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Aerodynamic Analysis of Propeller for Heavy Lifting Drone Applications Using Blade Element Momentum Analysis

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Abstract: Nowadays, drone technology is seen to be rapidly advancing in various fields and applications including photography, military, transportation, sports, and many more. Therefore, each drone designs require different aerodynamic requirements, which includes different types of propeller designs. By revolving and generating airflow, the propellers give drones or unmanned aerial vehicles (UAV) a lift force or thrust. This work examines the method to calculate the thrust force generated by propellers using the Blade Element Momentum Analysis which is programmed in MATLAB. This program is developed to perform the calculation of thrust and torque for a given propeller blade geometry. This investigation compares the thrust coefficient produced by different propeller designs a various rotation speeds and parameters using the extended blade element momentum theory. Five different types of propellers are analysed and simulated using the in-house MATLAB program. The effects of rotational speeds are then added to these databases. At low advance ratios compared to a generic blade element-momentum model, a considerable improvement in modelling accuracy is seen when results are compared to experimental ones. The calculation may overestimate performance by 5% to 10%.

Keywords: Unmanned aerial vehicles, propellers, MATLAB, coefficient thrust, advance ratios

1. Introduction

The use of flying drones is nowadays becoming more and more common and is found in various applications. Its flight is either controlled autonomously or by the remote control of a pilot/operator on the ground. Drones have been traditionally used by the military and are being explored for an increasing number of civil applications such as policing, firefighting, nonmilitary security work, inspection of power pipelines, and other applications[1]. For logistic applications Unmanned Aerial Vehicles (UAVs) have faster delivery times, decreased reaction times, increased accuracy, and lower human costs and time are all advantages of a UAV-based delivery system. UAVs make delivery services quicker and more convenient by eliminating the need for the labor[2]. The pursuit of high-efficiency propeller performance has been a never-ending effort since the invention of aircraft propellers. Initially, the design and optimization of propeller blades are focused on adjusting a small number of design factors, such as the number of blades, propeller diameter, type of airfoil, blade angle, and blade twist. As a result, researchers and engineers began to experiment with increasingly complex propeller designs and optimization approaches. To assess the blade performance, the advancement of technology must go through arduous testing methods. Furthermore, developments in numerical approaches have enabled simulation data to be more accurate and reliable. Propeller operations, performance measurement methodologies, and propeller blade design are all covered in this examination. The currently available propeller blade design, incorporates two main sections, conventional and unconventional propeller blade design [3]. The current work attempts to assist drone and propeller designers select and evaluate the aerodynamic characteristics of a propeller through using a programmed blade element momentum method.

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2. Methodology

In this chapter general describes an analytical theory method for propeller blades and analysis of propeller for heavy lifting drone application can be use. The method uses Blade Element Momentum (BEM) theory and computational tool namely MATLAB to complete the analysis thrust, and torque coefficient. The performance of a propeller is given by thrust, lift, drag and advance ratio.

2.1 Thrust

The force that propels an aeroplane through the air is known as thrust. The engines of an aeroplane produce thrust by accelerating a mass of gas. It is necessary to exert force that is stronger than drag. Thrust and drag must be equal to maintain a constant velocity, just as lift and weight must be equal to keep a constant height. Thrust is expressed by the following relationship:

$$Thrust = m/dt \; x \; dv \text{ [N]} \tag{1}$$

where, *m* is mass and dv/dt is the acceleration

2.2 Lift and Drag

Lift is generated when an object changes the direction of flow of a fluid. When the object and fluid move relative to each other and the object turns the fluid flow in a direction perpendicular to that flow, the force required to do this work creates an equal and opposite force that is lift. A drag force, which is the component of the surface force parallel to the flow direction, is always present when lift occurs.

$$L = \frac{C_L \times \rho \times V^2 \times S}{2} \tag{2}$$

$$D = \frac{C_d \times \rho \times V^2 \times S}{2} \tag{3}$$

The efficiency of a propeller is determined by the thrust coefficient and torque coefficient. The dimensionless coefficients for a given air density *r* and propeller rotational speed n allow the calculation of thrust, and torque by the propeller:

$$C_T = \frac{T}{\rho n^2 D^4} \tag{4}$$

$$C_Q = \frac{Q}{\rho n^2 D^5} \tag{5}$$

2.3 Advance Ratio

The ratio between the distance an aircraft moves from one revolution of a propeller's, under specified conditions, and the propeller's diameter. It is the ratio of the forward speed divided by the product of rotational speed and the diameter. All propeller performance is compared at the same advance ratio.

$$J = \frac{V_\infty}{nD} \tag{6}$$

2.4 Blade Element Method Theory (BEMT) Analysis

The blade element theory is an analytical method used to estimate the most effective methodologies available for determining the thrust and torque produced by the propeller. This method is a modification of the Blade Element Theory which also determines the behaviour of propellers. It is also possible to combine different analytical methods such as blade-element methods, the momentum theory, and sectional airfoil analysis to evaluate propeller performance.

