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Design and mechanical analysis of a 3D-printed biodegradable biomimetic micro air vehicle wing

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Abstract. The biomimetic micro air vehicles (BMAV) are unmanned, micro-scaled aircraft that are bio-inspired from flying organisms to achieve the lift and thrust by flapping their wings. There are still many technological challenges involved with designing the BMAV. One of these is designing the ultra-lightweight materials and structures for the wings that have enough mechanical strength to withstand continuous flapping at high frequencies. Insects achieve this by having chitin-based, wing frame structures that encompass a thin, film membrane. The main objectives of this study are to design a biodegradable BMAV wing (inspired from the dragonfly) and analyze its mechanical properties. The dragonfly-like wing frame structure was bio-mimicked and fabricated using a 3D printer. A chitosan nanocomposite film membrane was applied to the BMAV wing frames through casting method. Its mechanical performance was analyzed using universal testing machine (UTM). This analysis indicates that the tensile strength and Young's modulus of the wing with a membrane is nearly double that of the wing without a membrane, which allow higher wing beat frequencies and deflections that in turn enable a greater lifting performance.

1. Introduction

Bionic or biomimetic relates to the creation of artificial structures inspired by those found in nature [1]. This multi-dimensional observational information includes a wide assortment of fields, such as biology, physics, chemistry, mathematics, material science and also biomechanics. Biomimetic micro air vehicle (BMAV) is a micro-scaled aircraft that mimics the flapping wing movement of insects [2]. Dragonflies are highly agile flyers [3, 4] and they are capable of migrating across oceans, moving in any direction and suddenly changing course. They also can hover and accelerate quickly from a dead stop as well as from a hovering attitude. Their non-planar dynamic wings are long and narrow, and significantly larger than their body. The wings possess high power/weight ratio and exhibit excellent functional characteristics through the coupling and synergy of material, configuration and structure. In addition, the grooves in the wing hold an airfoil of air around it, which brings down the friction. The wings rotate around several axes, responding both to muscle actions and inertia effects. Dragonflies can have different flight maneuvers such as gliding, taking off, hovering and flapping. The wings enable the dragonflies to perform a very smooth and stable flight with a considerable agility. Indeed, they are one of the quickest and most agile flying insects in the living world. Dragonflies have one of the most interesting wing structures and remarkable features of nature in the science of engineering design. Both the micro and macro structures of dragonfly wings play a significant role in their performance, and this is the reason numerous researchers have attempted to concentrate on the impact of these parameters on wing controllability and efficiency.

The structural characteristics possessed by dragonfly wings provide a biological inspiration for the investigation and development of flapping-wing micro air vehicles. A study conducted by Chen *et al.*[5] reported that a dragonfly can accelerate at 4G (G-force) linearly and 9G in sharp turns while pursuing prey. Sunada *et al.*[6] and Dickinson *et al.* [7] revealed that the motion of dragonfly wing is controlled by the wing root muscle only, which is easier to mimic in a BMAV than the wing motions used by other insects. These qualities make dragonfly a preferred candidate to be bio-mimicked in a BMAV. BMAVs are typically imagined for use on military and civil missions, which have a limited duration, including police or military surveillance, indoor video mapping and remote sensing of hazard sites. The artificial wings of BMAV must be strong enough and flexible to tolerate the different forces created by flapping motion closely similar to a real insect. The main types of deformation that the wings experience during flight are twisting and bending, and these wings will have to be able to cope with the forces that operate on its surface. Several fabrication procedures for small insect artificial wings have been suggested. The microelectromechanical systems (MEMS) photolithography and etching method has been presented by Pornsinsirirak *et al.*, in which the membrane and vein of the wing are fabricated using parylene-C and titanium alloy (Grade 5), respectively [8]. Akin *et al.* presented non-natural wings that mimic the main venation structure of a beetle using thin Kapton film for the membrane and pre-impregnated carbon/epoxy fiber for the framing structure [9]. Meanwhile, Bao *et al.* described the design and micro-machining of the three-dimensional BMAV wing from stainless steel (SU-8) material using microelectromechanical system (MEMS) lithography [10]. Very limited articles have been written about the BMAV wing frame structures that encrust the membrane.

