The Influence of Carbon Fiber Propeller on the Brushless DC Motor Control

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The paper presents, from a comparative point of view, methods to increase the controllability of a drone. An important step in increasing the controllability is using light weight and resistant materials for the rotating parts of the drone. Also, the controllability can be increased by studying the structure of the propeller in order to reduce its moment of inertia.

Keywords: drone, moment of inertia, propeller, controllability, carbon fibre

The purpose of this paper is to present the methods to increase the control of a multi-copter. In order to increase the response of the multi-copter it is important to better control the brushless DC motors that powers the drone. One solution for better control of the brushless DC motors is presented in this paper.

During the implementation of the methods for increasing the controllability of the multi-copter drone, the structure must maintain its resistance and performance and moving capabilities.

In this case the drone must be able to move both on the air and on the ground and to be equipped with multispectral sensors.

There are many projects regarding only terrestrial drones or aerial drones, but this drone combines the advantages of the both systems (aerial and terrestrial movement): high mobility - it can reach the area of interest by alternation of the two movement types (aerial and terrestrial); the observation of interest points can be accomplished from close proximity due to the reduction of noise level in case of ground movement compared with the aerial movement; it increases the effective time used for observation. The ground movement consumes less energy than aerial movement.

Theoretical Consideration

In order to better control the brushless DC motor the transfer function must be considered.

The motor dynamics are modelled as a simple first order differential equation [1]:

$$J\dot{\omega} = \left[\left(v - \frac{\omega}{K_V}\right)\frac{1}{R} - i_o\right]\frac{1}{K_Q} - T_L \quad (1)$$

where:
- v - motor voltage;
- ω - motor speed;
- J - motor and propeller inertia;
- K_V - motor voltage constant;
- R - motor internal resistance;
- i_Q - no-load current;
- K_Q - motor torque constant;
- T_L - load torque.

The transfer function of the BLDC motor is [2]:

$$G(s) = \frac{\frac{1}{K_e}}{\tau_m \tau_e s^2 + \tau_e s + 1} \quad (2)$$

K_e is the phase value of the EMF constant [3].

$$K_e = 0.0605 \cdot K_t \quad (3)$$

The torque constant, K_t is:

$$K_t = \frac{9.554 \cdot P}{n \cdot I} \quad (4)$$

where:
- P - motor maximum power;
- n - maximum rotation speed;
- I - maximum current.

The mechanical constant is [3]:

$$\tau_m = 0.004 \frac{J \cdot R}{k_e \cdot k_t} \quad (5)$$

where:
- J- moment of inertia. Here we will consider as being the moment of inertia of the motor and propeller;
- R - electrical resistance of the motor.

The electrical constant is [3]:

$$\tau_e = \frac{l}{0.004 \cdot R} \quad (6)$$

where l is the electrical inductance of the motor.

Moment of inertia of the propeller

One of the methods to increase the controllability of the DC motor is to reduce the moment of inertia of the rotating parts, more exactly of the propeller.

One method to estimate the moment of inertia of the propeller is presented by Tomas Jiinec [5].

In order to determine the moment of inertia of the propeller, its weight must be measured and then the propeller is divided into several parts with known masses and dimensions.

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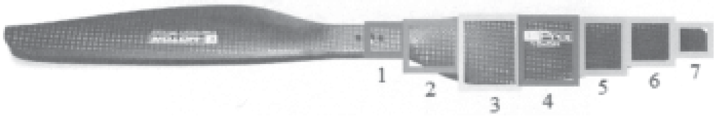

Fig. 1. Propeller divided for moment of inertia estimation

Table 1
OUTRUNNER BRUSHLESS MOTOR ROXXY 5065/ 09 SPECIFICATIONS

No. of cells	4-6 LiPo; 12-18 NiMH (23 V)
Current	35 A
Max current	45 A (60 sec)
No-load RPM	325 rpm/ V
Power at shaft	810 W
Max thrust	4600 g
Weight	377 g
Dimensions	D50 x L65 mm
Shaft diameter	6 mm

The moment of inertia of a thin rectangular plate of height h and of width w and mass m is given by the fallowing relations (Serway & Jewett n.d., p.304):

$$J_i = m\left(\frac{h^2}{12} + \frac{w^2}{12}\right) \quad (7)$$

The moment of inertia of the propeller will be:

$$J_p = 2 \sum^{total\ no\ of\ parts} J_i \quad (8)$$

Measurement of maximum load on the propeller

The maximum load on the propeller is achieved when the motor has the maximum rotation speed, at the maximum input signal.

