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Effects of blood in veins of dragonfly wing on the vibration characteristics

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ABSTRACT

How the blood in veins of dragonfly wing affects its vibration characteristics is investigated. Based on the experimental results of the wing's morphology and microstructures, including the veins, the membranes and the pterostigma, accurate three-dimensional finite element models of the dragonfly forewing are developed. Considering the blood in veins, the total mass, mass distribution and the moments of inertia of the wing are studied. The natural frequencies/modal shapes are analyzed when the veins are filled with and without blood, respectively. The based natural frequency of the model with blood (189 Hz) is much closer to the experimental result. Relative to bending modal shapes, the torsional ones are affected more significantly by the blood. The results in this article reveal the multi-functions of the blood in dragonfly wings and have important implications for the bionic design of flapping-wing micro air vehicles.

1. Introduction

Dragonflies fly in a highly maneuverable manner with their four flapping wings. They are capable of forward flight, backward flight, hovering, reversing direction instantaneously and accelerating rapidly. During flight, the beating wings accelerate the surrounding air to produce sufficient lift and propulsion [1,2]. Many previous researches focused on the aerodynamic performance of the flapping wings. The high-lift generation [3–7], flight efficiency [8–11] and stability [12,13] of the wings were comprehensively investigated. Both the motion of a wing and its three-dimensional shape contribute to the aerodynamics in flight. The insect wings are mainly passive structures and detailed studies of the structural features are necessary in determining the dynamic responses in the interaction with air. In addition, the understanding of aerodynamics of insect wings in turn facilitates the design of flapping-wing micro air vehicles.

Accounting for only 1–2% of the total body mass, the highly corrugated wings possess a high load-bearing capacity and structure stabilizing function. The pleats vary both along the spanwise direction and chordwise direction, increasing the flexural rigidity throughout the wing [14–18]. Combes and Daniel [19,20] studied the relationship between the venation pattern and the wing flexibility through finite element method (FEM) by calculating the displacement along the wing in response to a point force. Kesel et al. [21] developed several finite element models to study the expenditure of material in constructing the dragonfly wing. The effects of sandwich structure of veins on mechanical properties of dragonfly wing were studied by Wang et al. [22]. Rajabi et al. [23] investigated the microstructural and morphological aspects of dragonfly wings and determined the natural frequencies and mode shapes by FEM.

In almost all the numerical researches, the veins of dragonfly wing were considered as empty tubular structures with nothing inside. In our opinion, however, it is unreasonable, because the blood is not included in these researches. The biologist Arnold [24] introduced the blood circulation in some insect wings systematically and indicated that the veins of dragonfly wings are generally pathways for the blood, the tracheae as well as the nerves. Several distinct flow patterns were distinguished, involving longitudinal veins, cross-veins, and ambient veins. Based on this, the pattern of blood flowing in the right forewing of a *C.servilia Drury* is depicted in Fig. 1. He suggested that there were no major differences among the species or between the fore and hind wings of individuals.

In previous research, Zhao et al. [25,26] took a closer look at the ripple-like surface of the dragonfly veins through Environmental Scanning Electron Microscope (ESEM). They have estimated the mass and the moments of inertia of the anterior vein and found that both of them are increased by about 30% because of the blood inside. The relationship between blood flow rate and the stability of the vein was studied by a rotational elastic tube conveying fluid

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[27]. Besides, Chen et al. [28] investigated the material property of the leading edge vein of the dragonfly wing, and found that the loss of water contents increased the stiffness by approximately 20 times. As the blood may affect both the mass and the stiffness of dragonfly wings, it is predictable that the blood will certainly influence the dynamic behaviors of the wings.

In the present study, we develop more reasonable and realistic 3D model of a dragonfly forewing based on the results observed in experiment. The FEM is applied to simulate the wing models and the blood within the wing is considered. The properties such as mass, mass distribution and moments of inertia are calculated and the natural frequencies/modal shapes are analyzed. To our knowledge, the blood in veins may be the first time to be considered systematically in the analysis of a complete dragonfly wing.

2. Materials and methods

2.1. Experimental methods

The sample used is the right forewing of a *C.servilia Drury* collected in the suburbs of Shanghai. As shown in Fig. 2a and b, both the forewing and hindwing are composed of the membrane and veins. The brown mark of the pterostigma is located on the leading edge near the tip. The span length and the maximum chord width of the forewing are directly measured as 26.4 mm and 7 mm, respectively. The zigzag cross sections are observed for the profiles of the corrugation when the sample is cut into chordwise pieces. Corrugation is pronounced both near the leading edge and the base of the wing. As shown in Fig. 2c, the corrugated section located near the pterostigma is shallow and the leading edge vein has a notable rounded profile. The ESEM is used to investigate the microstructures of the membrane and vein. To avoid any change of the microstructures, the sample is taken off from the living body in a short time. First, the sample is embedded in epoxy and cured at room temperature, after fixed by 2.5% glutaraldehyde and 1% Osmium tetroxide. Then, it is immersed in liquid nitrogen for 1∼2 min to allow the occurrence of brittle fracture. Finally, the sections are coated with gold about 6 nm thick and observed under ESEM.

