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Design and Technology Verification of a Middle and Low Altitude Solar-Powered Airship

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Abstract: This paper first provides an overview of the development of airships in recent years. The current problems of middle and low altitude airships are also described. To resolve the problems above, a solution was proposed and a corresponding middle and low altitude solar-powered airship was preliminarily designed. An optimal design was completed on the basis of the existing LOTTE airship. In addition, the most suitable airfoil was determined to realize the optimum aerodynamic characteristics. Then numerical simulation analysis on the airfoil was conducted with ANSYS Fluent. A flight test was also carried out to verify the effectiveness and reliability of the airship designed, which provides a reference for the application and transformation of middle and low altitude solar-powered airships.

1. Introduction

Airship is a kind of aviation platform which relies on air buoyancy to overcome its own gravity. It is known for the irreplaceable advantages in time domain and spatial domain. Unlike aircraft, airship enjoys a broad view and can stay in the air for a long while [1]. Therefore, countries all over the world have conducted researches on airships with the purpose to enable the airships to stay in the air for a longer time. The United States and Europe are especially interested in high altitude airships (flying at an altitude of 20 km) and they have invested heavily in the reasoning and verification of these airships [2-4].

In order to achieve the goal of long flight, a middle and low altitude airship powered by solar energy was put forward and designed in this paper. Middle and low altitude airships (the flight altitude is usually below 3000m) have larger loading capacity and longer time of endurance. Therefore, these airships are particularly applicable to missions like aerial remote sensing and communications.

2. Overall Design of the Airship

Generally speaking, most of the airships at middle and low altitudes are non-rigid airships. The capsules of these airships are made of a special material through hot welding. These capsules are filled with lift gases (usually helium) whose pressure help to maintain the shapes of the capsules. Given factors like flight altitude, non-rigid airship is selected in the design.

Shape Design

The capsule of this airship is designed by referring to the LOTTE airship developed by the University of Stuttgart, Germany and then miniaturized [4]. Due to the excellent aerodynamic characteristics and high reliability of the LOTTE airship, scholars have done various studies on its development and application. Its generatrix equations are as follows:

$$\begin{cases} \bar{r}1 = C\sqrt{\bar{x}}, \quad 0<\bar{x}<0.08 \\ \bar{r}2 = C_1 + C_2\bar{x} - C_3x^{-2} + C_4x^{-3} - C_5x^{-4} + C_6x^{-5} \end{cases} \tag{1}$$

$$\bar{r} = \frac{r}{L}, \quad \bar{x} = \frac{x}{L} \tag{2}$$

Where r is the radius of the cross section of the airship, x is the distance between the cross section and the nose cone of the airship, and L is the length of the airship. C is 0.2277, C_1 is 0.0197 , C_2 is 0.7184 , C_3 is 2.375, C_4 is 5.0166, C_5 is 5.834 and C_6 is 2.4551. The length of the airship is set at . The slenderness ratio is and the maximum radius of the airship's cross section is $D=1m$. The volume is . The centroid, which is also the volume center of the airship, is $1.75m$ away from the airship head.

NACA0010 airfoil is used as the empennage and cruciform empennage is selected. The distance between the front end of the empennage and the head of the airship is $4m$. The overall shape design of the airship is shown in Figure 1:

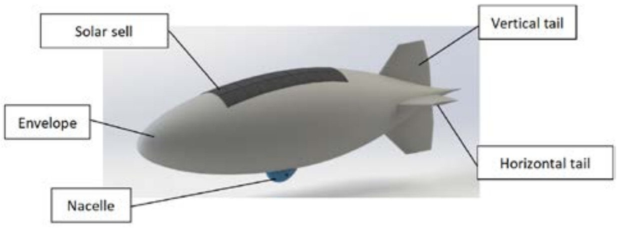

Figure 1: Schematic diagram of the airship

3. Numerical Simulation Analysis of Aerodynamic Characteristics of the Airship

In order to determine the aerodynamic characteristics of the airship in flight, ANSYS Fluent was used to analyze the aerodynamic characteristics of the airship designed in this paper. Then the drag characteristics, lift characteristics and pitching moment characteristics of this airship at different angles of attack were further determined [5].

3.1 Mesh Division

A rectangular outer fluid domain with a size of $24m \times 24m \times 8m$ was created in SpaceClaim and the center of the volume was taken as the origin. According to the airship model in this paper, unstructured meshes were applicable. Hybrid meshes were used, the majority of which were hexagons. To ensure the quality of these meshes, Fluent Meshing was adopted to draw the meshes required. Meshes at the empennage of the airship were denser than anywhere else and boundary layers were added as well. Besides, poly-hexcore mesh was chosen as the body mesh. Among these meshes, most were hexahedrons so that the number of meshes wouldn't be reduced when polygonal meshes were used nearby.