In our case, the brushless DC motor used is Outrunner Brushless Motor ROXXY 5065/ 09 [6], with the fallowing specifications (table 1).

Fig. 2. Outrunner Brushless Motor ROXXY 5065/ 09

The maximum rotation speed was measured using FASTCAM SA.1, high speed video camera. The measurement frame rate was 2000 fps.

The results obtained for the measurement of the rotation speed as a function of the input signal are presented in the table 2.

Table 2
RESULTS FOR ROTATION SPEED MEASUREMENT

Input signal [%]	Rotation speed [rot/min]
30	1690
40	2711
50	3870
60	4800
70	5850
80	6760
90	7380
100	7384

Fig. 3. Measurement of rotation speed using high speed video camera

In order to determine the maximum load, the fallowing procedure was used:

- the motor was connected to a ESC and a fully charged battery;
- the DC motor was mounted on a force sensor;
- the motor DC motor was controlled form a Matlab application;
- a maximum input signal was sent to the DC motor;
- the thrust force was measured by the force sensor.

The maximum load on the propeller is the maximum thrust force. The maximum measured thrust force is 29.1 N.

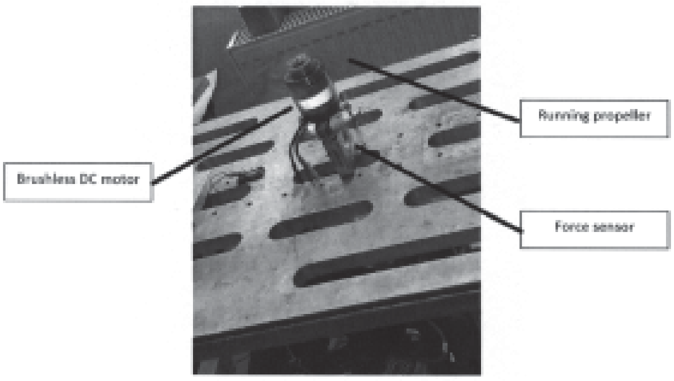

Fig. 4. Measurement set-up

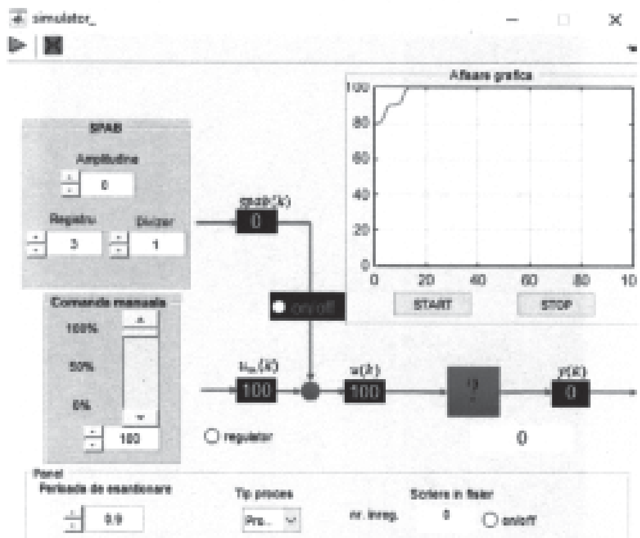

Fig. 5. Input signal from Matlab application

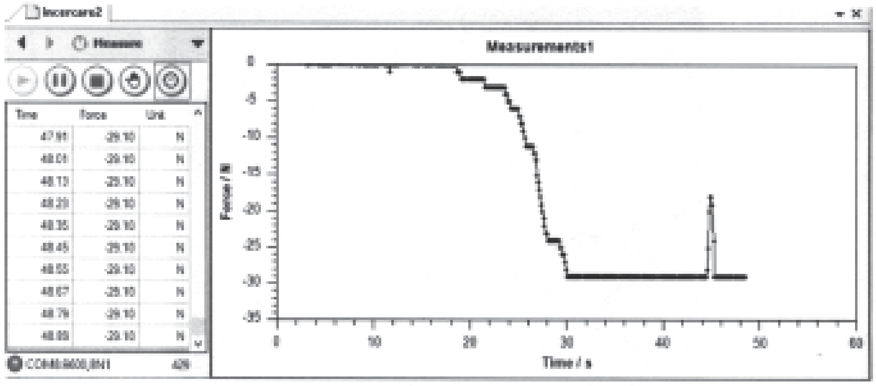

Fig. 6. Thrust force measurement results

Methods to reduce the moment of inertia of the propeller

One method to reduce the inertia of the propeller is to the use low density but resistant materials.

Another way to reduce the inertia of the propeller is to study the structure of the propeller. By studying the structure of the propeller it can be concluded that the use of a shell type structure of the propeller reduces its moment of inertia.

