Free vibration analysis of dragonfly wings using finite element method

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ABSTRACT
In the present work, investigations on the microstructure and mechanical properties of the dragonfly wing are carried out and numerical modeling based on Finite Element Method (FEM) is developed to predict Flight characteristics of dragonfly wings. Vibrational behavior of wings type structures is immensely important in analysis, design and manufacturing of similar engineering structures. For this purpose natural frequencies and mode shapes are calculated. In addition, the kind of deformation in each mode shape evaluated and the ratio between numerical natural frequency and experimental natural frequency presented as damping ratio. The results obtain from present method are in good agreement with same experimental methods.

Keywords: Mechanical properties, SEM, dragonfly wing, FEM, natural frequencies, damping ratio.

1. INTRODUCTION

Insect wings appear as highly functional and largely optimized structures in order to coordinate with their flight Characteristics. In fact a series of stabilizing constructional elements have been designed to cope with loading during flight. One such element is the vein system of the wing and its arrangement. Strong structures which stiffen the wing against aerodynamic bending and torsional moment.

Numerous studies have already been made on insect wings e.g. Ref. [1–7], etc. Studies about insect wings have emphasized on two similar characteristics of insects and that are the wings are kind of mechanism as well as they are typically smart engineering structures.

Therefore, they can cope with a variety of loads and their combination. For example, during up and down stroke, the mechanism 'wing' accelerates the surrounding fluid in such a way that the resulting aerodynamic forces enable the insect to fly and, simultaneously, the construction 'wing' has to cope these attacking forces [8]. In addition, insect wings impress one deeply with the marginal mount of building material used in their construction. Although the wings only occupy more than 1–2% of total body mass, they possess great stability and a high load-bearing capacity during flapping flight.

Insect wing have covered by light, high stability and very thin waxy layer [9]. This layer includes some important properties such as Hydrophobia and Anti-pollutant properties. This cuticle consists of two main components: first, Chitin includes long chain of crystalline polymers and the other is many of structural proteins.

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The wing membrane of insects is a natural biological membrane made mainly of structural proteins. The material and structural properties of the membranes, together with the venations of insect wings are associated with the flight of the insects themselves [10, 11].

Recently, have been shown that most membranes on insect wings undergo significant bending and twisting during flight, which may alter the direction and magnitude of aerodynamic force production, and the deformations of the wing membranes increase thrust production in some species by creating a force asymmetry between half-strokes, and can enhance lift production by allowing wings to twist and generate upward force throughout the stroke cycle. Therefore, the material and mechanical properties of the wing membrane, together with that of the wing vein, determine how the wing will change shape in response to these forces [10, 11].

As mentioned above, many researches have done on insect wings but until now, a few researches have done to calculate natural frequency of dragonfly wing. Zeng et al. [12] used noncontact quadrant position sensor to measure natural frequencies of dragonfly wings and Chen et al. [13] performed a base-excitation modal test and employed spectrum analyzer to calculate resonance frequency of dragonfly wing.

In this work, we investigate microstructure properties of dragonfly wing by SEM and create membrane and vein networks model, then are calculated base on FEM. In addition, we present a criterion to calculate the damping ratio for flapping wing.

In fact, the obtained results from insect wing in particular dragonfly wing (due to unique capabilities and complex structures), together with the average flapping frequency of dragonflies, may be useful to calculate optimized ratio of natural frequency and flapping frequency of the system that can be used to improve performance of Micro Air Vehicle (MAV). In addition, this is important that dragonfly wing is a largely optimized structure, because, it can bear many applied stresses with minimum expenditure material in constructing wing during flight.

2. INSPECTING MICROSCOPIC PROPERTIES OF DRAGONFLY WING USING SEM

Test samples were taken from the wings of the dragonflies that had died before 3 days and were preserved in a container with room temperature and humidity. We employed a SEM to observe and investigate the microstructure of the wing membrane and vein of the dragonfly. For observation under microscope, first we dipped the tested samples in liquid nitrogen a few minutes. After that, all the treated samples were coated with gold about 8 nm thick, and then, the samples were observed by using SEM. Finally, all tested data of SEM images were analyzed.

