Energy Consumption of Mini UAV Helicopters with Different Number of Rotors

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***Abstract*-This paper describes comparison of mini UAV (Unmanned Aerial Vehicle) helicopters with different number of rotors by their efficiency and flight duration. Firstly flight time of real quadrotor helicopter compared with theoretical results. Using same helicopter principle and characteristics models with different number of rotors were compared by their energy consumption in hovering and linear motion states.**

I. Introduction

At first the idea of unmanned aerial vehicles (UAV) started as hobby but in the last decades it found a huge potential both in military [1] and civilian spheres. UAVs are capable of carrying out work conditions where the surrounding environment is dangerous or not available to human. There is a wide range of applications performed by UAVs, such as police [2], rescue [3] and firefighter needs [4], research, cinematography and others spheres. They have exclusive capabilities like hovering, vertical takeoff and landing, limited launching spaces and good maneuvering.

UAVs have generated great interest in industrial and academic circles [5]. Lot of research is made in control, stability and controllability spheres. Those UAVs are not using innovative power sources and energy saving question is very important.

In this paper are described and compared helicopters with different number of rotors. Flight duration of real quadrotor helicopter (quadrocopter; helicopter with four rotors, located on same plane) [6] was compared with theoretical results. Then using same copter principle and characteristics (size, motors, rotors, battery and others) models with different number of rotors were compared. Was compared time of immovable hovering of UAVs and their linear motion flight duration time.

II. Object of Research

Real quadrotor helicopter involved in comparison was developed by Department of Mechatronics, NIU ITMO in St. Peterburg.

This quadrotor UAV have dimensions 500 x 500 x 90 mm and full weight 1.4 kg. Four motors Turnigy 28-30 750Kv (245 W) with Turnigy Plush 10AMP Electronic Speed Controllers (ESC) are used. 4900 mAh 11.1 V battery is used. On Fig. 1 is illustration of this quadrotor helicopter.

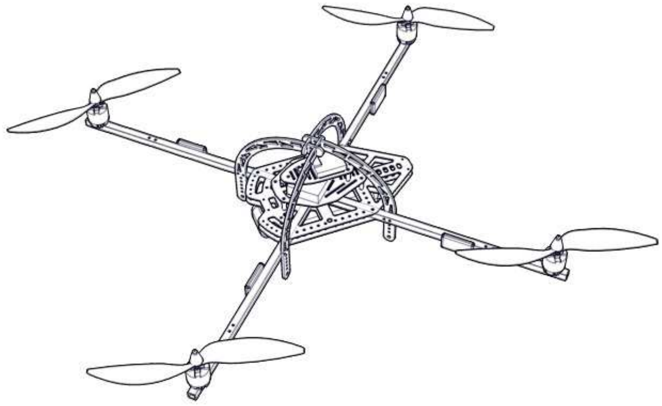

Fig. 1. Quadrotor helicopter model, developed by NIU ITMO.

III. Flow Analysis of Rotors

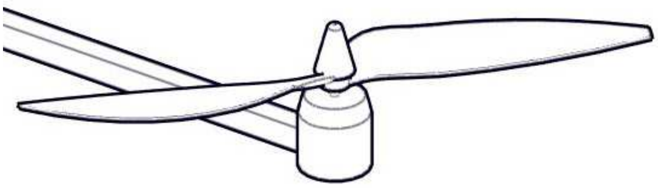

Fig. 2. One rotor.

In given model are used purchased rotors 10 x 4.5 from Draganfly Innovations (DF-1045CR). Rotor length is 10 inches and the pitch is 4.5 inches per revolution. To determine lifting force, that rotor is producing used Computational Fluid Dynamics (CFD) software SolidWorks Flo Simulation [7].

In first series of experiments used one rotor [8] [9] (Fig. 2) and determined force, that is produced on different rotation speeds of this rotor. Fig. 3 shows that near upper rotor edge lower pressure region appears. Same time near lower edge appears upper pressure regions, and this pressure difference, according to Kutta–Joukowski theorem [10], creates lifting force. Max pressure difference ca 6500 Pascal (Pa) at rotor rotation speed 7500 revolutions per minute (RPM). One rotor produces 7.03 newton (N) lifting force on 7500 RPM. Force dependence from rotor rotation speed is shown on Fig. 6 (F1).

