Angkasa Jurnal Ilmiah Bidang Teknologi
ISSN : 2085-9503 (Print)
ISSN : 2581-1355 (On Line)
Accredited Fourth Grade by Kemenristekdikti, Decree No: 148/M/KPT/2020
DOI : 10.28989/angkasa.v14i2.1226

Endurance estimation in hovering flight based on battery power requested on quadcopter UAV

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Article Info

Article history:

Received April 8, 2022
Accepted May 23, 2022
Published November 1, 2022

Keywords:

Endurance estimation
UAV propeller
Blade element theory
Thrust calculation
UAV hovering

ABSTRACT

In this era, Unmanned Air Vehicle (UAV) is growing. However, there are still weaknesses in using UAVs to carry out certain missions. One of the major problems is the energy and power required to use the UAV which impact the endurance of a UAV can hover. This study calculates the endurance and finds which configuration will produce the optimal endurance for battery power requested on a Quadcopter UAV. It starts by calculating the thrust of a propeller using blade element theory which ends in calculating endurance. Using four different types of propellers, an integral formulation was devised for a constant–power battery discharge process to predict the hovering time. The result shows that APC 1238 combined with battery 6S will produce the longest endurance. The methodology is applicable for a custom quadcopter UAV.

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1. INTRODUCTION

The development of Quadcopter Unmanned Air Vehicle (UAV) is growing year by year. More industries or even individuals are using UAVs to perform a variety of missions, such as delivery, inspections, retrieval, and close interaction with hard-to-reach environments, but there are still weaknesses in using UAVs to carry out all these missions. One of the major problems is the energy and power required to use the UAV. This problem impacts the range, speed, and most importantly, the endurance or flight time the UAV can hover.

Based on Peukert's modeling of the discharge process, early research evaluating the performance and sizing of battery-powered aircraft became accessible only at the beginning of the previous decade. The Peukert Law is usually used to calculate the battery capacity. To be more specific, Puekert Law establishes an equation that can be used to quantify the inherent losses involved with discharging batteries at high currents. The Peukert effect states that the higher the current drain, the lower the battery's effective capacity.

In Mun Jin Cho and Cheolheui Han research, “Estimation of Hovering Flight Time of Battery-Powered Multicopters”. They used Peukert Law with a constraint that was only carried out on hovering flight missions. They found that a battery pack with its cells connected in series has a longer hovering duration than a pack connected in parallel at the same battery weight. Since the battery pack with its cells connected in parallel has lower voltage and more nominal capacity than the pack connected in series, a UAV with a series cell can have a longer flight time or endurance [1].

Gustavo de Carvalho Bertoli also used this approach in his research about “Extending Flight Endurance Electric Unmanned Aerial Vehicles through Photovoltaic System Integration”. They reported that to estimate the increased endurance of the battery-powered UAV adapted with photovoltaic cells, they derived the Peukert Law equation in conjunction with the power provided by the solar cells, and this approach shows high accuracy[2].

Another model that can be used is Blade Element Momentum (BEM). This model is a combination of blade element theory and momentum theory; hence the name is Blade Element Momentum (BEM). BEM theory itself is used to calculate the required power to hover, and this theory lately will be combined with a purely measured battery model. BEM simulates the physical process that generates thrust and axial drag torque. For example, it models how each tiny blade element of a propeller generates a force and torque that is then combined to yield overall thrust and rotor drag. On the other hand, the momentum theory is a simple theory that calculates the thrust (T) based on a momentum balance. This theory is one of the popular theories to calculate the endurance of a UAV.

J Hnidka and D Rozehnal in their research about "Calculation of the maximum endurance of a small unmanned aerial vehicle in a hover". They used this theory to calculate Propeller Performance Characteristic (PPCH) with an assumption that the inflow velocity is equal to zero or without disturbance because this theory cannot compensate for the dynamic behavior of the propeller mounted on the UAV. So, only a small deviation on each propeller can be expected, and the rotor dynamics have no substantial impact on the results[3].

In Myeong-Hwan Hwang, Hyun-Rok Cha, and Sung Yong Jung research about "Practical Endurance Estimation for Minimizing Energy Consumption of Multirotor Unmanned Aerial Vehicles" also used momentum theory to calculate the required power for propulsion. The required power of the rotor for a forward flying aircraft is a sum of the induced power and the power for overcoming the drag, which according to momentum theory, the induced velocity will be obtained[4].

The main contribution of this study to a quadcopter UAV is the development of a completely analytical framework, which eliminates the need for laboratory tests on power plant components and battery packs. Since most of the approaches mentioned above are based on experiments and there are still many studies that estimate the endurance of quadcopter UAVs based on the battery, not from other parts of a UAV. The analytical framework starts by calculating the thrust of a propeller using blade element theory which ends in calculating endurance. This manuscript consists of methodology in chapter 2, result and analysis in chapter 3, and conclusion and recommendation in the last chapter.

2. METHODOLOGY

The methodology used in this study consists of blade element theory, momentum theory, endurance estimation, and optimization. It also includes an explanation of the quadcopter configuration and propellers used.

2.1. Blade Element Theory

There are many theories that can be used to estimate the aerodynamic loads (force and moment) of a propeller, such as Vortice Lattice Theory, Lifting Line Theory, Panel Method, and Aerodynamic Cycles. However, Blade Element Theory (BET) is one of the most frequently used methods to estimate the blade's aerodynamic loads. BET theory was developed by Glauert in 1935 and became a theory that is widely used by researchers because of its ease in analyzing and even designing a propeller. BET itself is a theory that breaks down a blade into multiple small parts to approximate the total force that is acting in a propeller. The forces and moments produced by a propeller with varying numbers of blades in one revolution are then integrated along the full blade's radius and azimuth angle. The total vertical and horizontal forces acting on the blade's center of pressure are as follows in Figure 1.