Dragonfly wing is shown in Fig. 1. and SEM image of dragonfly wing is demonstrated in Fig. 2. In this figure, the wing cells (a compartment of membrane between wing veins) are observed.

The three, four, five and multi sides frame involved membrane cause wing stiffness. These veins, guarantee wing stability against loading. The leading edge consists primarily of rectangular frames whereas the trailing surface is largely formed of hexagons and some other polygons with more than four sides.

Generally, the four sides frameworks have more stiffness. The square frame structure is slightly stiffer than the hexagonal structure. In the other side, membranes have prevented air passage through wings and also, in some wing parts, acted as under pressure membranes which cause veins framework stiffness. Fig. 3. have shown closer schema of six-sided frame. The observed random scratches in the figure induced by the environment agents e.g., bushes,

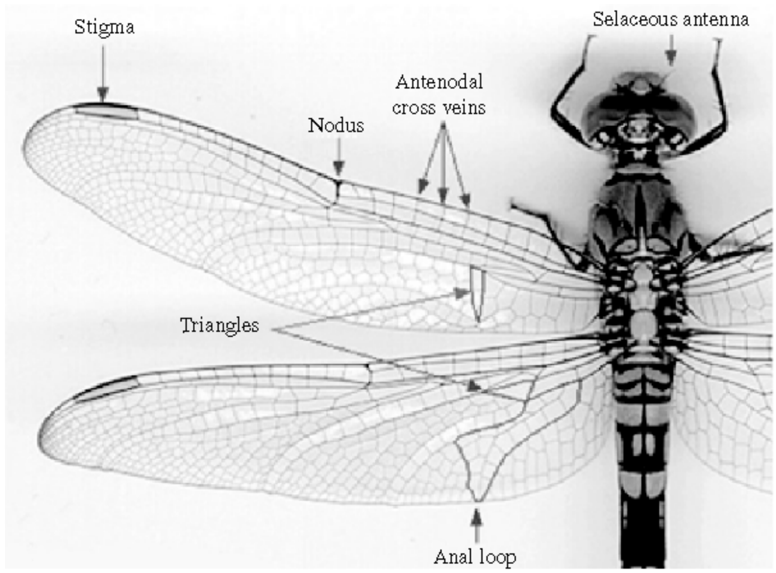

Figure 1 Image under observation dragonfly wing.

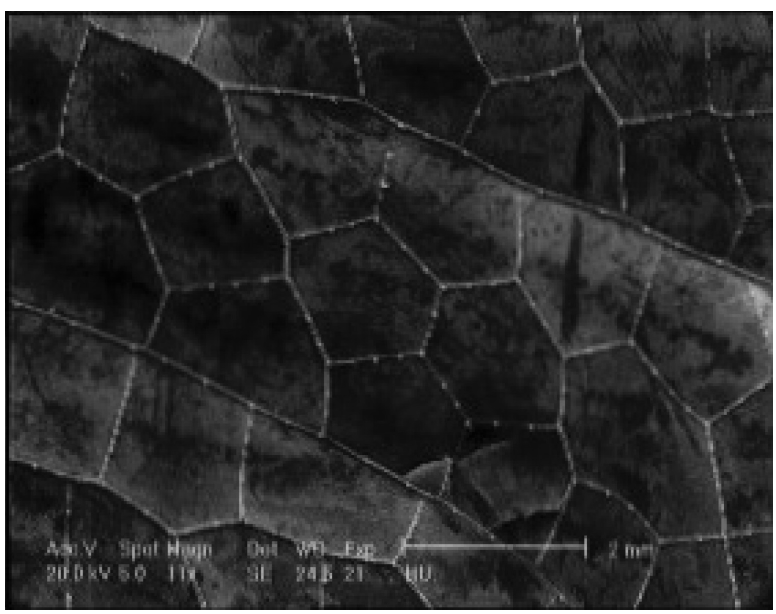

Figure 2 SEM image of dragonfly back wing.

grass, or other animals, because the untreated membrane of a dragonfly wing is smooth. We observed that the thickness variation of the wing is between 2–3 μm.

