Chinese Journal of Aeronautics, (2016), **29**(2): 411–423

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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Static strength analysis of dragonfly inspired wings for biomimetic micro aerial vehicles

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Received 8 July 2015; revised 30 October 2015; accepted 5 December 2015
Available online 23 February 2016

KEYWORDS

Biomimetic micro aerial vehicle;
Carbon fiber;
Finite element analysis;
Glass fiber;
Wing membrane;
Wing structure

Abstract This article examines the suitability of fabricating artificial, dragonfly-like, wing frames from materials that are commonly used in unmanned aircraft (balsa wood, black graphite carbon fiber and red prepreg fiberglass). Wing frames made with Type 321 stainless steel are also examined for comparison. The purpose of these wings is for future use in biomimetic micro aerial vehicles (BMAV). BMAV are a new class of unmanned micro-sized aerial vehicles that mimic flying biological organisms (like flying insects). Insects, such as dragonflies, possess corrugated and complex vein structures that are difficult to mimic. Simplified dragonfly-like wing frames were fabricated from these materials and then a nano-composite film was adhered to them, which mimics the membrane of an actual dragonfly. Finite element analysis simulations were also performed and compared to experimental results. The results showed good agreement (less than 10% difference for all cases). Analysis of these results shows that stainless steel is a poor choice for this wing configuration, primarily because of the aggressive oxidation observed. Steel, as well as balsa wood, also lacks flexibility. In comparison, black graphite carbon fiber and red prepreg fiberglass offer some structural advantages, making them more suitable for consideration in future BMAV applications.

1. Introduction

A biomimetic micro aerial vehicle (BMAV) is a type of micro-scaled aircraft that mimics the flapping wing motion of insects or small birds (e.g. hummingbirds). The additional lift gained by rapidly oscillating its wings, allows BMAV to attain lift with a very small wing surface area. This also allows them to be highly agile. The US Defense Advanced Research Projects Agency (DARPA) released a Broad Agency Announcement (BAA 97-29) in 1997, defining micro aerial vehicles to be less than 15 cm in any dimension. Later in 2005, DARPA defined nano aerial vehicles (BAA 06-06) as being no larger than 7.5 cm or heavier than 10 g (carrying a 2 g payload). The primary payloads envisioned for a BMAV are ultra-lightweight, compact electronic and surveillance detection equipment. Their miniature size makes them difficult to detect, easy to quickly deploy by a single operator, relatively inexpensive to

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Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2016.02.007
1000-9361

fabricate, and allows the potential to fly them inside buildings or compact spaces. BMAVs are envisioned for use on civil and military missions that are of a limited duration, such as remote sensing of hazard sites (e.g. chemical spill, radiation, high voltage power lines, etc.), indoor video mapping, and police or military surveillance.

