Parametric sensitivity study of unmanned buoyancy-lifting aerial vehicle

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Abstract. Buoyancy-lifting aerial vehicle is a new development direction of the near space vehicle. This paper presents two conceptual schemes of unmanned buoyancy-lifting aerial vehicle with different configurations. The general parameter design method is studied, and the general parameter calculation model is established. The general parameters of airship and the buoyancy-lifting aerial vehicle are compared and studied. Taking buoyancy-lifting aerial vehicle with single fuselage and dual wings as the research object, sensitivity analysis of parameters has been done. The results show that compared with the airship, the weight of the buoyancy-lifting aerial vehicle with single fuselage and dual wings is reduced by 23.0%. Weight of the buoyancy-lifting aerial vehicle with dual fuselages and dual wings is increased by 55.3% compared with the aircraft with single fuselage. Lift- buoyancy coefficient and cruise speed have important influence on the general parameters of the aircraft. With the energy density of the battery increasing from 400Wh/kg to 600Wh/kg, weight of the aircraft is reduced by 58.5%. Compared with the airship, weight of the buoyancy-lifting aerial vehicle is more sensitive to the propeller efficiency.

1 Introduction

Near space aircrafts have received wide attention in recent years because of their unique advantages [1]. Unmanned buoyancy-lifting aerial vehicle is a new type of aircraft that uses static buoyancy and aerodynamic lift to fly in the near space [2]. Buoyancy-lifting aerial vehicle can use advantages of aerostat and aerodynamic lift aircraft, and avoid weakness of the two kinds of aircrafts [3, 4]. Compared with high altitude airship and solar unmanned aerial vehicle, buoyancy-lifting aerial vehicle has the advantages of high cruising speed [5], strong wind resistance, good maneuverability and small geometric size [6].

A number of countries have carried out a series of studies on the near space buoyancy-lifting aerial vehicle [7, 8]. A hybrid aircraft called Sky Cat has been developed in the UK. The aircraft uses two hulls which are connected by the side, which is similar to a dual fuselages seaplane. This kind of configuration allows the aircraft to produce larger lift

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during cruise, so the volume of the hull can be reduced [9]. The Ohio airship company in America developed a buoyancy-lifting aerial vehicle called Dynalifter. The aircraft uses wing-body configuration, and it has gasbag to produce buoyancy and the wing to produce the dynamic lift [10]. The British hybrid airship company developed a hybrid airship called Airlander and succeeded in the first flight in August 17, 2016. The aircraft is able to land on the snow and the sea, and does not require the runway and landing. It can be applied to communications, measurement, freight, tourism and other fields [11].

As for the conceptual scheme and the general parameters of the buoyancy-lifting aerial vehicle, the scholars have also done some related research. Li et al. constructed a configuration of row flying-wings with high volume ratio based on NACA0030 airfoil [12]. Haque et al. designed a wing-body hybrid airship, the mission profile of the hybrid aircraft was designed, and a preliminary selection of the general parameters of the aircraft was made [10]. Song et al. demonstrated the operating mode of the buoyancy-lifting aerial vehicle, the conceptual design of the aircraft was carried out, and general parameters were optimized [13].

This paper presents two conceptual schemes of unmanned buoyancy-lifting aerial vehicle with different configurations, one is single fuselage-dual wings and the other is dual fuselages-dual wings. The calculation model of the general parameters of the buoyancy-lifting aerial vehicle is established, and the general parameters of the two schemes are compared and analyzed in detail. Aimed at single fuselage-dual wings scheme, parameter sensitivity study has been done.

2 Conceptual design

Unmanned buoyancy-lifting aerial vehicle not only has the internal gasbag and other static buoyancy components, but also has the wing and other aerodynamic lift components. The configuration layout of the unmanned buoyancy-lifting aerial vehicle is very different from conventional aircraft [14]. The fuselage produces static buoyancy by the huge volume, and the wing produces aerodynamic lift by the relative motion with the air flow. A new parameter lift-buoyancy coefficient k_L needs to be introduced in the calculation of the general parameters, and this parameter is defined as the ratio of the aerodynamic lift to the static buoyancy.

When the unmanned buoyancy-lifting aerial vehicle is at low altitude, the internal gasbag has enough buoyancy, so the aircraft can takeoff vertically. After rising to a certain height, the buoyancy decreases, the aircraft uses the aerodynamic lift of the wing to climb up to the predetermined height and keeps a long cruise. This paper studies two kinds of unmanned buoyancy-lifting aerial vehicles with different configurations, one is single fuselage-dual wings and the other is dual fuselages-dual wings, see figure 1.

