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A DC Motor Model with Steady Propeller Load for Electric UAV Applications

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Keywords：Electric propeller propulsion, DC motor, Motor Modeling, propeller performance.

ABSTRACT

The unmanned aircraft industry is developing safer, lower noise and more efficient power technologies to sustain the transportation industry. Electric motors have many advantages over internal combustion engines. For example, low noise, high torque, high energy efficiency and low maintenance costs. Therefore, hybrid power or electric drones are gradually becoming popular.

In this paper, a steady aerodynamic load DC motor model is built in MATLAB. In order to verify the model, several electric motor propeller propulsion set of UAVs have been simulated. It is applied to several simulations. The results of the simulation show the response of power consumption and thrust output to the voltage step input. Comparison of the specific power parameters with the experimental data has been made for model verification. The verification results are quite satisfactory and show the usefulness of this model.

INTRODUCTION

BLDC motors have been used in a wide range of industries, such as automotive, aerospace, and production plants. There have been many related studies on BLDC motor models and simulations (Juan *et al.* 2002; Tashakori *et al*. 2011; Gadewar *et al.* 2017). BLDC motors have been used in a wide range of industries, such as automotive, aerospace, and production plants. There have been many related studies on BLDC motor models and simulations (Lou *et al.* 2014; Ricardo *et al.* 2014). However, there is no relevant research literature provide valid estimates of propeller aerodynamic loads on DC motor model.

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Although the UAV actually uses a BLDC motor, in order to simplify the BLDC motor simulation, we assume that the difference between the BLDC and the DC motor in the commutation program is negligible, and replace the BLDC model with a DC model.

So in this paper we focus on establishing a feasible and effective steady-state air load model. The steady aerodynamic load of the motor model is the torque resistant generated by fixed speed rotating propeller. The concept of blade element method (Houghton *et al.*1980) and a 2D panel method flow solver are used to calculate the steady propeller torque. The steady propeller thrust is calculated in the same manner. DC motor mathematical model comes from the DC motor equivalent circuit. The governing equations come from Kirchhoff voltage law and Newton's second law. The motor simulation program is written in Matlab, and the fourth-order Runge-Kutta method (Gerald, 1978) is used to solve the initial value problem.

Accurate motor parameters appropriately describe the DC motor to provide accurate simulation results. For DC motors that do not have manufacturer information at all, motor identification technique can be used to determine motor parameters (Mohammed, 2009). Fortunately, most commercially available motors, the manufacturer provides K_v value of motor. The other motor parameters can be derives from the K_v value. The internal resistance and inductance of the motor are determined by the measurement method. The moment of inertia of the motor rotor, propeller and hub can be measured by a trifilar pendulum (William, 2007). The principle of trifilar pendulum uses conservation of energy and the Euler-Lagrange equation (Arfken, 2012).

In present study we have verified the steady aerodynamic load, the motor model with constant load, and the motor model with steady aerodynamic load. Air load verification was compared with the study results of the Brandt, J. B. and Selig, M. S. (2011). The verification of motor model with constant load is compared with the results obtained by Stefan (2005). Motor model verification with aerodynamic loads is compared to actual motor propeller thrusters. In the motor model verification with aerodynamic loads, the specific power is chosen as the comparison parameter.

The specific power is defined as electric energy consumption rate per unit thrust. The unit of specific power is Watt/kg. The comparison shows satisfactory consistency.

DC MOTOR MODELING

Governing Equations

DC motor mathematical model comes from the DC motor equivalent circuit. A series connect resistor and inductance are equivalent the inner resistance and inductance of armature coil. The governing equations come from Kirchhoff voltage law and Newton's second law:

$$V_s = Ri + L\frac{di}{dt} + K_e\omega\ , \tag{1}$$

$$T_e = K_f\omega + Jm\frac{d\omega}{dt} + T_L\ \ . \tag{2}$$

Assuming the current and rotation speed being the states functions of the thrust system, thus rewrite the above equations as the state equations:

$$\frac{di}{dt} = -\frac{R}{L}i - \frac{K_e}{L}\omega + \frac{1}{L}V_s\ , \tag{3}$$

$$\frac{d\omega}{dt} = \frac{1}{Jm}K_T i - \frac{1}{Jm}K_f\omega - \frac{1}{Jm}T_L\ . \tag{4}$$

The motor model is written in Matlab program, and the fourth-order Runge-Kutta method is used to solve the motor equation. The initial conditions settings are as follows. $t_1 = 0,\ i_1 = 0$ and $\omega_1 = 0$.

