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SIMULATION OF WIND EFFECT ON A QUADROTOR FLIGHT

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ABSTRACT

Different disturbances should be taken into account to solve the quad rotor flight control problem. Wind effect is a disturbance in a quad rotor flight control system. A model of wind effect on quad rotor flight was developed in this paper. The model is a number of elements: the model of wind velocity change, the model of a gust ("wind step"), the model of wind velocity change depending on a flight altitude, the model of wind direction change. The model of wind velocity change takes into account wind velocity increasing and decreasing. The wind force expression depending on the effective influence area on a quad rotor was derived. The steps of the wind disturbances simulation algorithm are given here.

Keywords: model, wind force, Control Quad rotor, simulation, algorithm, gusts, wind directions, wind velocity.

1. INTRODUCTION

Quad rotors are small-sized aerial vehicles equipped with four rotors. Quad rotors have simple design, and they are used in the following tasks: photography of plants, environmental monitoring, transportation of small cargos, etc [1, 4].

The quad rotor control tasks consist in accuracy of orientation in space, motion along desired track, automatic take-off and landing [5, 9]. Effective control task solution is related to the tasks of simulation of uncontrollable effects on a considered aerial vehicle. The wind disturbances are uncontrollable effects. Analysis of wind effect on quad rotor flight dynamics is referred as a complex problem, and its solution has no sufficient deal of interest. Wind effect is considered as a constant in many research papers. Constant wind effect does not reflect real flight conditions and as a result it leads to wrong conclusions about high accuracy of quad rotor control.

2. WIND EFFECT SIMULATION

The influence of meteorological conditions should be taken into account for the quad rotor flight control problem solution. The main meteorological conditions are the changes of temperature, pressure, air density and air motion (wind) [10]. Wind has major influence on the flight dynamics. Influence of temperature, pressure and air density change is not essential at the operational altitude of quad rotor flight.

Analysis of wind effect allows separation the constant (systematic) component and the variable (turbulent) component. The constant component specifies a constant wind velocity value. The variable component specifies gusts. Estimation of main meteorological conditions influence is made as a rule using statistical models of meteorological conditions deviation from their climatic values [11]. The wind velocity will be considered as a vector random value in this paper. The wind velocity is defined in the point $r=(x, y, z)$ by the formula

$$V(r) = V_s(r)+V_v(r), \qquad (1)$$

where $V(r)$ is the full wind velocity, $V_c \in R^3$ is the systematic component, $V_v \in R^3$ is the variable component.

Wind effect can be considered from the micro approach and macro approach point of view. According to the micro approach a set of points r fills a space around the quad rotor frame. Velocity and direction of wind in each point will be different. Wind effect will have influence on different elements of the quad rotor with a specific velocity and direction at each time point (Figure-1(a)).

According to the macro approach the whole quad rotor is connected with the point r. The point r is located in the origin of the body-fixed frame. Wind influence on the different elements of construction has equal magnitude and direction at any time point (Figure-1(b)).

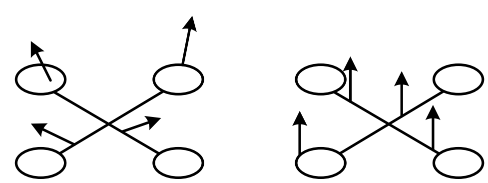

Figure-1. Approaches to analysis of wind effect on quad rotor.

Probabilistic models of wind representation according to micro approach are given in [10] with the use of:

- Approximation of wind autocorrelation functions by analytical expressions;
- No canonical decomposition of wind velocity components;
- Canonical decomposition of the wind velocity components;
- Shaping filters of the wind velocity components.

Appropriateness of micro approach use is open to question for the simulation of wind disturbances on a quad rotor. It is connected with laboriousness and absence of methods for wind characteristics measuring in different points around a quad rotor. For this reason the use of macro approach is more reasonable for simulation of wind disturbances.

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While developing the model, two characteristics of wind will be considered. These are the magnitude and the direction of wind velocity.

The model of a wind velocity "step" and the model of a gust are suggested in [11]. The magnitude of wind velocity is specified at wind velocity "step" at the moment t_0 by the following formula:

$$|V| = \begin{cases} 0, & t < t_0, \\ \frac{V_m}{2}\left(1-\cos\left(\frac{\pi(t-t_0)}{d_n - t_0}\right)\right), & t_0 < t < d_n \\ V_m, & t < t_m. \end{cases} ; \qquad (2)$$

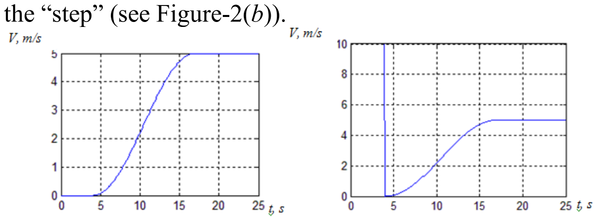
The magnitude of wind velocity is specified at the gust by the following formula:

$$|V| = \begin{cases} 0, & t < t_0, \\ V_m \sin\left(\frac{\pi(t-t_0)}{d_m - t_0}\right), & t_0 < t < d_m \\ 0, & t < t_m. \end{cases} ; \qquad (3)$$

where d_n is interval of wind increasing; V_m is the gust magnitude; d_m is duration of the gust; t_m is the maximum flight time.