Earlier studies have demonstrated that insect's wings are one of the best samples of design integrity [2, 11-13] because they are super lightweight composite structures with complex shapes at both the micro and macro stages. The utilization of lightweight structural materials is essential in numerous applications such as biomedical applications, ground vehicles, aircraft and packaging to enhance its efficiency and cost [14]. Recent studies on biomimetic air vehicles (BMAV), which are taken as a kind of micro-scaled flapping winged aircraft that imitate the flapping wing movement of birds, bats or insects [15], have interested scientists to search for high efficiency lightweight materials. Nowadays, the researchers are studying about technologies in determining flying patterns of a group of BMAV [16]. Accordingly, the BMAV must be mass-produced using reasonable materials for executed in a cost effective manner. In addition, due to the range and power limitations, missions may be performed one-way, with no intention to return the BMAV to its original launch point [17]. These requirements lead to the need for BMAV to be fabricated from bio-degradable materials (similar to insects). The wing structure and membrane is generally the largest part of the BMAV design. Therefore, there is much interest in fabricating lightweight biodegradable wings.

2. Methodology

2.1. Material

PLA(Polylactic acid) is one of the two most commonly used 3D printing materials (with the other being ABS). This biodegradable material has the virtue of being odorless and does not warp significantly like the other 3D printing materials. Due to its low melting point, using PLA as a 3D printing material does not require a heated bed. 3D printer can be used to fabricate complex structures. MakerBot Replicator 2X experimental 3D printer that was used in this study was purchased from Makerbot (Brooklyn, USA). Grey PLA printing filament was purchased from MyDuino and used as received. CAD designs were drawn and visualized in Solidworks Software and transferred to 3D printable format using the Makerbot Desktop Software supplied with the Makerbot Replicator 2X.

2.2. CAD design and manufacturing method

Dragonfly wings have a very complex and fine structure, which is hard to replicate. Sivasankaran *et al.* used the Canny edge detection method on digital images of dragonfly fore and hind wings, and the spatial network analysis method to create simplified model from the detailed model [18]. They demonstrated that the spatial network analysis is a suitable approach to simplify a complicated insect wing structure such as dragonfly. This simplified dragonfly wing (for use on a BMAV) was modelled using Solidworks computer aided design (CAD) software and transferred into a 3D printer compatible file. A MakerBot Replicator 2X experimental 3D printer was configured to "fine printing method" for this research since the sample size was approximately 8 cm with a thickness of 0.5 mm. Both fore and hind wings were fabricated using bio-based Polylactic Acid (PLA). Figure 1 shows the 3D model of a simplified dragonfly wing structure and Figure 2 presents the fabricated dragonfly wing model.

Lin *et al.* studied the potential of utilizing 3D printing technologies to fabricate bio-inspired shapes and they had successfully fabricated 3D printed polymer based bio-inspired shapes [19]. It was mentioned that geometrically structured shapes and designs occurred naturally for a reason and they possessed enhanced mechanical properties and provided inspiration for materials design. Kao *et al.* fabricated PLA-based scaffolds for bone tissue engineering using 3D printing technique [20]. They fabricated high-resolution scaffolds that were comparable to readily available scaffolds by utilizing the advantages of PLA. In addition, Stansbury and Idacavage reviewed the possibilities of 3D printing method to be expanded into a conventional production method for polymers [21]. They mentioned that 3D printing technologies had already altered many industrial and academic operations with their robustness and simplicity in fabrication of any design without requiring molds or dies. Therefore, it will be interesting to study the possibilities of producing a 3D printed the PLA-based wing structure and evaluate its performance.

