UDC 534.23

Oleg V. Dusheba, Master, PhD student;
Petro V. Lukianov, PhD, Associate Professor
(Kyiv Polytechnic Institute named after Igor Sikorsky)

Aerodynamic calculation of a quadrotor type air taxi

This paper presents an aerodynamic calculation of a quadrotor-type air taxi. In particular, for the given sizes of the quadrotor blades, the lift, thrust and torque are calculated for certain angles of blade attack. The obtained calculation data allow us to establish the permissible flight weight of the air taxi.

Introduction

Recently, the problem of fast movement in densely populated megacities, as well as in complex geographical areas, has been solved by using quadrotor air taxis. This kind of transport is rapidly spreading around the world. This is evidence of its promise and relevance to human needs.

An aircraft of this type has four identical propellers symmetrically arranged in relation to the quadrotor cabin. Air taxis are relatively small in size, designed to carry only a few people. Therefore, air taxis have a weight that is approximately equal to that of a conventional car, with a speed of 100km/h to 200km/h. This type of transport is developing rapidly and is in demand.

1. Current state of research

One of the most important issues in the design of an aircraft is its aerodynamic and power calculation. A number of works are devoted to the issue of aerodynamic calculation of quadrocopters. Thus, papers [1, 2] present the calculation of the main aerodynamic characteristics of a quadrotor during aggressive maneuvers. The calculations took into account the interconnection of flight speed, incoming flow velocity, induction velocity, thrust, and torque.

1. Aerodynamic calculation

2.1 Aerodynamic model, general relationships

1.Since the rotor of a quadrotor rotates in the horizontal plane, similar to a helicopter rotor, we will use the theory of the blade element to calculate the aerodynamics and dynamics of the quadrotor [3]. Figure 1 shows a cross-section of a blade located at an angle θ of the blade to the horizon. We decompose the total aerodynamic force F into horizontal F_x and vertical F_z components (see Fig. 1):

$$F_x(r) = L(r)\,sin\,\varphi\,(r) + D(r)\,cos\,\varphi\,(r),$$

$$F_z(r) = L(r)\, cos\, \varphi\,(r) - D(\,r)\, sin\, \varphi\,(r) \qquad (1)$$

Accordingly, the total flow velocity U can be decomposed into two components: the horizontal component u_T and the vertical component u_p.

$$U = \sqrt{{u_p}^2 + {u_T}^2},$$
$$\varphi = arctan(\,u_p/u_T) \qquad (2)$$

The aerodynamic angle of attack is $\alpha = \theta - \varphi$.

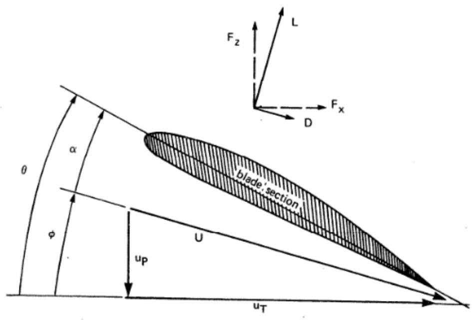

Fig. 1 Distribution of forces on the blade element [3].

Lift L and drag D are written in terms of the appropriate coefficients as follows:

$$L(r) = \frac{1}{2}\rho V^2(r) \cdot c(r) \cdot Cy(\alpha(r))$$
$$D(r) = \frac{1}{2}\rho V^2(r) \cdot c(r) \cdot Cx(\alpha(r)) \qquad (3)$$

Let us denote the blade moving forward with the index "f" and the blade retreating with the index "r", V is the linear speed of rotation of the blade. Then expressions (3) will be written:

$$U_f = \sqrt{{u_p}^2 + (u_T + V)^2}$$
$$U_r = \sqrt{{u_p}^2 + (u_T - V)^2}$$

$$L_f(r) = \frac{1}{2}\rho U_f^2(r) \cdot c(r) \cdot Cy(\alpha_f(r)$$
$$L_r(r) = \frac{1}{2}\rho U_r^2(r) \cdot c(r) \cdot Cy(\alpha_r(r))$$
$$D_f(r) = \frac{1}{2}\rho U_f^2(r) \cdot c(r) \cdot Cx(\alpha_f(r))$$
$$D_r(r) = \frac{1}{2}\rho U_r^2(r) \cdot c(r) \cdot Cx(\alpha_r(r))$$

$$Fz_f(r) = L_f(r) \cdot \cos\varphi_f(r) - D_f(r) \cdot \sin\varphi_f(r)$$
$$Fz_r(r) = L_r(r) \cdot \cos\varphi_r(r) - D_r(r) \cdot \sin\varphi_r(r)$$
$$Fx_f(r) = L_f(r) \cdot \sin\varphi_f(r) + D_f(r) \cdot \cos\varphi_f(r)$$
$$Fx_r(r) = L_r(r) \cdot \sin\varphi_r(r) + D_r(r) \cdot \cos\varphi_r(r)$$

(4)