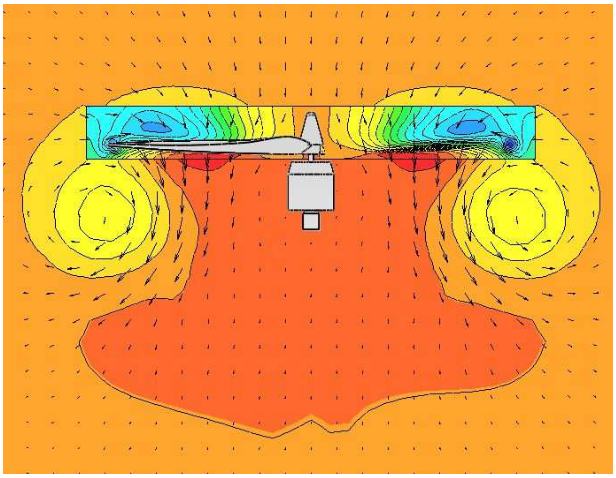

Fig. 3. Pressure distribution near rotor.

In second experiment series pair of coaxial rotors [11] is used. In this scheme of rotor alignment are used same rotors, but since they rotate in opposite directions left and right hand rotation versions of rotors are used (Fig. 4).

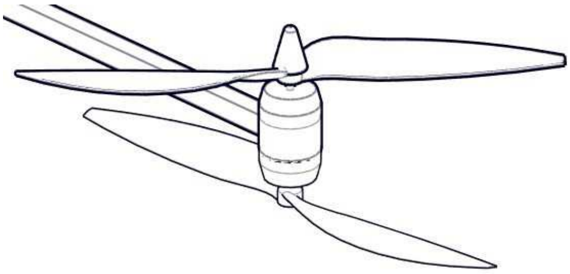

Fig. 4. Two coaxial rotors.

If both rotors have same rotation speed they compensate each other rotating moment. Each rotor have own motor and changing their rotation speed inside pair it is possible to rotate platform. For holding aircraft in air and for directional flight each pair of rotors rotates same speed. Fig. 5 – air velocity around coaxial rotors (max velocity 50 meters per second (m/s) at 7500 RPM).

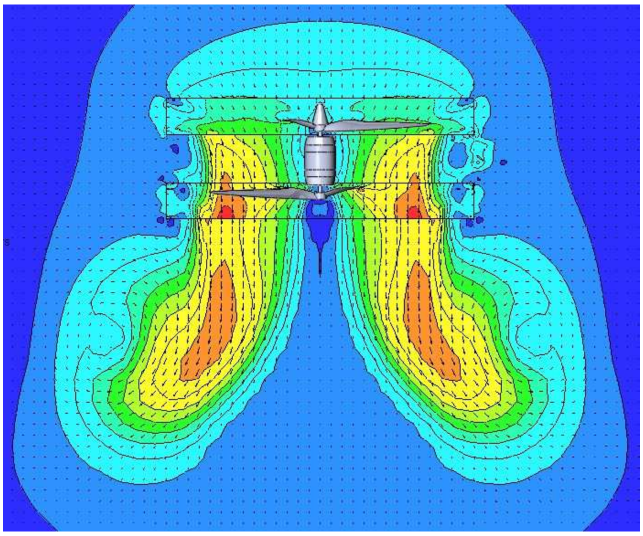

Fig. 5. Air velocity distribution near coaxial rotors.

On Fig. 6 is shown rotor pair lifting force (N) dependency on rotor rotation speed (RPM) (F2). X axis shows each rotor rotation speed and Y – combined lifting force of both, upper and lower rotor (estimated distribution: 65 % force given by upper and 35 % by lower rotors).

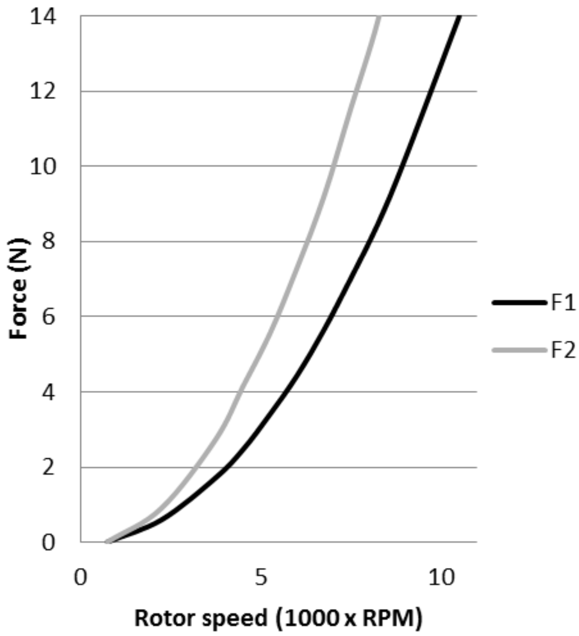

Fig. 6. Produced lifting force dependency on rotor rotation speed (F1 – one rotor, F2 – two coaxial rotors together).

