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An Experimental Study of Center of Gravity and Lifting Moment Control of Flapping-Wing Ornithopters

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ABSTRACT: Aiming at realizing the safe flight, take-off and landing of ornithopters while simultaneously reducing the requirements on structural strength, this study explored a control method for flight posture in which the net moment was generated by changing the position of the center of gravity (COG). Firstly, five square panes were prepared by connecting five identical square acrylic glass panes of the same weights via joints and their COG positions were adjusted by moving the balancing blocks. Next, free falling experiments were conducted on these five-square-pane structures with different COG modes (centrally-configured, internally-configured and external-configured COG, respectively). Results show that the centrally-configured structure kept a line-shaped posture and fell to the ground stably while the internally-configured structure kept a concave-shaped posture and fell to the ground stably, and the externally-configured structure kept a convex-shaped posture and fell to the ground stably. It can thus be concluded that the generated net moments in different directions caused by the different COG positions of the five-square-pane structures were the main cause for the difference in landing posture. This study not only achieved effective control of the landing posture of the five-square-pane structure, but also provided a significant reference for practical ornithopter designs that have lower energy consumption, more favorable flight performances and higher energy utilization ratio.

Keywords: Center of gravity (COG) control; Lifting moment; Net moment; Flapping flight

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I. INTRODUCTION[1]

Ornithopters, also referred to as flapping-wing aircrafts, are a class of bionic aircraft that were developed in the 1990s by imitating the flight mode of a bird; specifically, by using only a pair of wings, both the lift force and thrust are generated simultaneously so as to achieve flapping-wing flight[1],[2]. Compared with fixed-wing or rotated-wing aircrafts, flapping-wing aircrafts exhibit a series of remarkable advantages such as favorable maneuverability, flexibility and high aerodynamic efficiency[3], prompting much research across the world. Current research is mainly focused on the mechanisms of flapping-wing flight and the development of flapping-wing aircrafts. The unsteady aerodynamic characteristics of flapping flight increase the importance of investigating the flapping-wing flight mechanism. Many aerodynamicists and biologists explored and proposed some high-lift mechanisms for bionic flapping wings, namely, the clap and fling mechanism[4], delayed stall effect[5], rotational circulation mechanism, wake capture mechanism[6][7] and skew plate effect[8]. Meanwhile, with the further development and interdisciplinary applications of bionics, air science, micro-design, micro-manufacturing and micro-control, microornithopters made great strides in many aspects including bionic flight mechanism, energy and drive, control, communication, and so on [9][12]. However, the behavior of large-sized ornithopters have remained poorly investigated to date[13][15]. Jones developed a flapping-wing structure having two pairs of wings on both the top and the bottom with a wing span of 1270 mm that can produce flapping and pitching motions, and carried out related wind tunnel tests[13]. In February 2007, K. Nakazato, a Japanese professor, designed a large-scale remote-controlled ornithopter with a wing span of over 3 m and realized its successful flight; this ornithopter had a weight of 2.6 kg, a flapping frequency of 2 Hz and a climbing height of 100 m[14]. Accordingly, the investigation of large-size flapping-wing aircraft began to change from pure theoretical analysis and calculation to practical development.

Just as the dreams of flight seen by human beings were realized by means of fixed-wing and rotated-wing aircrafts, in the future means of trans-

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portation will experience significant changes, and enter a new three-dimensional era if the newly-developed, large-size flapping-wind aircraft can achieve flexible take-off and landing, and stable flight. Accordingly, the development of large-size ornithopters is of great significance. The Beijing Implant Aircraft Co., Ltd, has made several breakthroughs in this field. This study considered five square panes with three different center of gravity (COG) modes for performing free falling experiments at an initial velocity of zero and simulated the ornithopter's motion postures during the landing process. The present study can provide significant guidance for enhancing the safety and reducing the energy consumption of large-size ornithopters.

II. EXPERIMENTAL SCHEME

2.1. Experimental equipment

The present experiments were performed in the Chenzhuang Experimental Base of the Beijing Implant Aircraft Co., Ltd. As shown in Fig. 1, the experimental equipment consists of a hydraulic lift with an operating voltage of 308 V and an operating power of 2.2 KW (QYSJY0.3-7, Jinan Minyang Hydraulic Lifting Machinery Co., Ltd.), five square acrylic glass panes with identical shapes and masses, five identical cylindrical balancing blocks and Dyneema Fiber kite lines. Specifically, the size of a square acrylic glass pane was 300 × 300 × 3 mm, with a density of 1.18 g/cm^3; the diameter, column height and weight of the balancing block were 32 mm, 5 mm and 31 g, respectively.

