Rotor Aerodynamic Analysis of a Quadrotor for Thrust Critical Applications

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Abstract—**Field robots are becoming more useful in search and rescue operations due to their ability to be deployed into a disaster site with minimal assessment to the area. This allows a rescue team to respond swiftly, increasing the possibility of survival for victims. In this paper, an aerodynamic analysis was conducted on the rotors of a quadrotor unmanned aerial vehicle (UAV) intended to be utilised in search and rescue operations. A combination of blade element and vortex theory was investigated to model the aerodynamics of a fixed pitch propeller, used in the rotors of the vehicle. This model was simulated using the JavaProp© software package to establish the performance characteristics of the rotorcraft. This was necessary to determine the efficiency of the rotors and possible payload capacities. The rotorcraft also requires high thrust capabilities in order to cope in harsh environments of disaster sites.**

Keywords - Quadrotor, UAV, Aerodynamics

I. INTRODUCTION

The utilisation of field robots in search and rescue operations has become more relevant. This is due to the fact that robots are expendable in relation to human life [1]. The prospect of an airborne robot for these purposes is even more attractive, as a large percentage of rescue missions conducted using robotic assistance have been aborted due to the robot struggling to navigate the harsh terrain of a disaster site. This was evident during the World Trade Centre tragedy in 2001 [2]. The use of a flying robot would be more advantageous in a reconnaisence mission due to the ability to fly over any type of terrain. Other research groups have also embarked on similar endeavours with great success. The Centre for Robot-Assisted Search and Rescue (CRASAR) assisted in Haiti with two robots called the iSENSYS, a conventional helicopter drone, and AirRobot which is a quadrotor drone [3]. The quadrotor helicopter was chosen as a UAV platform for the research because of its ability to hover and the small rotor sizes allowable. A proposed structure for the rotorcraft is depicted in Figure 1. A conventional helicopter would be challenging to introduce into a confined space, such as a mine shaft, because of its large main rotor. Even a diminutive collision could result in an extensive amount of damage. The disadvantage of implementing a quadrotor helicopter over its conventional counterpart however, is the lift capabilties. It is therefore important that the rotorcraft is aerodynamically efficient. In a harsh environment, the UAV would require large amounts of thrust force to perform corrective manouvres and maintain stability.

Figure 1: Proposed quadrotor structure

The analysis presented in this paper was conducted to confirm if miniature fixed pitch propellers designed for model fixed wing aircraft could be utilised to form part of the rotor of a quadrotor helicopter. This would drastically simplify the task of constructing the rotorcraft, as the design and manufacture of a new propeller to suit the application is expensive.

The propellers that have been modelled for this analysis are counter rotating 12”x4.5 slow flyer fixed pitch propellers manufactured from polyethylene. The geometry profile is shown in Figure 2. They are intended to be coupled with 12 V Maxon ec-i40 brushless direct current motors (BDCM). These motors have desirable speed, torque and weight characteristics for such an application [4]. BDCMs are also advantageous because they do not produce any sparks. This makes them safe

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to operate in fire hazardous environments. The target weight for the robot is 4 kg including all payloads.

Figure 2: Counter-rotating fixed pitch propellers used for the quadrotor

II. QUADROTOR HELICOPTER OPERATION

Similar to a conventional helicopter, a quad-rotor helicopter is a six-degree-of-freedom, multivariable, strongly coupled, and under-actuated system. The main forces and moments acting on a quad-rotor helicopter are produced by its rotors [5]. It is arguably a simpler setup from conventional helicopters, as quad-rotor helicopters can be controlled exclusively by variation in motor speed and do not require any complicated actuators. Two pairs of rotors rotate in opposite directions to balance the total torque of the system.

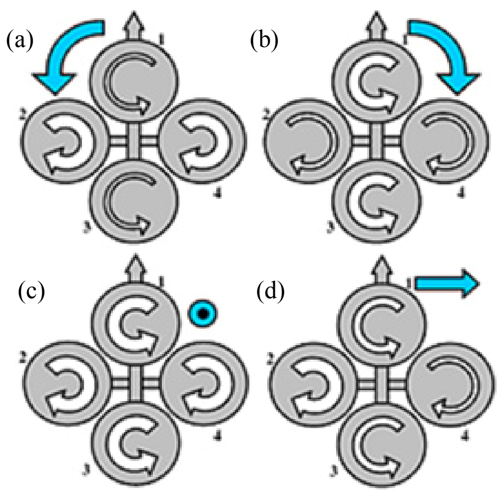

Figure 3: Quad-rotor dynamics, (a) and (b) difference in torque to manipulate the yaw angle (ψ); (c) hovering motion and vertical propulsion due to balanced torques; and (d) difference in thrust to manipulate the pitch angle (θ) the roll angle (ϕ).

