The effect of different motor constants to an commercial propeller

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Abstract. This paper discussed the performance of a propeller with different motor constants such as the speed constants and motor resistance. The performance that was compared are the thrust, torque and total efficiency. There are many motors developed by the manufacturer, but the datasheet given are not complete and lack the information such as rotational speed and torque. This information is useful for designers and hobbyists to size their UAV or multicopter. In the market, there are many types of motors that make it difficult to choose the best motor. This research will perform analysis from the datasheet obtained from the manufacturer to see the effects of different motors to the propeller performance. It was gathered that for lower K_v such as KV980, it is better when higher torque than thrust is required. But for motor with speed constant above 1250 to 1400, the choice of motor will not have significant effect on the propeller performance. However, when size increase with higher K_v (more than 1400) the efficiency will drop.

1. Introduction

Recent research in developing Unmanned Aerial Vehicle (UAV) either a quadrotor, fixed wing UAV or any other unconventional UAV design are based on experience and off-the-shelf items. The development of quadrotor is common worldwide where the information to assemble a quadrotor is abundant and can be found easily. However, when it comes to design a UAV from conceptual design to design validation, verification and testing, it requires technical knowledge that comprises of structural design, aerodynamics, control, navigation and propulsion. This information is lacking from our technical community. Nowadays, the drone community starts to move from conventional quadrotor and fixed wing UAV to a mix of both configurations. The best for range is in a fixed wing UAV and good manoeuvrability is in a multirotor-styled UAV. Hybrid UAV is now trending research topic, but the knowledge and technicality of the design is not yet fully understood.

Hybrid UAV can range from tilt-wing, tilt-rotor, dual-system UAV and tail-sitter UAVs. These names imply the configuration of UAV transition style, for example, tilt-wing is based on the configuration that the wing can be tilted to change mode from vertical take-off or hover mode to cruising mode such as DHL parcelcopter and GL10. Tilt-rotor configuration is based on the rotor that can be tilted to achieve the same mode as a tilt-wing. Dual-system UAV is the easiest configuration of hybrid UAV as it combines both quadrotor and fixed wing design. In vertical and hover mode, the

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quadrotor propulsion system will be activated and once the desired cruising speed is achieved, the fixed wing system will be activated, and the quadrotor will be deactivated. Finally, the transition between modes for tail-sitter configuration is done by tilting the whole UAV body to perform the transitions. Y. Ke et. Al [1], H. Gu et. al. [2] performed experimental testing to combined the two modes and were successful. Even though the papers cited that the flight test was successful, but there is no research which focus on the compatibility of the motors, propeller and wing design to achieve the desired mode nor the dynamics of the transition.

Based on Ashraf M.K. and Alex R.S.[3], the authors developed a chart for tilt-rotor UAV that enables to define the preliminary design parameters based on the power loading and wing load of both fixed-wing and rotorcraft. This can be a fast solution to decide on the preliminary sizing without using numerical optimization methods. Based on Y Ke. et. al.[1], the preliminary design parameters were taken into account for a tail-sitter configuration. It was emphasis that a good match between a DC motor, electronic speed controller (ESC) and propeller is important to provide sufficient thrust for the UAV especially to perform transition. H. Gu et. al. [2], were able to developed the dual system UAV. The propulsion system was taken based on the take-off weight and the required thrust. These and other researchers were able to design and developed a UAV from off-the-shelf mechanism but the matching of propulsion system were not detailed out. In this research, the relation between propeller sizes and motor KV will be studied. Hattenberger G. et. al. [4], perform experimental characterization of the electrical propulsion system. They varied different propeller with a single motor type and were able to gain an equation to simplify the equation between Aerodynamic Power and Electrical Power. UAV and Multirotor uses Direct Current (DC) motor and commonly used DC motor is the brushless DC Motor due to its advantages such as longer lifetime and less noise. However, there are numerous motor specifications produced by the manufacturer and the variation in terms of the motor constants are not that difference. The problem with the motor specification given by manufacturer especially for remote control UAV purposes are not well documented. Sometimes as a UAV or multirotor designer and hobbyist, the matching of propellers to motor is not trivial. The question is the effect of different motors to a single propeller. In this paper the study of the effect of propeller to a motor will be discussed and to see whether the different KV motor actually affects the thrust generated by the same propeller.

