ARTIFICIAL INSECT WINGS WITH BIOMIMETIC MORPHOLOGY AND STIFFNESS

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ABSTRACT

Wing morphology and stiffness are crucial in lift force generation during flapping flight. In this investigation, we present both fabrication and characterization methodologies for artificial insect wings with biomimetic morphology and stiffness using laser cutting and bonding of multilayer materials. Two distinctive achievements have been accomplished: (1) simple and versatile fabrication for the wing shape and venation pattern; and (2) good matches of mass, fundamental natural frequency and stiffness to the real biological insect wings. As such, these works provide a new class of biomimetic artificial insect wings in the field of Flapping-wing Micro Aerial Vehicles (FMAVs).

INTRODUCTION

Insect inspired Flapping-wing Micro Aerial Vehicle (FMAV) has drawn large research attention due to their high agility and maneuverability in the last decade [1]. To realize the final takeoff of a FMAV in insect scale, one basic task is to generate sufficient lift force from the view of bionics. According to biologist's research, many insect wings undergo a dramatic flexible deformation during flapping motions in the flight, and the three dimensional wing shape caused by flexible deformation provides large upsurge in lift force [2]. Since insect wings are actuated by the flight muscles at wing base where the wing is connected to the thorax, the insect itself merely has no active control over the wing's flexible deformation [3]. In other words, the deformation is passively caused by aerodynamic loads on the wing surface and it is mainly determined by wing morphology and its overall stiffness. Therefore, to achieve high lift force for the FMAV, one crucial step is to emulate the morphology and stiffness of real insect wings.

To fabricate artificial insect wings with biomimetic features, the wing should be lightweight as well as strong enough to sustain aerodynamic load. Besides, wing morphology and stiffness should be highly analogous to real insect wings. With the state-of-art fabrication methods, such as casting molding [4-6] and etching [7], the biomimetic wing morphology of the artificial wings can be well achieved by emulating real insect wing's outline and venation pattern. Due to lack of similarity in stiffness and density properties to the biological wings, the aerodynamic performance of these artificial wings is not efficient during flapping flight. To overcome above problems, laser cutting technique [8] is introduced to fabricate artificial insect wings with light weight and good match of wing outline recently, while its limitation is that the wing venation pattern is highly simplified and biomimetic morphology can not be well reproduced. Given that, it is still challenging to fabricate artificial insect wings with both biomimetic morphology and stiffness.

In this investigation, we present both fabrication and test method for artificial insect wings with biomimetic morphology and stiffness. Laser cutting of carbon fiber-based multilayer materials and thin Mylar are utilized to emulate the venation pattern and wing shape of different insects such as bee and cicada. To investigate the stiffness of the artificial insect wings, a test system is designed and fundamental natural frequencies of different wings are obtained. In pursuit of biomimetic stiffness, artificial insect wings with different thickness of carbon fiber layers in wing venation are fabricated and their stiffness are estimated. Compared with the existing method by using casting molding or etching, the fabrication method presented by this investigation demonstrates much simplicity in process but significant improvement in artificial wing's performance.

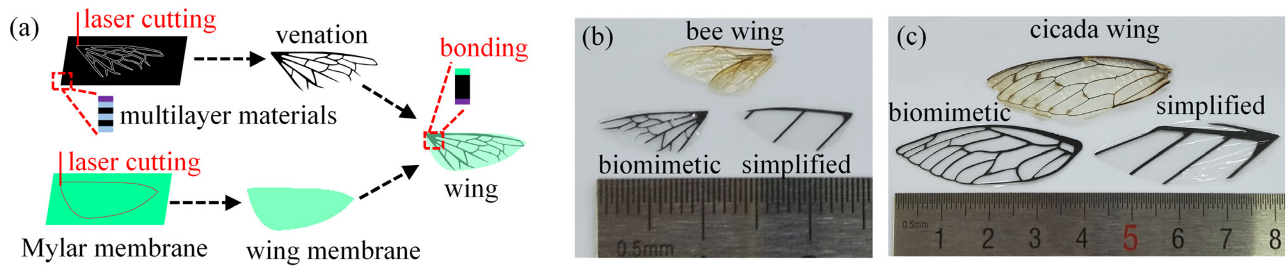

Figure 1: (a) The artificial insect wing consists of two parts: wing venation and wing membrane. Laser cutting technique is used to cut carbon fiber-based multilayer materials as the wing venation and thin Mylar as the wing membrane. The two parts are then bonded to complete the fabrication process. (b) and (c) Photos of the artificial wings with simplified (bottom-right corner) and biomimetic (bottom-left corner) wing venation in comparison with the real bee and cicada wing, respectively.

