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Design and Analysis of Biomimetic Nose Cone for Morphing of Aerospace Vehicle

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Abstract

Morphing capability is absolutely vital for aerospace vehicle to gain predominant functions of aerodynamics, mobility and flight control while piercing and re-entering the atmosphere. However, the challenge for existing aerospace vehicle remains to change its structure of nose cone agilely. This paper carries out a lot of observational experiments on honeybee's abdomen which enhances the flight characteristics of honeybee by adjusting its biomorphic shape. A morphing structure is adopted from honeybee's abdomen to improve both the axial scalability and bending properties of aerospace vehicle, which can lead to the super-maneuver flight performance. Combined with the methods of optimum design and topology, a new bionic morphing structure is proposed and applied to the design of morphing nose cone of aerospace vehicle. Furthermore, simulations are conducted to optimize the structural parameters of morphing nose cone. This concept design of biomimetic nose cone will provide an efficient way for aerospace vehicle to reduce the aerodynamic drag.

Keywords: bio-inspired design, honeybee, morphing nose cone, aerospace vehicle, flight characteristic

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1 Introduction

Aerospace vehicle, distinguished from the aircraft in general sense, is a new style of plane designed to accomplish re-entry missions[1–4]. As the aerospace vehicle experiences extreme aerodynamic load between atmosphere and outer space, the design, assembly and operation of aerospace vehicle are completely different from those of traditional aircraft. An effective approach to improve the flight stability and aerodynamic performance of aircraft is to alter the geometric characteristics of outer configuration in various ways[5–8].

There have been a large number of studies on the morphing structure of aircrafts in recent years, which mainly focused on the morphing wing of aircraft[9–15]. The idea of morphing wing was first put forward by Clement Ader in 1890[16]. The early stage of the study on the morphing wing mainly focused on the design of rigid body morphing wing, which was applied in subsonic flight and supersonic flight. Following the span morphing concepts of Ivan Makhonine, an aircraft named 'MAK-10' was designed, which had telescopic wings[17]. Since then, there was a rapid development in variable-sweep wing. Next, the development of morphing wing mainly focused on the design of flexible body morphing wing. To further improve the aerodynamic characteristics, Rockwell Corporation firstly put forward an active flexible wing to lighten the weight of aircraft[18]. Subsequently, NASA and DARPA carried out a series of experiments on the intelligent morphing structure, include the technologies of Mission Adaptive Wing (MAW), Active Flexible Wing (AFW), Active Aeroelasticity Wing (AAW), and so on[19]. These technologies aimed at lightening the weight of aircraft and improving the flow performance by the changing of bending moment and torque of wing. Wrobleski evaluated the feasibility of research results on "Smart Wing", targeting BAC1-11 and MAW F-11[20]. To satisfy the high-performance requirements of bearing load and large deformation of skin structure, Murugan and Friswell[21] designed a flexible skins of morphing wing with curvilinear fiber composites to achieve the stiffness requirements of in-plane and out-of-plane. Wu *et al.* designed a deployable bistable structure for the morph-

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ing skin of aerospace vehicle, and further proposed a method and implementation for the stability optimization of bistable compliant mechanism[22–24].

For a reentry vehicle, the geometric configuration of nose cone has remarkable influence on drag reduction and aerodynamic characteristics. Numerous studies on the design of nose cone have been carried out[25–28]. Mathew *et al*.[25] presented a preliminary design of metallic heat shield of a typical launch vehicle. Zhao *et al*.[26] presented a supersonic transpiration-cooling test on a nose cone with non-uniform wall thickness. Their design of nose cone was proved effective in overcoming the crucial puzzle about cooling stagnation point. To improve the heat dispersion on the surface of a nose, Gerdroodbary *et al*.[27] adopted various counterflowing jets to reduce the heat load. Deepak *et al*.[28] presented a shape optimization method for drag reduction of nose cone in the hypersonic flight experiments. Li *et al*.[2] developed a mechanical design of morphing nose cone, which was very effective for space vehicle to reduce the aerodynamic drag.

In recent decades, the researches on the morphing structure of aircraft have highly increased. However, there are still some technical problems needed to be solved. For instance, the aerodynamic configuration, parameter optimization, reliability design of morphing structure urgently need to be studied[29]. Though the morphing structure has been used in aircraft, an effective approach has not been found to adapt the change of aerodynamic load in the aerosphere and outer space. As is known to all, insects have been on earth for over 350 million years, most of which have the ability to fly. They can adjust and optimize their self-structure to achieve optimal flight characteristics in real time during flight[30]. Mimicking the morphing structure of flying insects is an effective way to design the structure of morphing nose cone, which can reconfigure the aerodynamic profile of the vehicle autonomously. More recently, flying animals that morph to accomplish higher level objectives like foraging, perching, and migration have provided new paradigms for optimizing the mission performance of small UAVs[31]. Truong *et al*. designed a foldable wing based on the hind wing of a beetle, which could utilize its unfolded configuration to generate reasonable thrust during flapping motion[32]. Stowers and Lentink developed a passive wing morphing mechanism of flapping wings inspired by the wing morphology of bat and bird. This mechanism enabled the flapping-wing micro air vehicles to fly in extreme conditions without sophisticated control[33]. Huang and Siao[34] proposed a two-phase integrated bionic design system for engineers to create practical bionic designs and provided a verification process to evaluate the performance of final bionic products.

There are some astonishing resembles in the ability of changing configuration between the aircraft's nose cone and honeybee's abdomen. In this paper, we find that honeybee's abdomen can perform bending deformation to achieve better aerodynamic characteristics. Further, the physical structure and curl exercise of honeybee's abdomen is elucidated. Inspired by the variable biomorphic shapes of honeybee's abdomen, a morphing nose cone of aerospace vehicle based on the contour parameters of honeybee's abdomen is designed.

The remainder of this paper is organized as follows. Section **2** introduces our experimental methods and experimental data. In section **3**, a morphing nose cone of aerospace vehicle inspired by variant structure of honeybee's abdomen is designed. A simulation analysis for the space deployable mechanism with ADAMS is carried out in section **4**. The last section summarizes the whole paper.

2 Materials and methods

2.1 Experimental specimens

The experimental specimens of this study were adult foraging worker honeybees (*Apis mellifera ligustica*), which were collected from Beijing and housed in a single hive at Tsinghua University, Beijing, China (40.00˚N, 116.33˚E). We only collected the worker bees which fly out of the hive to gather pollen as our specimens.

2.2 Movement observation of honeybee abdomen

Sixty honeybees were collected in a transparent cage. After a few weeks, we used a high-speed imaging system (Olympus i-SPEED TR) with a zoom lens (Navitar 12X Zoom) to capture the bending motion of bee abdomen at 1000 frames per second.

As shown in Fig. 1, the thorax of honeybee was fixed on a single-axis precision positioner. In each experiment, we used the camera (Nikon AF-S DX) to record the whole process of abdominal movements over three hours.