The curves of wind velocity at the wind "step" are shown on Figure-2.

The change of wind velocity in compliance with (2) at t_0=4, d_n=13, t_m=25 is shown in Figure-2(a). Formula (2) does not allow simulation the wind velocity decrease and taking into account the component of velocity before the "step" (see Figure-2(*b*)).



a *b*

Figure-2. Changing of wind velocity at the "step" (model (2)).

To take into account above mentioned disadvantages a modified model is given. The modified model is specified with the following formulas:

$$|V| = \begin{cases} V_0, & t \le t_0, \\ V_0 + \frac{|V_m - V_0|}{2}\left(1-\cos\left(\frac{\pi(t-t_0)}{d_n - t_0}\right)\right), & t_0 < t \le d_n, V_m \ge V_0, \\ V_0 + \frac{|V_m - V_0|}{2}\left(\cos\left(\frac{\pi(t-t_0)}{d_n - t_0}\right)-1\right), & t_0 < t \le d_n, V_m < V_0, \\ V_m, & t \le t_m. \end{cases} ; \qquad (4)$$

where V_0 is the wind velocity before the "step".

To simulate systematic wind component at long time intervals, we consider the following variables:

- $n(t_m)$ is the discrete random variable determining a number of wind "steps" at the flight time t_m;
- $t_i(t_m, n)$ is the discrete random variable determining the moment of a wind "step" start;
- $d_i(t_0, n)$ is the discrete random variable determining the duration of gust;
- $v_i(n)$ is the discrete random variable determining a gust magnitude.

For random values generation the following limitations will be applied: $n\in[0, t_m/10]$, $d_i\in[0, t_{i+1}-t_i]$, $v_i\in[0, V_{max}]$, $|v_i-v_{i-1}|/d_i< a$ (*a* is the restriction of the rate of "step" rise).

The simulation results at t_0=[0; 9; 16; 19] (*c*), V_m=[1; 4,5; 0; 1] (*m/s*), d_n=[7, 5, 2, 5] (*c*), t_m=25 *s*, V_0=0,5 *m/s* are shown on fig. 3.

The simulation results reveal that model (4) allows simulation the increase and decrease of wind velocity taking into account the velocity of wind before "step". Using this model the systematic component V_s of wind velocity can be simulated.

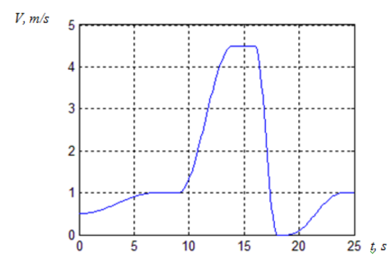


Figure-3. Changing of wind velocity (model (4)).

The gust simulation results at t_0=[0; 9; 16; 19] (*c*); V_m=[3; 4,5; 0,75; 1] (*m/s*); d_m=[0,5; 0,75; 2; 1] (*c*), t_m=25 *s* are shown on figure 4. The results of formula (3) simulation revealed that simulation with gusts is made taking into account also variable component of the wind velocity V_v.

Let's accept the azimuth ψ_w of the point from which wind blows as a wind direction. The azimuth is measured from the north point through the east [12]. Axis OX of the inertial frame OXZ points to the North. Wind direction changes at each wind velocity "step"

$$\psi_{w(i+1)} = \psi_{wi} \pm \Delta\psi_w, \qquad (5).$$

where $\Delta\psi_w$ is the random value of wind direction change.

The curves of the wind velocity magnitude and direction changing for the quadrotor flight time 180 *s* are shown on Figure-5.

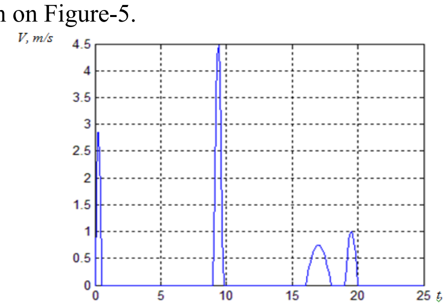


Figure-4. Changing of wind velocity at gusts (model (3).

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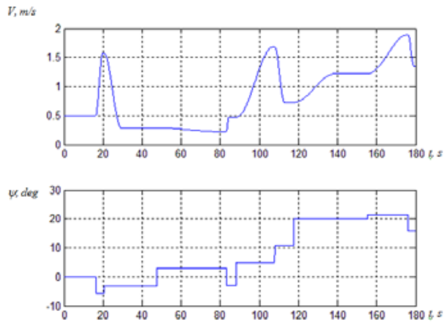

Figure-5. Wind velocity magnitude and direction changing.

The maximum change of wind direction is determined as 10°. The simulation results show effectiveness of the proposed approach to the simulation of wind velocity and azimuth.