Constant Load Verification

In order to validate DC motor model, we analyzed a sample problem and compared the results with Stefan's work. The motor parameters are shown in Table 1, and the result show the motor speed is absolutely same with reference as shown in Fig. 1.

Table 1. Parameters of sample motor

V_s (Volt)	6
R (Ω)	12.5
L (H)	0.091x10^{-3}
K_f (Nm-s)	1.38x10^{-8}
J_m (kg-m$^{2)}$	0.005x10^{-7}
T_L (mNm)	0.023 is applied at 0.05s
K_e (Volt/rpm)	0.001216
K_t (Nm/A)	1.05x10^{-3}
K_v (rpm/Volt)	47130

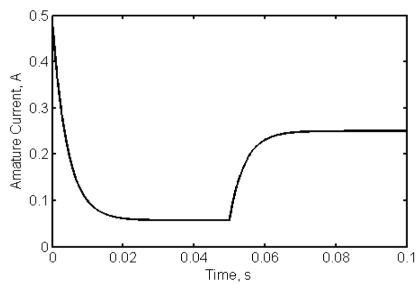

Fig. 1. Motor speed is same with reference

STEADY AERODYNAMIC LOAD

At dynamic state, the aerodynamic load is a function of rotation speed, advance speed, Reynolds number and time. At steady state, the air load is a function of rotation speed, advance speed and the Reynolds number. The Reynolds number is referred the chord length at 75% of the diameter of the propeller blade. Under an incompressible flow field and a fixed forward speed situation, the air load of the propeller can be expressed as a function of the rotational speed.

The aerodynamic load is basically the propeller resistant torque generated by its own rotation. A process combined blade element concept and 2D flow panel method solver are used to calculate the steady propeller torque.

Steady Quadratic Aero Load

The concept of blade element depicts that the propeller blade is superposed by a number of elements as shown in Fig. 2. Each element has its thickness, position, chord, twist angle, angle of attack and aero load. The aero load on each element can be calculated and superposed together into a force and torque acting on the propeller.

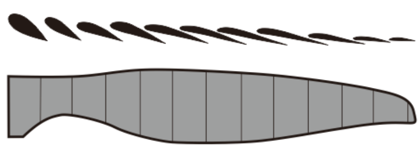

Fig 2. Propeller blade element concept

A 2D flow solver XFOIL (Mark, 1989) is used to calculate the lift coefficients and drag coefficients of chosen airfoil which represent the cross section profile of every element. The lift and drag coefficients are calculated in proper angle of attack.

The lift coefficients C_L and drag coefficients C_D are normalized lift and drag forces. The actual lift and drag forces acting on each element can be obtained by inverse normalization operation. Finally, the total lift and drag of propeller are obtained by summing up all the individual lift and drag of each element. The torque of the propeller is obtained by converting the lift and the drag force to the right coordinate and multiplying with the adequate arm. A flow chart of the process to calculate the steady propeller aero load is shown in Fig. 3.

