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Stiffness evaluation of the leading edge of the dragonfly wing via laser vibrometer

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Abstract

The material property of the leading edge vein (LEV) of the dragonfly wing is investigated. A new vibration method is developed using laser vibrometer and mini-shaker. The natural frequency of a cantilevered LEV is determined via lateral oscillation. As a result, the elastic modulus of a LEV sample from a dragonfly wing is found to be in the range of the elastic hydrocarbon polymer, while a dead dragonfly is similar to low density polyethylene. The loss of water contents in the veins increases the stiffness of the LEV by approximately 20 times.

Keywords: dragonfly, the leading edge vein, elastic modulus, vibrometer.

1 Introduction

Dragonflies fly in a highly manoeuvrable manner. They are capable of developing fast forward flight, hovering and backward flight. Bionic micro-air-vehicles (MAVs) with such flight capabilities can be used in various applications, including military reconnaissance, search, rescue and so on. In order to mimic the effective dragonfly flight, the bionic model has to be built with similar structural and material properties.

So far, only methods of estimating the elasticity of the whole insect wing have been developed [1-5]. The flexural stiffness obtained by Combes and Daniel [1-4] is based on

the assumption that the wing is a continuous beam with material uniformity. Similarly, the structure of a dragonfly wing is simplified to a model wing with an equivalent flat material in the FEM modelling used by Bao and co-workers [5] in their research of the visco-elastic constitutive relation. However, these are very general approximations. The actual wing property is much more complicated due to the presence of cross-veins and corrugations. Optimally, the wing should be dissected according to their functional structure into different parts such as veins and membranes, and the property of each part should be analysed separately, and then combined to form the ultimate wing model.

In the present work, the wing is separated into veins and membranes, and the elastic modulus of the leading edge vein (LEV) is studied for the first time by a vibration method using laser vibrometer. Applications of laser vibrometer in measuring vibrations of micro-structures have been recognized across different disciplines in recent years, ranging from testing musical instruments [6] and thin film resonators [7], to measuring micro-structures in insects [8, 9]. The elasticity of the LEV is directly obtained and compared with existing materials, giving us a guideline to what type of material to choose for a realistic reconstruction of the framework of a dragonfly wing.

2 Materials and methods

2.1 Insects

The insect used for the experiment was the dragonfly yellow-winged darter *Sympetrum flaveolum*. The dragonflies were caught alive near Nanyang Lake in Nanyang Technological University, Singapore.

2.2 Experimental set-up and procedure

In order to obtain the elastic modulus of the LEV, its natural frequency was determined via vibration test. Firstly, the dragonfly was anaesthetised for 5 min, and

then one of its hindwing was removed at the wing root. Secondly, a sharp shaving blade was used to cut out the LEV from the wing to reduce the distortion of the LEV when cutting to minimum. Thirdly, 5 mm long LEV sample was cut from the straightest section near the wing root for investigation.

Fig. 1. Schematic drawing of the set-up of the vibration test (not drawn to scale).

In the vibration experiment, a laser vibrometer (PSV-400, Polytec) was used as detector and a mini-shaker (Type 4810, Brüel & Kjær) as external exciter. The sample was attached to the mini-shaker via a custom-made clamp (Fig.1), with the clamp holding half of the sample and the other half protruded. A sinusoidal wave form was applied to the mini-shaker via a function waveform generator (33120A, Agilent) to excite the testing samples by lateral vibration. The vibrometer with an infrared beam was used to make non-contact measurements of the vibration quantities of the testing sample as the shaker excited the sample. The laser beam was fixed at a single spot on the sample (Fig. 1); and the vibrometer was set to record the vibration using single-point acquisition setting.

Before the actual experiment, samples from a dead dragonfly wing were tested to determine the optimal range of frequency for the shaker to excite the sample. After the preliminary testing of the dead samples, it was found that the operating frequency was best ranged from 0 to 50 Hz. Therefore, a sinusoidal waveform was applied with a

sweep time of 200 s to excite the sample with a range of frequency from 0.01 to 50 Hz. In the experiments, a total of 35 readings were collected and studied for each sample.

After the vibration test, the dimensions and mass of the sample were measured immediately to facilitate further analysis. The sample was cut to reveal its cross-section. The dimensions of the cross-section and the effective length of the sample were obtained via scanning electron microscope (SEM S360, Leica). Due to the non-conductive nature of dragonfly wings, they were coated with 6 nm thick of gold before viewing in SEM, using the mini sputter coater (SC7620, Polaron) for 60 seconds at 1.7 kV and 10 mA. Moreover, the mass of the sample was measured using an electronic micro-balance (MT5, Mettler) with a precision of 0.001 mg. The whole experiment for the fresh sample was completed within one hour during which time the mass and the flexural stiffness of the wing does not change appreciably [3].

2.3 Calculation

Daniel and Combes [4] described the motion of an elastic wing by the classic fourth order Euler-Bernoulli beam equation, which is also applicable in the present experiment.

Hence, the deformation of the sampled LEV is described by:

$$\frac{d^2}{dx^2} \left(EI \frac{d^2 v}{dx^2} \right) = q(x) \quad (1)$$

where v is the deflection of the beam in the z direction; EI , the flexural stiffness; and $q(x)$, the distributed load. Due to the identical directionality of inertia force and the distributed load, the sample is excited in simple harmonic motion, hence

$$q(x) = \mu \omega^2 v \quad (2)$$

where μ is the mass per unit length of the beam and ω is the frequency of vibration.