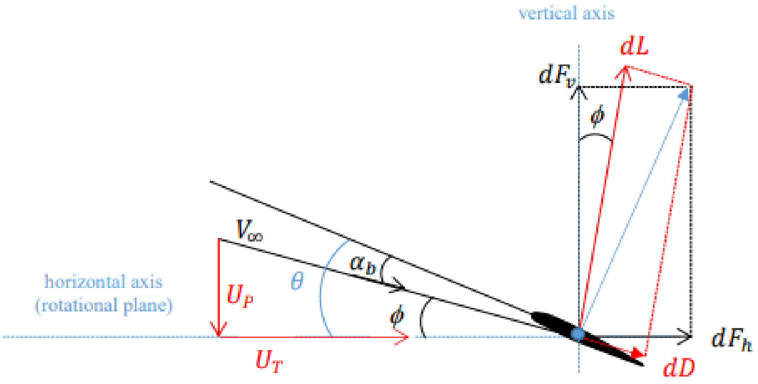


Figure 1. Total Forces Acting on a Blade

Some simplifications or assumptions are performed to integrate forces and moments acting on the blade [5]:

1. The propeller blades are assumed to be a rigid body.
2. The angle of attack, αb changes the lift coefficient of the blade airfoil linearly.
3. The blade's pitch angle, θ, varies linearly with its radial position.
4. The chord length is considered to be constant along the radius.
5. Because the force of lift operating on a blade is at least one order of magnitude more than drag, the contribution of drag force, dD, in the calculation of thrust force is minimal, so it can be ignored.
6. The local inflow angle, φ, is assumed very small.
7. On the blade section, only lift and drag forces are supposed to act.
8. Flow is assumed inviscid and incompressible.

Based on the assumptions mentioned above, the analytical result known as Classical Blade Element Theory is presented below:

$$T = \Omega^2\left(\frac{1}{6}\rho A\sigma a\theta_0 R^2 + \frac{1}{8}\sigma a\rho A\theta_{tw}R^2\right) + (V\cos\alpha)^2\left(\frac{1}{4}\rho A\sigma a\theta_0 + \frac{1}{8}\sigma a\rho A\theta_{tw}\right) + \Omega(V\sin\alpha + v_i)\left(-\frac{1}{4}\sigma a\rho AR\right) \quad (1)$$

The parameters in equation 3.3 are dependent on the geometry of the blade propeller and the density of air, and they can be calculated if the appropriate data is given. In this research, all the parameters such as the geometry of the blade propeller and the density of air, are available for the quadcopter that will be used. Even though all of the relevant data is available, this approach is slightly less accurate because there are some assumptions made previously. However, this BET approach is still more accurate than other approaches in calculating thrust because, in its calculations, many parameters involve the geometry of a propeller blade. In contrast, other approaches do not involve propeller blade geometry as much as the BET approach. For example, if we want to calculate thrust using the aerodynamic cycle approach, in this formula, there are only two parameters of propeller blade geometry that exist in this formula. Otherwise, both the propeller and the rotor are assumed to be aerodynamic cycles, with kinetic energy and work as input and output, respectively.

2.2. Momentum Theory

When a quadcopter UAV is in hovering mode, momentum theory can be used to calculate the induced velocity. The theory is based on fluid mechanics conservation laws called mass, momentum, and energy conservation of fluids for example such as air, to calculate the force exerted on a rotor. To calculate the induced velocity, the following assumptions were established based on [5]:

1. The flow is inviscid, incompressible, and quasi-steady.
2. The flow is one-dimensional and there is no velocity discontinuity.
3. The disc is infinitesimally thin, and the pressure is evenly distributed.
4. At all spots on the disc, induced velocity is considered to be uniform.
5. Because the rotor has an infinite number of blades, it can be thought of as a round disc.
6. The disc is infinitesimally thin.

The following Figure 2 depicts the airflow across the rotor disc.

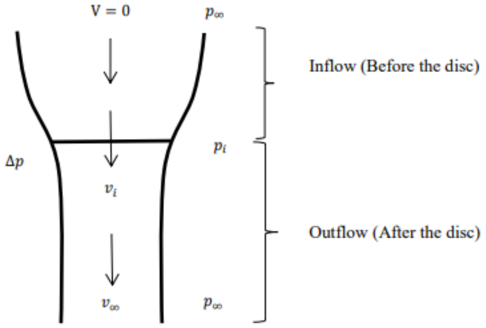


Figure 2. Airflow Through Rotor-Disc in Hovering

Using the above-mentioned pressure relation and energy conservation, the following relationship can be created in the inflow component.

$$p_\infty = p_i + \frac{1}{2}\rho v_i^2 \tag{2}$$

After doing some iterations, the thrust force can be expressed as follows:

$$T = \rho A v_i v_\infty = 2\rho A v_i^2 \tag{3}$$

$$v_{i,h} = \sqrt{\frac{T}{2\rho A}} = \sqrt{\frac{mg}{2\rho\pi r^2 N_r}} \tag{4}$$

Equation 2.4 is the induced velocity in hovering flight where the *m* is the weight of the quadcopter, *r* is the radius of the propeller, and N_r is the number of rotors

2.3. Marsha Noir UAV Configuration

Marsha Noir UAV is the name of the quadcopter used in this study. Marsha Noir UAV is a custom quadcopter made by Aviation Engineering IULI students' batch 2016. This UAV was created to meet the requirements for the System Design subject at IULI. This subject requires IULI students to design something. For the 2016 batch, they get the opportunity to design this UAV. This quadcopter can already be flown, and to fly it, we used software to assist flying the quadcopter. The software that is being used for the quadcopter is Ardupilot. ArduPilot is an open-source autopilot software suite for unmanned vehicles that can operate both fixed and rotary-wing aircraft. Developed by enthusiasts to operate model planes and rovers, the autopilot has evolved into a full-featured and reliable autopilot that is utilized by industry, research organizations, and amateurs alike. The design and dimension of the quadcopter are shown in Figure 3.