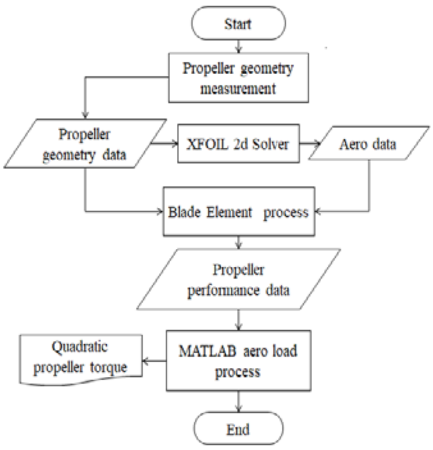

Fig. 3. Steady propeller aero-load process

Validation of the Aero Load Calculation

Commercially available propellers are designated by diameter and pitch in inches. Considering propeller as screw in the air, the pitch is defined as the distance that the element at 75% radius travels for each revolution. We take a propeller with a diameter of 11 and pitch 8 for verification simulation. The calculated propeller aero-load are compared with the experimental data of AIAA 2011-1255 papers (Brandt *et al*. 2011). Since NASA researchers have conducted extensive wind tunnel tests on propeller performance in the early days (Gray *et al*.1943, 1945). We follow the previous researchers to use the following parameters to describe the performance of propeller. These parameters are Advance ratio J, propeller efficiency η, thrust coefficient C_T and power coefficient C_P. The definition of these parameters can refer to the NASA reports (Gray, 1941).

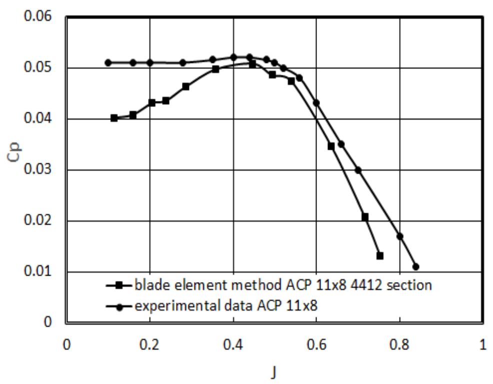

Fig. 4. Power efficiency

Considering equation (2), under no-load and steady state condition, the second and the third terms

The calculated propeller aero-load are converted to C_T, C_P and η. Basically the comparison results were shown in Fig. 4, 5 and 6 with satisfactory consistency.

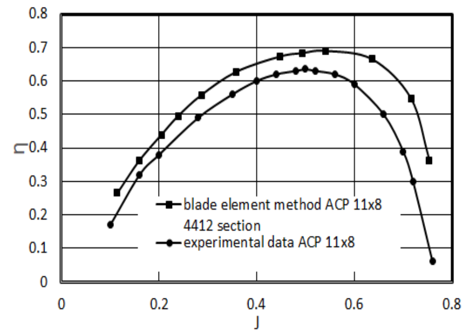

Fig. 5. Propeller thrust coefficient

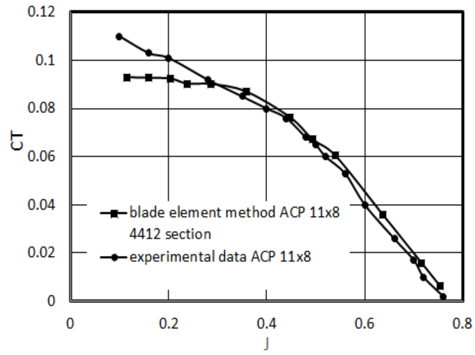

Fig. 6. Propeller efficiency

PARAMETERS OF MOTOR MODEL

For most of the BLDC motor, K_v values are easy to regain by manufacturers or distributors. As long as there is a K_v value, the K_e value can be derived. The definition of back electromotive force coefficient which state that K_e is the induced armature voltage per angular velocity and the definition of K_v is the rpm per volt of the electric power. Physically K_e and K_v are reciprocal to each other. Accordingly following relation K_e is derived.

$$K_e=1/K_v \ . \tag{5}$$

Assuming no loss and electrical power equal to mechanical power, the relation between torque coefficient K_t and emf coefficient K_e can be obtained by following derivation.

$$V_s i = T_e \omega \ , \tag{6}$$

$$K_e = V_s / \omega = T_e / i = K_t \ . \tag{7}$$

In the metric system the values of K_t and K_e are the same to each other with different units.