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FABRICATION

Figure 1a presents schematic diagram of the fabrication method. The artificial insect wing consists of two major parts: wing venation and wing membrane. The wing venation is cut into designed topology from carbon fiber based multilayer structures by using high precision laser cutting technique. The same technique is used to cut wing membrane from thin Mylar. The two parts are then bonded to complete the fabrication process.

Figure 1b and Figure 1c show the artificial bee and cicada wings, respectively, with biomimetic venation (bottom-left corner) as compared with the real insect wings to demonstrate similar morphology including wing shape and venation pattern. In this investigation, artificial wings with simplified venation are also fabricated by the same method (bottom-right corner) as control group.

Before fabrication process begins, the laser cutting path is determined based on the photograph of real insect wings. Figure 2a illustrates the detailed fabrication process of the artificial insect wings. (1) A unidirectional carbon fiber sheet (30μm-thick) is glued to the substrate (wax paper) by epoxy resin. (2) Another layer of unidirectional carbon fiber sheet (30μm-thick) is glued to the first layer of carbon fiber sheet with a certain angle. The angle between the two carbon fiber layers is based on the main supporting veins in the real insect wings. Then a layer of isotropic tinfoil (11μm-thick) is glued to the carbon fiber layers as the top layer. (3) Wing venation is cut by the computer-controlled laser cutting technique. (4) The superfluous materials around the venation are removed and the wing venation is released from the substrate and turned over. Since the substrate surface (wax paper) is nonstick, the thin epoxy resin layer is coated to the carbon fiber layer. (5) The wing membrane (2.5μm-thick Mylar) is cut by the laser cutting technique. (6) The wing membrane is glued to the venation through a thin layer of epoxy resin. (7) The semi-finished artificial insect wing is cured under 80ºC for 120 minutes. The epoxy resin solidifies in high temperature to form a strong bonding of different layers. (8) The finished artificial insect wing is released from the substrate.

For artificial wing with simplified wing venation, only two layers of carbon fiber sheets are used as strengthening material for the wing venation (Figure 2b).