A quad-rotor setup is controlled by manipulating thrust forces from individual rotors as well as balancing drag moment. For hovering, all rotors apply a constant thrust force as illustrated in Figure 3(c), thus keeping the aircraft balanced. To control vertical movement, the motor speeds are simultaneously increased or decreased, thus having a lower or higher total thrust but still maintaining balance. For attitude control, the yaw angle (ψ) may be controlled by manipulating the torque balance, depending on which direction the aircraft should rotate. The total thrust force still remains balanced, and therefore no altitude change occurs. This can be shown in Figures 3(a) and 3(b). In a similar way, the roll angle (ϕ) and pitch angle (θ) can be manipulated applying differential thrust forces on opposite rotors, as illustrated in Figure 3(d) [6; 7].

Although this may seem simple in theory, practically, there will be many factors which need to be taken into account. One of the greatest challenges will be to achieve stability in an outdoor environment. Especially a disaster area where there will be many obstacles and possibly harsh winds [8].

III. ROTOR AERODYNAMICS

As with conventional helicopters, most of the aerodynamic significance of quad-rotor helicopters lies within their rotors, influencing the natural dynamics and power efficiency. Research at the Australian National University has shown that an approximate understanding of helicopter rotor performance can be obtained from the momentum theory of rotors [7]. This performance is very important as a search and rescue rotorcraft must be able to produce enough thrust force to counter any bursts of external forces applied to it in order for it to stabilise itself. It should also be able to carry the payload of equipment such as cameras, sensors, etc.

There are five aerodynamic influences which act on a rotor. These may be illustrated in Figure 4 [9]. The first is called ground effect F_{IGE}. This refers to the variation of the thrust co-efficient when the rotor is in close proximity to the ground. The second influential aerodynamic force occurs as a result of horizontal forces acting on all the blade elements, known as the hub force H, and the third influence, referred to as rolling moment R_M, is the combined moment due to the lift at each point along the radius of the rotor [8]. The most important influences though, are thrust T and drag moment Q. It is these quantities that will be manipulated to operate the rotorcraft.

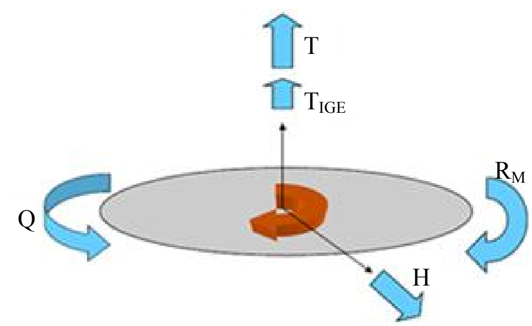

Figure 4: Aerodynamic forces and moments on a rotor

IV. PROPELLER ANALYSIS

The propellers used in the rotors are fixed pitch, signifying that the pitch angle β, sometimes referred to as the blade angle, remains fixed. However, this should not be confused with constant pitch, as the pitch can vary along the length of the propeller blade but cannot be adjusted. As shown in Figure 2, propeller geometry can be complex, where the chord length c and airfoil profiles vary along the length of the blade. The pitch angle determines the pitch of the propeller p, which is the distance that the propeller moves through the air for each revolution, much like a screw. This is why propellers are sometimes referred to as 'air screws'. This relationship can be described as,

$$p = 2\pi r \tan\beta \quad (1)$$

Where r is the distance along the blade where the specific pitch angle exists. Because of the variation that exists, a ratio is commonly used known as the pitch diameter ratio,

$$p/D = \pi x \tan\beta \quad (2)$$

Where D is the diameter of the propeller and x is the relative radios of the blade section and may be represented as,

$$x = r/R \quad (3)$$

Because of the variation of β and c throughout the length of the radius, the angle of attack α is also varied [10]. This is can be shown graphically in Figure 5 [11].

