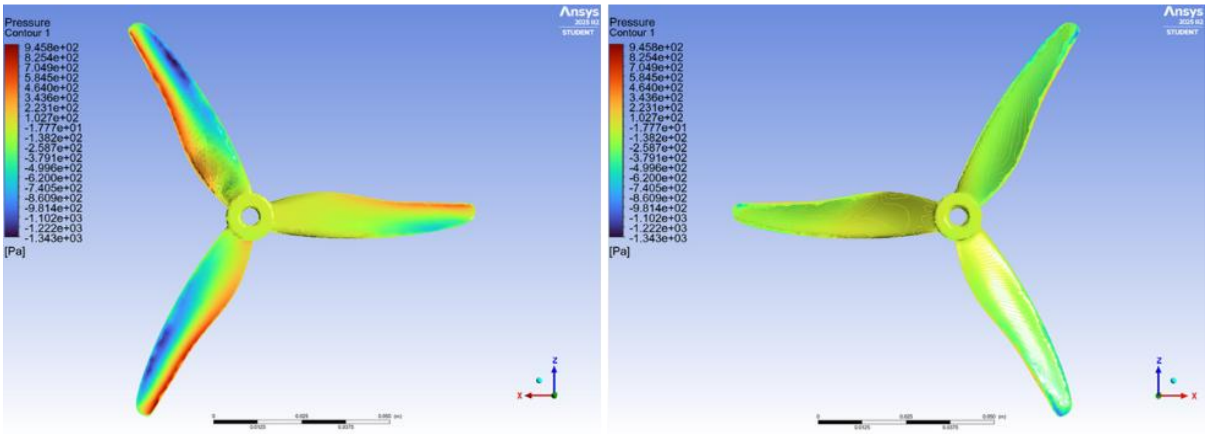

Figure 5: Pressure contours for upper (left) and lower (right) surfaces of tri-blade propeller

There are 2 primary phenomena associated with ground effect that are applicable to my quadcopter. Firstly, considering the propellers' proximity to the ground, the strength of the wingtip vortices is reduced, which also reduces induced drag. Another is an air cushion being formed, due to the downwash being compressed between the propeller and the ground. It must first be understood that, at low altitudes, the downwash must flow radially outwards which disturbs the smooth flow of air from the intake of the propeller. This creates an area of highly turbulent air beneath and around the quadcopter. And as this recirculating air cannot be considered to be steady, a constantly changing pressure field is produced. Therefore, as the quadcopter rises, the downwash has more room to dissipate and hence reducing ground effect.

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This explains the vertical instability observed at low altitudes and why it is reduced by climbing higher.

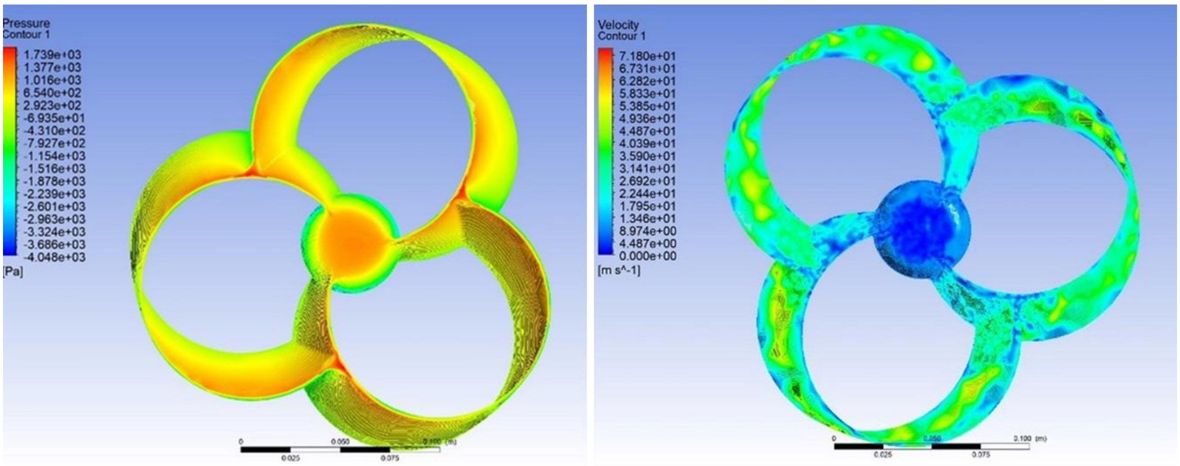

Figure 6: Pressure (left) and velocity (right) contours for toroidal propeller

To counteract the wingtip vortices, I decided to investigate toroidal propellers as a potential option. This is because unlike conventional propellers, toroidal propellers connect each blade via a closed-loop structure – eliminating the wingtip itself, the resulting vortices and blade flutter. By comparing the CFD models in Figure 6 for both propeller designs, it was evident that toroidal propellers offer an even pressure distribution across the upper surface and reduced tip velocities. I also tested the performance of these propellers by 3D-printing them in PLA and attaching them to my quadcopter. However, during initial testing at higher speeds, the propellers failed completely at the hub, as shown by the fracture lines in Figure 7. After examination, I found that the forces pulling the blades radially outward combined with the internal shear stresses exceeded the low fracture toughness of PLA, causing it to fracture. To combat this, I plan to re-print the propellers with a higher infill density to make it mechanically stronger and ideally out of PETG which is far less brittle and less susceptible to fracture. An alternative is sending the design to a third-party manufacturer, but I'd prefer to prototype and test the design more before finalising an order.

Figure 7: 3D-printed PLA toroidal propellers with fracture lines