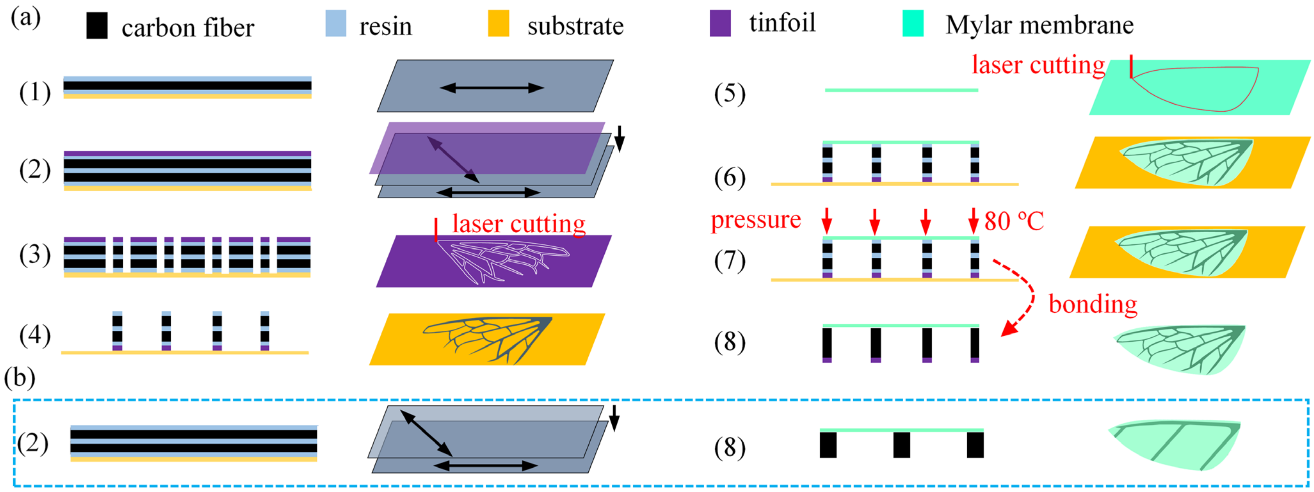

Figure 2: (a) The detailed fabrication process flow of the artificial wing by using two layers of carbon fiber and a layer of tinfoil as wing venation. (b) The method to make artificial wing with simplified wing venation by using two layers of carbon fiber as the wing venation.

For the artificial insect wings, the venation serves as supporting structure which determines the stiffness of the whole structure. The difficulty in fabrication process is the one-time forming of the complex wing venation pattern and its structural strength to sustain aerodynamic load. Since the carbon fibers in the unidirectional carbon fiber sheet serves as strengthening material only in one direction while the distribution of veins in wing venation is reticular. When the whole venation is cut from a single layer of carbon fiber sheet, the joint sections of different veins will be too fragile to sustain aerodynamic load. To avoid this problem, the conventional method [8] is to cut the wing venation as several parts separately and then piece them together manually. However, this method is only suit for artificial insect wings with simplified venation and the processing precision is affected by manual assembling.

In this investigation, multilayer structure is adopted for wing venation to guarantee structural strength of the artificial insect wings. Figure 3a and 3b show SEM photos of a section of the simplified wing venation and the enlarged view of both horizontal and diagonal directions strengthened by carbon fibers. For artificial insect wings with biomimetic wing venation, a layer of isotropic strengthening tinfoil is added to the carbon fiber layers considering the multiple directions of the veins in wing venation. Besides, since the wing venation is cut from the multilayer structure as a whole, manual assembling of venation is not included in the fabrication process, which improves the processing precision and efficiency.

It is noted that during the curing process, different layers deform in different direction, which results in warpage of the wing surface as shown in Figure 3c (top-right corner). To prevent warpage, an additional weight is put on the wing surface to restrain the free deformation of each layer. Besides, the heating temperature and time are also critical in the curing process. The heating temperature should be relative low to slow down the deformation rate and the heating time should be long enough to ensure all the epoxy resin are solidified.

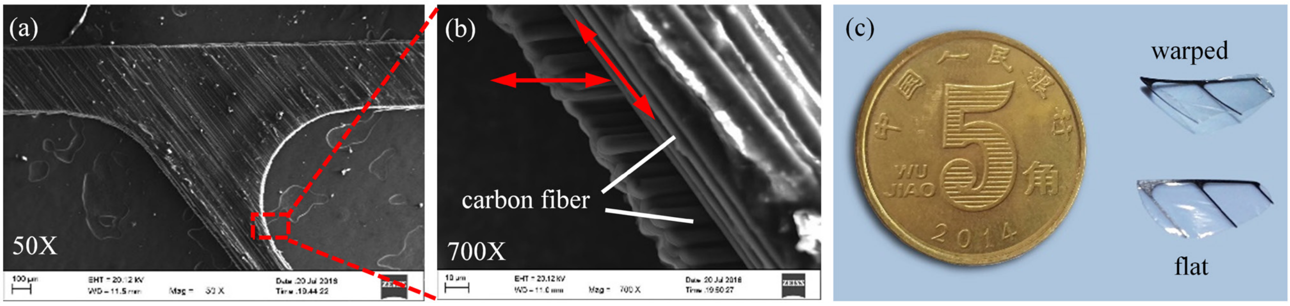

Figure 3: (a) SEM photo of a section of the wing venation. (b) Enlarged view of the venation as strengthened in both horizontal and diagonal directions by carbon fibers. (c) Warped and flat artificial insect wings beside a 50-cent coin.

BIOMIMETIC STIFFNESS

During insect's flapping flight, insect wings deforms to achieve maximum lift force. The flexibility of insect wings is mainly determined by its stiffness. To investigate the stiffness of the artificial wings, one practical approach is to measure its natural frequency (or resonant frequency) as the structural stiffness can be given by:

$$k = 4m\pi^2 f^2 \tag{1}$$

Where k is wing stiffness; m is wing mass and f is fundamental natural frequency.