2. Methodology

There are many motors developed by different manufacturer such as DJI, SunnySky, KDE Direct and T-Motor, but there is no indication the type of motor and propeller to be used for a mission. The datasheet given by DC motors manufacturers are not complete, however these motors are the most used by designers and hobbyist. This research will perform analysis from the datasheet obtained from the manufacturer to see the effects of different motor to the propeller performance. Most datasheet of motor will give information on the current, thrust, total efficiency and electrical power from the static thrust test but not the corresponding rotational speed and torque. Most of the time, when designing a UAV or multicopter we are interested in the rotational speed to the thrust and torque of the propeller-motor combination. As describe earlier, the datasheet given by manufacturer are not complete as most of them did not state the rotational speed and torque required for a propeller motor match testing. The following described the DC motor parameters:

$$Q_m(i) = (i - i_0)/K_v \tag{1}$$

$$\Omega(i,v) = (v - i\Re)K_v \tag{2}$$

$$\eta_m = \frac{P_{shaft}}{P_{elec}} = \frac{Q_m\Omega}{iv} \tag{3}$$

Where Q_m, Ω and η_m are the motor torque in *N.m*, rotational speed in *rad/s* and motor efficiency respectively and a function of current, *i* and motor terminal voltage, *v*. Q_m, Ω and η_m depend on the motor constants which can be measured by static benchtop experiments and are normally stated in the motor datasheet. These motors constants are the speed constants, K_v usually in RPM/volts but here we will use rad/s/volts, the no-load current i_0 and the motor resistance, $\Re$.

The propeller used for UAV and multirotor will also defined the performance of the UAV. These parameters are the thrust, *T* (N), propeller torque Q_p (N.m) and propeller efficiency, η_p. The parameters are given as shown:

$$T(\Omega,V) = \frac{1}{2}\rho(\Omega R)^2 \pi R^2 C_T(J, R_e, \text{geometry}) \tag{4}$$

$$Q_p(\Omega,V) = \frac{1}{2}\rho(\Omega R)^2 \pi R^2 C_q(J, R_e, \text{geometry}) \tag{5}$$

$$\eta_p = \frac{TV}{Q_p\Omega} \tag{6}$$

Here the *V* is the flight velocity, C_T is the thrust coefficient and C_q is the torque coefficient and these coefficients depend on the advance ratio *J*, Reynolds number R_e and the propeller geometry. For off-the-shelf propellers, the thrust and torque coefficients will not be given, and thus numerical or theoretical method can be used to estimate the them. As can be seen from equation 2, the rotational speed can be computed if the motor terminal voltage is known however since the motor is a brushless DC motor, an electronic speed controller (ESC) is required to change the speed of the motor rotation and these means that the motor terminal voltage will vary depending on the ESC output. In the test bench the terminal voltage of the motor is not measured, and it will be difficult to estimate the voltage. Based on G. Gupta and S. Abdallah [5], they developed a semi-empirical approach to estimate the thrust coefficient which can be used to calculate the rotational speed based on equation 4. Here the estimated thrust developed by [5] is given as:

$$C_T = \frac{4}{3}k\theta\left[1-(1-e_d)^3\right] - k\left(\sqrt{k(1+k)} - \sqrt{k}\right)\left[1-(1-e_d)^2\right] \tag{7}$$

Where *k* is $N_bc/2d$, *c* is the propeller chord, *d* is the propeller diameter and N_b is the number of propeller blades. $\theta = \tan^{-1}(p/\pi d)$, here *p* is propeller pitch distance. The value of *c/d* and the effective propeller diameter, e_d can be obtained from table below:

Table 1. Estimated effective propeller diameter[5]

p/d	*Typical ed*
p/d<0.4	0.91
0.4≤*p/d*<0.8	0.88
0.8≤*p/d*<0.9	0.86
p/d≥0.8	0.8

Table 2. Estimated *c*/d ratio [5]

| *d* (inch)	*c*/d
4	0.09
5-6	0.1
7-9	0.11
10-12	0.12

Now, by having this we can calculate the rotational speed, Ω of the propeller-motor by using this equation:

$$\Omega(i,v) = \frac{2T(\Omega,V)}{\rho R^4 e_d{}^4 \pi C_T} \tag{8}$$

It can also be seen that there are two (2) torques – propeller torque and motor torque. The torque of the propeller will be the same as the motor at the equilibrium operating speed, Ω of the motor/propeller combination. The torque of the motor will be absorbed by the propeller. In order to see whether the estimated thrust coefficient will yield an acceptable estimation of the rotational speed, a static test bench was done on a sample of motor/propeller matching and compared to one of the motor specification given by the manufacturer.
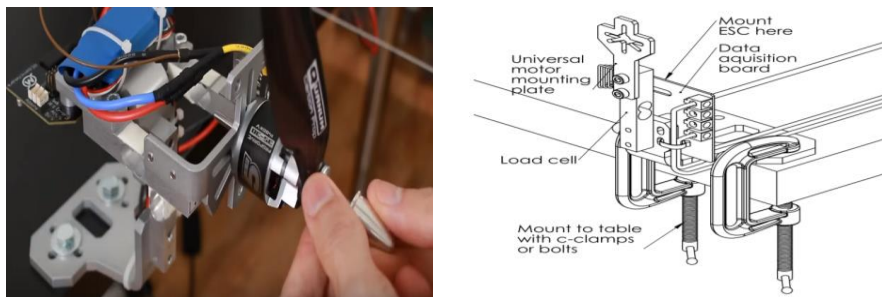
Figure 1. Dynamometer Series 1520 and static test setup [6]
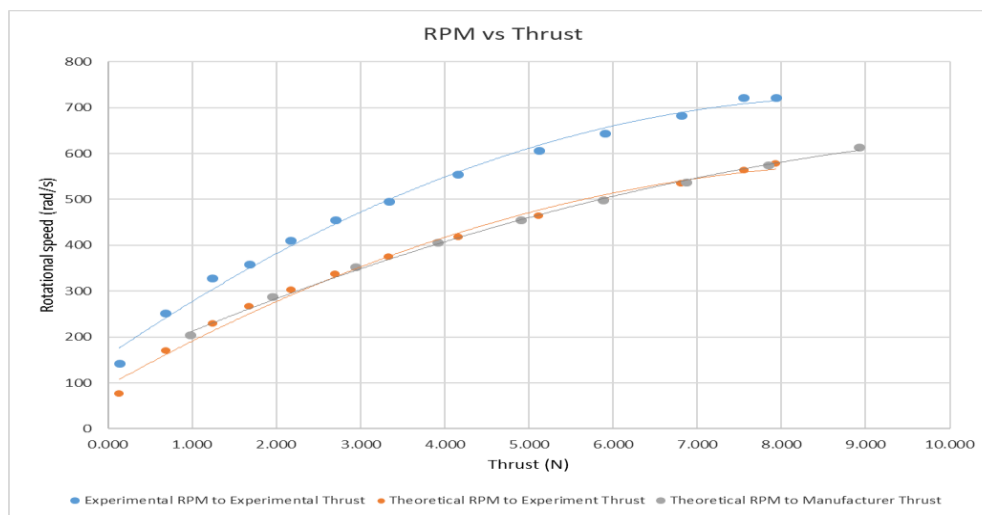
Figure 2: Comparison of estimated rotational speed between manufacturer, expeimental and theoretical thrust.

As can be seen from figure 2, the estimated rotational speed calculated from the experimental thrust and manufacturer thrust correlate well with each other and having an average relative error to the semi-empirical thrust to be less than 3.2%. However, the estimated rotational speed when compared with the measured rotational speed have a large average relative error of 32%. Since we are to study the effect of different motors to a propeller where the information is obtained from manufacturer datasheet, the estimated rotational speed can be used since it correlates well with thrust value in the manufacturer data sheet. For the analysis the propeller used is an APC 9047. The DC motor used is SunnySky brushless DC motor [7] and the specification is given in table 3.


9 inch diameter

Figure 3: APC 9045 Propeller

3. Analysis and discussion

In order to study the effect of the different motor constants to a propeller performance, the motors specification as shown in table 3 are used with a single propeller of diameter 10 inch and pitch 4.7inch. The power supply is a 11.1V lithium-ion battery.

Table 3. Motors specification

Kv (rpm/v)	Kv (rad/s/v)	No load current (A)	Motor Resistance, $\Re$ (mOhm)	Number of stator	Number of poles	Weight (g)
1400	146.6077	1.3	55	12	14	72
1400	146.6077	0.9	65	12	14	59
1250	130.8997	1.1	63	12	14	72
1250	130.8997	0.6	79	12	14	58
980	102.6254	0.3	133	12	14	58.5