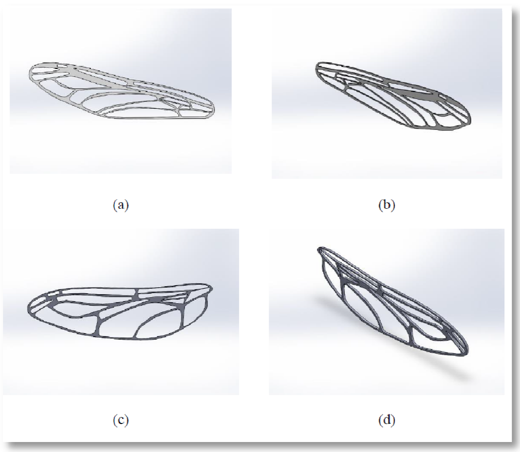

Figure 1. 3D CAD design of dragon wing: (a) Top view of fore wing, (b) Iso view of fore wing, (c) Top view of hind wing, (d) Iso view of hind wing

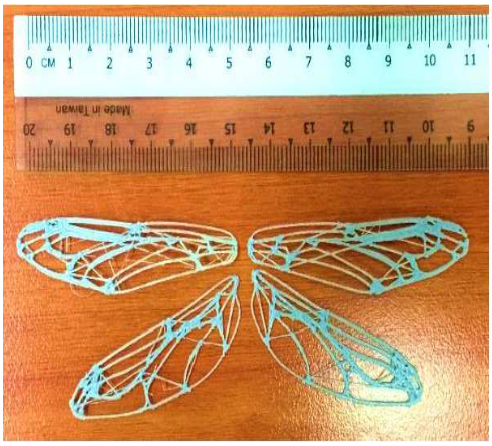

Figure 2. Fabricated dragonfly wing

2.3. Membrane
The dragonfly's wing membrane is primarily composed of chitin. Although chitin is naturally available in large quantities, it is underutilized in commercial applications due to its insolubility in common organic solvents and its intractable bulk structure. Chitosan was examined to solve these problems. Chitosan is a biodegradable and biocompatible natural polysaccharide composed of linear polysaccharide 1,4 -linked 2-amino-deoxy-b-D-glucan [22]. Once the wing structure was printed out, the exposed top surface layer required sanding to remove jagged material remains on the structure. The structures were then submerged in one of the selected chitosan nanocomposite film solutions in a Petri dish. A drying time of 48 hours was required. Specification of the wings is listed in Table 1 and Figure 3 depicts the complete design process.

2.4. UTM machine parameter setting
Mechanical properties were analysed for all composite material samples by using the Shimadzu AGS-X series tensile tester machine according to the ASTM D638-14 method (i.e. standard test method for tensile properties of plastic). A low capacity load cell was used to increase the sensitivity of the break due to the wing structure thickness. The wing structures were pre-conditioned in a dry cabinet 48 hours before the testing was conducted. A crosshead speed of 5 mm/min was used for each test. Figure 4 illustrates the experiment setup.

Table 1. Specification of wing structure

Specification	Fore wing	Hind wing
Base width (mm)	7.00	8.50
Centre width (mm)	12.50	14.40
Tip width (mm)	7.23	8.50
Length (mm)	56.00	48.00
Mass without membrane (g)	0.12	0.08
Mass with membrane (g)	0.18	0.15