One material that has a low density and a very good mechanical resistance is the carbon fibre.

Table 3
CARBON FIBRE CHARACTERISTICS

Characteristics	Value
Elastic modulus	70 GPa
Poisson's ratio	0.1
Shear modulus	5 GPa
Mass density	1880 kg/m^3
Tensile strength	600 N/mm^2
Compressive strength	570 N/mm^2
Thermal expansion coefficient	2.1 K^{-1}

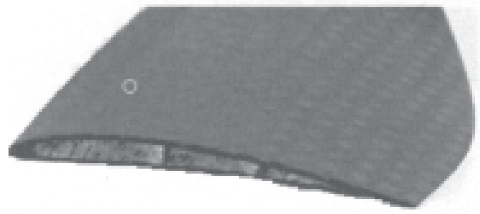

Fig. 7. Shell type propeller form Tiger motor

Propeller analysis

For the validation of the results, a simulation analysis was done, using SolidWorks, to compare the two type of propeller structure.

The mesh used for this model is a solid type mesh, with a curvature based mesher and 4 Jacobian points.

The simulation was carried out for a single blade of the propeller. The blade was considered fixed at the margin near the rotor shaft. The load on the propeller bade was considered to be a 14.5 N distributed force.

For both normal and shell type structures of the propeller blade, the simulation results were similar and both structures can be used at this load.

The resulted displacement for the shell type structure of the blade at maximum load was 11.6 mm, approximately the same as the one resulted during the measurement of the maximum load (11.5 mm), when a normal structure blade was used.

The propeller blade characteristics, obtained from SolidWorks are presented in the table 4.

In conclusion, regarding the mechanical resistance, both structures of the propeller blade can be used with the same confidence.

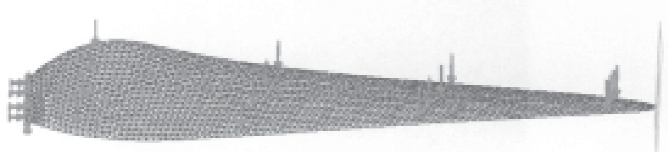

Fig. 8. The load on the propeller blade

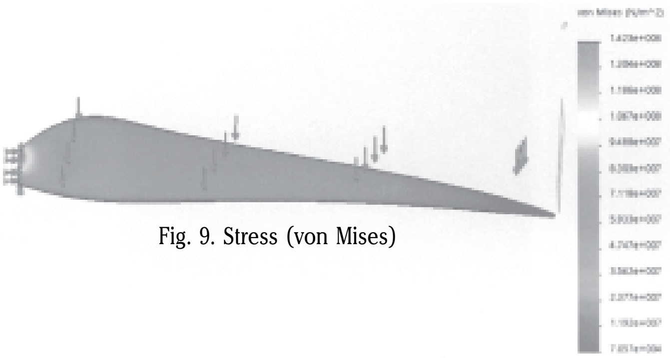

Fig. 9. Stress (von Mises)