Fig. 1. Aerodynamic configuration of unmanned buoyancy-lifting aerial vehicle.

For single fuselage configuration, the wings are on both sides of the fuselage, and V-tails are on the rear of the fuselage. The structure of the aircraft is simple, the volume efficiency of the fuselage is high and the surface area is small. For the dual fuselages configuration, the fuselages are on both sides of the wing, and V-tails are on both sides of

the fuselages. The structural stiffness of the aircraft is high, the volume efficiency of the fuselage is low and the surface area is large.

Different from traditional aircrafts, the unmanned buoyancy-lifting aerial vehicle studied in this paper uses the hybrid energy system combined with the solar cell and the energy storage battery. The cycle of the energy system is 24 hours. Solar cells are laid on the upper surface of wings and fuselages. Solar cells convert solar energy into electricity for power systems, airborne devices, and payloads during the day, and store the excess energy in the energy storage battery. The energy storage battery is the power supply for the aircraft during the night.

3 Calculation models of general parameters

3.1 Solar cell model

The unmanned buoyancy-lifting aerial vehicle is powered by solar energy, and the energy consumption of its equipment and payload is also from solar energy. Therefore, the solar cell model needs to be researched first [15].

The vertical irradiation intensity of the sun is given in equations (1) and (2) [16, 17].

$$I_0 = I \left[\frac{1 + \varepsilon \cos(A)}{1 - \varepsilon^2} \right]^2 \quad (1)$$

$$A = 2\pi(n - 4) / 365 \quad (2)$$

where I is the solar constant, ε is the eccentricity of the earth, n is the number of days in a year.

The radiation power per unit area of the sun at time t of a day is shown in equation (3).

$$P_{\text{solar}}(t) = I_0 \sin \beta \quad (3)$$

where β is the solar altitude angle.

The total energy generated by solar cells in a cycle period is shown in equation (4).

$$E_{\text{solar_pr}} = \int_{t_1}^{t_2} P_{\text{solar}}(t) dt S_s \eta_s \quad (4)$$

where η_s is the conversion efficiency of solar cells, S_s is the area of solar cells.

The mass of solar cells can be calculated by equation (5).

$$m_s = S_s A_s \quad (5)$$

where A_s is the surface density of solar cells.

3.2 Aerodynamics model of aircraft

The aerodynamic forces of the unmanned buoyancy-lifting aerial vehicle mainly come from the wing and the fuselage. The aerodynamic models of the wing and the fuselage are required.

The lift generated by wings is shown in equation (6).

$$L_w = \frac{1}{2} \rho_{\text{air}} V^2 C_{lw} S_w \quad (6)$$

In the above equation, V is the cruising speed, ρ_{air} is the density of the air, S_w is the area of wings, and C_{lw} is the lift coefficient of wings. If the lift-drag ratio of wings is K_w , the drag of wings is shown in equation (7).

$$D_w = \frac{L_w}{K_w} \quad (7)$$

The buoyancy of the fuselage L_f and the drag D_f of the fuselage are shown in equations (8) and (9).

$$L_f = \rho_{\text{air}} V_f g n_f \quad (8)$$

$$D_f = \frac{1}{2} \rho_{\text{air}} V^2 C_{df} V_f^{\frac{2}{3}} n_f \quad (9)$$

In the formula, n_f is the number of fuselages, C_{df} is the volume drag coefficient of fuselages, V_f is the volume of the fuselage, and g is the gravitational acceleration.

3.3 Energy storage battery model

The energy of the unmanned buoyancy-lifting aerial vehicle is all provided by the energy storage battery during the night, and the energy needed to be stored in the energy storage battery during the night is given in equation (10).

$$E_{ba_n} = (P_{mo} + P_{pa}) t_n / \eta_{ba} \quad (10)$$

In the above equation, P_{mo} is the input power of the motor, P_{pa} is the power of the payload, t_n is the length of the night in a day, and η_{ba} is the discharge efficiency of the battery.

The energy within the time period between the sunrise and the power balance is provided by the battery and the solar cells, so the energy that the battery needs to store in the daytime is shown in equation (11).

$$E_{ba_d} = 2((P_{mo} + P_{pa}) t_{sb} - E_{solar_r} \eta_{ba}) / \eta_{ba} \quad (11)$$

In the above equation, t_{sb} is the length of the time between the sunrise and the power balance, and E_{solar_r} is the energy provided by solar cells during this time.