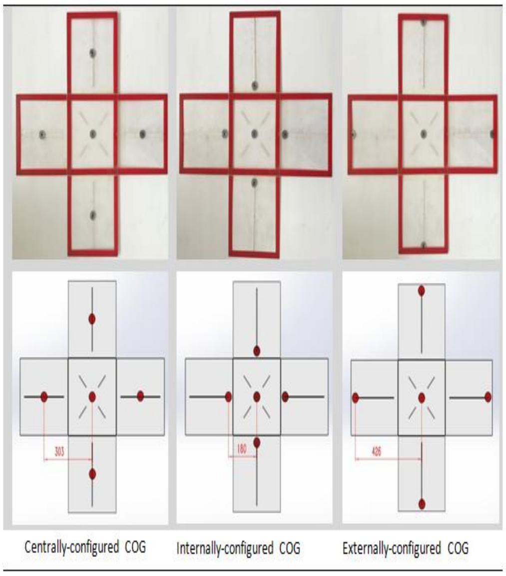
Fig.1. QYSJY0.3-7 series hydraulic lift

2.2. Experimental method

2.2.1. Preparation of the five-square-pane

Five square-shaped acrylic glass panes were connected by joints to form a cross-shaped five-square-pane structure. The four panes around the central pane can rotate freely around the joint. Next, five identical balancing blocks were fixed at different positions on the surface of the five glass panes for altering the position of the COG of this five-square-pane structure, and the adjustable distance of the balancing block was 246 mm. Three different COG modes were used in this study, namely, the centrally-configured COG, internally-configured COG and externally-configured COG. Table 1 displays the layouts of the five-square-pane structure with different COG modes, the corresponding experimental models and physical parameters. Finally, the ends of five Dyneema Fiber kite lines were fixed on the balancing blocks for pulling the five square glass panes.

Table 1 Experimental equipment images and corresponding model schematics.



2.2.2. Free falling experiments

Initially, the five-square-pane structure with centrally-configured COG was lifted to the position at 7 m above the ground using a hydraulic lift; next, the five-square-pane structure was pressed over a fixed plate so that five glass panes in the structure were at a same horizontal plane; finally, the whole structure fell freely at an initial velocity of 0, the process being referred to as free falling in this study. During the falling process, the motion postures of the five panes were recorded by a camera. In the next step, the COG position was changed by moving the balancing blocks. For each COG mode, the experiments were repeated thrice.

2.3. Video processing

The free fall of the five-square-pane structures with different COG positions were recorded, and the acquired videos were analyzed using the Adobe Premiere Pro software. In order to gain a more in-depth knowledge of the motion postures of the five-square-pane structures in free fall, the selected videos segments of the experiment were cut; subsequently, by means of single-frame analysis, the detailed information regarding the motion postures of the structures in the whole free falling processes was acquired; the images in the free falling process were then cut and combined, and the image series that can best represent the free falling processes of the five-square-pane structures were acquired for describing the experimental phenomena.

III. EXPERIMENTAL RESULTS

The motion postures of the five-square-pane structure with the centrally-configured COG were first described in detail. Next, by changing the COG position, the motion postures of the five-square-pane structures with different COG positions were analyzed and the differences in motion postures among these three different structures with different COG modes were compared.

3.1. Motion posture of five-square-pane structure with centrally-configured COG during free fall

Fig. 2 shows the typical image series that represented the free fall of the five-square-pane structure with the centrally-configured COG. It can be easily observed that, at the beginning of release, the five-square-pane structure fell in a convex-shaped posture; with the increase of falling distance, the convex angle decreased gradually, and the falling of the structure exhibited a line-shaped posture that occupied 1/3 of the whole falling height; next, the five-square-pane structure dropped to the ground assuming a line-shaped posture, i.e., the five glass panes in this structure fell to the ground almost at the same time. For the five-square-pane with the centrally-configured COG, free fall experiments were repeated several times in the same way and the experimental videos confirmed the favorable repeatability of the experimental process.

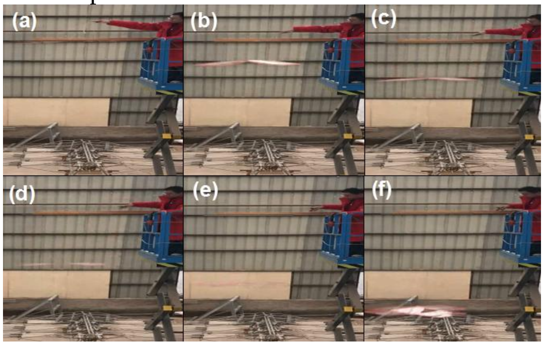


Fig.2. Falling movement gesture of five-parts square plate with the center of gravity middle

3.2. Motion posture of five-square-pane structure with internally-configured COG during free falling process

Fig. 3 shows the typical image series that represents the free fall of the five-square-pane structure with internally-configured COG. It can be easily observed that, during the initial release, the five-square-pane structure fell in a convex-shaped posture; with the increase of falling distance, the convex angle decreased gradually to zero, taking up half of the falling height; subsequently, the four surrounding glass panes were rotated so that the whole five-square-pane structure dropped at a concave-shaped posture and the concave angle increased as the falling distance rose; finally, the five-square-pane structure fell to the ground assuming a concave-shaped posture, i.e., the middle glass pane first touched the ground followed by the surrounding four panes. For the five-square-pane with an internally-configured COG, free fall experiments were also repeated several times in the same manner and the acquired experimental videos confirmed the favorable repeatability of the experimental process.