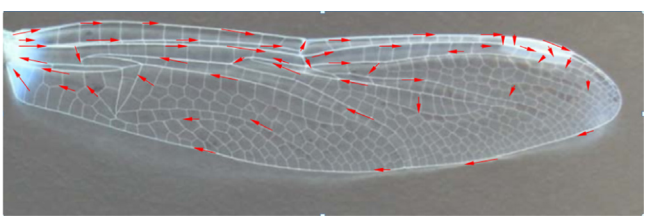

Fig. 1. Patterns of blood circulation in the forewing of *C.servilia Drury*.

There are mainly two types of veins, the longitudinal veins and the cross veins. The longitudinal veins extending from the base to the tip act as girders to stiffen the wing. The cross veins connect the longitudinal ones to keep the structure stability. The thin and transparent membrane is divided into small cells by veins. All of them form a three-dimensional structure of the wing. The veins at different locations are basically tubular structures with wide-ranging sizes (Fig. 2d). The cross-sections are characterized by symmetric annular shapes. The pterostigma is like a box with irregular cross sections. It is connected with the veins in topology and can accept blood from the surrounding veins [24]. The dimensions of both the veins and membranes decrease from the base/leading edge to the tip/trailing edge.

2.2. Material properties

The extremely thin and flexible wing membrane is mainly composed of chitin, which is conducive for membrane to take a variety of deformations during flight. The reticulate veins made of

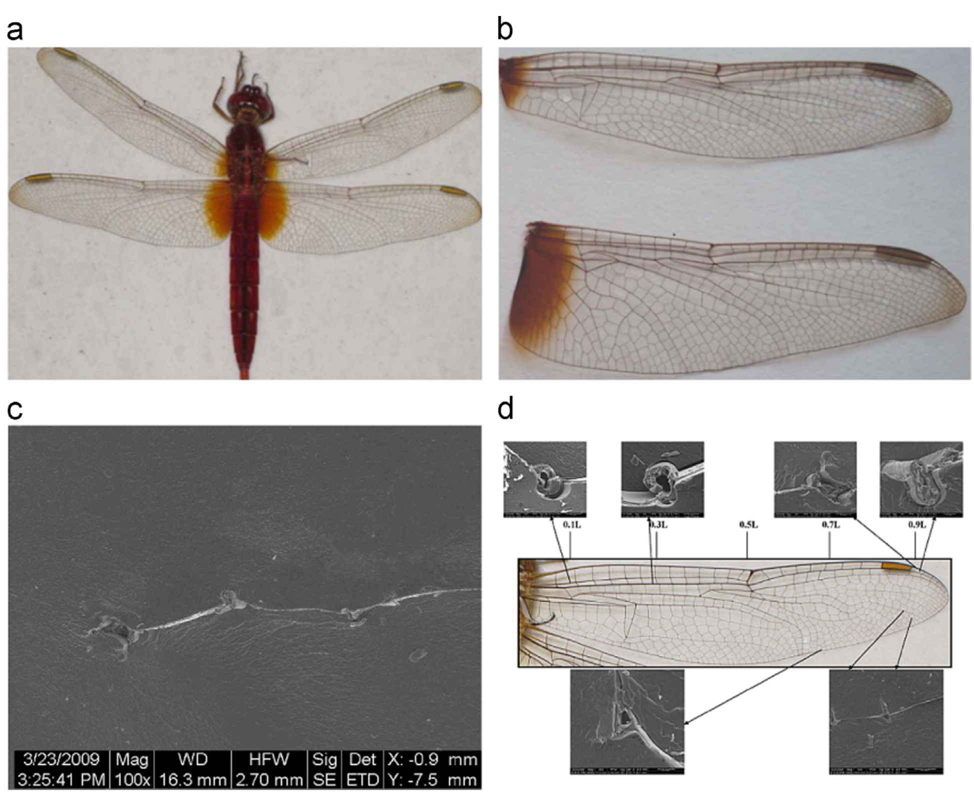

Fig. 2. Morphology and detailed structure features of a dragonfly (*C.servilia Drury*) wings observed by ESEM. (a) The entire living body, (b) the right forewing and hindwing, (c) the zigzag cross section near the pterostigma of the wing, (d) the tubular veins in different locations.