Double Propellers Synchronous Control Based on Cross-coupling Control for Buoyancy-lifting Aircraft

Su Jianli¹,ª, Wang Hua²,ᵇ

¹School of Astronautics, Beihang University, Beijing 100191, China
²School of Astronautics, Beihang University, Beijing 100191, China

E-mail: ¹sujianli509@163.com, ᵇwhua402@163.com

Keywords: buoyancy-lifting aircraft; synchronous control; cross-coupling control; flight test

Abstract. To solve the double propellers synchronous control problem of the buoyancy-lifting aircraft, a control approach which uses cross-coupling method to control the double propellers is proposed. Firstly, the lateral-directional stability and manoeuvrability of this type of aircraft with double propellers are analyzed. Secondly, the cross-coupling control method is used to study the speed synchronization performance of the double propellers to improve the control accuracy. The simulation results show that, the double propellers speed synchronization control system based on the cross-coupling control method has a good control performance and better anti-disturbance. Finally, based on the control theory, the cross-coupling controller of the buoyancy-lifting aircraft with double propellers was designed, and ground run test and flight test are carried out. The experiment results show that the control method proposed has better performance and resistance.

1. Introduction

Traditional aerostat gets lift relies on the lighter-than-air gas in the body [1]. In order to increase buoyancy, the volume must be increased, which will bring a lot of problems. Buoyancy-lifting aircraft is a new concept of vehicle which has the advantages of both aerostat and usual aircraft. Buoyancy-lifting aircraft has buoyancy and aerodynamic lift at the same time, and can provide lift several times more than the conventional airship with no size growth. In the civil and military fields, compared with traditional aircraft, the buoyancy-lifting aircraft has the characteristics of less energy consumption, heavy load, small volume, high speed and strong wind resistance. It has a wide range of applications, for example, express delivery, power line, long-distance transportation, communication relay, disaster relief and other aspects [2-4].

As one of the most popular research fields, Sanswire Networks Company in the US developed a kind of ear space aerostats, which named Stratellite [5]. In China, Li [6-7] proposed a new type of tandem buoyancy-lifting aerostat with a smaller volume. In Beihang University, the detailed research on the configuration and structure of a buoyancy-lifting aircraft was discussed by Su [8] through the CFD method. A method based on improved non-dominated sorting multi-objective genetic algorithm is applied to develop the inflatable airfoil structure optimization of a buoyancy-lifting aircraft by Shi [9].
In this paper the lateral-directional stability and manoeuvrability of the buoyancy-lifting aircraft with double propellers are analyzed. And three advanced control strategies have been adopted and compared. The third control technique is cross-coupling controller which shows a good performance compared to Master-slave controller and parallel controller. The proposed cross-coupling controller was implemented in buoyancy-lifting aircraft, and the flight test results showing excellent synchronous control performance.

2. Buoyancy-lifting aircraft
The main task of this paper is the research of buoyancy-lifting aircraft with double propellers which is sweep flying wing layout.

2.1. Some geometric and performance characteristics
The structure of the buoyancy-lifting aircraft is shown in Figure 1. The aircraft is mainly composed of capsule, vertical stabilizer, rudder, elevator, double propellers.

![Figure 1. Buoyancy-lifting aircraft with double propellers](image)

The sweep flying wing layout buoyancy-lifting aircraft with a vertical stabilizer has lateral-directional stability. Some geometric and performance characteristics of the aircraft are shown in Table 1.

| Table 1. Some geometric and performance characteristics |
|--------------------------------------------------------|
| Wing Span | 3m          |
| Wing Area  | 1.8 m²      |
| Horizontal Tail Area | 0.5 m²   |
| Vertical Tail Area | 0.3 m²   |
| Maximum Takeoff Weight | 35 kg     |
| Cruise Speed | 20 m/s     |

2.2. Dynamics model
The nonlinear dynamics lateral-directional model of the buoyancy-lifting aircraft with double propellers established [10-11]:

\[
\begin{align*}
\dot{\upsilon} &= pw - ru + g \cos \phi \sin \phi + Y / m \\
\dot{\phi} &= p + q \sin \phi \tan \theta + r \cos \phi \tan \theta \\
\dot{\psi} &= q \sin \phi \sec \theta + r \cos \phi \sec \theta - \Gamma_1 pq - \Gamma_2 pr + \Gamma_3 \dot{l} + \Gamma_4 n \\
\dot{p} &= \Gamma_5 pq - \Gamma_1 pr - \Gamma_3 \dot{l} + \Gamma_6 n
\end{align*}
\]

And
\[
\begin{align*}
\Gamma_1 &= I_x x z - I_{xz}^2
\quad \\
\Gamma_2 &= I_{xz}(I_{xz} - I_x y + I_z) / \Gamma \\
\Gamma_3 &= I_z / \Gamma \\
\Gamma_4 &= I_x / \Gamma \\
\Gamma_5 &= I_x (I_{xz} - I_y) + I_{xz}^2 / \Gamma \\
\Gamma_6 &= I \, / \Gamma
\end{align*}
\]
\[
\begin{align*}
Y &= \frac{q b}{2 V_a} (C_{y p} p + C_{y r} r) + \bar{q} (C_{y \beta} \beta + C_{Y \delta} \delta_i) \\
l &= \frac{q b^2}{2 V_a} (C_{y p} p + C_{y r} r) + \bar{q} b (C_{y \beta} \beta + C_{y \delta} \delta_i) + \Delta T d_m \sin \theta_m \\
n &= \frac{q b^2}{2 V_a} (C_{y p} p + C_{y r} r) + \bar{q} (C_{n \beta} \beta + C_{n \delta} \delta_i) + \Delta T d_m \cos \theta_m
\end{align*}
\]