Fig. 2.1 shows the parameters, velocities, and forces of a blade element, where V_{up} is the vertical take-off speed, V_i is the induced velocity, r is the linear velocity of the blade element at the position where the radius is r, at the axis of the propeller, r = 0, the linear velocity is 0, and at the tip of the propeller, r = R, the linear velocity is R, where rotor angular velocity is velocity and R is the propeller radius [4].

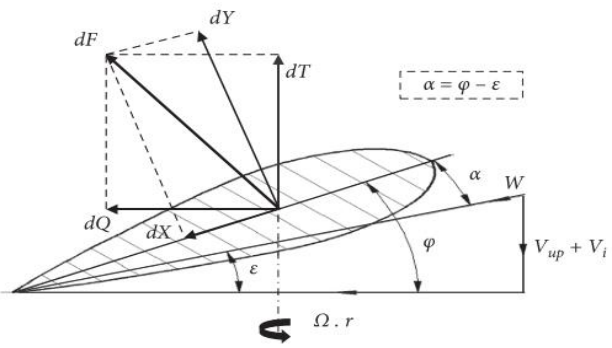


Fig. 1 - Parameters, velocities, and forces of a blade element

As shown in Fig. 1, W can be calculated according to the following equation:

$$W = \left(V_{up} + V_i\right) + \Omega R \tag{7}$$

The lift, resistance, and power generated by the blade throughout the working process are referred to as aerodynamic performance. According to blade element momentum theory, the lift, C_l, and drag coefficients, C_d, are required to compute the lift and drag created by blades. They are described as follows:

$$C_l = \frac{Y}{\frac{1}{2}\rho W^2 S} \tag{8}$$

$$C_d = \frac{X}{\frac{1}{2}\rho W^2 S} \tag{9}$$

where ρ is the air density, S is the effective area of the blade element, Y is the airfoil lift, and X is the airfoil drag. S can be calculated according to

$$S = b \cdot \Delta r \tag{10}$$

where b denotes the chord length and r refers to the blade element length. Once the airfoil has been defined, characteristic curves for lift and resistance can be produced. According to and the Reynolds number Re, C_l and C_d are determined for the lift and resistance curves, respectively.

$$Re = \frac{\rho V_f l}{\mu} \tag{11}$$

where V_f is the freestream velocity, μ is the kinetic viscosity, and l is the characteristic dimension, which is usually defined as either local chord length or chord length at 75% of radius. Therefore, the differential lift of the element, dY, and drag of the element, dX, can be calculated according to equations (2-12) and (2-13), as

$$dY = (C_l \frac{1}{2}\rho W^2 b)dr \tag{22}$$

$$dX = \left(C_d \frac{1}{2}\rho W^2 b\right) dr \tag{13}$$

The net force on the blade element along the rotation axis, dT, the net force on the blade element along the vertical rotation axis, dQ, and the lift force, T, and drag force, Q, created by a single blade can also be calculated as

$$dT = \cos(\varepsilon)dY - \sin(\varepsilon)dX, \tag{14}$$

$$dQ = \sin(\varepsilon)dY - \cos(\varepsilon)dX \tag{15}$$

Combined with the above theory, a calculation model for the selection of blade parameters UAVs is established and a MATLAB program is written to perform the calculations. The basic calculation flowchart of the model is shown in Fig. 2.