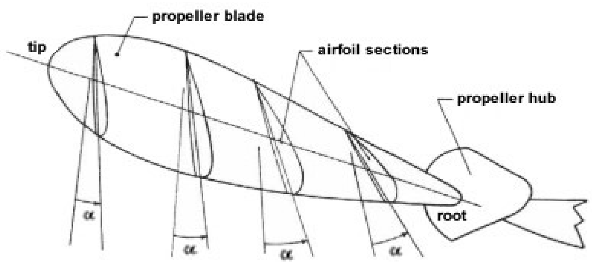

Figure 5: Typical fixed pitch propeller geometry

It was therefore evident that to conduct an effective analysis of a propeller of this type, momentum-blade element theory should be used and the blade should be analysed in sections across its radius and then integrated to determine the overall performance and characteristics. In Figure 6, an infinitesimal cross section dr, a length r away from the centre of the propeller was considered. The dashed line in the figure represents the zero lift line. The velocity V_E is the induced air velocity and enters the blade at an angle α to the zero lift line. The velocity V is the advance velocity of the propeller and the velocity ωr is the velocity due to rotation. The angle Φ is the angle of resultant flow. The dimensionless co-efficient of lift C_L is dependent on angles α, β and Φ and the co-efficient of drag C_D is a function of C_L and Mach and Reynolds numbers. The lift dL generated is always orthogonal to the line of zero lift. The thrust dT, which is the effective upward force perpendicular to the plane of rotation, is a component of dL [10; 12]. The drag dD is the force acting adjacent to the airfoil and the force dF_Q is the component of dD which creates the drag moment dQ where,

$$dQ = dF_Q r \quad (4)$$

The local lift and drag may be expressed as,

$$dL = \frac{1}{2}\rho V_E^2 c C_L dr \quad (5)$$

$$dD = \frac{1}{2}\rho V_E^2 c C_D dr \quad (6)$$

Where, ρ is the density of air. Vortex theory was analysed to determine the thrust and drag moment. In the same manner in which a wing works, the aerodynamic lift on a propeller blade can be related to a bound circulation Γ around the blade, as shown in Figure 6. This bound circulation may be expressed as,

$$\Gamma = \frac{1}{2} c C_L V_E \quad (7)$$

Using the change in bound circulation, the local thrust and drag moments are,

$$dT = \rho(\Omega - \omega) r d\Gamma \quad (8)$$

$$dQ = \rho(V - v) r d\Gamma \quad (9)$$

Where, Ω and V are the global rotational and advance velocities respectively. From this, the local efficiency of the propeller can be found,

$$\eta_{local} = \frac{VdT}{\Omega dQ} \quad (10)$$

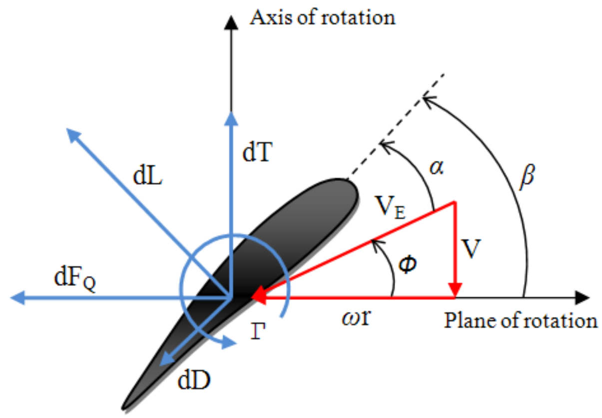

Figure 6: Vector diagram for a section dr a length r away from centre of the propeller

To determine the overall efficiency of the propeller, a ratio of the product of the thrust and advance velocity and the power P must be found [10].

$$\eta = \frac{TV}{P} \quad (11)$$

However, the thrust and power may be represented as,

$$T = \rho C_T D^4 n^2 \quad (12)$$

$$P = \rho C_P D^5 n^3 \quad (13)$$

It must be noted that D here refers to the rotor diameter and not drag. From this, the efficiency may be represented as,

$$\eta = \frac{V}{nD}\frac{C_T}{C_P} \quad (14)$$

The velocity ratio in this expression is known as the advance ratio J,

$$J = \frac{V}{nD} \quad (15)$$

V. Aerodynamic Numerical Simulation

A numerical simulation was conducted based on the above theory using the JavaProp© software package. The geometry of the propeller shown in Figure 2 was modelled based on the chord length and pitch angle and the advance speed was set low as the rotorcraft would not travel at high speeds transversely through the air as in the case of a fixed wing aircraft. For the simulation, both local and overall analysis was conducted. The first investigation conducted was the thrust and drag moment properties of the rotor. These results are shown in Figure 7 and Figure 8.

