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Non-contact magnetic driving bioinspired Venus flytrap robot based on bistable anti-symmetric CFRP structure

Zheng Zhang [a,b,*], Dandi Chen [a], Huaping Wu [a], Yumei Bao [a], Guozhong Chai [a]

[a] Key Laboratory of E&M (Zhejiang University of Technology), Ministry of Education & Zhejiang Province, Hangzhou 310014, PR China
[b] School of Civil Engineering, The University of Queensland, St Lucia, QLD 4072, Australia

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ABSTRACT

The Venus flytrap takes advantage of its bistability to generate rapid closure motion for capturing its prey. A bioinspired Venus flytrap robot with bistable artificial leaves is presented in this paper. Non-contact electromagnetic driving method is proposed to actuate the Venus flytrap robot's artificial leaves, which are made of anti-symmetric carbon fiber reinforced prepreg (CFRP) cylindrical shells. Magnetic force is generated by using the electromagnet and applied on the shell's curve edge to unbend the shell, and then the bending process transmits from one edge to the whole surface. The required magnetic force for the snap-through process of the bistable CFRP structure is determined from experimental test and compared with the result of finite element simulation. The test of the snap-through process of the Venus flytrap robot show that the Venus flytrap robot can generate a rapid snapping motion by the electromagnet actuation.

1. Introduction

In recent years, the bioinspired and biomimetic designs have become more popular than ever for its comprehensive properties and potential engineering applications. The Venus flytrap, as an interesting insectivorous plant among these, has been attracting the attention of many researchers. When insects or small animals touch the trigger hair of the Venus flytrap, its two leaves can close rapidly to capture the prey, as shown in the Fig. 1.

The active trapping mechanism of Venus flytrap was first presented by Williams [1] and Jacobson [2]. Then a dynamic response model of the Venus flytrap was founded [3] and then a Venus flytrap robot, also known as robotic flytrap, based on the model by using ionic polymeric metal composite (IPMC) artificial muscles as sensors and actuators was designed by Shahinpoor [4]. A Venus flytrap robot by the means of two IPMC actuators and one proximity sensor is presented by Shi [5,6]. Both above two researchers regarded the capture process of Venus flytrap as a single active deformation process. According to Forterre's research [7], the morphing motion of the Venus flytrap is composed of two processes: one is an active biochemical process, and the other is a passive elastic deformation process. The active biochemical process is caused by a rapid loss of turgor pressure in 'motor cells' [8]. The reason for the passive elastic deformation process is the existence of the bistability of its special leaves which is induced by its geometric characteristic. Therefore, the Venus flytrap leaf is a bistable structure with two different stable states: opening state with leaves being flat and closing state with leaves being coiled. Based on this interesting characteristic of the Venus flytrap, some bioinspired Venus flytrap robots have been developed by the use of bistable composite structures. A Venus flytrap robot made from cross-ply bistable CFRP structures and actuated by shape memory alloy (SMA) springs was developed by Kim et al. [9–11]. The Venus flytrap robot is able to complete the shape transition process in a short time under the actuation of SMA springs, which is similar to the capture mechanism of real Venus flytrap. However, the cross-ply bistable CFRP structure has two contrary curvature directions in the interchange of two stable states [12], it doesn't exactly depict the real curvature change of the Venus flytrap. Therefore, the bistable anti-symmetric CFRP structure which has the same curvature direction at the two stable shapes [13] is chosen to act as the artificial leaf in present paper to mimic the real Venus flytrap predation behavior.

Due to the similar deformation mechanism between the bistable laminated CFRP structure and the Venus flytrap's leaves, the bistable laminated CFRP structure is appropriate to be used to design a Venus flytrap robot. The bistable laminated CFRP structures were studied by researchers for its unique bistability

* Corresponding author at: Key Laboratory of E&M (Zhejiang University of Technology), Ministry of Education & Zhejiang Province, Hangzhou 310014, PR China. Tel.: +86 571 88320244.

E-mail address: zzhangme@zjut.edu.cn (Z. Zhang).

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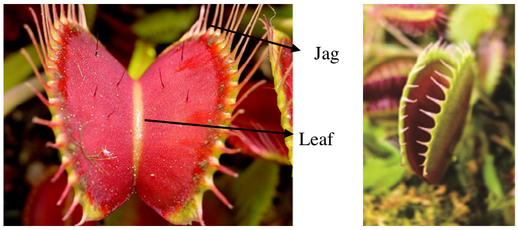

Fig. 1. Venus flytrap in the nature.

[14–16]. In addition, it is widely used in smart structures and deployable structures with kinds of actuations [17–22]. Dano et al. [23], Schultz et al. [24] and Hufenbach et al. [25] used shape memory alloy (SMA) wires or macro fiber composites (MFCs) as the actuator to induce the snap-through action of cross-ply bistable CFRP structure. As references described above, these trigger forces applied to driving the cross-ply bistable CFRP are at a low intensity. The bistable anti-symmetric CFRP structure needs larger trigger force than cross-ply bistable CFRP structure so it is usually loaded only by mechanical forces in experiments [26,27].

