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Evaluation of Brushless Motors Parameters Used in Aeromodeling

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Abstract: This article proposes a technique for evaluating the brushless motors parameters used in the domain of aeromodeling. Given the interest by this type of motor, in-depth analyzes have been made to determine its power consumption. For the simulations, an 11”×4.5” propeller was used. The brushless motor chosen is from the category of permanent magnet synchronous machines.

Keywords: aeromodeling, energy requirement, brushless motor, power consumption, permanent magnet synchronous machines

1. INTRODUCTION

At present time, more and more research work are devoted in design of prototypes in the field of aeromodeling. Many models are designed to meet different needs. To obtain an operational model, the study of the propulsion system is essential. The use of motors, especially brushless motors, is very common. The torque and thrust produced by the motor-propeller coupling are exploited to make the drone fly.

2. TORQUE AND THRUST PRODUCED BY A PROPRLLER

The torque and the thrust produced by a propeller depend on many parameters: physical parameters related to the environment status, parameters related to the propeller, and the speed of rotation of the motor that is used. These elements are essential in determining the power consumption.

2.1 Parameters

Civilian drones must meet certain conditions for their operations to be authorized. In this research work, attention is focused on altitude.

2.1.1 *Air density and athmospheric pressure*

The variation of air density as a function of atmospheric pressure is given by :

$$\rho = \frac{273.P_a}{101325(273 + T_t)}\rho_0 \qquad (1)$$

where:

ρ_0 is the air density at sea level such that ρ_0 = 1,293 kg.m^{-3}, T_e the temperature in °C, at an altitude h, and P_a the atmospheric pressure at a given altitude.

The atmospheric pressure P_a varies according to the altitude h and the temperature T_t, and we have [1]:

$$P_a = 101325\left(1 - 0.0065\frac{h}{273 + T_t}\right)^{5,2561} \qquad (2)$$

2.1.2 *Propeller parameters*

The diameter D_p, the pitch H_p, and other parameters shown in Table 1 are used to design a propeller.

Table 1. Parameters of a propeller [1]

Setting	Value	Setting	Value
A	5	**e**	0,83
E	0,85	**C_{fd}**	0,015
λ	0,75	**K_0**	6,11
ζ_p	0,5	-	-

2.2 Theoretical calculations

Two intermediate parameters, denoted C_M and C_T, are used to determine torque and thrust, such as [1]:

$$C_M = \frac{1}{8A}\pi^2 C_d \zeta^2 \lambda B_p^2 \qquad (3)$$

$$C_T = 0,25.\pi^3 \lambda \zeta^2 B_p K_0 \frac{\varepsilon.arctan\left(\frac{H_p}{\pi D_p}\right)}{\pi A + K_0} \qquad (4)$$

with

$$C_d = C_{fd} + \frac{\pi A K_0^2}{e}\frac{\left(\varepsilon.arctan\left(\frac{H_p}{\pi D_p}\right)\right)^2}{(\pi A + K_0)^2} \qquad (5)$$

If ω_m is the rotational speed of the motor expressed in rotations per minute (RPM), k the value of the drag coefficient and b the value of the thrust coefficient, the torque and the thrust produced by a propeller are given by the relations:

$$\mathrm{M} = k.\omega_m^2 \qquad (6)$$

$$\mathrm{T} = b.\omega_m^2 \qquad (7)$$

with

$$k = \rho.C_M.D_p^5 \qquad (8)$$

$$b = \rho.C_T.D_p^4 \qquad (9)$$

The coefficient k is expressed in N.m.s^2, while the coefficient b is expressed in N.s^2

2.3 Simulation results

Table 2 shows the values of the coefficients k and b, for different types of propellers, of dimension $D_p \times H_p$.

Table 2. Coefficients k and b

Propeller	10×5	10×7	11×4,5	11×7
k	9.10^{-6}	15.10^{-6}	12.10^{-6}	22.10^{-6}
b	5.10^{-4}	7.10^{-4}	6.10^{-4}	10.10^{-4}

For the simulations, an 11”×4.5” propeller was used.

Figure 1 shows the variation of the torque as a function of altitude and rotor speed on which, the propeller is fixed.