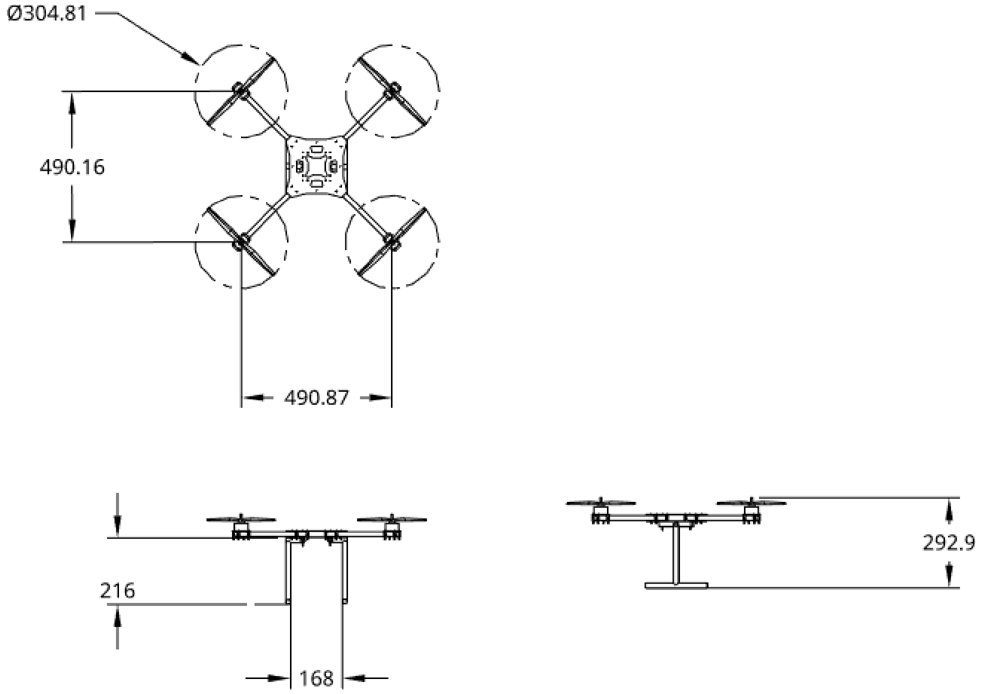


Figure 3. Marsha Noir UAV Dimension (unit in mm)

Each Motor has about 490 mm of clearance and the diameter of the propeller of about 304 mm. The ground clearance is set to about 216 mm and the width from leg to leg about 168 mm, enabling the quadcopter to carry a payload underneath its belly. There are many components in making this quadcopter, the configurations that are used by Marsha Noir UAV are shown in Table 1 and the picture of the Marsha Noir Quadcopter is shown in Figure 4.

Table 1 Specification of Marsha Noir Quadcopter

Components	Details
Wheel Base	490.87 mm
Propeller	4x 13 inch
Motor	4x T-Motor MT 4006-13
Battery Capacity	2200 mAh Li-Po Battery
ESC	Hobbywing Xrotor 40A ESC
Receiver	Radiolink R6DS Reciever
GPS Module	Ublox NEO-7M Precisions GPS Module Built-In Compass
Power Module	Power Module with Amass XT90 Plug Connector
Battery Plug	Connector XT90 Male & Female
Transmitter	Radiolink AT9 Transmitter
Controller Board	Ardupilot APM 2.8
RC Software	Ardupilot Module 1.8
Weight	1.8 Kg

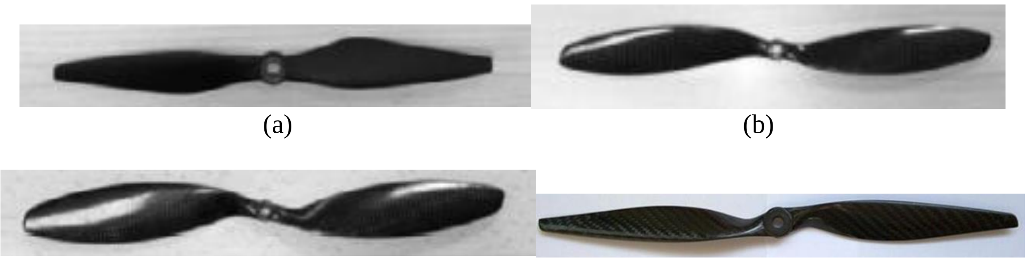
Figure 4. Picture of Marsha Noir Quadcopter

2.3 Propeller Selection

In this study, the authors chose the APC propeller 1365, which is the default propeller of the Marsha Noir Quadcopter UAV, the second propeller is the APC propeller 1038, and the last is the APC propeller 1238. The 1038 and 1238 propellers were chosen because these two propellers are suitable when paired with a motor used by the Marsha Noir Quadcopter. These two propellers have fairly complete data that can be used to perform calculations in finding thrust. To be more specific, the data of each propeller is shown in Tabel 2.2 and the shape of each propeller is shown in Figure 5.

Table 2. Propeller Data

No	Propeller	Diameter [inch]	Γ [inch]	$\bar{c}$ [mm]	c_{75} [mm]	θ_{tw} [rad]
1	APC 1038	10	3.8	21.5	18	0.34779
2	APC 1147	11	4.7	25.3	29	0.2556
3	APC 1238	12	3.8	28.4	31	0.2697117
4	APC 1365	13	6.5	19	22	0.075931



(a) (b)

(c) (d)

Figure 5. Shape of APC Propeller: (a) 1038, (b) 1147, (c) 1238, (d) 1365

2.4 Endurance Estimation

An integral formulation was devised for a constant–power battery discharge process to predict the hovering duration by imposing the balance between required and available power. In this study, the calculation of endurance or flight time of a quadcopter UAV that uses a Li-Po battery is carried out during hovering flight conditions. The entire procedure for estimating the hovering flight time for a given multirotor configuration is detailed in Figure 6.