IV. Helicopters with Different Number of Rotors

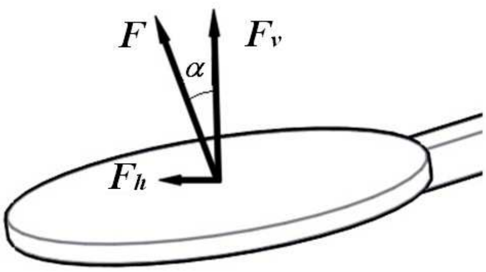

Fig. 7. Force distribution in horizontal flight.

To unify our models we will compare helicopters with same motors and rotors. Mass of platform is combined from 1080 g – platform base (including body, battery, controller and other equipment) and each rotor system mass - 80 g (includes 57 g motor, rotor, ESC, wiring and other component masses). Centers of helicopters masses are located in the centers of models. Also idealized room conditions without winds are used [12].

For holding aircraft immovable in the air all rotors must rotate same speed and create force that compensates mass of platform. For horizontal flight helicopter must be sloped in the direction of flight. All motors and rotors are immovable about the body of UAV and when platform is sloped forces from rotors also aligned with angle (F, α on Fig. 7).

Decomposing force F will get vertical (lifting) force F_v and horizontal (pulling) force F_h (1), (Fig. 7).

$$F_v = F \cdot \cos\alpha, \quad (1)$$
$$F_h = F \cdot \sin\alpha,$$

where :
F – force, produced by rotor,
α – slope angle.

To provide only horizontal flight it is needed that sum of all lifting forces F_v will be equal of gravity force. Will take into account that our platform is moving forward with velocity 2 m/s. From equation 2 finding needed force F_h.

$$F \cdot \Delta S = \frac{m \cdot v^2}{2}, \quad (2)$$
$$F_h = \frac{m \cdot v^2}{2 \cdot \Delta S},$$

where:
ΔS – movement,
m –mass,
v – velocity,
F (F_h) – force (pulling).

A. Four Rotor Helicopter

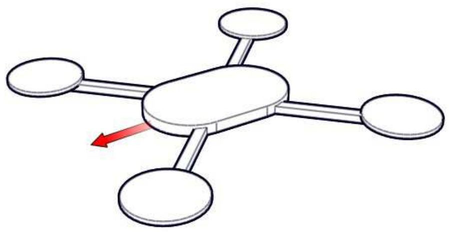

Fig. 8. Four rotor helicopter.

Overall mass of four rotor system [13] (Fig. 8) is 1.4 kg and 3.5 N force is needed on each rotor to hold aircraft in air in horizontal direction and to get this force 5334 RPM of rotor speed needed.

Platform is moving in horizontal direction with velocity 2 m/s and totally 2.8 N of F_h is needed (2). Each rotor needs generate 0.7 N of this force. To reach those forces angle α 11.3 degrees is needed, so total force of each motor is 3.57 N and to get this force 5386 RPM of rotor speed is needed. When platform is sloped F_v must be 3.5 N.

B. Three Rotor Helicopter

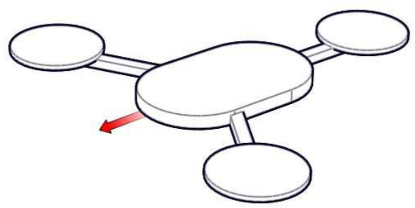

Fig. 9. Three rotor helicopter.

On three rotor helicopter - tricopter (Fig. 9) [14] with mass 1.32 kg each rotor must reach 4.4 N on 5967 RPM to hold platform immovable. For horizontal flight pulling force 2.64 N (F_h) needed and to reach this each rotor must generate 0.88 N of it. Those parameters are able to keep when slope angle is 11.31 degrees and 4.49 N force on 6024 RPM is produced by each motor.

C. Eight Rotor Helicopter

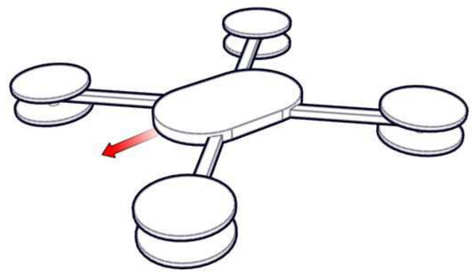

Fig. 10. Eight rotor helicopter.

Eight rotor helicopter - octocopter (Fig. 10) is similar to four rotor model, but instead of each rotor used pair of coaxial rotors. To hold aircraft with mass 1.72 kg in air each pair must generate 4.3 N lifting force and 4656 RPM rotor rotation speed is needed on each rotor. For horizontal flight with velocity 2 m/s each rotor must rotate with 4700 RPM.

D. Six Rotor Helicopter

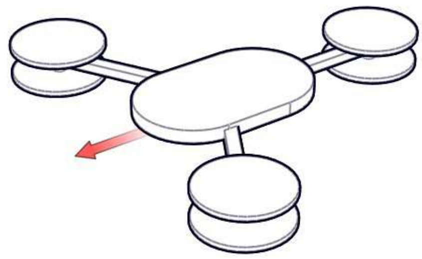

Fig. 11. Six rotor helicopter.