From the calculation, the propeller performance can be obtained and is shown in the following figures.
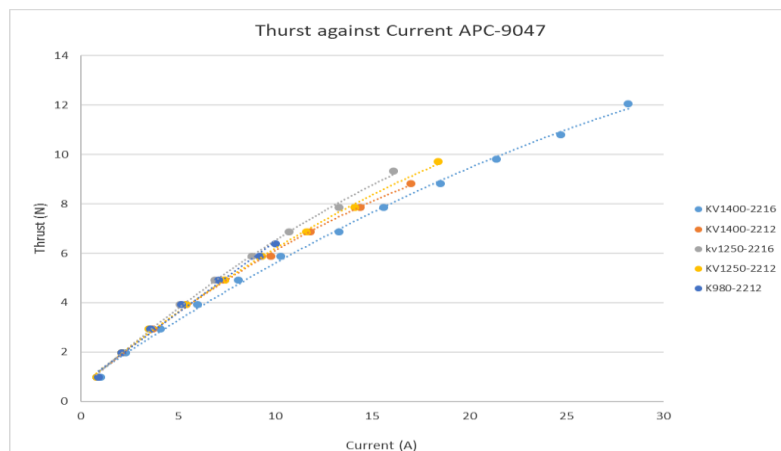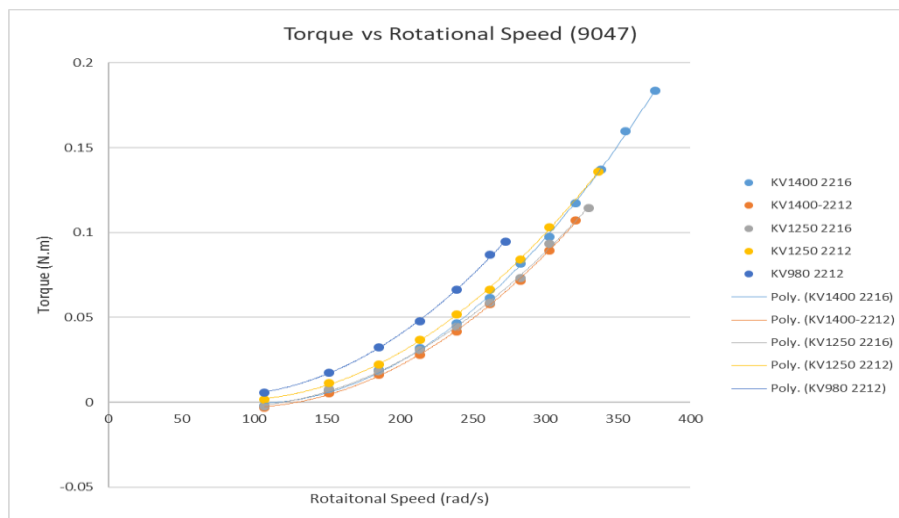

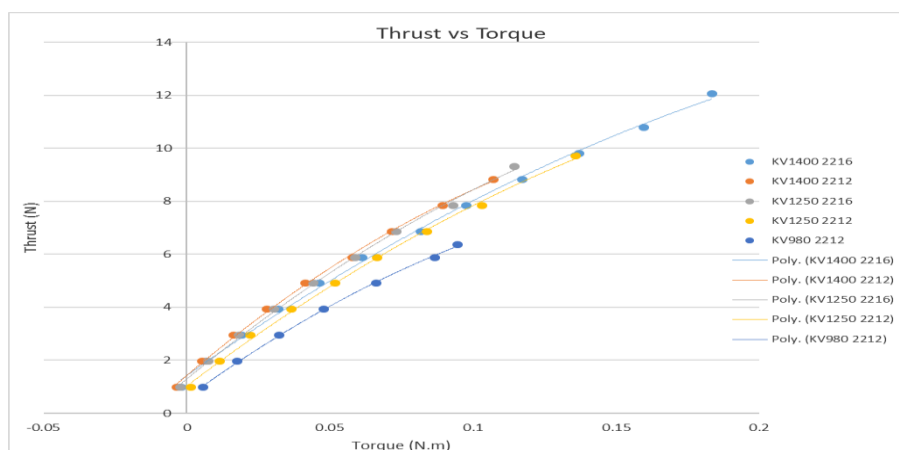**Figure 4**: Thrust against current for different motors with APC-9047
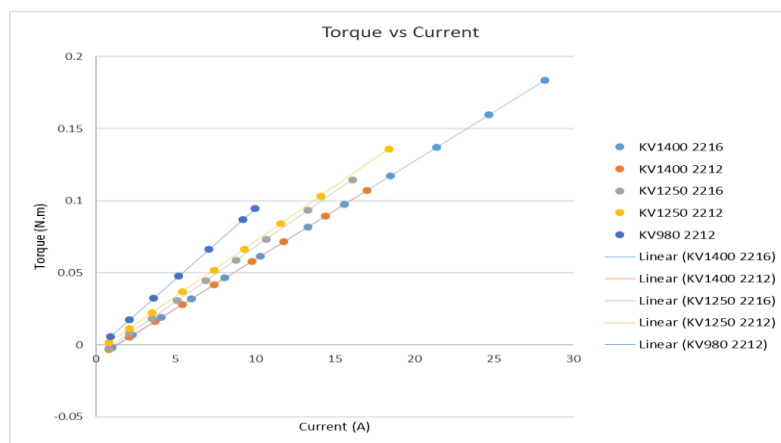
Figure 5: Torque against current for different motors with APC-9047