In order to derive viscous friction coefficient K_f, on the right hand side are vanished. Plus considering the electric torque, T_e, is the product of torque coefficient and current. Equation (2) can be rewritten as:

$$T_e = K_f\omega = K_t i \quad . \tag{8}$$

In no load condition, armature current, $i = V_s/Z$, is obtained by measured source voltage and impedance. The above equation could be further rewritten as

$$K_f\omega = K_t i = K_t V_s \,/\, Z \quad . \tag{9}$$

Recalling that K_e is induced armature voltage per angular velocity, the motor friction coefficient is expressed as following.

$$K_f = K_t K_e/Z \quad , \tag{10}$$

where $Z = R + iX$, the real part of impedance is the armature resistance R and the imaginary part is the reactance X.

Measurement of Inner Resistance

The inner resistance R of the motor coil is usually very small and difficult to be measured directly. So, it needs to measure the current and voltage simultaneously and apply Ohm's law to calculate the inner resistance. In order to protect the motor coil it will be necessary to connect a resistor in between while the current and voltage measuring.

Measurement of Inductance

In order to measure the inductance L of the brushless motor, a low-voltage AC power is applied to any two of the three connectors of the motor coil and measured AC current which can be used to calculate the coil impedance. An oscilloscope is used to measure the voltage and an AC current meter is used to measure the AC current. The reactance is obtained by the relation, $X = \sqrt{Z^2 - R^2}$. Once the reactant is known, the motor inductance can be calculated by following relation.

$$L = X/(2\pi f) \quad . \tag{11}$$

Measurement Moment of Inertia

The moment of inertia of the motor rotor, propeller and hub can be measured by a trifilar pendulum. The principle of trifilar pendulum uses conservation of energy and the Euler-Lagrange equation. From Euler-Lagrange equation, the trifilar pendulum's dynamic equation in terms of torsion angle is obtained, which is quadratic ordinary differential equation. The natural frequency is the coefficient of zero order term. The relationship between the moment of inertia and frequency or period is as follows.

$$J_m = \frac{R_d^2 mgT^2}{4\pi l} \quad . \tag{12}$$

Therefore, by period measurement, the moment of inertia of the rotation parts can be calculated.

DC MOTOR MODEL WITH AERO LOAD

Combinations of DC Motor and Propeller

There are three different DC motor and propeller combinations are simulated.

(1) 2612 1000K_v motor with 11×4.7 propeller.

(2) 3020 1100K_v motor with 20×8 propeller

(3) 8826 135K_v motor with 29×9.5R propeller

The motor size is expressed in four digits. The first two digits represent the motor diameter and the last two digits represent the motor height. Propeller size is expressed in diameter × pitch. The unit of the motor size is given in millimeter; on the other hand the unit of the propeller is given in inches.

Aerodynamic Load in the DC Motor Modeling

The air load in the motor model will not properly describe the physical phenomena of the flow field if it is a constant or linear function. If the 3D flow solver is used to calculate the air load and then put into the motor model, although the flow field physical phenomenon can be accurately described, the time and cost increase will result in the financial support being unsustainable. Therefore, considering the limited time and financial support, the more suitable method is to assume that the air load is in steady state at each time step, and is only a function of rotating speed at specified Reynolds number and advance velocity.

In the study of this paper, we convert the air-load data calculated by the blade element method into a quadratic function in terms of rotating speed and put it into the motor model. Actually, the propeller torque data is converted to quadratic functions in terms of angular velocity. The propeller thrust data is converted to quadratic functions in the same manner. In order to validate and compare with static data, we calculate the static torque and thrust function as follows. The coefficients for different combinations are listed in Table 2 and Table 3.

$$T_L(\omega) = a\omega^2 + b\omega + c \quad . \tag{13}$$

$$T_H(\omega) = p\omega^2 + q\omega + r \quad . \tag{14}$$

Table 2. Coefficients of propeller torques

	No.1	No.2	No.3
a	1.829*10^{-7}	2.266*10^{-6}	3.599*10^{-5}
b	1.583*10^{-5}	4.154*10^{-5}	0.001745
c	-0.0007762	-0.0004738	-0.06851

Table 3. Coefficients of propeller thrusts

	No.1	No.2	No.3
p	1.733*10^{-5}	0.000485	0.000912
q	0.0002237	-0.0001643	-0.00312
r	-0.03995	-0.009597	-0.1431

Motor Parameters in the DC Motor Modeling

The motor parameters used for the aero-load motor simulation are measured and derived by using the aforementioned method for individual combinations.

