Aerospace Science and Technology 49 (2016) 259–268

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Spatial network analysis to construct simplified wing structural models for Biomimetic Micro Air Vehicles

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ARTICLE INFO

Article history:
Received 21 January 2015
Received in revised form 27 August 2015
Accepted 6 December 2015
Available online 10 December 2015

Keywords:
Biomimetic Air Vehicle
Dragonfly wing
Canny edge detection
Spatial network analysis
Proximity index

ABSTRACT

A procedure for designing a simplified, dragonfly-like wing model that is suitable for use in a Biomimetic Micro Air Vehicle (BMAV) is presented. BMAV are a relatively new class of micro-scaled unmanned air systems that mimic the flapping wing propulsion system of flying biological organisms (like insects). Many insects (e.g. dragonflies) have complex wing vein and membrane patterns that are too small to fabricate using many types of machine cutting tools (e.g. micro laser cutting). Structural dynamic modification using the spatial network analysis approach is used to create a simplified model. Our objective was to minimize the wing vein patterns so that they were within our fabrication tolerances. Simulations were performed for both the detailed and simplified models. The natural frequency and corresponding mode shapes, modal assurance criterion (MAC) and static bend-twist coupling results were very similar. This analysis shows that a simplified model can be designed and fabricated to closely biomimic a real dragonfly wing.

1. Introduction

Insect flight is an interesting topic of study for aerodynamic researchers, because they are very maneuverable and have high load bearing capacities [1–5]. Their superb flight agility can be largely attributed to their complex wing structure. The wings of a flying insect generally contribute only 1%–2% of the total body mass of an insect [6]. These lightweight wings must be able to flap millions of times throughout an insect's lifespan; while enduring collisions, torsional loads, and many other forms of deformation [7]. Biomimicry of these attributes in an aircraft is highly desired. This has motivated research into a new class of micro-sized unmanned aircraft called Biomimetic Micro Air Vehicles (BMAV). Due to their small size and weight, BMAV would be ideal for flying indoors or in enclosed spaces. Fitted with micro cameras or sensors, they could be used to examine potentially hazardous areas (e.g. toxin spills, high voltage power lines, criminal activities, hostile forces, etc.) without endangering a human pilot [8].

Several researchers have examined different structural aspects of insect wings. This research can be broadly organized into the following categories: building materials [9], the structure or venation pattern [8,10], aerodynamic characteristics [5,11], and wing beat resonance [3,4]. Bushan and Sun [1] made a comprehensive study on the structure and mechanical properties of the dragonfly wings and their effect on flight maneuverability. A cicada wing, with vein and membrane structures, was modeled using an optimized topology structure. Ren et al. [11] conducted a study which examined the effect of a dragonfly's wing structure on its dynamic flight performance. The study created a simulation that modeled the longitudinal veins as a sandwich microstructure. The simulation was able to withstand more torsional deformation than the actual wing, with little effect on its flapping frequency and bending deformation.

Dragonflies (*Odonata*) are of high interest for BMAV researchers due to their agility. They are able to hover or perform many aerial acrobats (e.g. flying forward, backward, upward, and downward), because of the mechanical construction of their wings. They have a highly corrugated wing structure that consists of complex, wing membrane patterns (e.g. quadrilaterals, pentagons and hexagons). Each pattern contributes to the wing's flexibility and stiffness, which determines its ability to withstand deformations. Some research has been conducted to biomimic the wing structure of dragonflies [12,13]. However, none of these works biomimicked the actual wing structures of dragonfly. Although other insect wings (e.g. cicada, beetle, etc.) have been replicated, dragonfly wing structures are very complex making this difficult. Dragonfly wings are highly corrugated in pattern, with differing thickness and tubular structures. Replicating an exact copy is not a practical approach, due to

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http://dx.doi.org/10.1016/j.ast.2015.12.005
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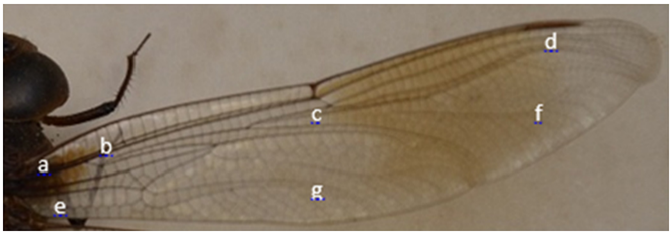


Fig. 1. Main parts of a dragonfly wing. (a) Radial; (b) Costa-leading edge (rectangular pattern throughout) the stiffest pattern of all parts; (c) Nodus (part of the vein which is much thicker than the others, plays a pivotal role in the dissipation and storage of mechanical energy); (d) Pterostigma (behaves as a dampener); (e) Anal margin and supercosta; (f) Small hexagonal patterns which are compactly arranged ranging from 0.0001 to 0.0002 m in size; (g) Large quadrilateral and hexagonal patterns ranging from 0.0002 to 0.0004 m in size.

