Design Analysis of Ducted Propeller for Bicopter Drone Propulsion

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Abstract. Drones nowadays have become an important part of people's lives. Drones for transporting people or goods are considered to develop into reality. To be effective and efficient, the drone should be light but have big propulsion for big lift and thrust forces. This paper presents a way to improve the performances by designing usage of only 2 propulsion motors with ducted and special fan blades. The special designed fan blades theoretically will produce more thrust with smaller propeller size and lower RPM since combine the lift blade and momentum thrust effects. The required propulsion force to fly the drone with its payload is analyzed and determined. Then the torque, rpm, airfoil type, Thrust Coefficient, and blade twist angles can be determined based on that propulsion force. Afterward, an evaluation is performed with fluid dynamics simulation tools to predict the forces acting on the propeller.

1. Introduction

Unmanned Aerial Vehicle (UAV), commonly called a drone, is an aircraft system that is being flown from afar. Ranging from simple hand-operated short-range systems to durable and high-altitude systems. If previously the drone was only used for a variety of needs that were military or reconnaissance, currently drones were found for other activities such as photography, regional mapping and even for entertainment media [1].

Indonesia currently needs to improve their air transportation sector. Especially on the logistics distribution. The biggest problem that Indonesia facing now in terms of air transportation is limited space. It is difficult to find a suitable place for aircraft runways, especially in remote areas [2]. To overcome this, UAVs or drones can be used because of their flying mechanism that can do VTOL (Vertical Take-Off and Landing).

The development of UAV leads to the solution of two main problems, namely increasing battery life and increasing payload [3]. To overcome this problem, it can be done by making propellers that have huge thrust and high efficiency. To get a large thrust force, a duct can be used which is believed to increase thrust by 94% [4] as well as using special designed blades. Better battery capability and larger payload are increased by reducing the number of propeller drones to 2 motors or commonly called as bicopter, but with the consequences cost of uneasy stability control. The current bicopter aircrafts, i.e. Chinook and V22-Osprey, all are operated nicely wit their heavy weights but still with some technology secrets.

The propulsion thrust is produces from a combination of momentum theory and lift force blade such as rotary wing. The so called Blade Element Momentum Theory is implemented in the design analysis
that is determining the designed ducted propeller blades, which produce big thrust and suitable for flying the bicopter drone.

2. Methodology
The model is based on the approximation calculated thrust force that is required by the drone. The dimension of the drone is designed to be of 45.8 cm x 30 cm x 15 cm. With the weight of 1.75 kg, the thrust to weight ratio is 2:1, and the total drag force is predicted based on calculation of 0.0715 N. So the total thrust required is 34.33 N, or 17.16 N for each propulsion motor. The dimensions and shape of the design of the drone can be seen in the illustration shown in figure 1.

![Figure 1. Drone Dimensions.](image)

The total drag is divided into 2 sections which is body drag and propeller drag. We took a note on the body with the exposed surface area A, drag coefficient Cd, take off velocity V and air density ρ. Then, we can define the body drag [4]:

$$ D = \frac{1}{2} \rho V^2 A C_d $$  \hspace{1cm} (1)

To calculate the propeller drag, first we need to determine the resultant velocity W with the velocity triangle theory. To do so, we used the Blade Element Momentum Theory to calculate the local forces on a propeller blade. It uses the Blade Element Theory. We focused our attention on a propeller with radius R, rotating at an angular speed Ω, with air velocity at the inlet $V_{in}$, and tangential velocity $U$ [5]:

$$ U = \Omega R $$  \hspace{1cm} (2)

$$ W = \sqrt{U^2 + V_{in}^2} $$  \hspace{1cm} (3)

Then, we can get the propeller drag with [6]:

$$ D = \frac{1}{2} \rho W^2 R c(r) C_d $$  \hspace{1cm} (4)

Where $c(r)$ is the chord of the airfoil.

The elementary thrust and torque can be obtained alternatively from the lift and drag acting on the blade element as below [7]:

$$ dT = Bc \frac{1}{2} \rho W^2 R (C_l \cos \phi - C_d \sin \phi) dr $$  \hspace{1cm} (5)

$$ dQ = Bc \frac{1}{2} \rho W^2 R (C_l \sin \phi + C_d \cos \phi) dr $$  \hspace{1cm} (6)
where $B$ is the number of blades, $W$ is the resultant velocity with reference to the blade and $\phi$ is the angle of the vector $W$ with the plane of rotation of the propeller, as proposed by Houghton et al.