Some trends of motor parameters are observed. The larger the motor power, the smaller the internal resistance and the larger the inductance. Moment of inertia increases as the diameter of the propeller increases. The larger the K_v value, the smaller the K_e value and vice versa. The K_t value and the K_e value are the same in the metric system. K_f is inversely proportional to the dynamic impedance. In this study, we take the largest possible K_f value. The motor parameters for different combination were listed in Table 4.

Table 4. Motor parameters of different combinations

combination	No.1	No.2	No.3
R (Ω)	0.22	0.2	0.12
L (H)	15.4x10^{-3}	14.91x10^{-3}	729.3x10^{-3}
J_m (kg-m^2)	4.745x10^{-5}	335.534x10^{-5}	842x10^{-5}
K_v (rpm/volt)	1000	1100	135
K_e (volt-s/rad)	0.00955	0.00877	0.0707
K_t (Nm/A)	0.00955	0.00877	0.0707
K_f (Nm-s)	4.7x10^{-6}	2.8x10^{-6}	1.51x10^{-5}

Simulation Power of DC Motor and Propeller

The initial values of the current and angular velocity of the motor propeller system are both set to zero. The input signal to the system is an external power supply voltage step function. Table 5 shows the external power supply voltage inputs for different combinations.

Table 5. Voltage inputs of different combinations

combination	No.1	No.2	No.3
V_s (volt)	11.2	11.2	32.0

The fourth-order Runge-Kutta method is used to solve the system equation which yields the current and angular velocity for each time step, then power and thrust are also calculated for each time step. Figs. 7, 8 and 9 show the power responses for the combination of 1, 2, and 3.

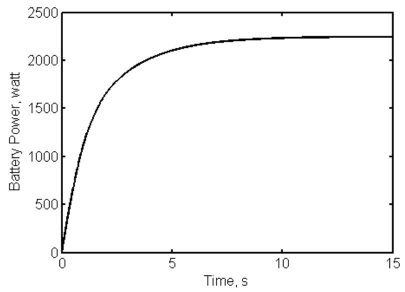

Fig. 7. Electric power response of combination 1

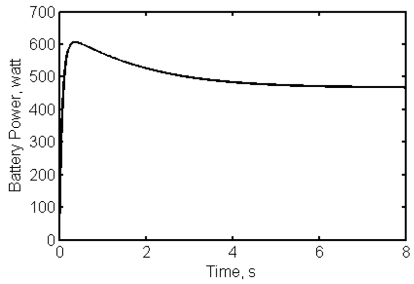

Fig. 8. Electric power response of combination 2

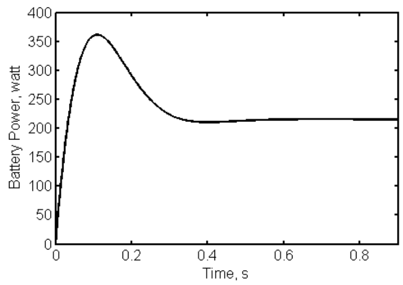

Fig. 9. Electric power response of combination 3
F

The simulation results show that the three combinations will eventually converge to a steady state. The rise time of combinations 1 and 2 is about 0.02 seconds. The rise time of combination 3 is about 4.0 seconds, which is relatively slow. The power settling time of these three combinations is 0.3s, 6s and 8s, respectively, and combinations 2 and 3 are slower. The maximum percentage of overshoot of power response is 80%, 30% and 0%, respectively, and the overshoot of combination 1 reaches 80%. If the system power supply margin is insufficient, it may cause system failure.