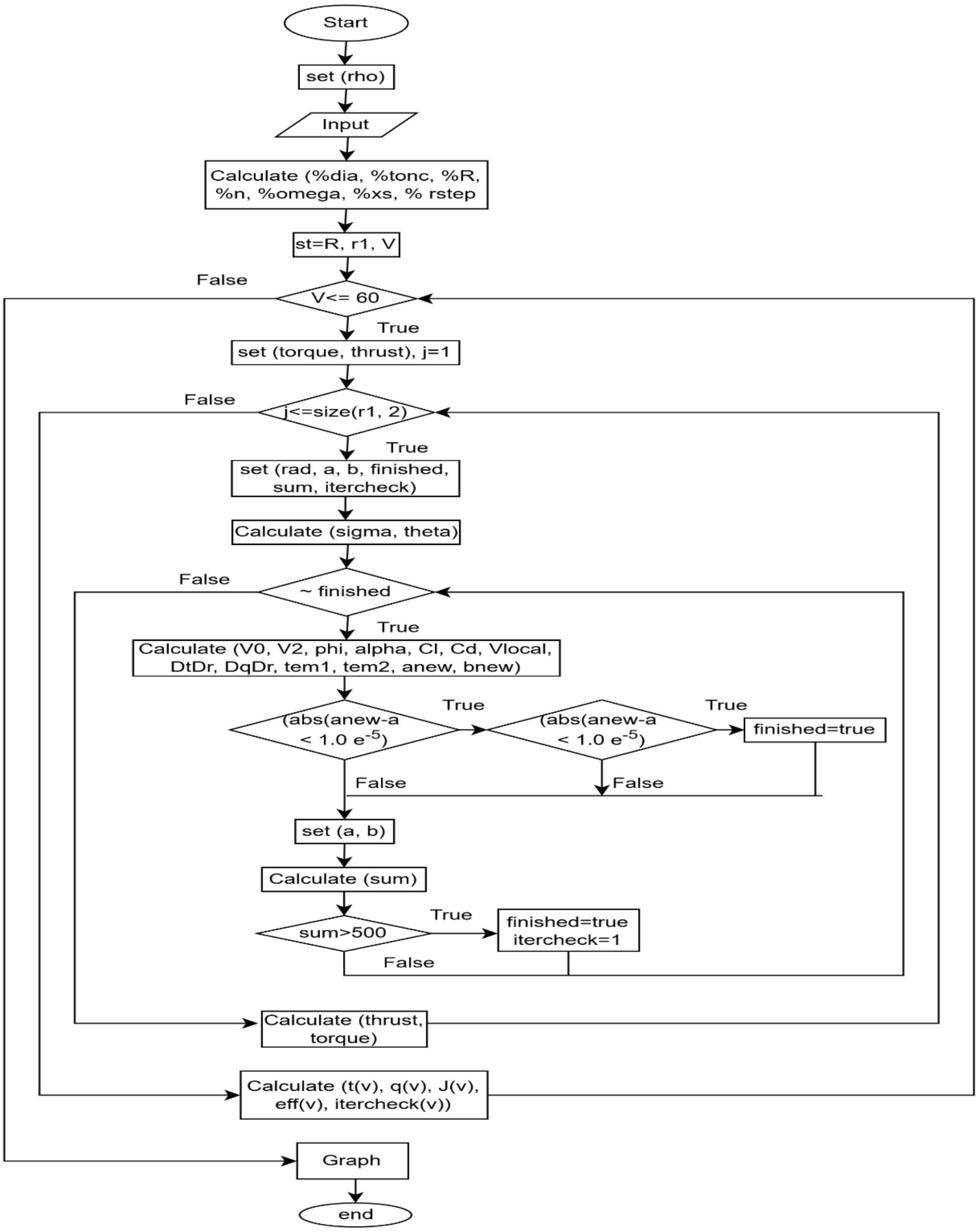


Fig. 2 - Calculation flowchart of the model

2.3 Validation of Propeller Performance

The programming versions of this propeller analysis technique can be used to determine the thrust and torque coefficients for a typical linearized aerofoil section and a relatively simple propeller design. The change of with radius is determined from the standard pitch equation under the assumption that the blade has a constant pitch (p). The BEMT model is programmed in MATLAB platform. The input parameters are the propeller chord length, pitch distances, airfoil parameters, propeller radius, speed of rotational of propeller and number of blades. The iterations are conducted along the blade radius.

Table 1 - Geometry parameter of propeller against value

Parameter	Value
Chord (m)	0.2
Pitch (m)	0.6
Diameter Propeller (m)	1.6
RPM	2000
No. Blade	2

The empty space at input value would be filled up by the geometrical parameters of the propeller as shown in Table 1 above. The user interface for these inputs in the MATLAB program is shown in Fig. 3. The number for the blade's first line chord length is 0.2 metres, followed by the second line's pitch distance of 0.6 metres, and a diameter of 1.6 metres with a rotational speed of 2000 RPM. The value for the last line's number of blade propellers is two.