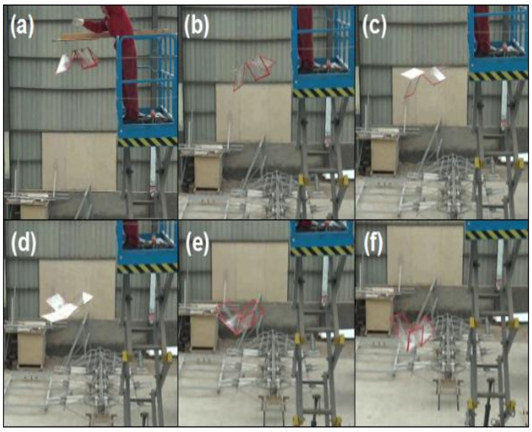


Fig.3. Falling movement gesture of five-parts square plate with the center of gravity inside

3.3. Motion posture of five-square-pane structure with externally-configured COG during free falling process

Fig. 4 shows the typical image series that represents the free fall of the five-square-pane structure with the externally-configured COG. It can be easily observed that, at the beginning of the release, the five-square-pane structure fell in a convex-shaped posture; with the increase of falling distance, the convex angle increased gradually to a constant value that took up 2/3 of the fall height; next, the five-square-pane dropped to the ground in a convex-shaped posture, i.e., the four surrounding panes first fell to the ground followed by the middle pane. For the five-square-pane with an externally-configured COG, free fall experiments were also repeated several times in the same way; according to the acquired experimental videos, the falling process of the five-square-pane with an externally-configured COG possessed favorable repeatability.

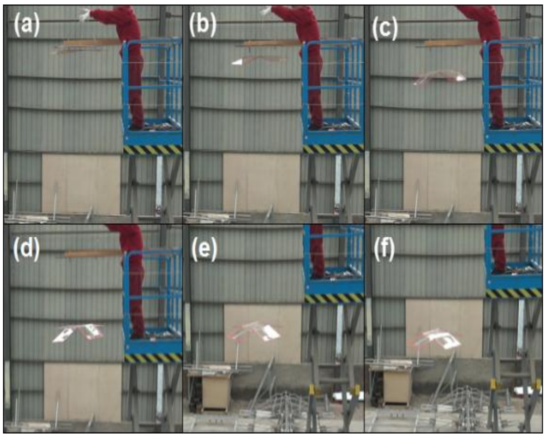


Fig.4. Falling movement gesture of five-parts square plate with the center of gravity inside

3.4. Comparison of the falling process among the five-square-pane structures with different COG modes

As shown in Figs. 2~4, the five-square-pane structures with different COG modes showed obvious convex-shaped posture in the initial period of falling. Accordingly, at the instant of release with an initial velocity of 0, the five glass panes in the structure, which were connected with joints, were not completely in the same horizontal plane. Therefore, the convex-shaped posture of the whole structure can be as attributed to errors caused by experimental operations, that need to be reduced. Through further comparison, it can be understood that the COG position plays a key role in the falling posture of the five-square-pane structure.