Simulation Thrust of DC Motor and Propeller

The thrust response curves for different combined motor propeller systems are shown in Fig. 10, 11 and 12. The rise time of thrust of individual combinations are 0.2s, 7.0s and 6.0s.

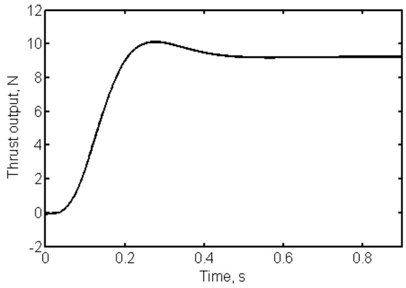

Fig. 10. Thrust response of combination 1

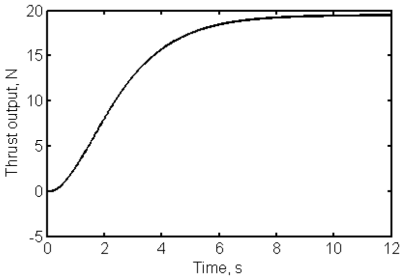

Fig. 11. Thrust response of combination 2

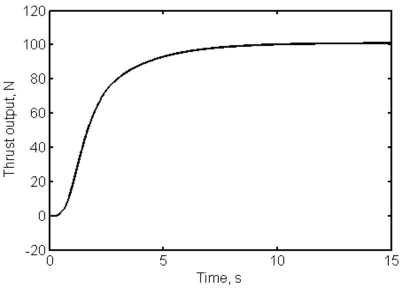

Fig. 12. Thrust response of combination 3

The thrust overshoot of the combination 1 is 10%, and the thrust overshoot of other two combinations are of 0%. The thrust simulation results show that the thrust responses of combinations 2 and 3 are delayed. It can be problematic if the combination is used in a control system that requires a quick response.

VALIDATE THE MODEL WITH AERO LOAD

In the motor modeling with aero-load validation, the specific power is chosen as the comparison parameter. The specific power is defined as electric energy consumption rate per unit thrust. The specific power is an important parameter in flight range estimation (1975) of electric UAVs.

The experimental data for specific power in this study is the rate of energy consumption measured under static thrust. The experiment uses a commercially available small electric motor test bench. Install different combinations of motor propellers on the test bench and control the PWM signal to obtain the thrust and power data of the corresponding voltage.

The simulation uses an air load of zero relative wind speed, and the input voltage is varied to obtain the corresponding steady state power and thrust. This verification method compares the steady-state specific power at zero relative wind speed.

Figure 13, 14 and 15 show comparisons of the different combinations of power simulation results and experimental data. The comparison results showed satisfactory consistency.