The energy needs to be stored in the battery during one cycle is shown in equation (12).

$$E_{ba} = E_{ba_d} + E_{ba_n} \quad (12)$$

If the energy density of the battery is ρ_{ba} [18], the mass of the battery is given in equation (13).

$$m_{ba} = E_{ba} / \rho_{ba} \quad (13)$$

3.4 Propulsion system model

The required power P_{cr} of the unmanned buoyancy-lifting aerial vehicle is shown in equation (14).

$$P_{cr} = (D_w + D_f) V \quad (14)$$

The input power P_{mo} of motors is shown in equation (15).

$$P_{mo} = P_{cr} / (\eta_{mo} \eta_{pr}) \quad (15)$$

where η_{mo} is the efficiency of the motor, and η_{pr} is the efficiency of the propeller.

The mass of the propulsion system is shown in equation (16).

$$m_{po} = P_{cr} \eta_{po} / A_{po} \quad (16)$$

where η_{po} is the ratio between the maximum power and the rated power, and A_{po} is the power density of the propulsion system.

3.5 Structural weight model

The fuselage is combined with outer skin, structure and ballonnet. The mass of the outer skin of the fuselage is shown in equation (17).

$$m_{\text{skin}} = n_f S_f (1 + k_{\text{skin}}) A_{\text{skin}} \quad (17)$$

In the equation, A_{skin} is the surface density of the outer skin, k_{skin} is the suture coefficient, and S_f is the surface area of the fuselage.

The mass of the ballonnet is calculated in equation (18).

$$m_{\text{bal}} = n_f S_f \eta_{\text{bal}} (1 + k_{\text{bal}}) A_{\text{bal}} \quad (18)$$

η_{bal} is the area coefficient of the ballonnet, k_{bal} is the suture coefficient of the ballonnet, and A_{bal} is the surface density of the ballonnet in the above equation.

The mass of the fuselage structure is calculated from equation (19).

$$m_{\text{str}} = m_{\text{skin}} \eta_{\text{str}} \quad (19)$$

where η_{str} is the structure coefficient. The total mass of the fuselage is shown in equation (20).

$$m_f = m_{\text{skin}} + m_{\text{bal}} + m_{\text{str}} \quad (20)$$

If the surface density of the wing is A_w , the mass of the wing is calculated in equation (21).

$$m_w = S_w A_w \quad (21)$$

The mass of the tails is calculated in equation (22).

$$m_t = \eta_t m_{\text{skin}} \quad (22)$$

where η_t is the mass coefficient of the tails.

4 Calculation method of general parameters

Based on the energy balance and force balance of unmanned buoyancy-lifting aerial vehicle, the calculation model of general parameters was established in this paper. All the energy required by the aircraft is from the solar energy, so it is necessary to construct a solar energy balance analysis method in one cycle.

The energy required for the aircraft within the time period between the power balance points is provided by the solar cell. Set the length of the period to be t_d , the energy supplied by solar cells is shown in equation (23).

$$E_{\text{solar}_d} = (P_{\text{mo}} + P_{\text{pa}}) t_d \quad (23)$$

The total energy supplied by the solar cell within a cycle period is shown in equation (24).

$$E_{\text{solar}_re} = 2E_{\text{solar}_r} + E_{\text{solar}_d} + E_{\text{ba}} \quad (24)$$

The balance equation of the solar cell is given by equation (25).

$$E_{\text{solar}_re} = E_{\text{solar}_pr} \quad (25)$$

The lift of the unmanned buoyancy-lifting aerial vehicle is combined with the static buoyancy and the aerodynamic lift, so it is necessary to construct a force balance analysis method, which is shown in equations (26) and (27).

$$L_w + L_f = m_a g \quad (26)$$

$$L_w / L_f = k_L \quad (27)$$

where m_a is the total mass of the aircraft.

5 Configuration analysis

The buoyancy-lifting aerial vehicle of single fuselage-dual wings configuration and dual fuselages-dual wings configuration are studied in this paper. The influence of configuration on the general parameters is analyzed in detail. General parameters of the two configurations and the airship are calculated under the same condition. The input parameters are shown in table 1.

Table 1. Input parameters for calculation.

Parameters	Input value
Flight altitude H /km	20
Cruising speed V /(m/s)	25
Flight latitude	40°N
Mass of payload m_{pa} /kg	100
Conversion efficiency of solar cell η_s /%	24
Energy density of battery ρ_{ba} /(Wh/kg)	500

The general parameters of three kinds of aircrafts are calculated, which are shown in table 2.