2.2. Drag force, torque

An important aerodynamic characteristic is the total thrust force, which can be calculated using the following formula [3]:

$$T = 2\int_0^R Fz(r)dr + \int_0^R Fz_f(r)dr + \int_0^R Fz_r(r)dr \qquad (5)$$

The torque is calculated accordingly using the formula:

$$Q = 2\int_0^R r \cdot Fx(r)dr + \int_0^R r \cdot Fx_f(r)dr + \int_0^R r \cdot Fx_r(r)dr \qquad (6)$$

3. Analysis of numerical calculations

Since the purpose of the study is to determine the possible weight of an air taxi, the parameters of one of the existing air taxi concepts [4] were taken as the design data (see Fig. 2). Blade length $R = 2{,}8$ m, blade chord c varies from 0.217 m to 0.176 m with a geometric torsion of 12°, rotational speed $\Omega = 500$ rpm, and a linear blade tip speed of approximately $V_{tip} = 170$ m/s. The blade profile was taken from NACA 0010. But in our case, we assumed number of blades 4 per rotor.

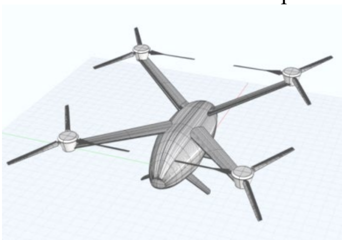

Fig. 2. General view of a quadrotor air taxi [4]

Figures 3 and 4 show the calculation of the aerodynamic characteristics of the quadrotor in hover mode at $Re = 2 * 10^6\ m/s$.

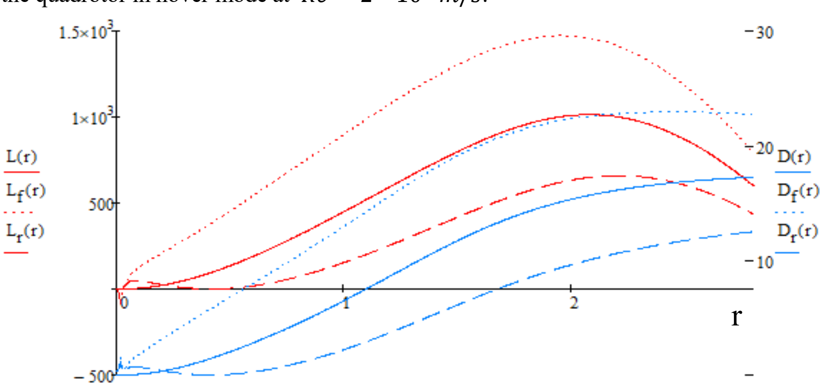

Figure 3. Distribution of lift and drag force components on the blades

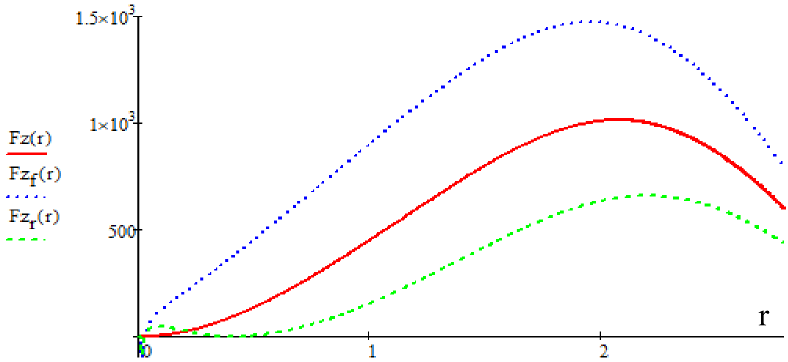

Figure 4. Distribution of thrust forces on the blades

In addition to the aerodynamic characteristics shown in Figures 3 and 4, the total thrust T and total torque Q were calculated. The obtained values of $T = 6936\ N$ and $Q = 282.866\ N \cdot m$ show that the total thrust force is capable of lifting 2800 kg, which is quite comparable to the weight of a modern passenger car. It should also be noted that during horizontal movement, the thrust of the engines will only increase.

References

1. Haomiao Huang, Gabriel M. Hoffmann, Steven L. Waslander, Claire J. Tomlin. Aerodynamics and Control of Autonomous Quadrotor Helicopters in Aggressive Maneuvering// 2009 IEEE International Conference onRobotics and Automation,12-17May,Kobe,Japan. https://ieeexplore.ieee.org/document/5152561.
2. Gabriel M. Hoffmann, Haomiao Huang, Steven L. Waslander, Claire J. TomlinAIAA Guidance, Navigation and Control Conference and Exibit, 20-23 Augest,Hilton Head, South California.// https://doi.org/10.2514/6.2007-6461
3. Wayne Jonson. Helicopter Theory. Dover Publication, Inc.,New York,1980,p.1111.
4. Patricia Ventura Diaz, Seokkwan Yoon. Computational study of NASA's Quadrotor Urban Air Taxi Concept. AIAA SciTech Forum,6-10 January 2020,Orlando,FL.,p.21. https://ntrs.nasa.gov/api/citations/20200000444/downloads/20200000444.pdf