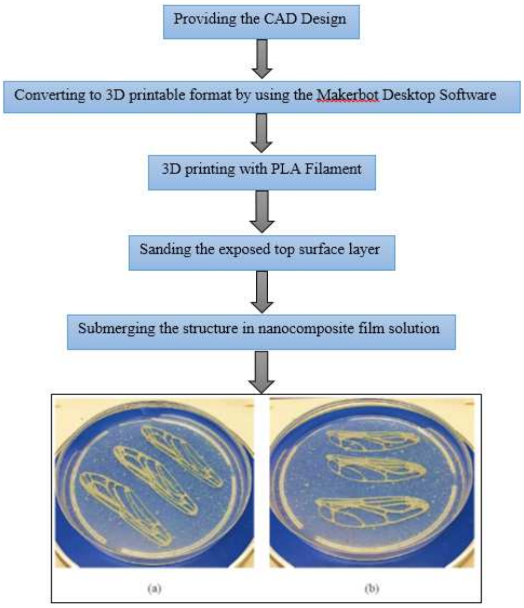

Figure 3. Design process: (a) Forewing, (b) Hindwing

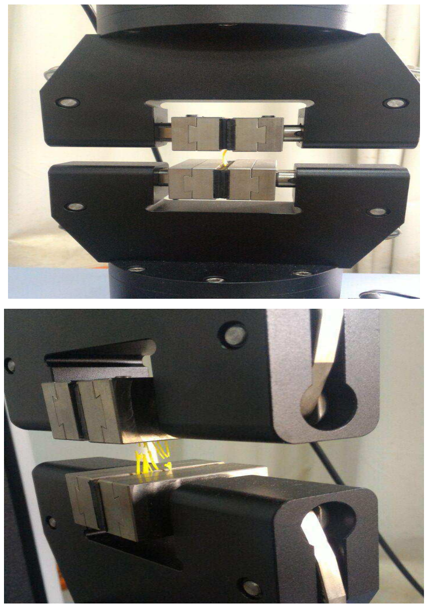

Figure 4. Experimental setup

According to the principle of tensile testing, the material strain, ε can be taken as:

$$\varepsilon = \frac{\Delta L}{L_0} \tag{1}$$

where ΔL is the increase of length in the tensile force direction and L_0 is the original sample gauge length. Correspondingly, the material stress, σ can be calculated as follows:

$$\sigma = \frac{F}{A_0} \tag{2}$$

where F is the tensile force applied on the sample and A_0 is the cross-sectional area of the sample. By employing Hooke's law, the Young's modulus, E of the material is:

$$E = \frac{\sigma}{\varepsilon} \tag{3}$$

Due to the nonlinear mechanical characteristics of biomaterials, the elastic force and the deformation do not exhibit a clearly defined elastic limit. Therefore, the offset method was used to compensate errors. The value of 0.02% was set off on the extension axis and a line was drawn parallel to the straight-line portion of the loading curve. By this principle, tensile strength, Young's modulus and elongation at the break were calculated. At least three samples were tested for each wing structure.

3. Result and discussion

All samples of the PLA fore wing and hind wing, with and without membrane, were tested and analyzed. The forewing PLA sample without membrane exhibited tensile strength of 3.25 MPa as shown by Figure 4a. Addition of the nanocomposite film as membrane increased the tensile strength to 6.280 MPa as illustrated by Figure 5a. A similar trend can be seen for the hindwing PLA sample without membrane, which obtained the lowest tensile strength of 2.96 MPa, and the value was increased to 4.89 MPa after adding the membrane to the wing structure as shown by Figure 5b. On the other hand, for the Young's Modulus as depicted by Figure 5c, PLA forewing without membrane recorded the lowest stiffness of 134.90 MPa and it was significantly increased up to 334.51 MPa with the addition of the membrane. As the Figure 5d displayed, the PLA hindwing stiffness was equal to 158.95 MPa and, as expected, a considerable raise up to 223.64 MPa was achieved by adding the membrane. All in all, addition of nanocomposite membrane increases the tensile strength and Young's modulus of the samples. The increment of tensile strength could be linked to the formation of more stable network due to the attractive interactions between the wing structure and the nanocomposite film. The compaction of this network also leads to increase in stiffness.