In order to generate a proper trigger force for the bistable anti-symmetric CFRP structure, a kind of magnetic actuation is presented in this paper. It is well-known that magnetic force can be applied without contact and easily adjusted by changing the applied current when using an electromagnet. Magnetic actuations are widely used in some smart structures for these advantages. A penta-stable structure was designed by Zhao [28], utilizing the mechanical-magnetic coupling effects of five arranged permanent magnets. Nam [29] developed a micro crawling robot which was driven by external magnetic field. It can crawl through a tunnel freely by the friction generated from the magnetic force. Sendoh [30] used an adjustable magnetic field to acquire required magnetic force and moment to drive micro robot. A kind of microrobot prototype for force sensing was presented by Jing [31]. Because of the limitation of the usual actuation and the advantages of the electromagnet such as no-contact and adjustable characteristics, electromagnet driving method is chosen to act as the actuation of the bistable anti-symmetric CFRP structure.

Therefore, A Venus flytrap robot with its leaves made of bistable anti-symmetric CFRP structures and driven by an electromagnetic actuation is presented in this paper. First, the basic principle of the artificial leaf made of bistable anti-symmetric CFRP shell and the new actuation method based on electromagnet are given. Subsequently, experimental tests and finite element analysis are conducted to determine the required magnetic force for the snap-through motion. The comparison of the experimental and numerical results is given. Finally, the capture motion of the Venus flytrap robot is performed successfully and the closure posture of Venus flytrap robot is achieved.

2. Venus flytrap robot's design and assembly

The schematic of a novel Venus flytrap robot, which can close rapidly like a real Venus flytrap, is shown in Fig. 2. In order to mimic the shape of the real leaf, the artificial leaf is made of bistable anti-symmetric CFRP structure which has two positive curvatures at its stable states. The deformation process can be triggered to snap through by an electromagnet. This section focuses on the design and assembly of the Venus flytrap robot. The corresponding capture motion is realized using the magnet actuator. In order to keep the artificial leaf close completely at the second stable state, the length and the layups of the bistable shell have to be designed to acquire the demand curvatures, which are discussed together with the actuation method in this section.

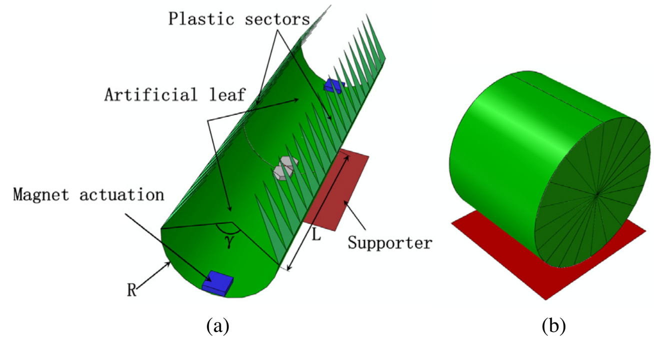

Fig. 2. Two stable states of the Venus flytrap. (a) Opening state; (b) Closing state.

2.1. The artificial leaf

The anti-symmetric CFRP shell has two unique features compared with the real Venus flytrap's leaf: (a) The actual Venus flytrap leaves are doubly-curved leaves both in the opening and closing stable states, its curvature changes during the whole snap process. The anti-symmetric CFRP shell has a positive curvature in one direction and a zero curvature in the other direction at the initial stable state, the positive curvature turns to zero and the zero curvature turns to positive when it changes to the second stable state. (b) The deformation of both kinds of leaves from the initial stable state to the second stable state is induced by a trigger force. The difference is that the actuation in the actual Venus flytrap is induced by the internal 'motor cells' while the trigger force in the Venus flytrap robot is an external magnetic force.

It is important for the Venus flytrap to keep the insect from escaping. Therefore, the leaf of Venus flytrap should close completely and rapidly, so does the artificial leaf. For this purpose, proper bi-stable shells with particular geometric parameters should be selected. As also shown in Fig. 2, the opening and closing states of the Venus flytrap are given. The geometric parameters of the Venus flytrap robot's first stable configuration (Fig. 2(a)) are: $L = 100$ mm, $R = 25$ mm, $\gamma = 180°$, thickness of lamina $t = 0.12$ mm and the layup is $[45°/-45°/45°/-45°]$. According to the finite element analysis of different geometrical parameters at the first stable state, the results show that the artificial leaf of the Venus flytrap robot with this dimension can close completely at the second stable state. Subsequently, the bistable anti-symmetric CFRP shells were manufactured using a cylindrical steel mold with a pre-load on the upper part using carbon-fiber/epoxy prepreg. The material properties of the used shell are listed in Table 1. The bistable anti-symmetric CFRP shells' specimens are testified to have a good performance in bistability and the deformation processes agree well with the numerical results. The closing state of the leaf at the second stable state, shown in the Fig. 2(b), depends on the geometric parameters at the first stable state and the material properties [26,27]. Therefore, the selected artificial leaf can close completely at the second stable state by adjusting the geometric parameters of the first stable state before specimen manufacturing.

2.2. Triggering actuation

The capture motion of the bistable CFRP structure is divided into two processes: triggering actuation and snap-through process. The snap-through process occurs automatically when the

Table 1
The material properties of carbon-epoxy lamina.

E_{11} (GPa)	E_{22} (GPa)	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)	ν_{12}	t_{ply}
105.55	7.065	5.17	5.17	5.17	0.31	0.12