Table 2. General parameters of aircrafts with different configuration.

Parameters	Airship	Single fuselage-dual wings	Dual fuselages-dual wings
Total weight m_a /kg	7030.7	5412.4	8406.1
Length of the fuselage l_f /m	119.7	69.1	63.5
Volume of the fuselage V_f /m ³	79862.3	15370.1	23871.4
Surface area of the fuselage S_f /m ²	10591.9	3530.7	5965.9
Wing area S_w /m ²	0.0	958.6	1488.8

It is known from table 2 that compared with the airship, the weight of the buoyancy-lifting aerial vehicle of single fuselage-dual wings is reduced by 23.0%, the length of the fuselage is reduced by 42.3%, the volume of the fuselage is reduced by 80.8%, and the surface area of the fuselage is reduced by 66.7%. The reason for the above phenomenon is that the buoyancy-lifting aerial vehicle has wings, the aerodynamic lift makes the volume of the fuselage reduce obviously, so the surface area and the weight of the fuselage are reduced.

Compared with single fuselage-dual wings configuration, the weight of the dual fuselages-dual wings configuration is increased by 55.3%, the length of the fuselage is reduced by 8.1%, the surface area of the fuselage is increased by 69.0%, and the wing area is increased by 55.3%. The reason is that the total volume efficiency of the fuselage of the dual fuselages-dual wings configuration is reduced obviously. Under the same volume, the surface area of the dual fuselages is increased by 26.0% compared with the single fuselage.

6 Sensitivity study of general parameters

It is known from the configuration analysis that compared with the dual fuselages-dual wings configuration, single fuselage-dual wings configuration has great advantages in weight and geometry size, so parameters sensitivity of the single fuselage-dual wings configuration is studied.

6.1 Lift-buoyancy coefficient

Under the condition of different lift coefficients of the wing, the effects of the lift-buoyancy coefficient on the total weight and the wing area of the buoyancy-lifting aerial vehicle are shown in figure 2.

Fig. 2. Effects of lift coefficient and lift-buoyancy coefficient on general parameters.

Figure 2 shows that under the same lift coefficient, total weight of the aircraft is reduced with the increase of the lift-buoyancy coefficient. Wing area is increased first and then reduced with the increase of the lift-buoyancy coefficient. This is because when the lift-buoyancy coefficient is small, the buoyancy is the majority, so the area of the wing is very small. With the increase of the lift-buoyancy coefficient, the wing needs to produce more lift, so the area of the wing increases. When the lift-buoyancy coefficient is increased to a certain extent, the increase of lift can effectively unload for the fuselage, so the buoyancy needs provided by the fuselage is reduced and the weight of the fuselage is reduced, this further reduces the area of the wing and forms a useful positive feedback.

Under the same lift-buoyancy coefficient, with the increase of the lift coefficient, the weight and the wing area of the aircraft are reduced. So, the use of high lift aerodynamic design can effectively reduce the total weight and the wing area of the aircraft.

Under different cruising speed, the variation curve of the total weight with the lift-buoyancy coefficient is given in figure 3.

Fig. 3. Variation of total weight with lift-buoyancy coefficient under different cruising speed.

It is known from figure 3 that under different cruising speeds, the effects of the lift-buoyancy coefficient on the total weight of the buoyancy-lifting aerial vehicle have different rules. When the cruising speed is lower than 17m/s , the total weight is increased with the increase of the lift-buoyancy coefficient. This means that under low cruising speed, the airship has more advantages on the total weight than the buoyancy-lifting aerial vehicle. When the cruising speed is around 17m/s , the change of the total weight is very small with the lift-buoyancy coefficient. This means that under this speed, the weight of the airship and the buoyancy-lifting aerial vehicle is similar. When the cruising speed is higher than

17m/s, the total weight is reduced with the increase of the lift-buoyancy coefficient. This means that under high cruising speed, the buoyancy-lifting aerial vehicle has more advantages on the total weight than the airship. The speed under which the total weight does not change with the lift-buoyancy coefficient is the critical velocity V_c . When the cruising speed is lower than V_c , it is better to design an aircraft to an airship. When the cruising speed is higher than V_c , it is better to design an aircraft to a buoyancy-lifting aerial vehicle.