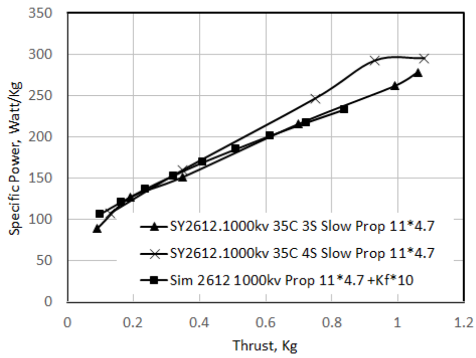

Fig. 13. Specific power of combination 1

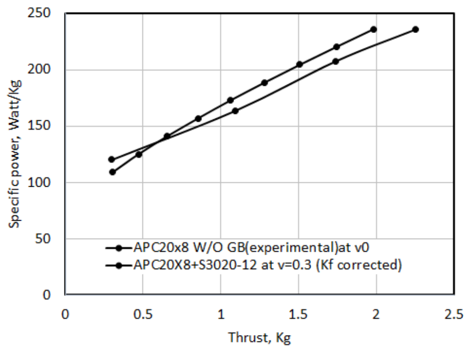

Fig. 14. Specific power of combination 2

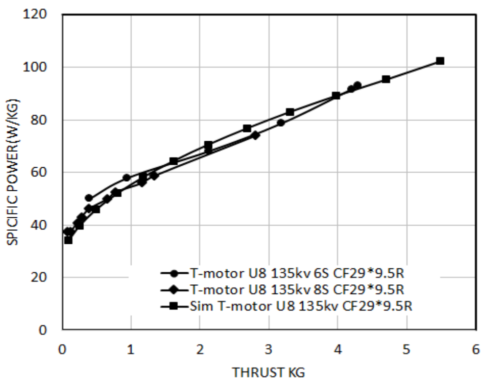

Fig. 15. Specific power of combination 3

In the case of zero relative wind, the relationship between the specific power and the thrust is basically linear. Nowadays most aircraft are installed with one or two engines, such a design is less efficient for electric aircraft. The specific power vs. thrust curve shows that an aircraft can be operated efficiently if it is designed to install a large number of electric motors.

CONCLUSIONS

A basic process has been developed to model the electric motor propeller thruster for UAV applications. The blade element concept and 2D flow panel method solver are used to calculate the steady propeller aero-load. The DC model is used to replace the BLDC motor model. Instead of 3D flow solver and BLDC model, the 2D flow solver and DC motor model have been used and validated to be satisfactory which demonstrate the feasibility of simplicity of the model.

Although there are open software supports in the process development, there are challenges to overcome. Several necessary efforts are made on motor parameters identification, moment of inertia measurement, blade element method programing, and nonlinear first order ODE system solver programing…*etc*. All these efforts have integrated and make this process functional.

The fast calculation ability of the process makes itself a suitable tool for UAV motor propeller matching point analysis. It can be used for off-design analysis in the further matching optimization study, where several DC motor modeling with Aero Loading analysis items are waiting to be conducted, such as simulations of various relative wind speed conditions, simulations of propeller variable pitch conditions, and simulations of different motor K_v value combinations.

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NOMENCRATURE

A	reference area, m^2
a	2nd order term coefficient of torque function
b	1st order term coefficient of torque function
c	constant of torque function
C_D	drag coefficient
C_L	lift coefficient
C_P	power coefficient
C_T	thrust coefficient
D	propeller drag, Newton
e	back electromotive force, voltage
f	frequency, Hz
g	gravity acceleration, m/s^2
i	electric current, Amp
J	advance ratio
J_m	moment of inertia, kg-m^2
K_f	friction coefficient, Nm-s
K_t	torque coefficient, Nm/A
K_v	velocity coefficient, rpm/volt
L	lift, Newton
ℓ	length of trifilar pendulum rod, meter
m	mass, kg
n	angular speed, rps
P	power, watt
p	2nd order term coefficient of thrust function
q	1st order term coefficient of thrust function
R	inner resistance, Ω
R_e	Reynolds number of propeller
R_d	Radius of trifilar pendulum disc
r	constant of thrust function
T	period, sec
T_e	electric torque, N-m
T_H	Thrust function, N
T_L	Propeller torque, N-m
t	time, sec
V_∞	free stream velocity, m/s
V_s	source voltage, volt
X	reactance, Ω
Z	impedance, Ω
η	propeller efficiency
ω	angular velocity, rad/s

穩態螺旋槳負載直流馬達模型於電動無人機之應用

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摘要

無人飛機正朝向更安全，安靜，高效率方向開發新技術，以維持航空產業的永續發展。電動馬達比內燃式發動機具有更多優點。例如低噪音，高扭力，高能源效率和低廉的維修成本。在可見的未來，混合動力或電動式無人機將逐漸變得更流行。

本文提出穩態螺旋槳氣動負載直流馬達的數學模型並用電腦程式進行性能模擬。為了驗證此模型，對於不同組合的馬達和螺旋槳推進機組進行性能模擬。並將比功率參數與實驗數據進行對照比較，驗證結果令人滿意而且顯示出此模型的實用性。