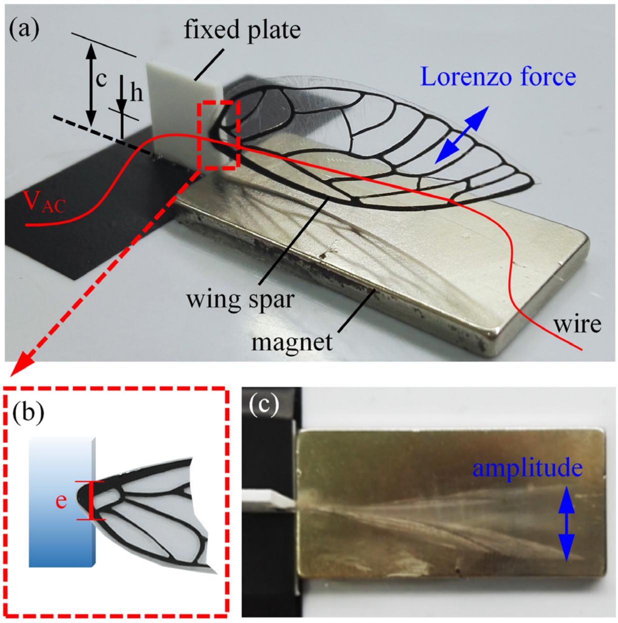

Figure 4: (a) The schematic diagram of the setup to measure the natural frequency of the wings. (b) Enlarged view of the chord width where the wing is glued to the fixed plate. (c) Photo of the artificial wing with large vibration amplitude under resonant state.

Considering the wing mass is in milligram grade, conventional testing techniques such as contact exciting system is no longer applicable. In this investigation, we designed a non-contact exciting system to measure the fundamental natural frequency of wings with different sizes. As shown in Figure 4a, a conductive wire is attached to the wing surface with a distance "h" to the wing spar and the wing is placed in a steady magnetic field. When frequency of the AC current matches the wing's natural frequency, the wing is excited into resonance by Lorenzo force with large amplitude (Figure 4c). In this vibration system, the conductive wire is made of Si-Al alloy with diameter of 20 micrometers and its mass (0.007mg for bee wing and 0.02mg for cicada wing) added to the wing surface is negligible compared with the wing mass.

It is noted that the wing and the fixed plate form a cantilever system. The natural frequency of the wing is largely affected by the chord width ("e") where the wing is glued to the fixed plate (Figure 4b). For each type of wings (bee wing or cicada wing), "e" is kept as a constant.

Table 1 gives the natural frequency of the artificial cicada wings when the conductive wire is attached to different location of the wing surface. The test results vary little with different values of "h/c", which validates that the natural frequency is not related to excitation point.

Table 1: Natural frequency of artificial cicada wings with different locations of conductive wire.

Wing types	**Frequency** (Hz)		
	h=0.25c	h=0.5c	h=0.75c
Simplified	99.2	99.4	99.7
Biomimetic	105.6	104.5	104.2

Table 2: Mass, natural frequency and stiffness of artificial cicada wings with different wing spar.

Wing spar thickness	**mass** (mg)	**frequency** (Hz)	**stiffness** (N/m)
71μm	13.2	30.4	0.48
122μm	15.4	105.4	6.75
231μm	20.4	146.9	17.38
Real cicada wing	15.2	135.2	10.09

In real cicada wings, the wing spar is much stronger than other veins in the venation. To ensure the stiffness of artificial cicada wing is close to that of its nature counterpart, the key is to change the thickness of the wing spar. After wing mass and natural frequency being obtained by experiments, the stiffness can be calculated by equation (1). Table 2 gives the basic parameters of the artificial cicada wings (biomimetic) with different thickness of wing spar. The test results show that the stiffness of the artificial wings can be easily adjusted by changing the thickness of the supporting venation.