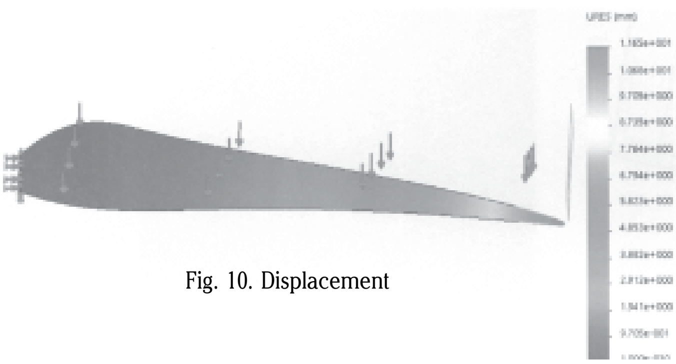

Fig. 10. Displacement

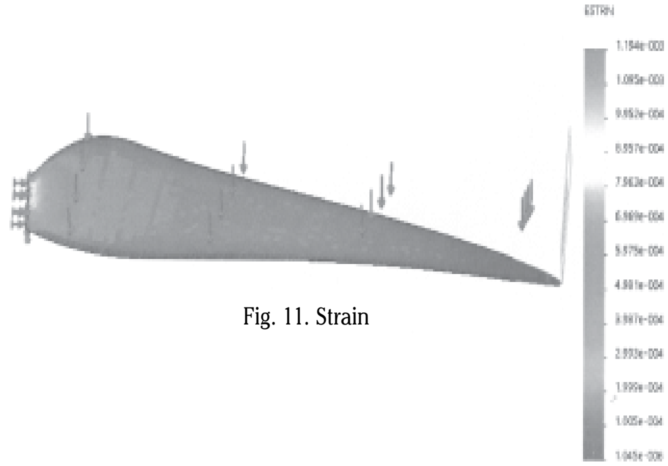

Fig. 11. Strain

But, regarding the transfer function of the brushless DC motor, the system with shell type structure of the blade presents (curve 1in fig. 12) presents better response to step input signal then the system with normal type propeller blade (curve 2 in fig. 12).

Table 4
PROPELLER'S BLADE CHARACTERISTIC

Characteristics	Shell type propeller	Normal type propeller
Mass	6.8 g	9.7 g
Moment of inertia	I_{xx}=22340 g·mm^2 0.2234·10^{-4} kg·m^2	I_{xx}=29512 g·mm^2 0. 29512·10^{-4} kg·m^2

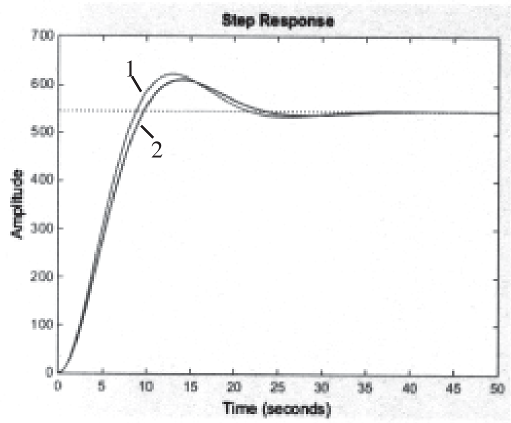

Fig. 12. Motor and propeller assembly response to step signal input (system with shell type structure of the blade – 1, system with normal type propeller blade –2)

The response of the system to step input signal is given figure 12.

Conclusions

In the case of multi-copter type drones it is important to have increased controllability. As it was shown in this paper, a method to increase the controllability is the choice of a light weight and resistant material and the type of the structure of the propeller.

A propeller with a smaller inertia increases the controllability of the drone and can assure the same mechanical resistance with correct choose of the material.

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