As shown in figure 4 and figure 5, the torque and thrust increase as current increases. From the graph it can be seen that the torque motor constants with speed constants of KV1400, KV1250 is the same for both size 2216 and 2212. Even when there is a difference in the motor resistance and no-load current. This means that the torque produced by the motor with same K_v will be the same for the same type of propeller. So the effect of torque to motor type for the same K_v is not important. Whereas for the thrust, it is shown that the speed constants of KV1400, KV1250 for the same stator diameter 2212 is about the same where as for KV1400, KV1250 with motor size of 2216 differs a lot. KV1250 2216 will produce more thrust for less current compared to KV1400 2216. If we require more thrust in shorter time, KV1250 is suitable. KV980 also produces more thrust at small current value and have more torque. It is useful for vertical take-off landing configuration.

Figure 6: Thrust against Rotational Speed for different motors with Propeller 9047

Figure 7: Thrust against Torque for different motors with Propeller 9047

As shown in figure 6, KV980 will produce a higher torque with rotational speed. For the other motor rating, there is not much difference in the production of torque with the increase in rotational speed and thrust against torque as in figure 7. For all cases KV1400 2216 will gives the highest thrust. Figure 8 shows the result of efficiency against rotational speed, the lowest efficiency will be for KV1400 2216, whereas for the others, it can be seen that the efficiency is about the same irrespective of the speed constants.
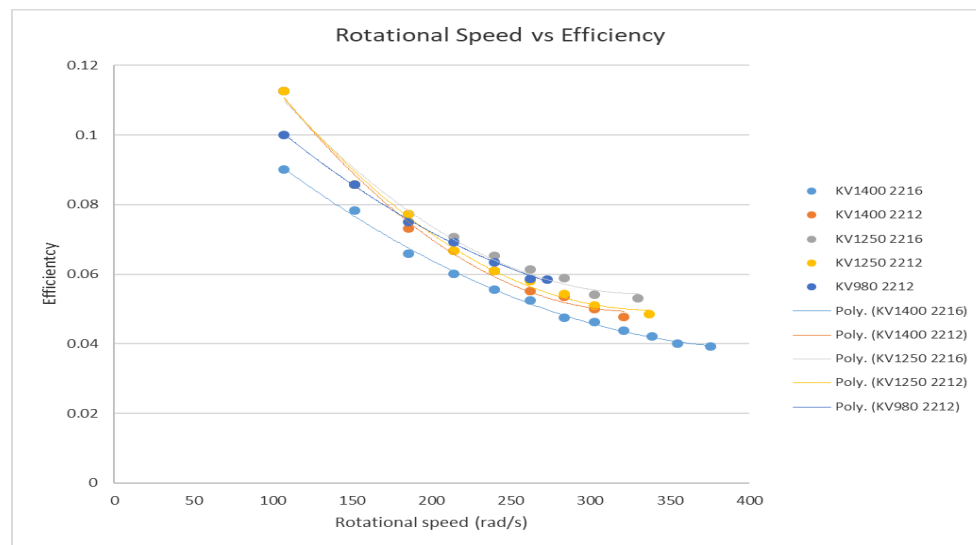
Figure 8: Efficiency against Rotational Speed

4. Conclusion

From the analysis and discussion, it can be seen for the same propeller, different motor constant will not severely affect the performance of a propeller. However, from the analysis and discussion, it can be concluded that the lower *Kv* 980 is better when the mission required more torque. For the others, the choice of *Kv* above 1250 from the experiment will not show significant difference in the thrust, torque and efficient. But as the *Kv* increase and the motor size increase, the efficiency of the propeller/motor will decrease but the maximum achievable rotational speed will increase. Those are the thing that will be compromised. Since there are many motor constants in the market, it should be noted that, motor constant between 1250 and 1400 will have little effect to the UAV and multicopter performance. In this paper, only the effect is discussed, further analysis to develop the modelling of different motor constants with different propellers will be done.

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