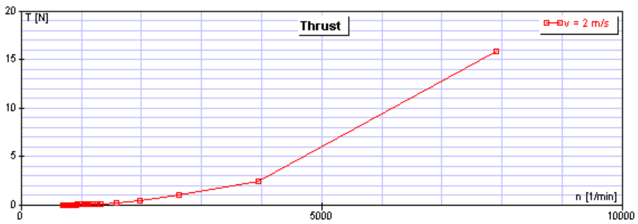

Figure 7: Graph of thrust VS rotor speed

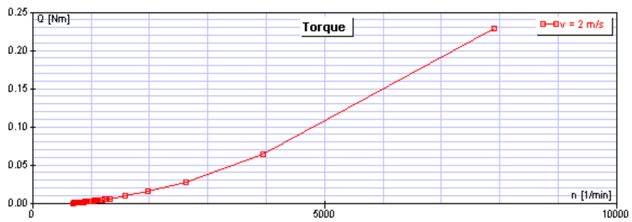

Figure 8: Graph of drag moment VS rotor speed

The co-efficient of lift and drag where also investigated along the length of the propeller blade. Figure 9 is a plot of the variation of these characteristics against the relative radius of the blade section. The local efficiency along the length of the propeller blade is shown in Figure 10. The overall aerodynamic properties of the propeller were investigated. The co-efficient of thrust and power are presented in Figure 11 and the change in these properties along the length of the propeller blade is presented in Figure 12. Figure 13 presents the overall efficiency with regards to the advance ratio. The plot of η^* refers to the efficiency of the optimal propeller.

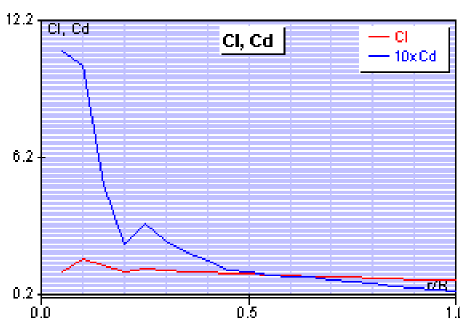

Figure 9: Graph of C_L and C_D VS relative radius

Also of interest was the loading along the length of the propeller blade. Figure 14 and Figure 15 illustrate the co-efficient of shear force and bending moment respectively that apply at different points of the blade. The final investigation was with regard to the flow field shown in Figure 16.