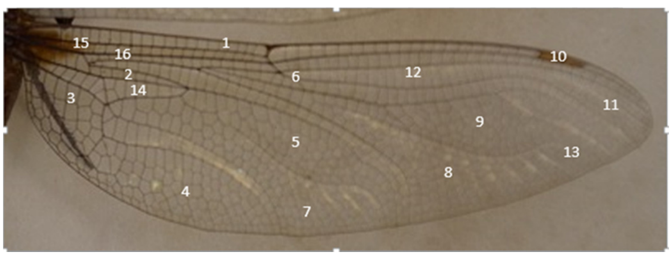


Fig. 2. Wing divided into subsections. (The numbered sections highlight the important regions that should be taken into consideration while creating the simplified model.)

limitations in fabrication methods. So a simplified model is needed that takes these limitations into consideration.

The objective of this paper is to create a simplified structural model of a dragonfly wing, utilizing spatial network analysis. In other words, the aim is to simplify the membrane pattern (as much as possible) while incurring only minimal changes in its structural properties (e.g. bending deformation and natural frequency) compared to an actual dragonfly wing. This simplified model is validated using Autodesk Simulation Multiphysics (2013 version) finite element analysis software. A few different types of aspects were used to validate the model: mode shapes and its corresponding frequency, MAC and static bend-twist coupling analysis. The constraints for this analysis were the natural frequencies assigned (cut-off frequency). The objective was minimization of patterns (regions) which indirectly contributes to the minimization of mass. The flapping frequency (wing beat) of dragonfly wings are 30 Hz, although its natural frequency can range from 120–170 Hz [3,4]. This is a reduction of 25–30% from its natural frequency. The analysis formulation was set to nonlinear for natural frequency and for a reliable analysis the frequency range was set from 0–100 Hz (cut-off frequency). Data from previous referenced work [3,4] was used to confirm the validity of these results. It is envisioned that these simplified models can be used to fabricate a future BMAV wing.

2. Simulation set up

2.1. Wing model overview

The dragonfly species used in this study is called *Diplacodes Bipunctata*. This species has a distinct red discoloration with a wing span and body length of approximately 0.055 m and 0.035 m, respectively. A digital image (resolution 1600 dpi) was taken of this dragonfly using a Nikon D7000 camera (Figs. 1 and 2). Both the fore and hind wings were modeled from this digital image. The image was imported into Matlab and segmented using the Canny edge detection algorithm, resulting in a logical image illustrated with point clouds. This grayscale image was then smoothed with a Gaussian filter to suppress noise. The main vein structures were manually traced out and divided into sections using splines and polygons. The smaller vein structures were then modeled, in a similar way, to match the detailed patterns and densities shown in the logical image. The spatial network analysis method was employed to perform the segmentations. An initial wire frame, two-dimensional scaled model was constructed using Rhinoceros 5.0. This was then exported into AutoCad 2015 to create a three-dimensional solid model (Fig. 3(a) and (b)).

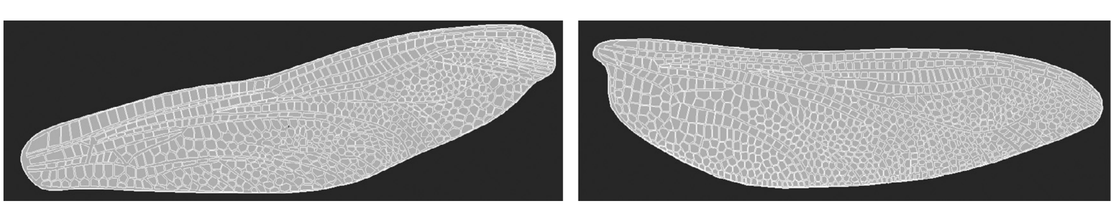
Although there is a difference in thickness across the wing, this difference is small. For example, the vein at the base and the tip of the wing differ by only 2×10^{-6} m [9]. Therefore in order to simplify the model, an average vein and membrane thicknesses of 2.5×10^{-6} m and 3.0×10^{-7} m were used, respectively [3,6,8].

2.2. Canny edge detection algorithm

An edge detection algorithm was required to define the different regions separated by veins in the image of the wing. The Canny edge detection algorithm (available in Matlab) is one of the most popular algorithms, because of its detection of edge at a low error rate. The algorithm runs in five steps which are: 1) use of a Gaussian filter to smooth the image to remove noise; 2) edges are detected where the computed intensity gradients are the largest; 3) local maxima are marked as edges; 4) use double threshold to detect potential edges; 5) track edge via hysterisis whereby final edges are determined by supressing all non-connected edges to a prominent edge.

2.3. Spatial network analysis

A spatial network (sometimes also geometric graph) is a graph in which the vertices or edges are spatial elements associated with geometric objects, which means the nodes are located in a space within a specified unit (e.g. radius or distance). The mathematically simplest realization is a random geometric graph where nodes are uniformally distributed onto a two-dimensional plane [6]. There are various methods of conducting spatial network analysis. Geographical Information Systems (GIS) [14] use this method to explore geographic spatial patterns. Our methodology is similar, but we are applying this algorithm (based on shape, angle and density) to a biological structure (a dragonfly wing). The idea of simplifying a dragonfly wing based on spatial network analysis, was in-



(a) (b)

Fig. 3. (a) Forewing detailed CAD model; (b) Hindwing detailed CAD model.