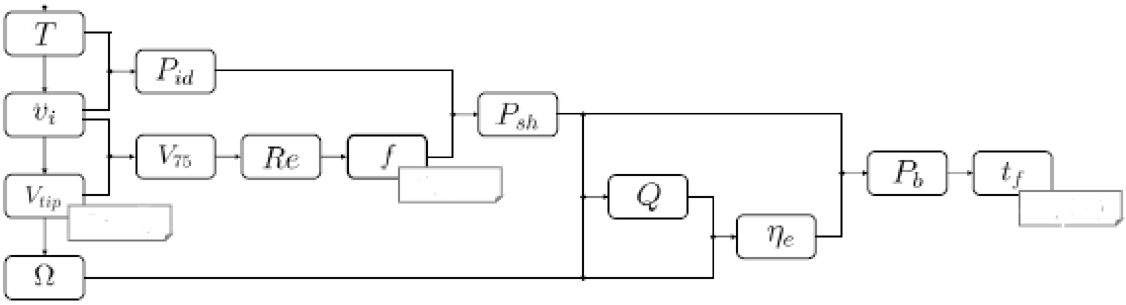


Figure 6. Procedure to estimate Flight Time of battery-powered Quadcopter at hovering condition [6]

The first step that must be done is to calculate the thrust generated by each propeller using the BET classical approach. Each propeller will produce a different thrust because each propeller has a different shape and size, from the diameter to the twist angle of the propeller.

Let's recall equation 2.1. The formula was obtained after several iterations and several assumptions [7]. Where Ω is the angular velocity which the value is provided by T-Motor manufacture and it can be found in reference [8], ρ is the density of air which the value is 1.225 kg/m^3, A is the area of the rotor which can be obtained with the formula below:

$$A = \pi r^2 \tag{2.5}$$

Which r is the radius of the propeller. The next parameter is σ which is usually called rotor solidity, which can be found using the below equation

$$\sigma = \frac{B\,\bar{c}}{\pi\, R} \tag{2.6}$$

Where B is the number of blades, $\bar{c}$ is the blade mean aerodynamic, and R is the rotor radius. The next parameter of the BET Equation is a which is the slope factor where the value is constant, which is the value corresponding to π. θ_0 and which θ_{tw}which are the pitch angle and twist angle of the propeller respectively. The pitch angle of the propeller is usually measured at a blade section located at 75% of the maximum propeller radius and it be calculated using the below equation

$$\theta_{75} = arctan\frac{\Gamma}{0.75\,\pi\, D} \tag{2.7}$$

Where, Γ is the pitch propeller, and D is the diameter of the propeller. Next, for the value of the twist angle usually provided by the propeller manufacturer, the range values for the twist angle of a propeller are 4 degrees to 20 degrees. V is the free stream velocity. Since this research calculation is carried out in hovering flight conditions, the free stream velocity here is equal to zero. Next is α which is the angle of attack, the value is also equal to zero since the quadcopter flight is in hovering mode. The last parameter is R which is the rotor radius. Most of the parameters in this BET classic formula are known, and some can be calculated.

After the thrust value of each propeller obtained, it can be used to find the induced velocity at hovering, v_i we can recall equation 2.15 to obtain the induced velocity. The result of this induced velocity is used to find the ideal induced power. On the basis of momentum theory, ideal induced power, P_{id} obtained as the product between the thrust generated by the single rotor at hover and the induced speed v_i, which is assumed to be uniform on the actuator disk. The formula of P_{id} is expressed below:

$$P_{id} = T\, v_i \tag{2.8}$$

Next step, we need to calculate the k_{tip} or the blade tip correction. This blade tip correction will be used to calculate the blade tip speed. The k_{tip} formula is as follows

$$k_{tip} = \frac{1}{4}\left(\frac{1+\sqrt{1+\frac{64}{\sigma C_{l\alpha}}\frac{\theta_{75}}{3}}}{\frac{\theta_{75}}{3}}\right) \tag{2.9}$$

Where σ can be obtained using equation 2.17, θ_{75} also can be obtained using equation 2.18, and $C_{l\alpha}$is slope of 2D lift coefficient, it can be assumed $C_{l\alpha} = 2\pi\, rad^{-1}$ which this formula based on thin airfoil theory. After K_{tip} obtained, blade tip speed, V_{tip} can be calculated with the following formula

$$V_{tip} = k_{tip}\, v_i \tag{2.10}$$

Before going further, the blade tip speed, V_{tip} need to be corrected with the function of induced velocity, v_i. The V_{tip} correction can be written as:

$$\hat{V}_{tip}(v_i) = \frac{k_{tip}\sigma}{(\Gamma/\mathrm{D})^2}[v_1 + v_2(\Gamma/\mathrm{D})^q](v_3 + v_4 v_i^r)v_i \tag{2.11}$$

Where the v_1, v_2, v_3, v_4, r, and q are coefficients obtained from the experiment conducted by Emanuele L. deAngelis, Fabrizio Giulietti, Gianluca Rossetti, Gabriele Bellani in their research. $v_1 = -9.144 \cdot 10^{-2}$, $v_2 = 2.599$, $v_3 = 2.525$, $v_4 = 7.784 \cdot 10^{-1}$, $q = 1.757$, $r = -5.831 \cdot 10^{-1}$. Knowing all these coefficients, the V_{tip} correction can be calculated. The results of V_{tip} correction can be converted to angular velocity, which later on the value can be used to calculate the torque of the motor. Proceed to the next step, we need to calculate the figure of merit, f. The figure of merit is expressed as a function of Reynolds number:

$$\hat{f}(Re) = f_0 + f_1\, Re + f_2\, Re^2 \tag{2.12}$$

Where,

$$f_0 = (\Gamma/\mathrm{D})^2[f_{00} + f_{10}(\Gamma/\mathrm{D}) + f_{20}(\Gamma/\mathrm{D})^2] \tag{2.13}$$

$$f_0 = (\Gamma/\mathrm{D})^2[f_{01} + f_{11}(\Gamma/\mathrm{D})] \tag{2.14}$$

$$f_0 = (\Gamma/\mathrm{D})^2 f_{02} \tag{2.15}$$

In the present framework, the figure of merit is expressed as function of few propeller parameters that can be extracted either from the propeller datasheet or from simple measurements. For the f_{00}, f_{10}, f_{20}, f_{01}, f_{11}, and f_{02} the coefficients that obtained from the experiment as well which conducted by Emanuele L. deAngelis, Fabrizio Giulietti, Gianluca Rossetti, Gabriele Bellani in their research. $f_{00} = 17.03$, $f_{10} = -56.28$, $f_{20} = 50.61$, $f_{01} = 5.19 \cdot 10^{-5}$, $f_{11} = -6.034 \cdot 10^{-5}$, $f_{02} = -1.033 \cdot 10^{-10}$. The Reynolds number can be calculated using the following formula:

$$Re = \frac{\rho c_{75} V_{75}}{\mu} \tag{2.16}$$

The Reynolds number is conventionally calculated at a blade radius of 75%, where μ is the dynamic viscosity of the air which the value is $1.81 \cdot 10^{-5}$. The c_{75} and V_{75} represent the local airfoil chord and relative airspeed respectively. V_{75} can be calculated using the following formula:

$$V_{75} = \sqrt{v_i^2 + (0.75\, V_{tip})^2} \tag{2.17}$$

After figure of merit obtained, the power delivered by each electric motor to its rotor shaft, P_{sh} can be calculated as follow:

$$P_{sh} = \frac{P_{id}}{f} \tag{2.18}$$

After the P_{sh} value is obtained, the torque applied by the electric motor to its rotor can be determined with the following formula:

$$Q = \frac{P_{sh}}{\Omega} \tag{2.19}$$

and the efficiency of electric motor, η_e also can be determined. Since in this study, the quadcopter is using T-Motor MT 4006-13, the efficiency is known which the value is 0.84 or 84%.

For the final step, we need to calculate power requested from the battery, P_b, it can be expressed as follow:

$$P_b = P_s + \frac{N\,P_{id}}{f\,\eta_e} \tag{2.20}$$

Where the P_s is the power to be absorbed by on board system which the ideal value is 5 Watt. After that, the endurance at hovering flight mode can be calculated with the following formula

$$t_f = \delta P_b^{\in} C_f^{\beta} \tag{2.21}$$

Where the δ, $\in$, and β are coefficient coefficients of Li-Po battery, which depend on battery technology, ambient temperature, and the number of series–connected cells and determined experimentally. The value of each coefficient should be $\delta > 0, \in < -1, and\ 0 < \beta < 1$ respectively. On the other hand, when electricity is given by Li–Po battery packs and no equipment to conduct ad hoc battery tests is available, the analytical results obtained in [9] can be used, particularly during the basic design stage. Let N_s be the number of battery cells, δ, and $\in$ can be obtained with the following formula, while β is a constant value which equals to 0.9664:

$$\delta(N_s) = -0.1067N_s^3 + 0.8960N_s^2 + 2.488N_s + 0.6299 \tag{2.22}$$

$$\begin{aligned} \epsilon(N_s) = 2.917 \cdot 10^{-4}N_s^3 - 1.375 \cdot 10^{-3}N_s^2 \\ +3.083 \cdot 10^{-3}N_s - 1.041 \end{aligned} \tag{2.23}$$

2.5 Endurance Optimization

Objective function in this study is to maximize the endurance of the quadcopter. An optimization function problem can be stated as follow:

$$\text{Max}\ (t_f\ (T\ (\theta_{tw}), S)) \tag{2.24}$$

Where the t_f is the endurance of the drone in hovering flight condition, T is the thrust, θ_{tw} is the twist angle of the propeller, S is the battery cells. The optimal endurance can be obtained when the twist angle of each type of propeller is varied and combined with different battery cells, which with variations in the twist angle and battery cells will produce different thrusts where this thrust value affects the endurance of the drone. From there we can determine the most optimal endurance for Marsha Noir quadcopter UAV.

There is also a constraint on optimizing the endurance of the quadcopter. The constraint problem can be stated as follow:

1. The drone only flies in hovering flight condition
2. All components on the drone have not changed. The type of propeller used remains the same, which are APC 1038, 1147, 1238, and 1365 propeller, only that the twist angle of each propeller is varied. The same as with the battery, the battery used still has the same capacity, which is 2200 mAh, only the battery cells are varied
3. The twist angle of the propeller varies from 1 degree to 40 degrees.
4. Battery cells are varied starting from 3S, 4S, 5S, and finally 6S
5. The optimal endurance chosen is when the drone has a thrust to weight ratio scale of equal with 1.5 or more

To achieve the longest endurance, it is start from varying or custom the twist angle of each type of propeller tested in this thesis. The twist angle of each propeller will be varied from 1 degree to 40 degrees. The purpose of varying this twist angle is to see whether the twist angle specified by the propeller manufacturer is optimal or not. By changing or varying the twist angle, of course, we will also get a varied thrust, which from these results, we can determine which twist angle can produce the longest endurance when the drone is hovering.

Besides producing different thrusts, varying the twist angle for each type of propeller can also affect the thrust-to-weight ratio on the quadcopter. For a drone, there are standards or classifications regarding the scale of the thrust to weight ratio that can be used and can be seen in Table 3[10].

Table 3. Drone Thrust to Weight Ratio Scale

Speed	Thrust-to-Weight Ratio	Usage
None	< 1.1	Paper Weight
Poor	1.1 – 1.2	Frustration
Flyable	1.2 – 1.5	Indoor
Better	1.5 – 1.9	Light Wind
Fast	1.9 – 3.0	Heavy Wind
Turbo	3.0 – 5.0	Arco and Racing
Rocket	> 5.0	

Since the purpose of this thesis is to estimate the thrust when hovering flight, which in the end the thrust will be converted into endurance, in this case, the thrust-to-weight ratio has an influence on how strong or fast the drone can lift and perform a hovering flight. The author uses the thrust to weight ratio scale equal to 1.5 and more because the 1.5 scale is the optimal limit for flyable drones.

In addition, the author also tried to change the battery cells. The initial configuration of the Marsha Noir Quadcopter UAV uses a 6S battery with a capacity of 2200 mAh as the power to fly this drone. In this study, the authors tried to change the initial battery cells from 6S battery to 3S, 4S and 5S, where the capacity is still the same. By changing the battery cells and twist angle of each propeller, it is hoped that we can get the most suitable configuration for the Marsha Noir Quadcopter UAV so that it can produce the longest endurance in hovering flight conditions.

3. RESULT AND ANALYSIS

This section shows all the results of thrust calculations using Blade Element Theory and also the results of endurance calculations after thrust is obtained in the form of a scatter plot. In addition, this chapter also explains how to find the most appropriate configuration to get the most optimal endurance by replacing battery cells and varying the twist angle on the propeller.