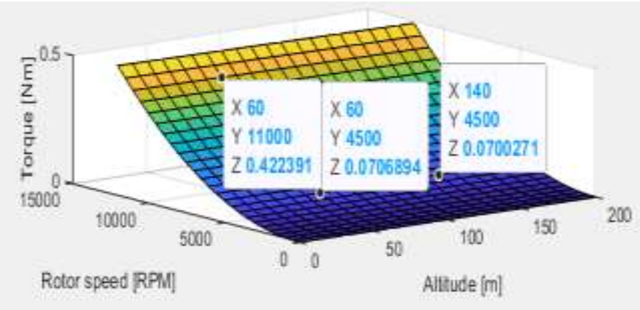

Figure. 1 Torque as a function of altitude and rotor speed

Figure 2 shows the variation of the thrust as a function of altitude and rotor speed on which, the propeller is fixed.

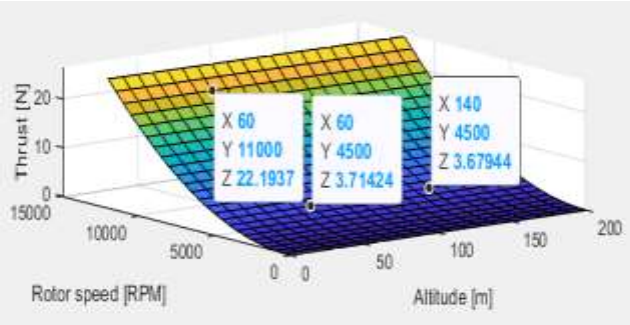

Figure. 2 Thrust as a function of altitude and rotor speed

It can be seen from these figures that the influence of altitude (X) on the torque and thrust (Z) produced by a propeller is insignificant, compared to the influence of speed rotor (Y).

3. BRUSHLESS MOTOR MODELING

In most of research on aeromodeling, brushless motor is used. It is an electric machine, of the category of synchronous machines. In this article, a three- phase brushless motor having a star connection is considered. Figure 3 shows the equivalent circuit of this type of motor.

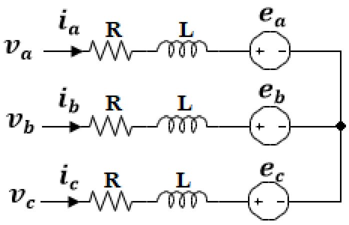

Figure. 3 Equivalent circuit of a three-phase brushless motor with star connection

3.1 Equations of the model

3.1.1 Electrical equations

The electrical equations that govern the operation of a brushless motor are given by:

$$v_a = Ri_a + L\frac{di_a}{dt} + e_a \quad (10)$$

$$v_b = Ri_b + L\frac{di_b}{dt} + e_b \quad (11)$$

$$v_c = Ri_c + L\frac{di_c}{dt} + e_c \quad (12)$$

with:

- $v_{a,b,c}$: voltages of the different phases a, b, and c
- $i_{a,b,c}$: currents in phases a, b, and c
- $e_{a,b,c}$: back electromotive forces or back emf
- R: armature resistance
- L: armature inductance

To operate at variable speed, the brushless motor must be able to be supplied at variable frequency by a three-phase voltage inverter. Figure 4 shows a simplified diagram of a brushless motor control.

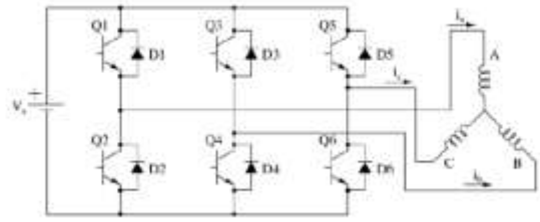

Figure. 4 Simplified diagram of the control of a brushless motor [2]

Switching control always makes it possible to have only one phase connected to the supply voltage, another phase connected to ground and another unconnected [3]. Also, the sum of the currents in each phase is always zero, i.e.:

$$i_a + i_b + i_c = 0 \quad (13)$$

Using this property and considering the voltages between the phases, the three electrical equations that govern the operation of a brushless motor can be reduced to two equations. Thus, we have:

$$v_{ab} = R(i_a - i_b) + L\frac{d(i_a - i_b)}{dt} + e_{ab} \quad (14)$$

$$v_{bc} = R(i_a + 2i_b) + L\frac{d(i_a + 2i_b)}{dt} + e_{bc} \quad (15)$$

3.1.2 Electromechanical equations

The electromagnetic torque generated by a brushless motor is given by equation 16:

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega_m} \quad (16)$$

Using the trapezoidal drive for the motor, the expressions for the back emf are defined by the following equations:

$$e_a = \frac{1}{2}k_e\omega_m Tra(\theta_e) \quad (17)$$

$$e_a = \frac{1}{2}k_e\omega_m Tra\left(\theta_e - \frac{2\pi}{3}\right) \quad (18)$$

$$e_a = \frac{1}{2}k_e\omega_m Tra\left(\theta_e - \frac{4\pi}{3}\right) \quad (19)$$

k_e is the electrical constant of the motor and $Tra(\theta_e)$ is a trapezoidal function defined by equation 20.

$$Tra(\theta_e) = \begin{cases} 1 \ \ si\ 0 \leq \theta_e < \frac{2\pi}{3} \\ 1 - \frac{6}{\pi}\left(\theta_e - \frac{2\pi}{3}\right)\ si\ \frac{2\pi}{3} \leq \theta_e < \pi \\ -1 \ \ si\ \pi \leq \theta_e < \frac{5\pi}{3} \\ -1 + \frac{6}{\pi}\left(\theta_e - \frac{2\pi}{3}\right)\ si\ \frac{5\pi}{3} \leq \theta_e < 2\pi \end{cases} \quad (20)$$

The relationship between the rotational speed of the motor and the electromagnetic torque can be written as:

$$T_e = k_f\omega_m + J\frac{d\omega_m}{dt} + T_L \quad (21)$$

k_f : coefficient of friction
J: moment of inertia of the motor
T_L: torque load

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By using equations (14), (15) and (21), we obtain the state space representation of a brushless motor. This representation is given in equation 22:

$$\begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{d\omega_m}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 & 0 \\ 0 & -\frac{R}{L} & 0 \\ 0 & 0 & -\frac{k_f}{J} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ \omega_m \end{bmatrix} + \begin{bmatrix} \frac{2}{3L} & \frac{1}{3L} & 0 \\ -\frac{1}{3L} & \frac{1}{3L} & 0 \\ 0 & 0 & \frac{1}{J} \end{bmatrix} \begin{bmatrix} v_{ab} - e_{ab} \\ v_{bc} - e_{bc} \\ T_e - T_L \end{bmatrix}$$

3.1.3 Switching sequences

The switching device needs information on the position of the rotor, measured by three Hall Effect sensors (Table 3). This is the angle θ_e mentioned in equation 20. The device must also supply the three phases of the motor, by three half-bridges making it possible to connect each phase either to the DC supply voltage, or to ground [3].

Table 3. Switching sequences

Switching interval	Position sensor			Switch closed		Phase current		
$0 - \pi/3$	1	0	0	Q_1	Q_4	+	-	off
$\pi/3 - 2\pi/3$	1	1	0	Q_1	Q_6	+	off	-
$2\pi/3 - \pi$	0	1	0	Q_3	Q_6	off	+	-
$\pi - 4\pi/3$	0	1	1	Q_3	Q_2	-	+	off
$4\pi/3 - 5\pi/3$	0	0	1	Q_5	Q_2	-	off	+
$5\pi/3 - 2\pi$	1	0	1	Q_5	Q_4	off	-	+

On Table 3:

- "+" means that the phase is connected to the power supply,
- "–" means that the phase is connected to ground,
- "off" means that the phase is not connected.

3.2 Simulations

3.2.1 Brushless motor parameters

The brushless motor parameters used for the simulations are shown in Table 4.

Table 4. Brushless motor parameters used in simulations [4]

Setting	Value	Unit
k_f	$7{,}93.10^{-6}$	N.m.s
J	$9{,}26.10^{-6}$	$kg.m^2$
n_p	8	-
R	0,6	Ω
L	0,28	mH
k_e	0,001	$V/rad.s^{-1}$

3.2.2 Presentation of the model

The brushless motor chosen is from the category of permanent magnet synchronous machines. We therefore used the Permanent Magnet Synchronous Machine or PMSM model from SimScape. The six switches of the inverter are made up of MOSFET transistors associated with diodes mounted in antiparallel so that current reversibility is possible.

Figure 05 shows the model adopted to control and/or measure:

- the torque created by the propeller,
- motor speed,
- the currents for each phase,
- the back emf. in each phase,
- and the power consumed by the motor.

