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ANALYTICAL METHODOLOGY FOR ASSESSING THE IMPACT OF AGRICULTURAL EQUIPMENT ON THE FLIGHT CHARACTERISTICS OF AGRICULTURAL DRONES

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Abstract. This article presents an analytical methodology for assessing the impact of agricultural equipment installed on agricultural drones on their flight characteristics. The study analyzes mass and balance, aerodynamic parameters, lift force, minimum flight speed, energy consumption, dynamic stability, and efficiency indicators using a hexacopter-type agricultural drone as an example. The effects of spraying, spreading, monitoring, and specialized technological equipment on aerodynamic drag, power consumption, and flight stability were evaluated using mathematical models. As a result of the research, a comprehensive analytical approach based on the sequence "parameter identification – mass and balance – aerodynamics – speed – power – stability – efficiency – optimization" was proposed.

Keywords: agricultural drone, aerodynamics, flight stability, energy consumption, power, agricultural equipment, mathematical modeling, optimization.

Introduction

The widespread implementation of digital technologies and automated control systems in modern agriculture has significantly increased the use of agricultural drones. Agricultural drones are innovative tools characterized by high efficiency in crop protection, mineral fertilizer application, monitoring, analysis, and precision farming operations. The functional capabilities of agricultural drones are directly related to the agricultural equipment installed on them. Additional equipment affects the drone's overall mass, aerodynamic characteristics, energy consumption, and flight stability. Therefore, comprehensive analysis and optimization of the technical and operational characteristics of agricultural drones have become one of the most relevant scientific challenges.

During the research, the main types of agricultural equipment installed on agricultural drones were studied. Spraying systems consist of a liquid tank, pump, nozzles, pipelines, and filters. These systems are primarily used for the application of herbicides, pesticides, and mineral fertilizers over agricultural fields. Seed and

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fertilizer spreading systems include granule spreaders, dosing mechanisms, and rotary distributors, which ensure the precise distribution of seeds and fertilizers at predetermined application rates.

For monitoring and analytical purposes, RGB cameras, multispectral cameras, and thermal imaging cameras are utilized. GPS modules, LiDAR systems, and atmospheric parameter sensors provide navigation and automatic control functions for agricultural drones. In addition, autopilot systems, telemetry modules, batteries, and specialized devices such as defoliant applicators or fog generators further expand the functional capabilities of agricultural drones.

A six-rotor hexacopter-type agricultural drone was selected as the research object. During the analysis, payload mass, empty drone mass, and additional equipment mass were considered as the primary mass parameters. Geometric parameters included the drone's height, width, length, support span, and rotor disk area. For aerodynamic analysis, the lift coefficient and aerodynamic drag coefficient were selected as the main parameters.

The total mass of the agricultural drone is determined as the sum of the empty drone mass, payload mass, and installed equipment mass:

$$m_0 = m_d + m_y + m_a$$

Depending on the agricultural task, the payload mass (m_{yi}) and equipment mass (m_{ai}) may vary. Such variations cause a shift in the center of gravity, which affects flight stability and maneuverability. Changes in the center of gravity require additional energy expenditure to maintain the drone's attitude and stable flight conditions.

To maintain stable flight, the lift force generated by the rotors must be at least equal to the total weight of the drone. The lift force depends on air density, rotor disk area, airflow velocity, and aerodynamic coefficients:

$$Y=\frac{1}{2}\rho_{air}V^2SC_y$$

The installation of additional agricultural equipment leads to an increase in the aerodynamic drag coefficient. This causes airflow turbulence, resulting in higher energy consumption and reduced battery operating time.

During the research, the minimum flight speed and optimal flight modes of the agricultural drone were determined. It was found that the minimum flight speed depends on the total mass of the drone, air density, rotor disk area, and lift coefficient:

$$V_{min}=\sqrt{\frac{2m_0g}{\rho SC_y}}$$

The proper selection of optimal flight speed and altitude makes it possible to reduce energy consumption and improve operational efficiency.

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The analysis of power and energy consumption is of great importance in the operation of agricultural drones.

The relationship between power and force can be expressed as:

$$N=X \cdot V$$

where:

- **N** – power (W);
- **X** – force (N), usually thrust or drag force;
- **V** – velocity (m/s).

An increase in force requires greater power, while higher flight speeds also lead to increased power demand.

During horizontal flight, power consumption depends primarily on aerodynamic drag and flight speed, whereas during vertical ascent it depends on thrust and induced velocity. The installation of additional equipment increases aerodynamic drag, resulting in higher overall energy consumption. Consequently, battery discharge accelerates and flight endurance decreases.

In the dynamic analysis of the agricultural drone, its six degrees of freedom were taken into consideration. Translational and rotational motions were analyzed using the Newton–Euler equations. It was found that oscillations and vibrations occurring during flight negatively affect both the maneuverability of the drone and the accuracy of spraying operations.

The translational motion is expressed by:

$$m\frac{d\vec{V}}{dt}=\vec{F}$$

and the rotational motion is expressed by:

$$I\frac{d\vec{\omega}}{dt}=\vec{M}$$

where:

- **m** – mass of the drone;
- **I** – moment of inertia;
- **V** – velocity vector;
- **ω** – angular velocity vector;
- **F** – resultant force vector;
- **M** – resultant moment vector.

Efficiency indicators were evaluated using the efficiency coefficient, operational productivity, and energy consumption. The efficiency coefficient represents the proportion of useful power relative to the total power consumed by the drone:

$$\eta=\frac{P_{useful}}{P_{total}}\times100\%$$

where:

- **η** – efficiency coefficient (%);

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- **Puseful** – power utilized for useful work;
- **Ptotal** – total power consumption of the drone.

The total power consumption of an agricultural drone generally consists of three components:

$$P_{total}=P_{flight}+P_{aerodynamic}+P_{equipment}$$

According to the analysis results, an efficiency coefficient ranging from 60% to 80% ensures high operational performance. Operational productivity depends on the working width, flight speed, and time utilization coefficient. Energy consumption is determined by total power demand and operating time, while the amount of energy consumed per hectare is considered an important indicator of agricultural drone efficiency.

The operational productivity is calculated as:

$$Q=\frac{B \cdot V \cdot K}{10}$$

where:

- **Q** – operational productivity (ha/h);
- **B** – working width (m);
- **V** – flight speed (m/s);
- **K** – time utilization coefficient (0.6–0.9);
- **10** – conversion factor from m^2/s to ha/h.

During the research, all parameters were integrated into a unified mathematical model. In this model, the mass of additional equipment, rotor disk area, and aerodynamic coefficients were considered as input parameters, while flight speed, aerodynamic drag, and power consumption were evaluated as output parameters. The results of mathematical modeling made it possible to optimize both the design of the agricultural drone and its flight operating modes.

Conclusion

In conclusion, a comprehensive analytical methodology for assessing the impact of agricultural equipment installed on agricultural drones on their flight characteristics was developed. Based on the analysis, a scientific approach founded on the sequence **"parameter identification – mass and balance – aerodynamics – speed – power – stability – efficiency – optimization"** was established.

The study demonstrated that the relationship among mass, power consumption, and operational efficiency in agricultural drone systems has a complex iterative nature. By selecting optimal aerodynamic configurations and flight modes, it is possible to reduce energy consumption, improve maneuverability, and significantly enhance spraying efficiency.

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The developed analytical methodology meets the requirements of precision agriculture technologies and has significant practical value for the design, development, and optimization of modern agricultural drones.

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