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Design of a hydraulically-driven bionic folding wing

Zhijun Zhang[a], Xuwei Sun[a], Pengyu Du[a], Jiyu Sun[b,*], Yongfeng Wu[a]

[a] School of Mechanical Science and Engineering, Jilin University, 5988 Renmin Street, Changchun 130022, China
[b] Key Laboratory of Bionic Engineering (Ministry of Education), Jilin University, 5988 Renmin Street, 130022 Changchun, China

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ABSTRACT

Membranous hind wings of the beetles can be folded under the elytra when they are at rest, and rotate and lift the elytra up only when they need to fly. This characteristic provides excellent flying capability and good environment adaptability. Inspired by the beetles, the new type of the bionic folding wing for the flapping wing Micro Air Vehicle (MAV) was designed. This flapping wing can be unfolded to get a sufficient lift in flight, and can be folded off flight to reduce the wing area and risk of the wing damage. The relationship between the internal pressures of the hydraulic system for the bionic wing folding varies and temperature was analyzed, the results show that the pressure within the system tends to increase with temperature, which proves the feasibility of the schematic design in theory. Stress analysis of the bionic wing was conducted, it was shown that stress distributions and deformation of the bionic wing under the positive and negative side loading are basically the same, which demonstrates that the strength of the bionic folding wing meets the requirements and further proves the feasibility of the schematic design.

1. Introduction

By nature, insects and birds are born to fly, their perfect flying skills were attractive by people. Although insects and birds have excellent flying abilities, the structure of their wings is greatly different. The wing of birds consists of muscles, bones, and feathers, while insect wings are moved by veins and membranes. By contrast, the insect wings are simpler and lighter, the lift of MAV is limited by size ranges. To meet MAV requirements, a flapping wing providing flight dynamics must be quite lightweight. So, the insect wing model with its simple structure and considerable aerodynamic forces becomes the first choice for designers.

Current research efforts resulted in the design of the bionic flapping wing of high performance (Keennon and Grasmeyer, 2003; Wood, 2008a, 2008b; Keennon et al., 2012). These aircrafts have a common feature: their flapping wings take over the membrane wing structure with a simple support. Despite the simple structure and light weight of the wing, its area is relatively large, while the membrane wing is easy to damage and inconvenient to carry.

Referenced to the beetle hind wing, there is proposed the four-plane theory (Haas and Wootton, 1996). By using the shape memory alloy wire as a driver, the automatic folding of the bionic wing was successfully realized (Muhammad et al., 2009, 2010; Nguyen et al., 2010). However, the shape memory alloy wire can be deformed only after heat treatment, so the two alloys should be used to carry out the folding and unfolding, respectively (Truong et al., 2014). The bionic folding based on the four-bar mechanism has an advantageous simple structure, its disadvantage is the need of external force to push the linkage mechanism realizing folding, otherwise, the wings would remain unable to form and adjust, so the wing cannot be modified in time if the morphology change is in a flutter. Models based on the wings of the birds and bats contributed to the design of a kind of the bionic folding wing (Stowers and Lentink, 2015). By using the centrifugal acceleration to unfold the wings, with this method, its wing can unfold without any additional device through the inertia force by itself, the states of the wing and flapping parameters are closely related, the structure is simple and has the ability to automatically adjust, but its expansion relies on the inertia force of the wings, so the total size of the wing is larger, and it cannot be further miniaturized.

The hydraulic mechanism of the beetle hind wing and the morphological changes in folding/unfolding were used to design a kind of the hydraulically-driven bionic folding wing. Investigations performed in this study are of importance for reducing the carrying size of MAV flapping wing, lowering the risk of damage due wing flapping, and extension of the MAV service life.

2. Schematic design of a bionic folding wing

The schematic design of the bionic folding wing was prepared based on the hydraulic expansion mechanism of *Dorcus titanus platymelus* hind

* Corresponding author.
E-mail address: sjy@jlu.edu.cn (J. Sun).

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wing (Sun et al., 2014). They suggest that its wing is unfolded due to the action of the hind wing hydraulic and elastic mechanisms, but the folding is affected by the elytra in combination with the thorax muscle. And then the wing was locked in the open position mechanically (Haas and Beutel, 2001). The wing extensor and flexor muscles, contracting simultaneously, lever open the wing, and surely the muscles and the blood pressure must operate synergistically. To reduce the complex action and total weight, a set of mechanisms to achieve folding / unfolding is used. The folding / unfolding mechanism consists of the hydraulic and elastic systems, they interact with each other to achieve the above effect.

The elastic system of the bionic folding wing is mainly composed of the elastic rope, slider, vein, and elastic hinge. The elastic hinge connects two veins to simulate the elastic portion of RA at the end of the hind wing venation and top hinge point; the elastic rope simulates the hind wing vein of the elastic protein (Haas et al., 2000).

The principle of the hydraulic system design is based on the property of the liquid to expand on heating. The liquid volume in the enclosed container is growing on heating. Since the vessel wall volume expansion coefficient is much smaller than that of the liquid and the wall will retard the liquid volume expansion, the internal pressure of the liquid builds up and pushes the slider. The concept of the system is to transform thermal energy into pressure energy of the liquid directly, then it is converted into the mechanical energy of the slider.

The folding / unfolding of the bionic folding wing are realized by the joint operation work of the hydraulic and elastic systems. The vein, elastic and hydraulic systems constitute a bistable entity in the folding wing, ensuring its stability during operation (Fig. 1).