6.2 Energy system parameters

The energy system of the unmanned buoyancy-lifting aerial vehicle includes solar cell system, energy storage battery system and energy management system. The weight of the whole energy system takes up about 45% of the total weight of the unmanned buoyancy-lifting aerial vehicle, so the parameters of the energy system have an important influence on the general parameters of the unmanned buoyancy-lifting aerial vehicle.

The main design parameters of solar cell system are surface density ρ_s and the conversion efficiency η_s of the solar cell. The effects of these two parameters on the total weight of the unmanned buoyancy-lifting aerial vehicle are shown in figure 4. Figure 4 shows that with the increase of the η_s , the total weight of the aircraft is reduced. With the increase of the ρ_s , the total weight of the aircraft is increased. Under the condition that $\rho_s = 0.35\text{kg/m}^2$, when η_s is increased from 20% to 30%, the total weight is reduced by 14.2%. It can be seen that improving the conversion efficiency of the solar cell can reduce the total weight of the unmanned buoyancy-lifting aerial vehicle, but the reduction is not significant.

The main design parameters of the energy storage battery system are the energy density ρ_{ba} and the discharge efficiency η_{ba} of the battery. The effects of these two parameters on the total weight of the unmanned buoyancy-lifting aerial vehicle are shown in figure 5. It is known from figure 5 that with the increase of ρ_{ba} and η_{ba} , the total weight of the unmanned buoyancy-lifting aerial vehicle is reduced obviously. Under the condition that $\eta_{ba} = 90\%$, when ρ_{ba} is increased from 400Wh/kg to 600Wh/kg, the total weight is reduced by 58.5%. Therefore, increasing the energy density of the battery can significantly reduce the total weight of the aircraft.

Fig. 4. Effects of parameters of solar cell on total weight.

Fig. 5. Effects of parameters of battery on total weight.

6.3 Propulsion system parameters

The parameters of the propulsion system of the unmanned buoyancy-lifting aerial vehicle mainly affect the weight of the propulsion system and the energy requirement of the aircraft, so it has an important effect on the general parameters of the aircraft. The effects of the power density of the propulsion system on the total weight of the unmanned buoyancy-lifting aerial vehicle are shown in figure 6. The figure shows that with the increase of the

power density, the total weight is reduced. When the power density is increased from 400W/kg to 800W/kg, the total weight is reduced by 8.1%. Therefore, the effect of the power density on the total weight of the unmanned buoyancy-lifting aerial vehicle is not significant.

Under different lift-buoyancy coefficients, the variation curve of the total weight of the aircraft with the efficiency of the propeller is shown in figure 7. When $k_L=0$, the aerodynamic lift of the aircraft is 0, the aircraft is an airship. When $k_L=3$, the aircraft is buoyancy-lifting aerial vehicle. It is known from figure 7 that with the increase of the efficiency of the propeller, the total weights of the airship and the buoyancy-lifting aerial vehicle are all reduced. When the efficiency of the propeller is increased from 65% to 85%, the total weight of the airship is reduced by 16.6%, and the total weight of the buoyancy-lifting aerial vehicle is reduced by 56.1%. It can be seen that the weight of the buoyancy-lifting aerial vehicle is more sensitive to the efficiency of the propeller. When $\eta_{pr} = 73.1\%$, the weight of the airship and the buoyancy-lifting aerial vehicle is same. When $\eta_{pr} < 73.1\%$, the weight of the airship is smaller. When $\eta_{pr} > 73.1\%$, the weight of the buoyancy-lifting aerial vehicle is smaller. From the above analysis, it is known that improving the efficiency of the propeller can effectively reduce the total weight of the buoyancy-lifting aerial vehicle.

Fig. 6. Effect of power density of propulsion system on total weight.

Fig. 7. Effect of efficiency of propeller on total weight.

7 Conclusion

In this paper, the general parameter calculation model is established, and general parameters of the aircraft with different configurations are studied. Compared with the airship, the weight of the buoyancy-lifting aerial vehicle of single fuselage-dual wings is reduced by 23.0%. Compared with single fuselage-dual wings configuration, the weight of the dual fuselages-dual wings configuration is increased by 55.3%. When the cruising speed is lower than the critical velocity, it is better to design an aircraft to an airship. When the cruising speed is higher than the critical velocity, it is better to design an aircraft to a buoyancy-lifting aerial vehicle. When energy density of the battery is increased from 400Wh/kg to 600Wh/kg, the total weight of the buoyancy-lifting aerial vehicle is reduced by 58.5%. Compared with the airship, weight of the buoyancy-lifting aerial vehicle is more sensitive to the propeller efficiency.

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