To simulate the wind velocity changes depending on altitude we will use the results of researches [13 - 15]. The average wind velocity is determined by the following formula:

$$V_{cz} = V_{0z}\left(\frac{z}{z_0}\right)^p, \qquad (6)$$

where V_{cz} is the wind velocity at altitude z, V_{0z} is specified (measured) wind velocity at altitude z_0, p is index of energetic wind profile.

The diagram of wind velocity depending on altitude is shown on Figure-6. Formula (model) (6) has shown a satisfactory result at difference z-z_0 less than 50 meters (V_0=3 m/s, z_0=1 m, p=0,1).

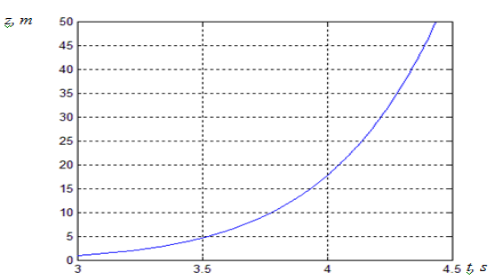

Figure 6. Diagram of wind velocity depending on altitude.

To simulate wind disturbances, a wind force which influences a quad rotor is much more essential than a wind velocity. This force can be determined by the following formula:

$$F_w = S_e A V_{cz}^{\ 2}, \qquad (7)$$

where S_e is the influence effective area; A=1/16·9,81=0,61 is the rate of wind velocity (m/s^2) conversion to pressure (N/m^2) [16].

Influence force is determined according to formula (7) by the wind velocity and orientation of a quad rotor with reference to the force direction.

For simulation tasks it is handier to use the components of formula (7) as projections on axes of the frame *OXYZ*

$$F_{wx} = S_{ex}A(V_{cz})^2\cos\psi_w,\ F_{wy} = S_{ey}A(V_{cz})^2\sin\psi_w. \qquad (8)$$

Let's represent a quad rotor as a cylinder component for the simplicity sake. The expression determining the quad rotor surface area will be equal to the sum of the area S_b of the lateral surface and the area S_o of bases.

$$S_k = S_b + S_0 = \alpha 2\pi rh + \beta 2\pi r^2, \qquad (9)$$

where h is the cylinder height, r is the cylinder radius, α, β are the fill factors of the cylinder area (depending on quad rotor design).

The first term in formula (9) determines the area of the cylinder lateral surface; the second term determines the area of the cylinder bases. Let wind influence a quad rotor construction uniformly (Figure-7).

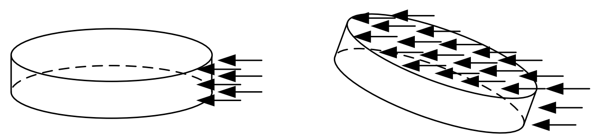

Figure-7. Wind effect on a quad rotor construction.

Let wind effects half a quad rotor area. Taking into account formula (9) we will get the expression for the effective area:

$$S_{ex} = \beta\pi r^2\sin\theta + \alpha\pi rh\cos\theta,\ S_{ey} = \beta\pi r^2\sin\phi + \alpha\pi rh\cos\phi, \qquad (9)$$

where ϕ, θ are the roll and pitch angles correspondingly.

So, the following algorithm can be proposed to simulate strength of wind effect.

Step-1. Specify basic data t_m, V_0, V_{max}, ψ_{0w}, $\Delta\psi_{wmax}$, z, z_0, p.
Step-2. Generate values: $n(t_m)$, $t_i(t_m, n)$, $d_i(t_0, n)$, $v_i(n)$.
Step-3. Calculate value V_s in conformity with (4).
Step-4. Calculate value V_{cz} in conformity with (4).
Step-5. At t=t_i calculate value ψ_w in conformity with (5).
Step-6. Calculate values S_{ex}, S_{ey} in conformity with (9).
Step-7. Calculate values F_{wx}, F_{wy} in conformity with (7).

This algorithm allows getting the axes components of the wind force in the inertial frame.

Let's consider the steady ascent of a quad rotor weighing 1 *kg* at altitude z=100 *m* with vertical velocity of 1 *m/s* without compensation of wind effect. The ascent path of the quad rotor under wind effect is shown on Figure-8.

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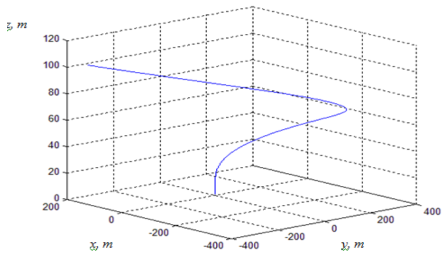

Figure-8. Ascent path of the quadrotor under wind effect. Bending of the flight path reflects the influence of wind disturbances on the quad rotor.

3. CONCLUSIONS

The offered model and algorithm allow researching the wind effect on quad rotors and other types of aircraft. The model allows taking into account a lot of parameters: wind velocity magnitude, duration of the wind velocity "step", duration of the wind velocity increase or decrease, a number of wind velocity changes, moments of wind velocity changes, dependence of the wind velocity on altitude, changing of wind direction, and dependence of wind strength on the influence effective area of a quad rotor. Also it allows researching the influence of different components of wind disturbances and improvement the effectiveness of quad rotor flight dynamics researching.

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