For our particular problem, the boundary conditions are (1) the deflection is zero at the cantilevered end of the sampled LEV, and (2) the internal shear force and bending moment vanish at the free end. They lead to an eigenvalue problem for free transverse vibration in which the eigenvalues are the squares of the natural frequencies of vibration [10]. Thus, the elastic modulus of the cantilevered LEV can be evaluated as

$$E = \frac{(0.0809)\omega^2 mL^3}{I} \quad (3)$$

where L is the effective length; E , the elastic modulus of the LEV; m , the mass of the LEV; and I , the moment of inertia of the LEV.

3 Results and Discussion

Through vibration tests, the fundamental natural frequency of the cantilevered LEV is directly obtained from the vibrometer. According to the SEM images shown in Fig. 2a, the LEV excluding the spine resembles a hollow rectangular tube with different thicknesses of its walls. Hence, the optimal geometric representation is a hollow rectangle, and the schematic diagram of the simplified cross-sectional area of the LEV (Fig. 2a) is used for the subsequent calculations.

The distortion of the image is due to the difficulties in mounting the sample vertically in SEM. Nevertheless, the actual width and height are measured along with the effective length (Fig. 2b,c,d). Assuming the distortion remains the same in both directions, the thicknesses of the walls can be obtained. The moment of inertia (I_y) of the cantilevered LEV on its Y' axis can then be calculated. For the samples investigated here, the mass (m) of the cantilevered LEV is 0.006 mg for both dead and fresh. Table 1 summarises all the variables measured and calculated in order to determine the elastic modulus (E) of the LEV using Eq. (3).

Fig. 2. Dimensions of the LEV from the dead dragonfly hindwing measured using SEM. (a) Cross-section of the LEV with its simplified sketch for calculation. The height (h) and width (w) of the LEV and the thickness (t_1 , t_2) of the LEV wall are defined accordingly. (b) Effective length of the cantilevered LEV. The sample is cut into two sections with lengths $L(1)$ and $L(2)$ respectively to reveal its cross-section, so that the effective length (L) is the sum of $L(1)$ and $L(2)$. (c) Height of the cantilevered LEV excluding the spine. (d) Width of the same LEV excluding the spine.

Table 1 Variables measured and calculated to obtain the elastic modulus of the LEV.

	m (mg)	ω_n (Hz)	w (mm)	h (mm)	t_1 (mm)	t_2 (mm)	L (mm)	I_y (mm ⁴)	E (MPa)
Dead	0.006	12.0	0.125	0.062	0.019	0.0054	2.35	1.5×10^{-6}	615
Fresh	0.006	9.5	0.072	0.109	0.011	0.0095	1.48	4.7×10^{-6}	30

The elastic modulus E is a measure of the stiffness of a given material. A smaller value of elastic modulus indicates a higher degree of elasticity of the material. The elastic modulus of the LEV from a freshly removed wing is 30 MPa while that from the dead dragonfly is 615 MPa. Here, the elastic modulus of the fresh sample is only 4.8% of that of the dead sample. The main difference between the dead sample and the fresh one is the loss of water contents in terms of blood in the veins and other body fluids.

The loss of water contents thus increases the stiffness of the LEV by approximately 20 times.

Comparing the elastic modulus of the samples with that of the other materials, it is observed that the elastic modulus for the fresh sample falls into the range of rubber with small strain while that of the dead sample is similar to low density polyethylene. Past studies have shown that insect wings consist of biological fibrous composite material and rubber-like elastomeric protein [11-14], in agreement with our findings.

4 Conclusions

The elastic modulus of the LEV of the dragonfly wing is evaluated using vibration method. The elastic modulus of the fresh LEV is 30 MPa, similar to rubber with small strain, and that of a dead sample is 615 MPa which is similar to low density polyethylene. Therefore, the material which would be most appropriate for the reconstruction of the LEV of a dragonfly hindwing model is an elastic hydrocarbon polymer, such as rubber. With the elastic modulus of the veins obtained, tensile tests can be performed in the future to obtain the elastic modulus of the membranes. By obtaining the material properties of the wing, and utilizing the flapping patterns [15], bionic MAVs resembling the real dragonfly flight could be built for excellent manoeuvrability.

References:

- [1]Combes SA, Daniel TL. J Exp Biol. 2003;206:2999-3006.
- [2]Combes SA, Daniel TL. J Exp Biol. 2003;206:2979-87.
- [3]Combes SA, Daniel TL. J Exp Biol. 2003;206:2989-97.
- [4]Daniel TL, Combes SA. Integr Comp Biol. 2002;42:1044-9.
- [5]Bao I, Hu JS, Yu YL, Cheng P, Xu BQ, Tong BG. Appl Math Mech. 2006;27:741-8.
- [6]VanKarsen CD, Sun RX, Soc Exptl M. 1997.
- [7]Hwang DG, Chae YM, Hwang KS, Kang JY, Lee SH. J Electroceram. 2012;29:225-34.
- [8]Alam MS, Wahab MA, Jenkins CH. Mech Mater. 2007;39:145-60.
- [9]Moir HM, Jackson JC, Windmill JFC. J Exp Biol. 2011;214:3165-72.
- [10] Freund LB, and Suresh, S. Cambridge: Cambridge University Press; 2003.

- [11] Gorb SN, Kesel A, Berger J. *Arthropod Structure & Development*. 2000;29:129-35.
- [12] Weis-Fogh T. *J Exp Biol*. 1960;37:889-907.
- [13] Gorb SN. *Naturwissenschaften*. 1999;86:552-5.
- [14] Kesel AB, Philippi, U. and Nachtigall, W. *Comput Biol Med*. 1998;28:423-37.
- [15] Y.H. Chen, M. Skote, Y. Zhao, Huang WM. *J Fluid Struct*. 2012;40:115-26.