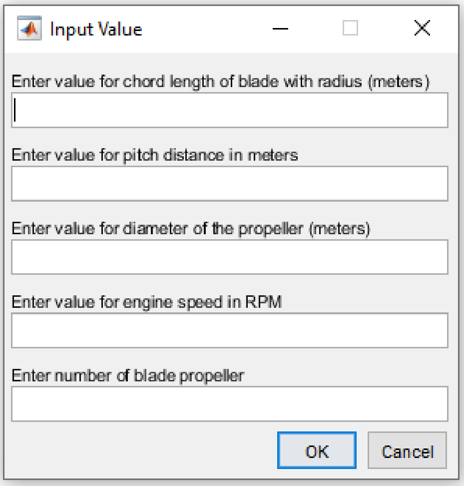


Fig. 3 - Interface or display input parameter value @MATLAB

The system will generate trends for the variables, such as graft, total torque, thrust, and advance ratio, that were examined. The graph below displays the general thrust-to-advance ratios pattern.

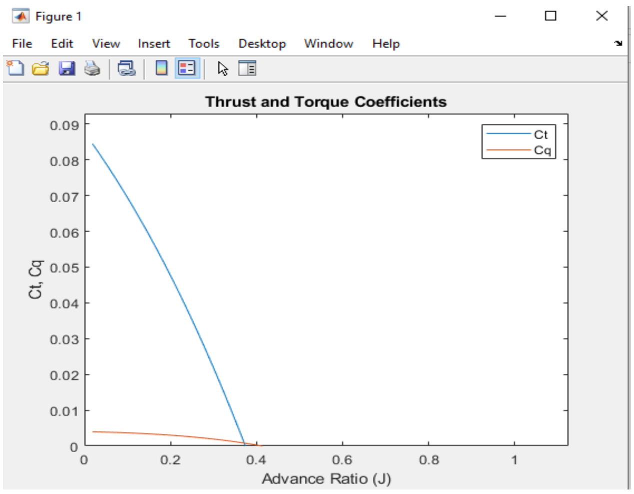


Fig. 4 - Function of advance ratio to trend propeller curves coefficient thrust

3. Results and Discussion

In determining the accuracy of methodology and formulas used in this research, a validation process is used. When based on analytical study, the blade element method is found to be the best method to apply. Results from studies are compared with those from the blade element method and it was found that the airfoil aerodynamic model is the most suitable model to validate the concept. Validation in research is important to prove that the data used to derive the conclusions are related and generally comparable. The result of the code programming was evaluated against experimental information obtained from the official NACA research website. The BEMT model, which can estimate propeller loads in a variety of flight conditions from hover to forward flight, is used to investigate propeller loads for unmanned aircraft applications.

3.1 Comparison with experimental data

The effects of the assumptions given in the standard BET on thrust force, the torque propeller obtained from the BEMT model, and a comparison of the model using coded programming via MATLAB are all shown in different subsections, respectively. Shown below are the results of the BEMT model's validation using Advanced Precision Composites (APC) Thin Electric propellers. The APC Thin propellers are use because they are heavily used for unmanned aerial vehicle (UAV). It showed a share similarity of an experiment performed using the blade element method with a Reynolds number of $1x10^6$ and a NACA 4412 section. The code programming for 5 various types of APC propellers, will be tested with of propeller geometry 10" x 5", 10" x 7", 14" x 12", 17" x 12", 19" x 12" and using 20mm chord. The following figure summarizes the rotational speeds (RPM) 5000, 3500, and 3000.

Table 2 - APC Thin Electric propeller tested against different geometry and rotational speed (RPM)