To demonstrate the versatility of the presented fabrication method, natural frequency of different bee wings are also tested. Figure 5 shows the amplitude versus driving frequency with respect to different types of wings under a voltage of 2.4V. Since the basic principle of the vibration system is forced vibration, the maximum flapping amplitude occurs when driving frequency matches the wing's natural frequency. Table 3 gives the mass, natural frequency and stiffness of different types of wings. With wing mass and natural frequency close to that of real insect wings, the calculated stiffness of the biomimetic wings are also close to that of real insect wings (2.32N/m for biomimetic bee wing and 6.75 N/m for biomimetic cicada wing; 2.01N/m for real bee wing and 10.9N/m for real cicada wing, respectively).

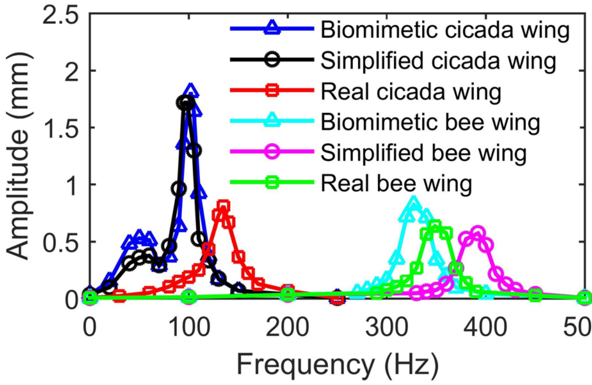

Figure 5: Vibration amplitude versus driving frequency with respect to different wings.

Table 3: Basic parameters of different types of wings.

Wing	**Type**	**Mass** (mg)	**Frequency** (Hz)	**Stiffness** (N/m)
Bee	Biomimetic	0.55	327.2	2.32
	Simplified	0.51	392.1	3.09
	Real	0.42	348.5	2.01
Cicada	Biomimetic	15.4	105.4	6.75
	Simplified	10.8	98.6	4.14
	Real	15.2	135.5	10.90

CONCLUSION

This paper presents both fabrication and characterization methodologies for artificial insect wings with biomimetic morphology and stiffness using laser cutting and bonding of multilayer materials. Different wing venation pattern and wing size are well achieved, which demonstrates the versatility of the fabrication method. The stiffness of the artificial insect wings can be easily adjusted by changing the thickness of the wing venation. With wing mass and natural frequency close to that of real insect wings, the stiffness of the biomimetic wings are also close to that of real insect wings. Future work aims at the aerodynamic performance evaluation on the artificial insect wings.

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REFERENCES

[1] Sims T W, Palazotto A N and Norris A, "A Structural Dynamic Analysis of a Manduca Sexta Forewing", *Int J Micro Air Veh.*, vol. 2, pp. 119-140, 2010.

[2] Young J, Walker S M, Bomphrey R J, et al, "Details of insect wing design and deformation enhance aerodynamic function and flight efficiency", *Science*, vol. 325, pp. 1549-1552, 2009.

[3] Combes S A and Daniel T L, "Flexural stiffness in insect wings I. Scaling and the influence of wing venation", *J. Exp. Biol.*, vol. 206, pp. 2979-2987, 2003.

[4] Shang J K, Combes S A, Finio B M, et al, "Artificial insect wings of diverse morphology for flapping-wing micro air vehicles", *Bioinspir Biomim.*, vol. 4, pp. 955-970, 2009.

[5] Tanaka H, Matsumoto K and Shimoyama I, "Fabrication of a three-dimensional insect-wing model by micromolding of thermosetting resin with a thin elastmeric mold", *J. Micromech. Microeng.*, vol. 17, pp. 2485-2490, 2007.

[6] Tanaka H and Wood R J, "Fabrication of corrugated artificial insect wings using laser micromachined molds", *J. Micromech. Microeng.*, vol. 20, pp. 75008-75015, 2010.

[7] Pornsin-Sirirak T N, Tai Y C, Nassef H, et al, "Titanium-alloy MEMS wing technology for a micro aerial vehicle application", *Sens. Actuators A, Phys.*, vol. 89, pp. 95-103, 2001.

[8] Wood R J, "Design, fabrication, and analysis of a 3DOF, 3cm flapping-wing MAV", in *Proc. IEEE/RSJ Int. Conf. IROS*, 2007, pp. 1576-1581.

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