Half of the blade thrust is created by momentum theory because blower blade type is also used in this design to uniform the lift distribution. Which is \[ T = \dot{m}(W - V_{in}) \] (7)

Where $\dot{m}$ is the mass flow rate through the cross sectional area.

Comparisons can be made between the characteristics of open and ducted propellers, as a function of the ducted propeller’s expansion ratio which is the comparison between duct exit area and rotor area. By holding any two variables fixed between the two configurations, the behavior of the other variables can be analyzed [9].

\[ \frac{T_{op}}{T_{dp}} = (2\sigma_d)^\frac{1}{3} \] (8)

Where $T_{op}$ is open propeller’s thrust, $T_{dp}$ is ducted propeller’s thrust and $\sigma_d$ is the expansion ratio.

2.1. Calculation

The calculation of the blade using Blade Element Momentum Theory, are divided into 3 parts, namely: root, MAC (Mean Aerodynamic Chord), and tip that can be seen in the illustration (Figure 2a, 2b, 2c), along with the speed triangle that it produces.
Figure 2c. Angle and Velocity Triangle at Tip

The airfoil type Selig S1223 was being modified a little bit to accomplish the desired angle. As stated at the introduction, the thrust from the propeller is a combination between lift that is produced by the rotary wing which is from the leading edge to a certain point around the trailing edge, and momentum theory that is produced by the blower blade shape that is around the trailing edge. That is why the angle at leading edge and trailing edge is different.

2.2. 3D Modelling & Simulation.

The 3D modelling is done by using Autodesk Inventor as the software. Selig S1223 with the characteristic shown in figure 3, is being used in designing this propeller. With the consideration of Reynolds number, alpha, and Lift coefficient needed by the propeller, and the airfoil coordinate to design the propeller can be obtained from the UIUC Airfoil Coordinate Database. The solid model then become an input on ANSYS Fluid Dynamics (CFX) Simulation for predicting the thrust and the torque that being produced by the propellers.

Figure 3. Airfoil characteristic of Selig S1223

The boundary conditions (Figure 4) that being used was set according to daily air condition in Jakarta.
3. Results and Discussion
The calculation has been done and so the result of the blade and duct design can be seen in figure 5a & 5b.
Based on the initial calculation, one ducted propeller should be able to generate 18,858 N of thrust at 5700 RPM which is the minimum required thrust for the drone to hover. The gyroscopic effect working on the drone should be neutralized by the propeller one another.

**Figure 6a.** Pressure Contour  
**Figure 6b.** Velocity Contour

It can be seen from figure 6a and 6b, that the biggest pressure occurs at the tip. This shows that it is true duct reduces tip losses so that it can produce maximum thrust, as should be the case where the biggest thrust is generated in the tip section. So that it will produce a thrust of 15,657 N. This result differs quite far from the expectations of manual calculation which is equal to 18,858 N. So that it gets an error of 15%. However, this is still in accordance with the Blade Element Momentum Theory error, which is an error that is still included in the range of 29%.

Can be seen in the illustration (Figure 2a, 2b, 2c), the angle is made into 10.10°, 8.10°, and 5.10° at the trailing edge (root, MAC, tip respectively) and 36,82°, 38°, and 43,8°, at the leading edge. So that it produces a speed of 12.5 m/s, 24 m/s, and 29 m/s. The results of this manual calculation are still included in the speed value range in the simulation results as can be seen in the Velocity Contour illustration (Figure 6b).

### 4. Conclusion

a) Bicopter can also be used as a alternative drone type for everyday use just like the current model on the market, i.e. quadcopter.

b) The design verification of the resultant speed between theoretical calculation and computer simulation is not converged yet. 15% difference is merely due to inaccuracy of the number of calculation points on blade, i.e. root-MAC-tip, and less optimum number of the meshing nodes as well. However this is relatively adequate for developing the capacity and performance improvements for scaling up a prototype.

c) Bicopter drones are most suitable for point to point air transportation of passengers or goods, since with only 2 propulsion motors the maneuverability of bicopter is more difficult.

### Acknowledgment

The authors would like to thank PITTA grant programme of the University of Indonesia for funding this study with contract number NKB-0796/UN2.R3.1-HKP.05.00/2019.

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