3.1. Thrust and Endurance Estimation

The first objective of this thesis is to calculate the endurance of the Marsha Noir Quadcopter UAV when attached with different propellers. In estimating the endurance, as mentioned in the previous chapter, the first step is to calculate the thrust of each type of propeller. All thrust calculations for each type of propeller are obtained using Blade Element Theory (BEM) when the drone is given 50% power. The thrust and endurance of Marsha Noir Quadcopter UAV is plotted in Figure 7.

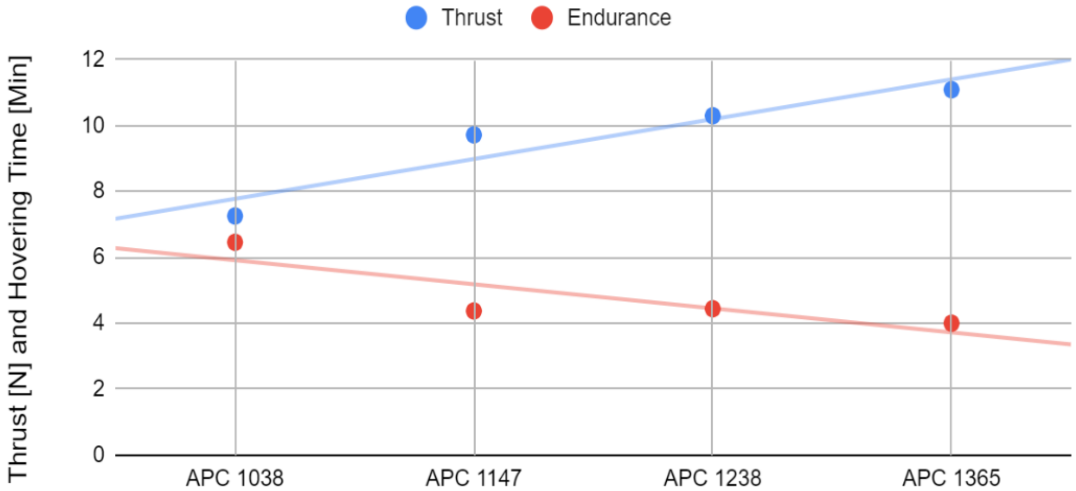


Figure 7. Plotting of Thrust and Endurance for Each Type of Propeller That Available in the Market Using Default Battery Cells (6S)

We can see that the endurance produced will be smaller if the thrust is bigger. In this calculation, if we attach the APC 1038 propeller to the Marsha Noir Quadcopter, this propeller is capable of producing a thrust of 7.25 Newton, and can perform a hovering flight for 6 minutes 27 seconds. Furthermore, if we attach the APC 1147 propeller to the Marsha Noir Quadcopter, this propeller is able to produce a thrust of 9.71 Newton and can perform a hovering flight of about 4 minutes 22 seconds. Next, if we attach the APC 1238 Propeller to the Marsha Noir Quadcopter, this propeller can generate a thrust of 10.29 Newton and is capable of hovering flight for 4 minutes 26 seconds. Lastly, if we pair the APC 1365 Propeller on the Marsha Noir Quadcopter, this propeller can generate thrust of 11.08 Newtons and is capable of hovering flight for 3 minutes 59 seconds.

3.2. Thrust and Endurance Optimization

To find optimal endurance, first of all, one of the propeller parameters, which is the twist angle is varied from 1 degree to 40 degrees and the thrust is calculated using Blade Element Theory when combined with several different battery cells, ranging from 3 cells to 6 cells. All calculations shown in this section are calculated when the drone is powered by 50% throttle. The optimal endurance can be obtained with finding a new twist angle of the propeller. The new twist angle be obtained based on the plot below:

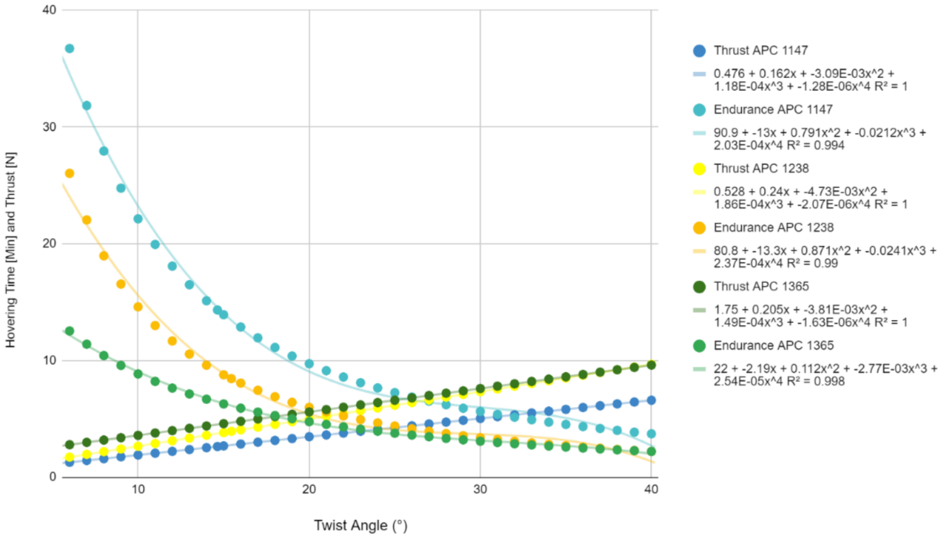


Figure 8. Plotting of Thrust and Endurance of Varied Twist Angle Combined with Battery 3S

