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The Role of Soft Vein Joints in Dragonfly Flight

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Abstract

Dragonflies are excellent flyers among insects and their flight ability is closely related to the architecture and material properties of their wings. The veins are main structure components of a dragonfly wing, which are found to be connected by resilin with high elasticity at some joints. A three-dimensional (3D) finite element model of dragonfly wing considering the soft vein joints is developed, with some simplifications. Passive deformation under aerodynamic loads and active flapping motion of the wing are both studied. The functions of soft vein joints in dragonfly flight are concluded. In passive deformation, the chordwise flexibility is improved by soft vein joints and the wing is cambered under loads, increasing the action area with air. In active flapping, the wing rigidity in spanwise direction is maintained to achieve the required amplitude. As a result, both the passive deformation and the active control of flapping work well in dragonfly flight. The present study may also inspire the design of biomimetic Flapping Micro Air Vehicles (FMAVs).

Keywords: dragonfly wing, resilin, soft vein joint, bionics and mechanics, flapping micro air vehicles

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1 Introduction

Dragonflies are very impressive flyers with excellent flight skills. During flight, they can produce sufficient aerodynamic forces by flapping the wings frequently. Besides the periodic flapping motions, deformations of the wings also play important roles in aerodynamics. Studies have shown that the wing can deform timely to improve the distribution of aerodynamic forces and acquire high lift in flight[1–5]. Different from birds and bats, there is no muscle in the main part of a dragonfly wing as well as other insect wings. Therefore, or most likely, the deformation of a dragonfly wing is caused passively by flight loads, including the aerodynamic forces induced by air flow and the inertial forces produced by flapping motion[6–9]. This passive mechanism is dominated by the wing structure characteristics and material properties, which helps understanding the insect flight. In addition, it could inspire the design of biomimetic Flapping Micro-Air Vehicles (FMAVs).

Deformations and aerodynamic performances of the dragonfly wing have been concerned in related to structures and materials. The relation between venation patterns and wing flexibilities was studied through measuring dozens species of insect wings[10,11]. The sandwich structure and nanomechanical properties of dragonfly veins are focused on experiments, and their effects on the wing deformation are studied through numerical simulations[12–14]. Corrugations could enhance the wing bending rigidity by increasing the section moment of inertia[15–17]. In aerodynamics, a well-defined cross sectional corrugation was considered to improve the aerodynamic performance of the wing[18–20]. The pterostigma on dragonfly wing works as lumped mass and could suppress flutter by inducing favorable inertial moments during flapping flight[21].

In recent years, a kind of hydrophilic protein named resilin was found at some vein joints in the wings of dragonfly as well as other insects. Vein joints of dragonfly wings were firstly classified as flexible or fused considering the distribution of resilin, which was expected to benefit the wing flexibility[22]. In addition,

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different kinds of vein joints in damselfly wings were experimentally investigated and the distribution was mapped in detail[23]. Later on, the vein joints were classified more specifically considering the amount of resilin on both sides of Odonata wings by means of fluorescence microscopy[24,25]. Although they tried to correlate resilin at vein joints with wing deformation and proposed the probable functions, more specific work is needed for further verifications. Recently, Rajabi *et al*. have investigated the deformations of single joints as well as vein joint combinations using the Finite Element Method (FEM) and found that resilin was beneficial to torsional deformation of the parts[26,27]. However, the effects of soft vein joints and their distribution on the mechanical behaviors of whole dragonfly wing are still unclear, especially the relations to the flight performance. In this paper, a complete model of a dragonfly wing is developed in consideration of soft joints with resilin. Both the deformation of the wing under aerodynamic loads and the active flapping motion are analyzed to study the function of soft vein joints in deformation of a dragonfly wing during flight.

2 Materials and methods

2.1 Finite element model

In this section, the commercial software ABAQUS is employed to develop a 3D finite element model from a dragonfly (*C. servilla*) forewing, as shown in Fig. 1. Membrane and veins are the fundamental structures of the corrugated dragonfly wing. Besides, the pterostigma near the wing tip is taken into consideration since it contributes a lot to the wing inertia.

Geometry parameters of the dragonfly wing are shown in Table 1. The maximum lengths in spanwise and chordwise directions are measured directly. The veins with circular sections are generally classified into three kinds based on their sizes, as they go smaller from proximal end to distal end and from leading edge to trailing edge. As shown in Fig. 1, vein I are the Costa (C), Subcosta (Sc) and Radius (R); vein II are the Media (M), Cubitus (Cu) and Anal veins (A); the remaining small veins in the trailing edge and most other cross veins are the vein III. The membrane is ultrathin and supposed to distribute evenly around the wing model. The wall of pterostigma is dense and much thicker than the adjacent membrane[28].

Wing membrane is modeled by the linear four-node shell element S4R and veins are modeled by the beam element B32. The blood inside a vein is taken into account by adding an equivalent mass to the vein[29,30]. The veins and membrane are idealized as isotropic materials with the Young's modulus being 2.8 GPa and 1.5 GPa respectively[31], and the Poisson ratio being 0.25 for both. The density of the whole wing is taken as 1.2 mg·mm^{-3}[32].

2.2 Modeling the soft vein joints

Vein joints with resilin in a dragonfly wing are considered as the soft vein joints compared with those without resilin in the present study. Two wing models are analyzed to perform a comparative study, in which all vein joints are fused of model I while the soft vein joints are considered of model II. Resilin was first discovered in insects by Weis-Fogh in 1960, the elastic modulus of which is around 0.1 MPa – 3.0 MPa, several orders of magnitude lower than that of the adjacent veins composed of chitin[33]. The significant difference in elastic modulus makes it reasonable to allow relative rotation of the veins at soft joints. As approximation, the corresponding rotational freedom of the vein at soft joints is

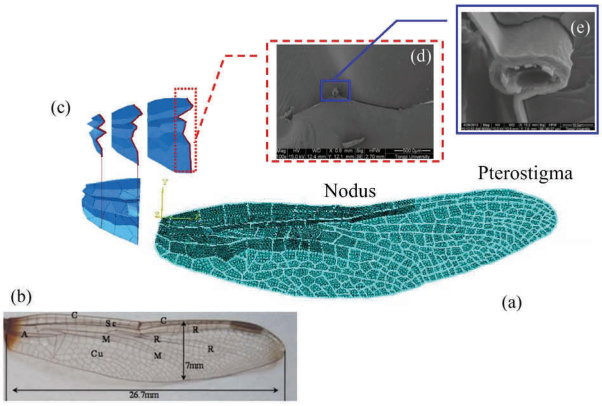

Fig. 1 Finite element model of a forewing (a) developed from the photograph of a dragonfly wing (b) with corrugated wing sections (c, d) and circular vein cross-section (e).

Table 1 Geometry parameters of the right forewing of a *C.servilla*

Geometry parameters	Value (mm)	
Spanwise length	26.7	
Maximum chordwise width	7	
Veins (outer radius/inner radius)	Vein I	0.16/0.11
	Vein II	0.105/0.075
	Vein III	0.045/0.03
Membrane thickness	0.002	
Pterostigma thickness	0.02	