Totally about 1.21 million meshes were drawn for this airship. Surface meshes on the body of the airship are shown in Figure 2:

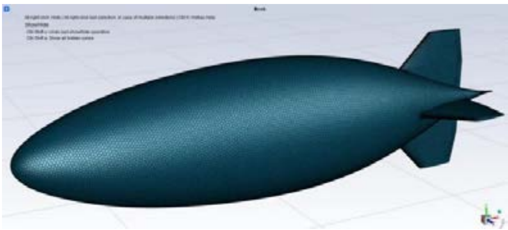

Figure 2: Surface meshes on the body of the airship

3.2 Calculation Settings and Boundary Conditions

The steady calculation was used and gravity was ignored. $k-\omega$ turbulence model was selected. To obtain convergent results, the Coupled algorithm was adopted. Parameters were set as follows. The inflow velocity was set at $30m/s$. Velocity inlet was set in both x direction and y direction so that the angle of attack could be altered by changing the velocities. Pressure outlet was set at the outlet boundary and far-field boundary. The static pressure was $0Pa$. No-slip boundary condition was applied to the wall boundary and symmetry boundary conditions were adopted.

The residual was set at 1×10^{-3} in calculation. The results were considered to be convergent when this condition was met. The results are shown figure 5 at the end of this paper.

It can be seen from the figure that the lift coefficient of the airship increases linearly with the angle of attack. The drag coefficient of the airship increases correspondingly as the angle of attack increases. This is easy to understand. Because the windward area of the airship increases as the angle of attack gets larger, thus resulting in the increase of the drag force. As the figure shows, for the pitching moment coefficient, there is a critical angle α_c of the airship model designed in the paper. The critical angle is about 15°. When the angle of attack is smaller than the critical angle α_c, the nose-up pitching moment of the airship will be dominant and the airship will enter the pitching unstable state. However, if the angle of attack becomes larger than the critical angle α_c, the nose-down pitching moment will surpass the nose-up pitching moment and the airship will enter the pitching stable state. The reason is as follows: for the airship, the lift provided by the empennage is about $2\sim3$ times that of the airship body. Therefore, when the angle of attack increases, the influence of the nose-up pitching moment of the airship body will be weakened by the larger nose-down pitching moment generated by the empennage, through which the angle of attack of the airship tends to decrease. The calculation results are consistent with the experimental results of the original LOTTE airship described in literature [6] and literature [7]. It proves that the miniaturized airship is as excellent as the original airship in terms of aerodynamic characteristics [6,7].

4. Calculation of the Airship Power System

The airship is powered by solar energy. During the day, the solar cells on the airship absorb solar energy. Part of the solar energy absorbed is used to support the flight of the airship. The remaining part is stored in the battery of the airship to enable the airship to fly at night or under the conditions of low light. Therefore, energy balance calculation should be included in the design of the airship to calculate the flight duration of the airship. In addition, the maximum output power can be determined when a balance is struck between solar energy and the lithium battery of the airship within 24 hours [8,9]. To calculate the data, it is necessary to find out how solar radiation changes on a certain day first [10,11]. The date selected was the 180th day of 2021, that was, June 29, 2021. The test was conducted in a place in East China with a north latitude of $31°52'$. The efficiency of the solar cells was 24.6% and the effective projection area of the airship was $2.6m^2$. The amount of solar radiation received by the airship before sunrise and after sunset are 0, during which time it is powered by the lithium battery only; while the condition in the daytime is different, the change of solar radiation with time can almost be represented by a sine function curve where the maximum value is reached at noon. Specific solar radiation can be calculated with the following formula:

$$\int_0^{h_3}(P_{tot}-P_{sc})dh+\int_{h_4}^{24}(P_{tot}-P_{sc})dh=\eta\cdot\int_{h_3}^{h_4}(P_{sc}-P_{tot})dh \tag{4}$$

Where P_{tot} is the balanced power, that is, the maximum output power when a balance is struck between solar energy and the lithium battery of the airship within 24 hours. P_{sc} is the amount of solar radiation under the effective projection area. The final result is shown in Figure 3:

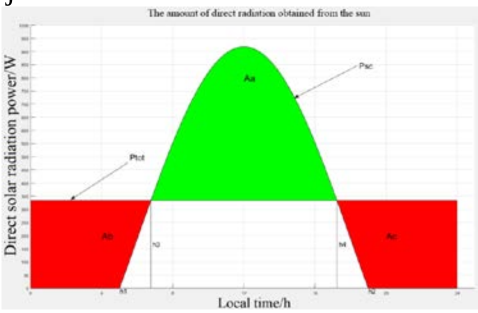

Figure 3: Diagram of energy balance

In this figure, A_a is the energy stored by the solar cells in the daytime under the effective projection area. A_b and A_c are the energy consumed by the airship during flight. It can be seen from the figure that the balanced power $P_{tot}=334.26W$, that is, the maximum output power of this airship is 334.26W.