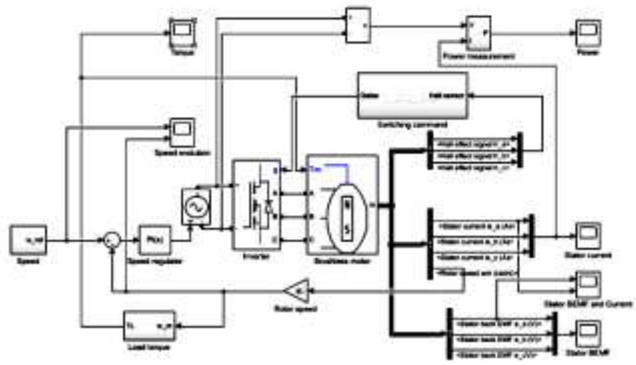

Figure. 5 Closed loop brushless motor speed control

3.2.3 Simulations results

In this section, X-axis represents time expressed in minutes. Figure 6 shows the reference speed, applied to the motor.

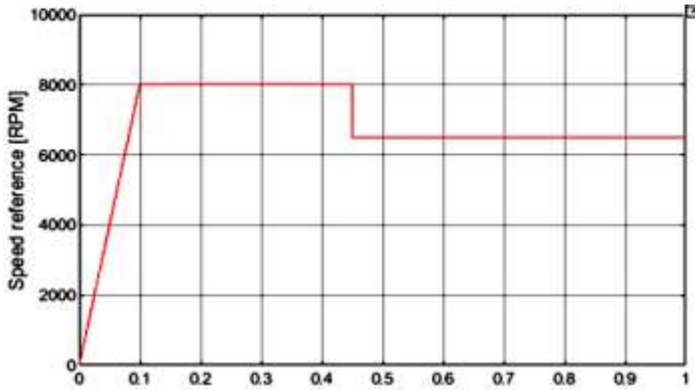

Figure. 6 Reference speed applied to the brushless motor

Figure 7 shows the variation of the torque created by the propeller, as a function of the engine speed (Equation 6).

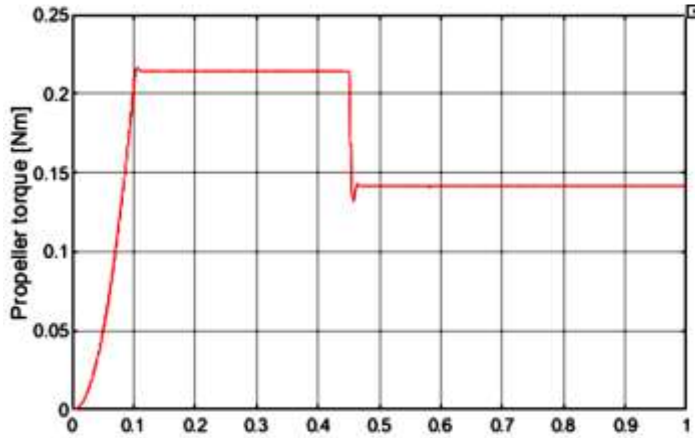

Figure. 7 Evolution of the torque created by the propeller

The torque created by the propeller is 0,2142 Nm when the motor reaches the speed of 8000 RPM. When the speed drops to 6500 RPM, its value is 0,1415 Nm.

Figure 08 represents the measured rotor speed.

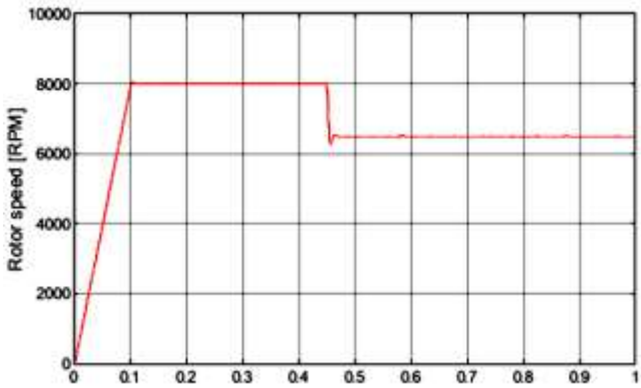

Figure. 8 Measured rotor speed

By comparing Fig. 6 and Fig. 8, it can be seen that the measured speed follows the reference speed.

The current variation in each phase of the motor is shown in Fig. 9.