Fig. 5 illustrates the motion postures during the falling processes of the five-square-pane structures with different COG modes. It can be observed that the four surrounding panes rotated around the joint, and the friction for this rotation can be neglected. From a mechanical point of view, five-square-pane structure fell freely from a height of 7 m, reaching the terminal velocity at approximately 2 m above the ground; afterwards, the structure fell to the ground at a constant velocity and in a straight-line configuration. During the free fall process, the middle pane remained in a line-shaped posture and eventually dropped to the ground. In this case, the five glass panes in the structure exhibited coincident COGs and centroids; on reaching the terminal velocity, the gravity equaled the lift induced by the difference in air pressure, suggesting that the structure reached moment equilibrium. Accordingly, the product of power and power arm equaled to the product of resistance and resistance arm. In this study, the vertically upward direction was assumed to be positive; therefore, the lift and gravity were regarded as the power and resistance, respectively. For the five-square structure with an internally-configured COG, the power, power arm and resistance remained unchanged, but the resistance arm was reduced due to the alternation of the COG mode; accordingly, the moment of the lift and lift arm (which was also referred to as lifting moment) exceeded the gravitational moment induced by the gravity and gravity arm, which destroyed the moment equilibrium; therefore, the four surrounding panes rotated upwards around the joints, causing the gravitational moment to decrease further, and the upward rotation of these four surrounding panes stopped after reaching the extreme points. For the five-square-pane structure with an externally-configured COG, the power, power arm and resistance remained unchanged, but the resistance arm increased due to the externally-configured COG; accordingly, the lifting moment was smaller than the gravitational moment, and the moment equilibrium was destroyed; afterwards, the four surrounding panes rotated downwards around the joints, during which the gravitational moment decreased. The following two situations may then occur: (1) if the panes rotate to certain degrees, the moment equilibrium conditions are satisfied and the surrounding panes stop rotating; (2) if the gravitational moment always exceeds the lifting moment, the rotation of the surrounding panes still stop when the joints reach the extreme points. When the rotation of a plane reaches the joint's extreme point, the material would be damaged to a certain degree. In practical applications, this condition should be avoided.

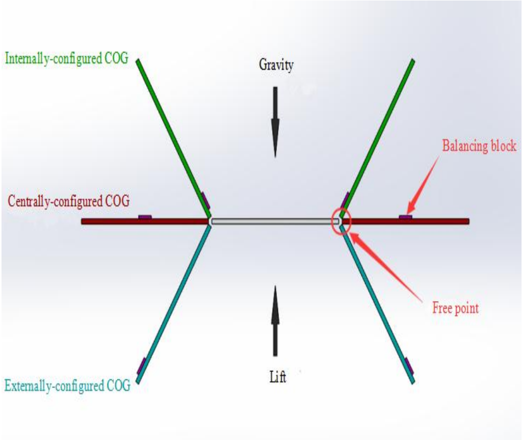


Fig.5. Comparison of falling movement gestures of the five-square-plate with three center of gravity configurations

A stated above, during free fall, the five-square-pane structures with centrally-configured, internally-configured and externally-configured COG positions experienced different situations, namely, zero net moment, upward rotation of net moment and downward rotation of net moment, respectively; accordingly, the respective structures exhibited line-shaped, concave-shaped and convex-shaped motion postures. It can thus be concluded that the direction of the net moment in the falling process can be altered by changing the structure's COG position, thereby achieving effective control of the falling posture. It should also be noted that a concave-shaped falling posture would further increase net moment of clockwise rotation, eventually resulting in damages to the flapping-wing joints. Therefore, the limiting condition of concave-shaped distortion should be avoided by effectively calculating the control parameters.

IV. DISCUSSIONS

In view of the adopted experimental method and available results, both the significance and limitations of the present study should be discussed. The importance, shortcomings and associated improvements will be described below.

Experimental results confirmed that the motion posture of a five-square-pane can be altered by changing the COG position. The application of this principle can provide some foresight and important guidance for the design, development and performance improvement of large-size manned flapping-wing aircrafts. In terms of energy consumption and thrust, the existing experimental results reveal that flapping-wing aircrafts perform poorly in swooping. Since sufficient swooping of the flapping wings is the premise for ensuring sufficient thrust of the ornithopter, high-efficiency flight with low energy-consumption and high thrust can be achieved by changing COG position of the ornithopter. Regarding the safety and stability, the net moments in different directions can be generated by changing the COG position of the ornithopter so as to achieve safe and stable landing, which is quite important for ensuring the overall flight safety and enhancing the stability.

Admittedly, the lift release method that was adopted in this study was the main reason that led to the convex-shaped motion posture of the five-square-pane structure during the initial period following the release. In future studies, we should seek more accurate release modes so that every pane in the structure can fall at the same moment without having an initial velocity imposed on them, thereby reducing the effects on the experimental results. This study conducted model tests on five-square-pane structures with different COG modes for investigating the flight characteristics of an ornithopter, and found that lower energy consumption, greater thrust and more favorable falling posture can be achieved by altering the COG of the flapping-wing so as to achieve high-efficiency flight. However, for a real ornithopter, more factors related to the actual flight and landing process should be considered, and a more complex control mechanism should be adopted, which needs further tests and investigations.

V. CONCLUSIONS

(1) Because of the different COG positions, net moments in different directions were generated, resulting in the rotation of the surrounding panes in the structure in different directions and thereby, in different motion postures.
(2) The landing posture of a five-square-pane structure can be controlled by reasonably changing the COG position, and this study provides reference data for the design of practical ornithopters with better performances and high energy efficiencies.
(3) This article indicates that in the design of flapping-wing aircraft, it is necessary to pay attention to the net moment of flapping wings. For a single flapping-wing aircraft, if the net torque is ignored, it will cause incomplete flapping.

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