According to the numerical simulation in Section 3, the drag force of this airship at the speed of $30m/s$ was $22N$. Taking into account the drag force and the balanced power determined in this section, the corresponding motor was carefully chosen. Besides, the solar circuit controller for the airship was designed by referring to literature [12]. Some basic parameters determined in the design above are listed in Table 1.

Table 1: Basic parameters of the airship

Airship parameters	Values
Length of the airship/m	4
Flight altitude/m	500
Total volume/m3	1.71
Area of the solar cells/m2	2.6
Available electric energy/W	334.26

5. Flight Test of the Airship

A prototype of this airship was made on the basis of the design parameters to verify the actual flight performance of the newly designed airship. Relevant flight test was completed. This test was conducted on June, 29, 2021 and it lasted for one day. The actual drag force, lift force and pitching moment were recorded during the test. Then the data was converted into corresponding coefficients and compared with the data in literature [6] and the data determined in the numerical simulation above. As shown in Figure 4 (a), Figure 4 (b), Figure 4 (c), these three sets of data are consistent with each other. Test results show that the aerodynamic characteristics of the miniaturized LOTTE airship during flight are as excellent as the original airship. The data of solar power at different time during the flight of the airship was collected. Then the curve shown in Figure 4 (d) was drawn with the data through fitting. It was found in the test that the actual balanced power exceeded the theoretical specification and reached 353.35 W. Therefore, the airship was able to stay in the air for a long while. In the final test, this airship flied for 8 hours without interruption.

The comparison between the design specifications and the actual specifications is shown in Table 2.

Table 2: Comparison between the design specifications and the actual specifications

Parameters	Design specifications	Actual specifications
Maximum flight speed/m	30	29.7
Total buoyancy/N	19.36	20.57
Area of the solar cells/m^2	2.6	2.6
Available electric energy/W	334.26	353.35
Endurance time/h	8	8

The simulation results and actual flight test results are shown below:

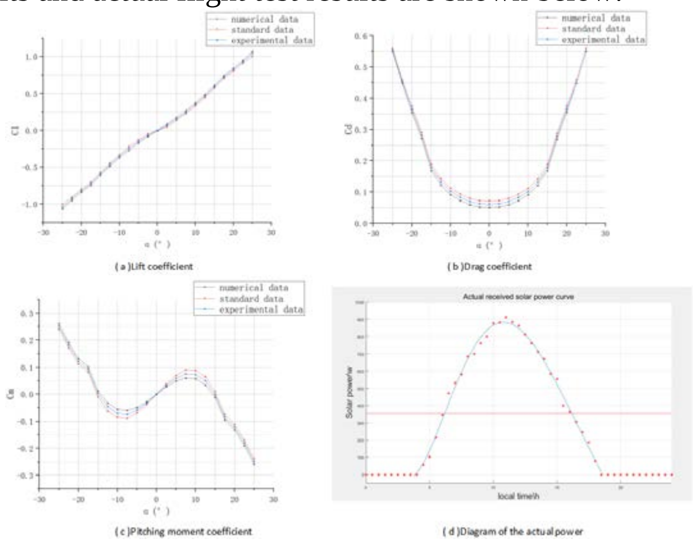

Figure 5: Test results diagram

It should be noted that for other kinds of non-rigid airship powered by electricity only, the duration of flight is generally limited within 2 hours. So, a great progress has been made. Photos taken during the actual flight are shown in Figure 5:

Figure 5: Photos taken during the actual flight

6. Conclusions

A brand new design for unmanned airship at middle and low altitudes was put forward in this paper. Corresponding test verification was completed as well. This paper aims to lay a solid foundation for subsequent in-depth development and provide reference for the design and development of UAVs flying at middle and low altitudes.

As shown by the results of the numerical simulation in this paper, the miniaturized LOTTE airship has good aerodynamic characteristics and can be used as middle and low altitude unmanned airship.

This paper confirms that it is appropriate to design the energy system of small UAVs by combining solar power with energy balance method. Therefore, it provides a new approach for the design of small UAVs.

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