Six rotor helicopter - hexacopter (Fig. 11) must generate 5.2 N of force by each rotor pair, and they can do it when have 5095 RPM of each rotor. To reach horizontal flight velocity 2 m/s each rotor must rotate 5143 RPM.

V. Power Consumption

For motor power consumption calculation is needed to know motors characteristics. Since given model is using brushless DC electric motor from company Turnigy, its characteristics are used. For this motor are available graphics with electric current for certain motor rotation speed on certain voltage. Also ECE (Electric Consumption Efficiency) 0.81 is used (combined from motor and ESC efficiencies).

In given helicopter with four rotors each motor power is 32.5 watts (W) and it means that using battery with capacity 54.5 watt per four (Wh) he can stay in air for 25 minutes. In real experiments of given UAV it can stay in air for about 20 minutes, but in given in this paper power consumption calculation main controller and RC module (Radio Control) power consumptions are not taken into account. Table 1 presents data about all described in this paper several rotors helicopters – rotors rotation speed, produced lifting forces, power consumption, flight duration and others.

In this calculation time and force, that is needed to slope UAV, is not taken into account. Fig. 12 presents comparison of hovering time of calculated platforms – t1. Columns t2 show how long concrete type of helicopter would fly, if its mass will be 1 kg.

TABLE I

CALCULATED DATA

Number of rotors	4	3	8	6
Mass (kg)	1.4	1.32	1.72	1.56
Each rotor (or pair) force (N)	3.5	4.4	4.3	5.2
Each rotor (or pair) force F_h (N)	0.7	0.88	0.86	1.04
Slope angle α (degrees)	11.31	11.31	11.31	11.31
Rotor speed (RPM), hovering	5334	5967	4656	5095
One motor power (W), hovering	32.5	40.3	23.8	29.4
Hovering time (min)	25.1	27.0	17.2	18.5
Time for 1 kg (min), hovering	35.2	35.7	29.5	28.9
Rotor speed (RPM), horizontal flight	5385	6024	4700	5142
One motor power (W), horizontal flight	33.2	41.2	24.4	30.0
Horizontal flight time (min)	24.5	26.4	16.7	18.1
Time for 1 kg (min), horizontal flight	34.4	34.9	28.8	28.2

Horizontal flight time is little bit smaller than hovering time (Table 1, Fig. 13), but ratio between them is same.

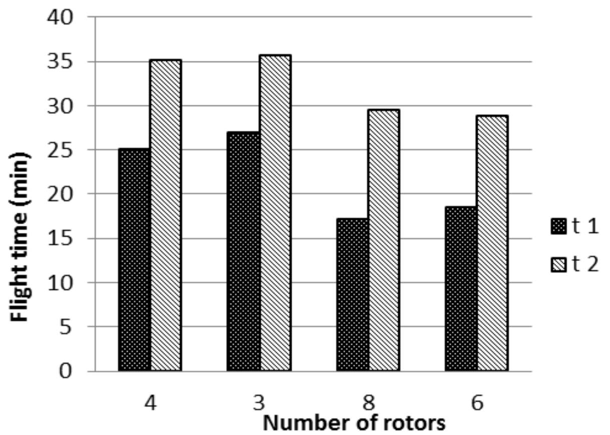

Fig. 12. Hovering flight duration comparison.

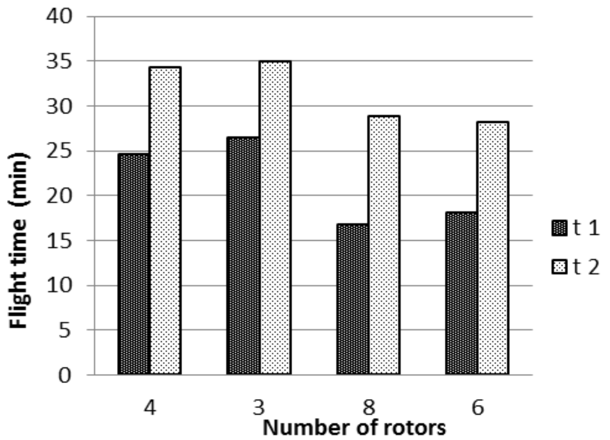

Fig. 13. Horizontal flight duration comparison.

VI. CONCLUSION

This paper describes theoretical calculation of energy consumption of real quardrotor helicopter and comparison with real tests data. Theoretically are compared helicopters with three, four, six and eight number of rotors. As results we can see that most efficient helicopter type from presented is model with three rotors, but difference with four rotor model is only 1.5 %. Models with pairs of coaxial rotors consume more energy, but theoretically they are more stable.

ACKNOWLEDGMENT

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