Figure 10: Graph of local efficiency VS relative radius

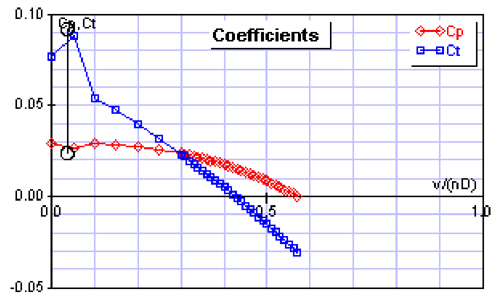

Figure 11: Graph of C_P and C_T VS advance ratio

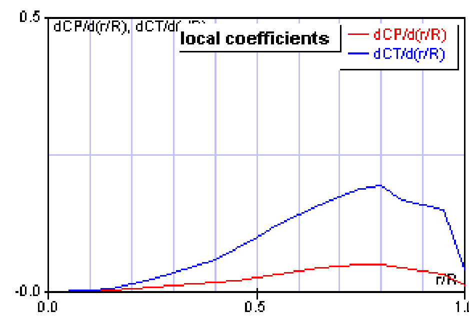

Figure 12: Change in C_P and C_T over the length of the propeller blade

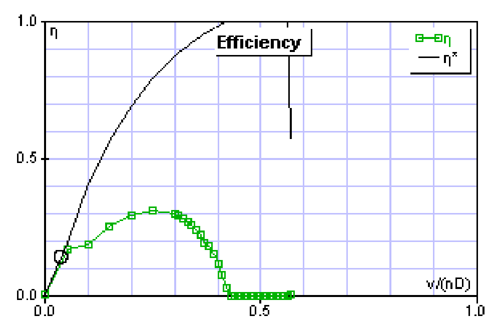

Figure 13: Graph of efficiency VS advance ratio

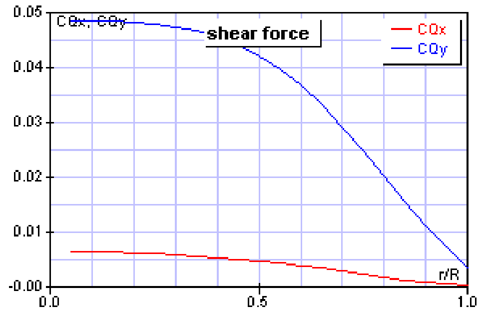

Figure 14: Graph of co-efficient of shear force VS relative radius

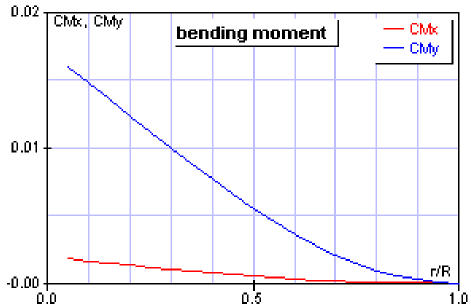

Figure 15: Graph of bending moment co-efficient vs relative radius

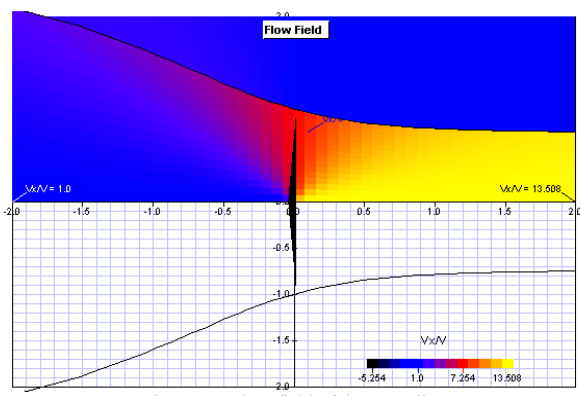

Figure 16: Flow field of the propeller

VI. Conclusion

From the above analysis, one can deduce that the performance of the propeller is poor. Both local and overall efficiencies, revealed in Figure 10 and Figure 13 respectively, are below 30%. This was expected as such propellers were designed to propel fixed wing aircraft transversely through the air. The pitch angle of the propellers in question was designed for best performance in cruise and would fare well at greater advance velocities. It would be desirable to design the pitch angle for best performance at take-off, due to the rotorcraft being propelled upward, where the advance velocities are low [12]. Figure 11 illustrates that the maximum thrust co-efficient C_T occurs at a very low advance ratio.

It is interesting to note however, that the thrust performance of the rotor is satisfactory. The BDCM used to power the rotor has a rating of 1010 kV [4]. Being powered by 11.1 V lithium polymer batteries, an approximate maximum rotational speed of 11000 rev/min can be achieved. From Figure 7, this implies that the propellers will be capable of producing sufficient thrust. The torque requirements are also satisfactory, as the motors have a specified stall torque of 0.459 Nm. This is sufficient to overcome the drag moment shown in Figure 8.

The loading along the propeller blade illustrated in Figure 14 and Figure 15 correlate with the co-efficient of lift and drag in Figure 9. The velocity stream depicted in the flow field diagram in Figure 16 also correlates with what was expected as typical air flow through a propeller [10].

It is therefore in the opinion of the author, that the propeller in question would be suitable to be utilised for the quadrotor UAV as an affordable alternative to the design and manufacture of a new propeller. However, to achieve optimal aerodynamic performance, the only option would be to design a propeller to suit the specific application of high thrust upward propulsion.

References

[1] D. Greer, P. McKerrow and J. Abrantes, "Robots in Urban Search and Rescue Operations", Australasian Conference on Robotics and Automation, Auckland, 2002

[2] R. Snyder, "Robots Assist in Search and Rescue Efforts at WTC", IEEE Robot Automation Magazine, vol. 8, 2001

[3] http://crasar.org/2011/page/4/, accessed 30th May 2011

[4] Maxon Motors Catalogue, May 2008 edition, pg199

[5] A.A. Mian and W. Daobo, "Modelling and Backstepping-based Nonlinear Control Strategy for a 6 DOF Quadrotor Helicopter", Chinese Journal of Aeronautics, vol. 21, 2008

[6] H. Huang, G.M. Hoffmann, S.L. Waslander and G.J. Tomlin, "Aerodynamics and Control of Autonomous Quadrotor Helicopters in Aggressive Maneuvering", IEEE International Conference on Robotics and Automation, Japan, 2009

[7] P. Pounds, R. Mahony and J. Gresham, "Towards Dynamically-Favourable Quad-Rotor Aerial Robots", Australasian Conference on Robotics and Automation, Canberra, ACT, 2004

[8] Y. Naidoo, R. Stopforth and G. Bright, "Development of an UAV for Search and Rescue Applications", IEEE Africon, Zambia, 2011

[9] S. Bouabdallah and R. Siegwart, "Full Control of a Quadrotor", International Conference on Intelligent Robots and Systems, 2007

[10] B.W. McCormick, "Aerodynamics, Aeronautics and Flight Mechanics", John Wiley & Sons, Inc, 1995

[11] http://www.pilotfriend.com, accessed 13th August 2011

[12] J. Roskam and C.E. Lan, "Airplane Aerodynamics and Performance", DARcorporation, 1997