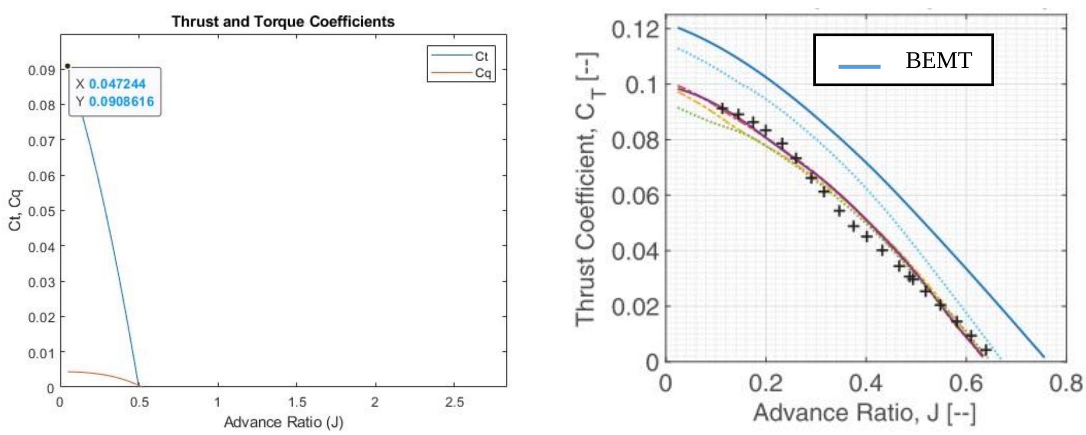
Model Propeller	Propeller Geometry	RPM
	10" x 5"	5000
	10" x 7"	5000
APC Thin Electric	14" x 12"	3500
T	17" x 12"	3000
T	19" x 12"	3000

The basic BEMT model regularly predicts values that are 30–40% above test data for smaller propellers and 5–10% above test data for the bigger propellers. This overestimation of thrust coefficient occurs at all advance ratios. Simulation software accuracy is greatly increased by combining the BEMT solution with the improved aerodynamic information created in this work. This is proved by the modelling of both thrust and efficiency, which increases accuracy to within 5% of experimental values at all advance ratios for smaller propellers and to within a maximum of 10% at the peak for bigger propellers.

This experiment aims to study the effect of rotational speed on propeller thrust, torque, and vary curve of graft pattern. For testing aerodynamic performance, the following five types of APC propellers with varying diameters and pitches are used. As an experiment, using the APC Thin Electric with geometry 10" x 5" as a reference, the analysis using MATLAB data obtained graph in figure 3.1 below shows that the thrust of the APC 10" x 5" is (-36.3778 N) whereas the torque (-3.0481 Nm). Estimate the chord at 0.02 m, and use the data generated by MATLAB to get the thrust and torque coefficients of (-3.1769) and (0.8115).

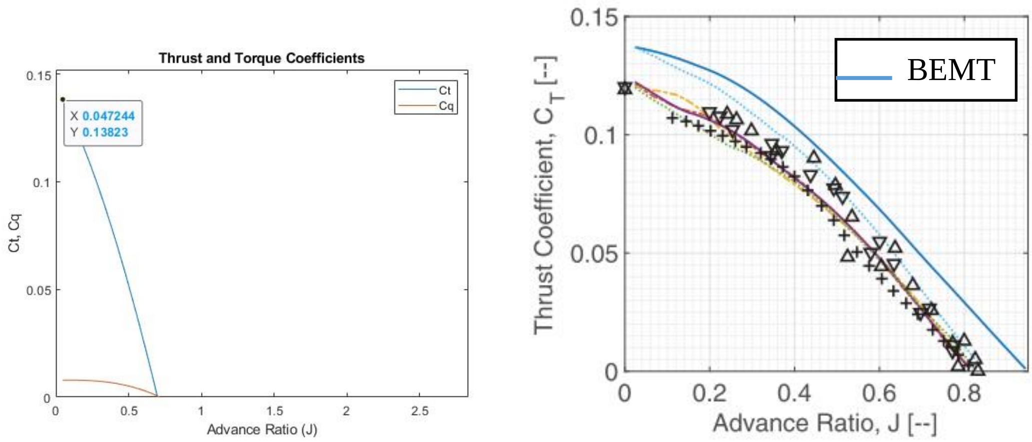
The comparison for both experimental and code programming results from MATLAB software is shown in the Fig. 5. Ct and Cq values for the thrust and torque coefficients were found. For the purpose of verification, appendix show the compare experimental and generic data graphically via MATLAB.

The thrust coefficient results obtained by R. MacNeill [20] with APC Thin Electric 10"x7" in propeller experimentally and obtained by the BEMT model are given in figure 3.2 shows below the change of pitch and remaining diameter, constant the rotational 5000 r/min, obtained the thrust of APC 10" x 7" is (-30.8046 N) and torque (-2.7091 Nm). Estimate chord 0.02m, the lift and drag coefficient obtain (-2.8410) and (0.0972) refer to the data generated by MATLAB. From the graph shown in Fig. 6, it can be observed that in general APC Thin Electric portray the same pattern which is the thrust increases when the pitch increase and RPM constant. This is the trend shown in other related papers such as the experimental research done by R. MacNeill. Fig. 7 shows the effect of thrust (-38.4257 N) and torque (-51588 N.m) with a rotating speed of 3500 r/min for propellers with a diameter of 14 inches (APC Thin Electric 14" x 12"). Figure shows a graph with coefficient thrust against advance ration with different speed. It is clear the size of APC 14" x 12" exhibits the same trend which is that thrust increase along the speed and pitch compared the experimental trend graft.