When the bionic wing is folded, the hydraulic system is not heated, the hydraulic cylinder does not operate, and the elastic rope of the system and elastic hinge are in the initial equilibrium state. When the wing is unfolded, the liquid in the hydraulic cylinder is heated by an external heat source, the liquid volume expands, and the pressure builds up, pushing the slider. Since the liquid pressure offsets a part of the elastic rope, the bionic wing will gradually unfold under the action of the elastic hinge.

The interaction forces of the elastic rope, hydraulic system, and the elastic hinge linked through the slider (Fig. 1) are related as

$$F_1 - F_2 = F_3 \tag{1}$$

where F_1, F_2, and F_3 are the forces exerted on the slider by the elastic rope, hydraulic system, and elastic system, respectively.

3. Structural design of the bionic folding wing

Veins are the main support structure of the bionic wing. The design of the bionic wing veins has its origin in the hind wing layout of *D. t. platymelus* (Fig. 2). The venation is shown in Fig. 2, where ScA is subcosta anterio, RA is radius anterior, MP_{1+2} is media posterior, CuA is cubitus anterior, AA is anal anterior, and AP_{3+4} is anal posterior, and J is jugal. However, the bionic wings cannot switch to some complex morphological changes just like the beetle hind wings, for this, some

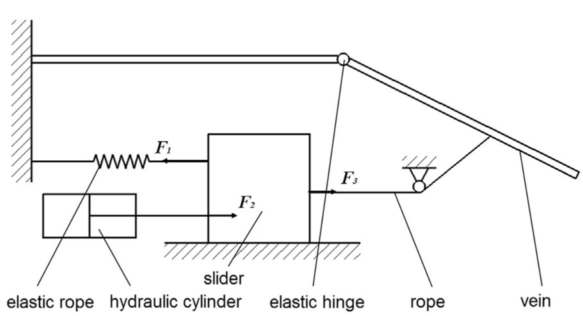

Fig. 1. The scheme of the folding/unfolding system of the bionic wing.

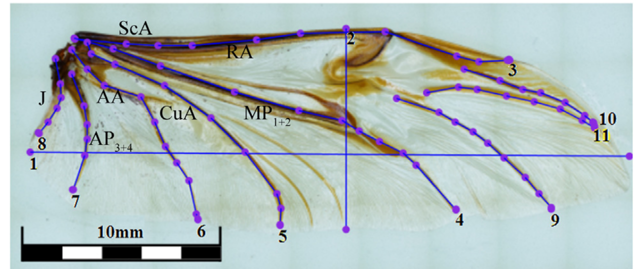

Fig. 2. The hind wing vein layout of *D. t. platymelus*. Where ScA is subcosta anterior, RA is radius anterior, MP_{1+2} is media posterior, CuA is cubitus anterior, AA is anal anterior, and AP_{3+4} is anal posterior, and J is jugal.

modifications and simplifications are necessary to suit the needs.

To achieve a lighter weight and sufficient strength of the bionic wing, the design maintains the main wing vein structure of the beetles, simplifies some tiny wing veins, and omits partial wing veins morphological changes in folding. The vein layout of the bionic wing is shown in Fig. 3. Fig. 3A- C are its front view, back view and side view, respectively. The bionic wing veins are mainly divided into the three types: leading edge, top, and posterior wing veins. Among them, the leading edge wing veins are used for simulating RA of the beetle hind wing. These veins are built of a circular catheter and support. The function of the catheter is to provide a guide rail for the slider in the folding / unfolding mechanism. The RA form a certain bending angle when the hind wing is fully unfolded, as well as to make a support angle for the bionic wing, with a tilt angle between the stent and the catheter. The top wing veins are the simplification of the top area of the beetle hind wing, which is connected to the leading edge veins with elastic hinges; the posterior wing veins offer the simplification of other veins of the beetle hind wing. The simplified wing veins do not fold and deform in the entire folding / unfolding, so these wing veins are fixed on the wing base.

In the beetle hind wing folding, the RA and MP_{1+2} wing veins change from the planar to three-dimensional structure, while the bionic wing cannot perform this operation. To avoid the effect of folding/ unfolding of the bionic wings interfering with each other, the leading edge and posterior wing veins are arranged in the two different planes and located on the two sides of the wing membrane.

The bionic folding wing is designed following the hind wing vein layout of *D. t. platymelus*. Therefore, the beetle wing geometry was measured and analyzed for determining the bionic wing vein parameters (Fig. 4). Beetle' wing sizes are too small, to avoid the problems associated with the manufacture of a bionic wing prototype, and the size of the prototype is suitably adjusted and magnified in the design. The specific parameters are shown in Table 1.

The new integral component is a flexible hinge is hinge with the cut in middle (Xin et al., 2003), which possesses supporting and guiding functions (Jing and Pan, 2016). According to the shape of the incision, a normal uniaxial elastic hinge can be classified as circular, oval, rectangular, hyperbolic, and others (Wang, 1997). In this study, the elastic hinge handles supporting and guiding jobs to control bending deformation, meanwhile it should have sufficient spring force under large angular deformation to ensure an effective expansion of the bionic folding wing. So the uniaxial elastic hinge with a circular incision was chosen for the design.

According to the research results by Paros (1965), when the pulling force F_x is applied in the x-axis direction of the uniaxial elastic hinge, its elongation (Δx) is:

$$\Delta x = \int_x \frac{F_x}{EA(x)}dx = \frac{F_x}{2Eb}\int_x \frac{1}{f(x)}dx \tag{2}$$

Where E is the elastic modulus of the material, $A(x)$ is sectional area of the elastic hinge cross section in the x-axis direction, b is the elastic