4. Conclusion

Biomimetic structures and designs are always exciting as they are imitation of the living surroundings. In this work, a biodegradable dragonfly inspired wings (forewing and hindwing) for BMAV application were designed using Solidworks software. 3D geometric PLA wing samples were printed using the Makerbot 3D printer. Constructing the wings using 3-D printer method had expedited the design fabrication period as it took less than 15 minutes. Therefore, several wings could be printed per day for testing purposes and ultimately for developing a BMAV. The printed wings were then casted with nanocomposite membrane. The mechanical test performed yielded a greater tensile strength and stiffness for the reinforced wings samples with the membrane, which would permit higher wing beat frequencies and deflections that in turn allowed greater lifting performance.

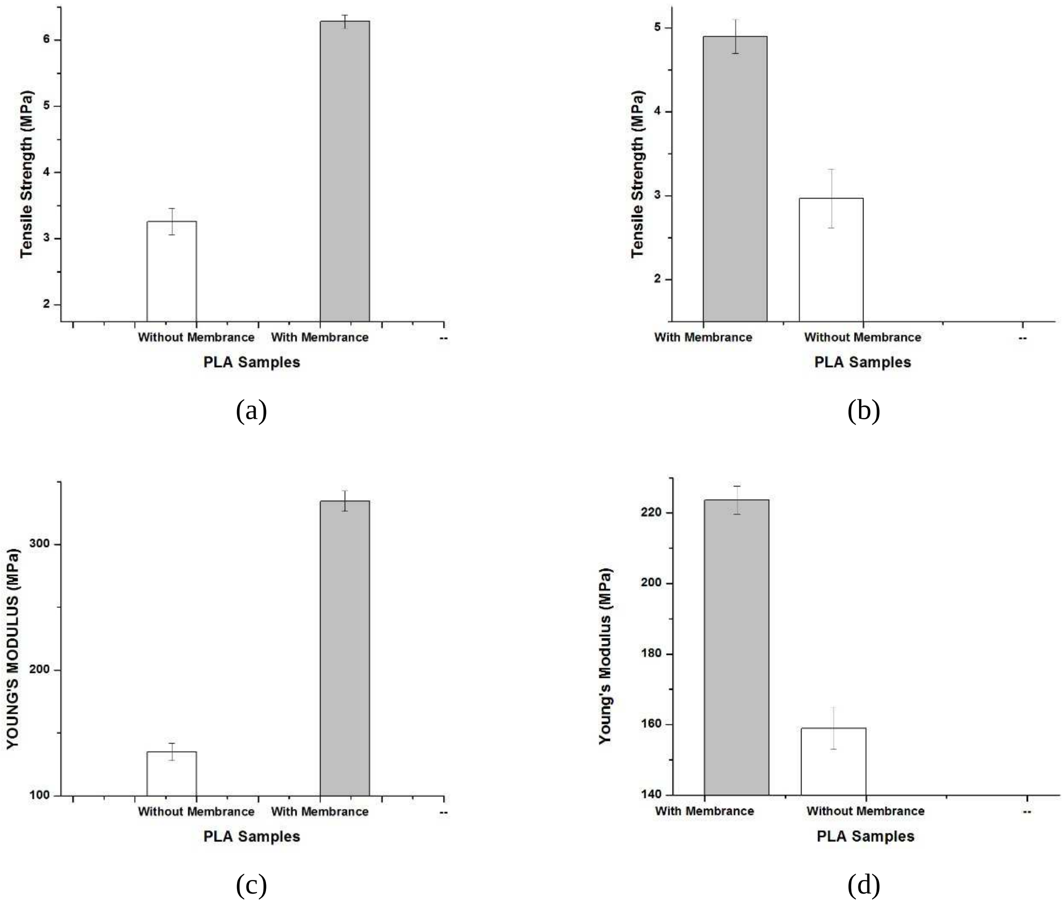

Figure 5. Average mechanical properties of PLA wing structure: (a) tensile strength of forewing, (b) tensile strength of hindwing, (c) Young's Modulus of forewing, (d) Young's Modulus of hindwing

Acknowledgments

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