The plot above is a thrust and endurance plot for each type of propeller combined with a 3S battery if the twist angle is varied from 1 to 40 degrees. The plot above will form a trendline that intersects each other and also produces their respective equations. It can be seen from the Figure 8, the equation thrust and endurance for APC 1147 can be written as follow:

$$y1 = -1.28 \cdot 10^{-6}x^4 + 1.18 \cdot 10^{-4}x^3 - 3.09 \cdot 10^{-3}x^2 + 0.162x + 0.476 \tag{3.1}$$

$$y2 = 2.03 \cdot 10^{-4}x^4 - 0.0212x^3 + 0.791x^2 - 13x + 90.9 \tag{3.2}$$

For APC 1238 propeller, we get the following equation:

$$y1 = -2.07 \cdot 10^{-6}x^4 + 1.86 \cdot 10^{-4}x^3 - 4.73 \cdot 10^{-3}x^2 + 0.24x + 0.528 \tag{3.3}$$

$$y2 = 2.37 \cdot 10^{-4}x^4 - 0.0241x^3 + 0.871x^2 - 13.3x + 80.8 \tag{3.4}$$

For APC 1365 propeller we get the following equation:

$$y1 = -1.63 \cdot 10^{-6}x^4 + 1.49 \cdot 10^{-4}x^3 - 3.81 \cdot 10^{-3}x^2 + 0.205x + 1.75 \tag{3.5}$$

$$y2 = 2.54 \cdot 10^{-5}x^4 - 2.77 \cdot 10^{-3}x^3 + 0.112x^2 - 2.19x + 22 \tag{3.6}$$

To get the intersection point we make it into y1=y2, where y1 is the equation for thrust and y2 is the equation for endurance, in which the goal is to get the factors from this polynomial equation. The factoring will produce four factors since the equation itself is the power of four. The quadratic polynomial equation here is chosen because when a trendline is created, the quadratic polynomial equation has the smallest R value compared to the polynomial equation with the power of two or three. One result of the factoring will be the optimal twist angle for each type of propeller with respect to the battery cells.

For the APC 1147 propeller, when equations 3.1 and 3.2 are factored, we will get four factors, which are, x1 = 30.1239, x2 = 44.6006, x3 = 14.8161 + 10.4855i, x4 = 14.8161 - 10.4855i. From these four factors, the factor x1 will be a twist the new angle for the APC 1147 propeller on the 3S battery where the value is 30.1239 degrees because the x3 and x4 factors are imaginary numbers so we can not use it as a new twist angle, while we do not use the x2 factor because it exceeds the limit of the twist angle variation range tested in this study.

Furthermore, for the APC 1238 propeller, when equations 3.3 and 3.4 are factored we will also get a value of 4 factors, which are, x1 = 30.2042, x2 = 41.5483, x3 = 14.9164 + 6.71264i, x4 = 14.9164 – 6.71264i. From these four factors, the new twist angle for the APC 1238 propeller when combined with the 3S battery is 30.2042 degrees.

Finally, for the APC 1365 propeller, when equations 3.5 and 3.6 are factored, we will get four factors, which are, x1 = 19.1297, x2 = 54.6992, x3 = 17.0811 + 20.596i, x4 = 17.0811 - 20.596i, from these four factors the one which will be the new twist angle for the APC 1365 propeller when combined with the 3S battery is a factor of x1 which is 19.1297 degrees.

This approach is repeated when the drone is paired with 4S, 5S, and 6S battery. After all, the twist angles of each type of propeller with respect to certain battery cells have been found, the next step is to recalculate the thrust using Blade Element Theory (BEM) with this new twist angle, after the thrust for each new twist angle is calculated, we can proceed to calculate the endurance. Using the method mentioned in section 2.4. The following table shows the calculation results for thrust and endurance along with the thrust to weight ratio scale of the new twist angle.

Table 4. Table of Thrust and Endurance with New Twist Angle

Propeller Type	Battery Cells	New Twist Angle [Degree]	Thrust [N]	Endurance [Min]	Thrust to Weight Ratio Scale
APC 1147	Battery 3S	30.1239	5.053034144	5.605595487	1.266424597
APC 1238	Battery 3S	30.2042	7.381901003	3.353051483	1.850100502
APC 1365	Battery 3S	19.1297	5.419849622	4.977136606	1.358358301
APC 1038	Battery 4S	32.0381	6.737363952	4.573067231	1.607962757
APC 1147	Battery 4S	23.182	6.75138073	5.007477227	1.61130805
APC 1238	Battery 4S	15.17	6.123529328	6.191715876	1.461462847
APC 1365	Battery 4S	7.27026	5.924440457	6.125143884	1.413947603
APC 1038	Battery 5S	28.5225	8.028693894	4.557255721	1.871490418
APC 1147	Battery 5S	12.9755	6.69314088	6.520801145	1.560172699
APC 1238	Battery 5S	11.5916	6.657647218	7.01993227	1.551899119
APC 1365	Battery 5S	1.28548	6.222131333	7.337276837	1.450380264
APC 1038	Battery 6S	20.3254	7.37155462	6.301081543	1.671554336
APC 1147	Battery 6S	8.96694	7.116577964	7.215310626	1.6137365
APC 1238	Battery 6S	9.70748	7.285619862	7.474697211	1.652067996
APC 1365	Battery 6S	-2.35336	6.372855954	8.623064789	1.445092053

From the table above, actually, all types of propellers with this new twist angle can make the drone flyable. However, according to the assumptions made in section 2.5, the row that is coloured green is the type of propeller with a new twist angle that makes the drone flyable optimally because the value of the thrust to weight ratio is greater than or equal to 1.5. We can see from the table that the endurance of Marsha Noir Quadcopter is most optimal when attached with the APC 1238 propeller, where the twist angle must be adjusted to 9,70748 degrees and combined with a 6S battery. In this configuration, we can see that the thrust generated is about 7.28 Newtons and is able to make the drone fly for 7 minutes 28 seconds.

Literature [6] become a comparison for this study since the endurance calculation carried out in this study uses a flow chart and several parameters such as battery coefficient that have been tested in this literature. In this literature, the endurance of DJI drones with different configurations is calculated. Some results in this literature can be seen in the following table and plot.