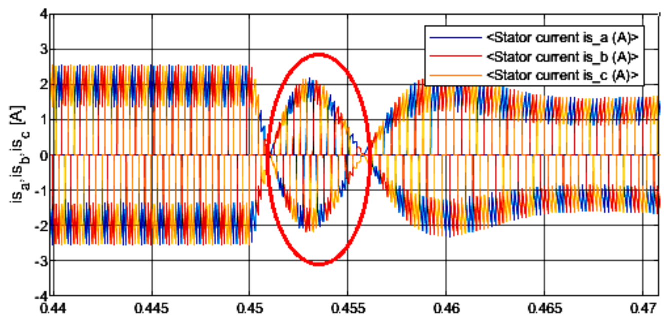

Figure. 9 Variation of phase currents

When the motor is running at 8000 RPM, the current in each phase reaches a peak of ±2.53 A. As the speed decreases, during the transition, this value decreases to ±2.18 A (circled in red). At the new speed of 6500 RPM, we have a peak of ±1.69 A.

Whatever the speed of the motor and taking into account the switching sequences of Table 3, if θ_{e^r} ϵ [0, $\pi/3$[, phase A is connected to the power supply and phase B, it will be connected to ground.

The variation of the back emf in each phase is given in Fig. 10.

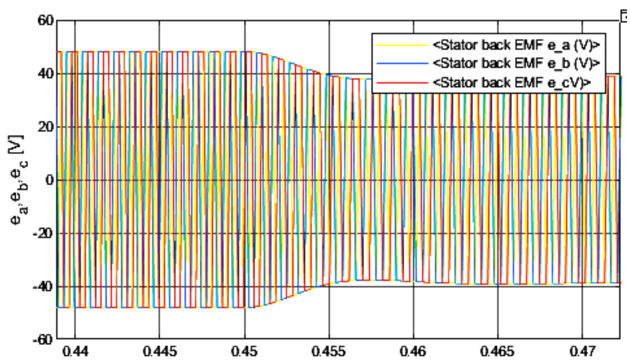

Figure. 10 Variation of the back emf

When the motor is running at 8000 RPM, the back emf in each phase reaches a peak of ±48 V. This value decreases, during the transition. At a speed of 6500 RPM, we have a peak of ±39 V.

Figure 11 shows the variations of the back emf and current in the same phase.

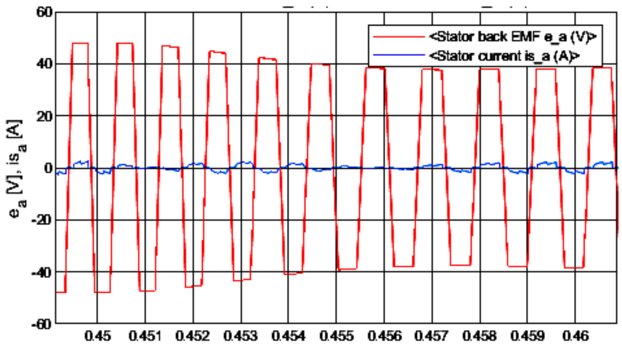

Figure. 11 Variation of the back emf and current in phase A

Figure 12 shows the evolution of the power consumption by the brushless motor.

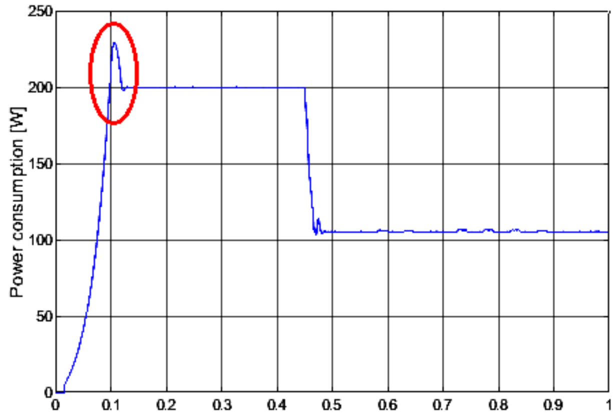

Figure. 12 Evolution of the power consumption by the motor

It can be seen that during starting, the power consumed by the motor reaches a peak of 229 W (circled in red). Afterwards, consumption stabilizes. At 8000 RPM, the motor consumes 200 W. When the speed decreases, the consumed power also decreases. In the simulation, it reaches 105 W for a speed of 6500 RPM.

4. CONCLUSION

Brushless motors have a considerable advantage in the aeromodeling domain. In this papers, the torque and the thrust that a propeller can produce are evaluated. The different parameters that are useful for the design of a propeller have been mentioned. It has been found that rotor speed has the greatest influence on the torque and thrust produced by a propeller.

Considering the interest that presents a brushless motor, its modeling is carried out in order to control the speed and to evaluate at the same time the power consumption. The SimScape tool from MATLAB-SIMULINK is used for the simulations.

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