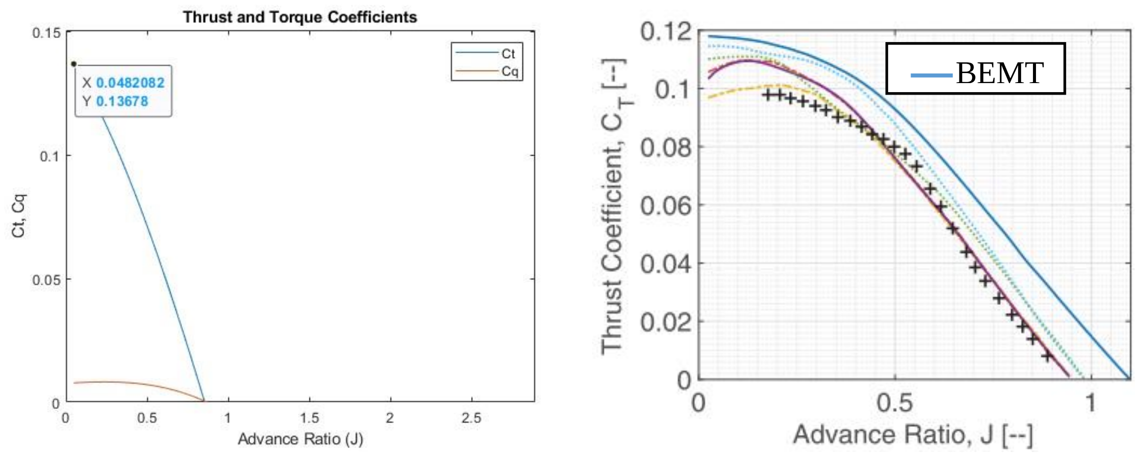
(a) (b)

Fig. 6 - Result experimental tests of APC Thin Electric 10" x 5" propeller (b) and MATLAB results of the thrust and torque coefficients as functions of advance ratio



(a) (b)

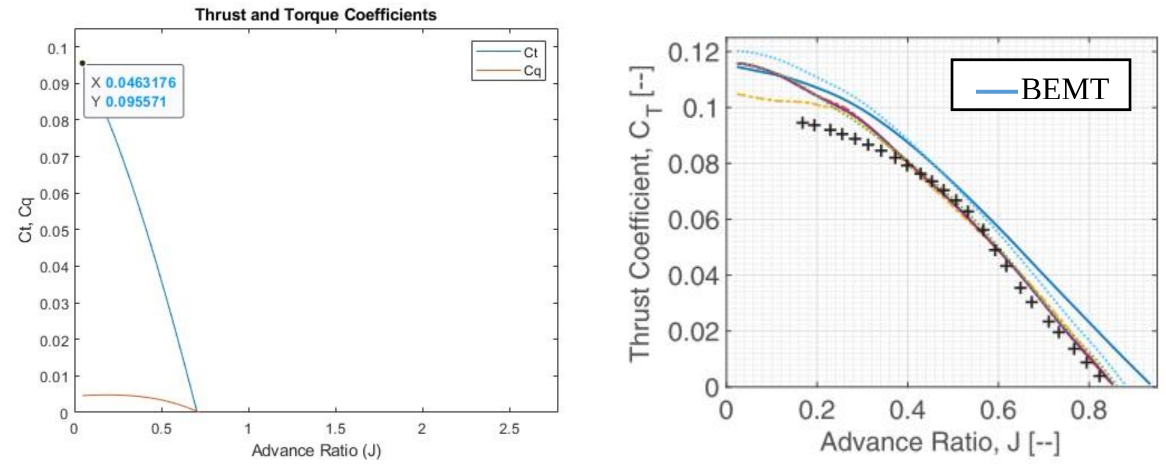
Fig. 7 – (a) Result experimental tests of APC Thin Electric 10 x 7 propeller; (b) and MATLAB results of the thrust and torque coefficients as functions of advance ratio