Like the wings of a flying insect, the artificial wings of BMAV must be flexible but strong enough to endure the aerodynamic forces produced by flapping motion. During flight, the wings undergo significant bending and twisting deformations that can alter the direction and magnitude of the aerodynamic forces generated.[1–5] Several fabrication methods for small insect-scale artificial wings have been proposed. Pornsin-sirirak et al. presented the first microelectromechanical systems (MEMS) photolithography and etching method, in which the vein and membrane of the wing are fabricated using a titanium alloy (Grade 5) and parylene-C, respectively.[6] Combes and Daniel measured the wing flexibility of several insects and found that the spanwise flexural stiffness was one to two orders of magnitude larger than the chordwise flexural stiffness.[2] The scope of their investigation is limited due to the diversity in venation as well as the complex cross-sectional and planform geometries of the insect wings. In contrast, the morphology and materials of artificial wings can be manipulated to understand the effect of these properties on wing flexibility. Tanaka and Wood investigated the effects of flexural and torsional wing flexibilities on lift generation in hoverfly flight using an insect-scaled mechanical model of an artificial wing.[7] Phan et al. created artificial wings that mimic the main venation structure of a beetle using prepreg carbon/epoxy fiber for the framing structure and thin Kapton film for the membrane.[8] Bao et al. describes the design and micromachining of a three-dimensional BMAV wing from SU-8 material using MEMS lithography.[9] Truong et al. created an artificial foldable wing that mimics the rotational motion of a beetle's wing base using a four-bar linkage system.[10] Kumar et al. created an artificial flapping wing inspired by a hummingbird. The wing frame was fabricated from carbon fiber and a polyethylene film was laminated on this to form the wing membrane.[11] Ko et al. presented a micro and nano-fabrication process that mimics a realistic beetle (*Atlas Dichotoma*) wing having the vein–membrane structure with an anti-wetting (hydrophobic) function. A vein structure made up of titanium-alloy was constructed. A Teflon membrane was designed using a centrifugal spinning process and "nanopillar forests" (like those on the surface of leaves and insect wings) were generated using a closely monitored ion treatment. The duration of ion treatment controlled the nanopillar pattern, which affected the hydrophobic characteristics of the wing created. Heat treatment was done to create superhydrophobic characteristics, bio-mimicking an actual beetle.[12] Cho et al., replicated the surface nano-structure of a dragonfly wing, which has an important role in its hydrophobic characteristics. The nano-structure on a dragonfly's wing consists of an array of nano-sized pillars (100 nm in diameter). Various substrates were used: silicon, glass, curved acrylic polymer and flexible polyethylene terephthalate (PET) film. The nano-structure was replicated using ultraviolet curable nano-imprint lithography (NIL) and polydimethylsiloxane (PDMS) molding. The hydrophobicity was measured by water-based contact angle measurements. The water contact angle of the replica made of cured polymer was 135° ± 2°, which was slightly lower than that of the original dragonfly's wing (145° ± 2°).[13] As can be seen, most past literature involves wing membrane materials. Very little has been written about the BMAV wing frame structures that encase the membrane.

In this article we describe a novel methodology of fabricating BMAV wings (based on the Diplacodes Bipunctata dragonfly) using three materials that are commonly used in unmanned aircraft structures: balsa wood, black graphite carbon fiber and red prepreg fiberglass. These are compared to wings made from stainless steel (Type 321), which are representative of metals that have a high load bearing capacity. (In contrast, the balsa wood wings represent a lightweight, low load bearing capacity material.)

Actual dragonfly wings consist of a highly complex pattern of vein structures. It is not practical to fabricate a BMAV wing that exactly matches this complex structure. A simplified model of this wing was created using spatial network analysis. This is a method that can be used to simplify a model based on the venation pattern density. This is described in detail in another article written by the authors of this work.[14] The wing membrane was formed by immersing the wing frame structures in a chitosan nano-composite suspension, with chitin whiskers as a physical reinforcement and tannic acid as the crosslinking agent, using the casting evaporation method.[15] After 48 h of solidification a nano-composite film with a thickness of 0.03 mm was created. Finite element analysis was conducted on the simplified models of these wings and compared to tensile and bending test measurements to verify the simulation results.

2. Methodology

2.1. Wing structure overview

Fig. 1 shows a comparison between the detailed vein structure models of the dragonfly wings and their corresponding simplified vein structure models. As Fig. 1 illustrates dragonflies have different forewing and hindwing geometries, so both were considered. As previously described, the simplified models were created using spatial network analysis.[14]

2.2. Fabrication of wing frame structures for experiment

Several geometrically identical wings were fabricated based on the two simplified models. (These models have exactly the same planform dimensions as the actual dragonfly wing.) Although the same nano-composite was used for each wing membrane, the frames were fabricated from four different materials: stainless steel (Type 321), balsa wood, black graphite carbon fiber laminates and red prepreg fiberglass laminates. Three samples of each wing type were tested to determine their tensile strength and bending performance. The mechanical properties of these materials are as stated in Table 1 (Note: the relatively thick stainless steel wing (0.01 m) is due to a fabrication limitation with our laser cutting machine. Attempts to fabricate thinner structures failed because of melting.). The compromise between minimizing the weight and maintaining adequate tensile and bending strengths are critical for BMAV wings.