Table 5. Predicted and Measured Performance Data for Different DJI F550 configurations

Configuration	W_0 [N]	Propeller	f	η_e	t_f est [min]	t_f meas [min]
MR6-9	18.51	1 (APC 0845)	0.683	0.646	10.03	9.83
MR7-9	13.24	1 (APC 0845)	0.676	0.625	13.45	13.05
MR8-9	18.86	4 (APC 1045)	0.668	0.584	10.88	10.77
MR9-9	13.59	4 (APC 1045)	0.654	0.557	14.15	14.13

Figure 9 is the plot of table 5. where the drone tested in this literature uses a battery with a capacity of 9 Ah and 4 cells, therefore, for comparison, the authors include endurance data when the Marsha Noir Drone uses a 4 cells battery with a capacity of 2.2 Ah. The MR6-9 and MR8-9 configurations are become a comparison because in this configuration the weight of the drone is closest to the Marsha Noir Quadcopter, where the Marsha Noir drone weights approximately 17.65 Newtons. We can compare if the DJI F550 drone is powered by a battery with a capacity of 9 Ah and 4 cells attached with APC 0845 and APC 1045 propeller, the endurance is around 9.83 minutes to 14.13 minutes, while the Marsha Noir Drone which is powered by a battery with a capacity of 2.2 Ah and 4 cells attached with APC 1038 and APC 1147 propeller, its can only fly for 4.57 minutes to 5 minutes. The results of the endurance calculation for the Marsha Noir Drone are quite reasonable, since Marsha Noir Drone uses a smaller battery capacity, of course, the endurance is also getting smaller. Besides that, the endurance point for the APC 1147 propeller is above the trendline of MR8-9 configuration where in this configuration the propeller used is APC 1045 propeller with a drone weight of 18.86 Newton. The same as the endurance point for the APC 1038 propeller which is located above the trendline of MR6-9 configuration where in this configuration the propeller used is APC 0845 propeller with a drone weight of 18.51 Newton. It is proved that if the quadcopter UAV is attached with a larger propeller diameter, the endurance produced will also be greater.

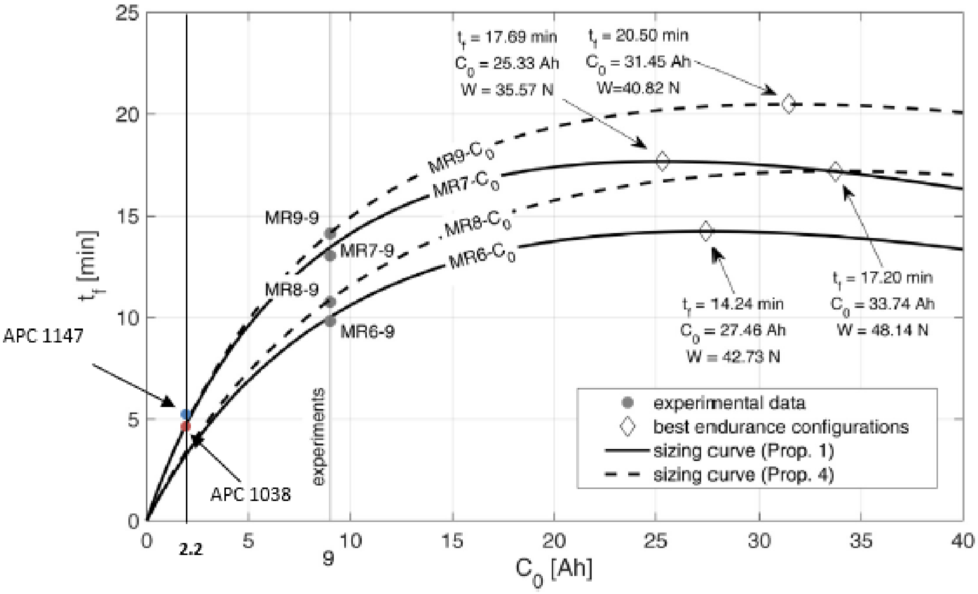


Figure 9. Comparison Results Plot where the blue and red dot are our result.

4. CONCLUSION AND RECOMMENDATION

The initial objective of this thesis is to estimate the endurance of the Marsha Noir Quadcopter UAV based on the thrust generated by the different types of propellers available in the market. These propellers include APC 1038, APC 1147, APC 1238, and the last one which is the default propeller from The Marsha Noir Quadcopter is an APC 1365 propeller. By applying the Blade Element Theory formula, the thrust for each type of propeller has been found and can be used to calculate the endurance of the Marsha Noir Quadcopter UAV.

Based on the calculation results, it can be concluded that by using the type of propeller on the market and the using default battery from the Marsha Noir Quadcopter which is a 2200 mAh and 6 cells battery, the APC 1038 propeller is the most suitable propeller to be installed in the Marsha Noir Quadcopter UAV. This type of propeller can generate a thrust of 7.25 Newton and make the drone fly for 6 minutes and 12 seconds in a hovering flight condition.

After estimating endurance with propellers available in the market, in this study the author also tries to find the most optimal configuration to produce the longest endurance by varying one of the parameters of the propeller, which is twist angle and also varying battery cells starting from 3S, 4S, 5S, and the 6S which has a power of 2200 mAh. Based on calculations, the most optimal endurance that can be achieved by this Marsha Noir Quadcopter is if we attach the APC 1238 propeller whose twist angle is adjusted to 9.70748 degree and combined with a 6S battery, with a configuration like this the drone can fly for 7 minutes and 28 seconds in a hovering flight condition.

This research has been resulting in the estimation of endurance based on the thrust generated by the propeller. It might be more interesting if the estimation of endurance is calculated through the other part of a drone, as an example is a battery, to see what is the difference generated when estimating the endurance of a drone based on other parts of a drone. In addition, the calculation of endurance will be more interesting if in the next study we can calculate endurance in conditions other than hovering flight, for example, when a drone is cruising.

The use of the Blade Element Theory (BEM) formula in calculating thrust in this study still uses many assumptions that make this formula simpler than the actual BEM formula, where the BEM formula actually contains slightly more parameters than the BEM formula used in this study one of those parameters is flow angle φ[11]. Since the calculations of endurance in this study use the steps and parameters available in this literature [6]. The results of the endurance calculation from this study can be said to be quite satisfying, however, this study would be better if we did an experimental flight on a drone to compare the calculation results with the actual results. By doing this experimental flight, of course, it can be a strong validation material for our calculation result.

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