(a) (b)

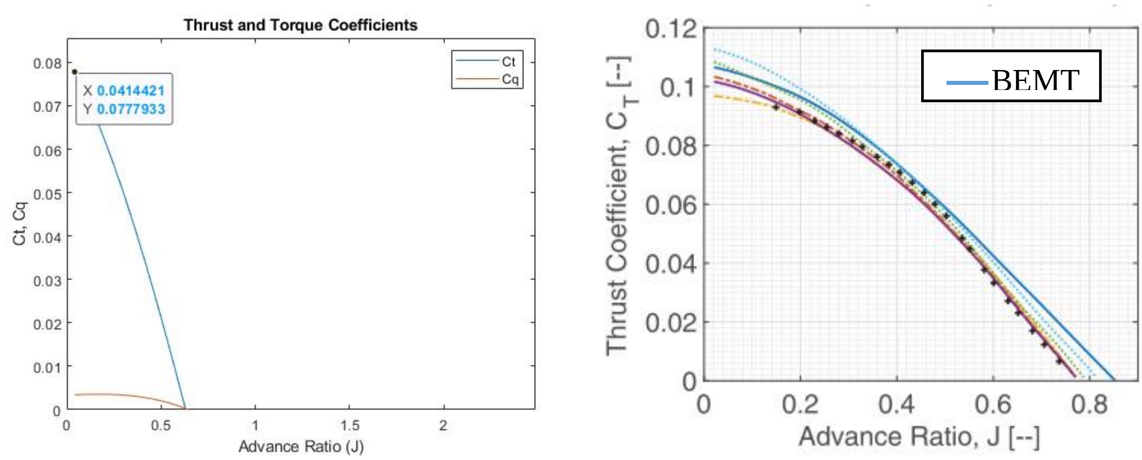
Fig. 7 – (a) Result experimental tests of APC Thin Electric 14" x 12" propeller; (b) and MATLAB results of the thrust and torque coefficients as functions of advance ratio

The propellers in Fig. 8 with a pitch of 12 inches APC Thin Electric and a diameter of 17 inches achieve a different layer graft curve with thrust (-54.1934 N) and torque (-8.4936 Nm). Change of the parameter APC thin electric 17"x12" propeller with respect to the advance ratio at 3000 RPM, at different propeller pitch is given increased thrust in Figure 3.4. Its decreasing trend with coefficient thrust is (0.09). Fig. 9 shows the effects of diameter on APC Thin Electric 19" x 12" with rotation speed of 3000 r/min, after which the graft trend remains constant with a pitch of 12 inches. (-69.6775 N) of force and torque were generated (-10.7481 Nm). As we can see, the pitch of the propeller plays a major factor in producing thrust. According to graph illustrated, the highest propeller pitch is capable of providing the highest amount of thrust with every rotation of RPM.



(a) (b)

Fig. 8 – (a) Result experimental tests of APC Thin Electric 17" x 12" propeller; (b) and MATLAB results of the thrust and torque coefficients as functions of advance ratio



(a) (b)

Fig. 9 – (a) Result experimental tests of APC Thin Electric 19" x 12" propeller; (b) and MATLAB results of the thrust and torque coefficients as functions of advance ratio

However, at low advance ratios, the opposite is true, which becomes more apparent for larger propellers, with under- predictions up to 10% when compared to test values. These differences combine to produce efficiency values around 35% and 20% larger than experimental data for small and large propellers, respectively. This application uses a blade element theory to determine the thrust and torque parameters of a simple propeller, and the solver may overestimate performance by 5 to 10%.

4. Conclusion

From literature studies, several methods were identified on estimating aerodynamic forces produced from rotary wings such as Computational Fluid Dynamics Calculation. An analysis was carried out on a model of propeller aerodynamic performance which was helped by a calculation via MATLAB code such as the lift coefficient (Cl), drag coefficient (Cd), advance ratio, efficiency, thrust, and torque acceptable ranges based on the airfoil. As a conclusion, the suitable method to estimate the aerodynamics performance of drone propellers in a variety of flight conditions would be using the Blade Element Momentum Theory (BEMT) which uses the combination of momentum theory with blade element theory. The BEMT has a long history dating back to Glauert (1935). This theory is still considered relevant for the study of rotor and propeller design. Its simple formulation lends itself to use in education and to quickly analyse new ideas

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