Where m: quality of the aircraft, g: acceleration of gravity, \( I_x, I_y, I_z, I_{xz} \): moment of inertia and inertia of the aircraft, \( u, v, w \): track speed in the aircraft coordinate system, \( p, q, r \): angular velocity of the aircraft body axis, \( \beta, \theta, \theta \): side slip angle, pitch angle, roll angle, \( Y, l, n \): lateral force, rolling moment and yaw moment, \( \bar{q} \): dynamic pressure, \( b \): span length of the aircraft, \( \delta_i \): yaw deflection angle, \( \Delta T \): difference between the left and right propeller pull, \( d_m \): distance from the propeller to the plane of symmetry of the aircraft, \( \theta_m \): engine mounting angle, \( V_a \): flight speed of the aircraft.

The relationship between the propeller tension \( T \) and the throttle \( \delta_i \) can be written as:
\[
T = \frac{1}{2} \rho S_p C_p ((k_m \delta_i)^2 - V_p^2)
\]

where \( \rho \): air density, \( S_p, C_p, V_p \): propeller pad area, tensile coefficient and incoming flow speed, \( k_m \): coefficient of throttle to propeller outflow speed.

3. **Simulation research on synchronous control of double propellers references**

If the double propellers at different speeds or are disturbed, the flight quality of the aircraft will deteriorate. Therefore, it is necessary to study the synchronous control and anti-disturbance of the double propellers.

In this section focuses on cross-coupling synchronous control structure strategy research, through the analysis of MATLAB/SIMULINK simulation and comparison, it is concluded that the cross-coupling synchronous control structure is suitable for the synchronous control strategy of buoyancy-lifting aircraft with double propellers.

3.1. Cross-coupled synchronous control
The main characteristic of the cross-coupling control structure of the double propellers is to compare the rotational speeds of the two propellers, to obtain the synchronization error of the rotational speed as an additional feedback signal, and then to compensate for the two propellers respectively. This control structure is suitable for the synchronous control of the buoyancy-lifting aircraft with double propellers. In this paper, one cross-coupling control structure is that its compensation is added in the front of controller is used. The cross-coupling control structure of double propellers control system is shown in Figure 2.

![Schematic diagram of cross-coupling control](image)

**Figure 2. Schematic diagram of cross-coupling control**

3.2. **Simulation and analysis**

In order to verify the advanced nature of the cross-coupling structure compared with the parallel control structure of the two propellers, their simulation models are built respectively in simulation experiment. The simulation model is built using MATLAB/SIMULINK.

This section focuses on the cross-coupling control structure simulation model, and then we compare its synchronization error with the parallel control structure.

In follow simulations, the initial reference speed in the simulation is set to 5000 r/min. The algorithm of simulation uses the PI control. The deadline of simulation is set to 0.2s. Load disturbances of 3N.m are added for the BLDCM2 at t=0.1s.

Figure 4 shows the synchronization error curve of the parallel control structure. Figure 5 shows the synchronization error curve of the cross-coupling control structure.

![Synchronization error curve of the parallel control structure](image)
Figure 4. Synchronization error curve of the cross-coupling control structure

In Figure 3, the synchronization error between two motors is more than 500 r/min. Between the two motors is independent of each other in this structure, synchronization error is very large, error response speed is slow.

In Figure 4, the maximum synchronization error between the two motors is not reach 200 r/min. After t=0.01s, synchronization error decreases rapidly and then gradually at t=0.06s tend to zero. Compared with the parallel control structure, the synchronization error of the cross-coupling control structure is obviously is reduced, and the corresponding error is faster.

4. Flight Test

The cross-coupling control structure was implemented and tested with the buoyancy-lifting aircraft with double propellers. Figure 5 shows the ground run test for the buoyancy-lifting aircraft using the parallel control structure and the cross-coupling control structure, respectively.

Figure 5. Ground run test

Figure 6 shows the test data for the aircraft using the parallel control structure. Figure 8 shows the test data for the aircraft using the cross-coupling control structure.

Figure 6. Test data using the parallel control structure
In Figure 6, the maximum yaw error is 82° which is very large. In Figure 7, the maximum yaw error is 21°. Compared with the parallel control structure, the synchronization error of the cross-coupling control structure in Figure 7 is obviously has better performance and resistance.

Figure 8 shows the flight test for the buoyancy-lifting aircraft using the cross-coupling control structure. Flight data is shown in the Figure 9.

5. Conclusions
This paper discussed a cross-coupling control structure for double propellers synchronous control problem and reported flight test results using this control structure to control buoyancy-lifting aircraft. It was shown that with the method the buoyancy-lifting aircraft has better performance and resistance than with the parallel control structure.
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