The microstructure of vein is a complex sandwich structure, which might be consider as multi-layers of chitin and protein meat with some fibrils such as at right diagram in Fig. 4. [14]. These fibrils in sandwich structures of vein can play important role in the enhancement

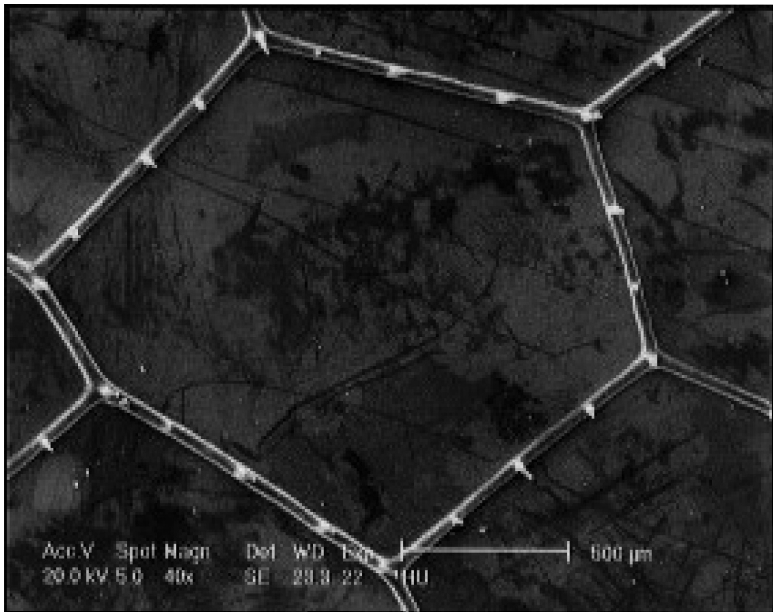

Figure 3 6-faced schema of bottom wing.

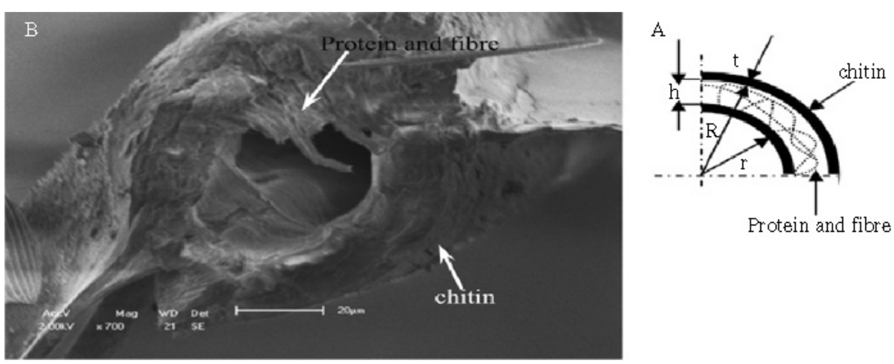

Figure 4 (A), (B) Microstructure of tubular vein.

fracture toughness and adapting to cope with the individual flight behavior for the dragonfly.

This is mainly because the sandwich microstructure could subject a rather greater torsional deformation in minimal mass based a mechanics view if the flexing stiffness of the vein keeps a constant. These micro structures and roles of tubular veins were reported in references [15, 16, 17, 18, 19].

3. METHOD

Preliminary studies have shown that the insect wing is such a complex construction, that an accurate model is necessary to determine the role of individual constructional elements. In this section, we modeled forewing of dragonfly *Odanata libellulidae.* The modeling and analysis is based on ANSYS software.

In this paper, we have presented a model of dragonfly wing. The presented model consist of two elements: pipe elements (elastic straight 3D-pipe16 with 2 nodes) as 'veins' and shell

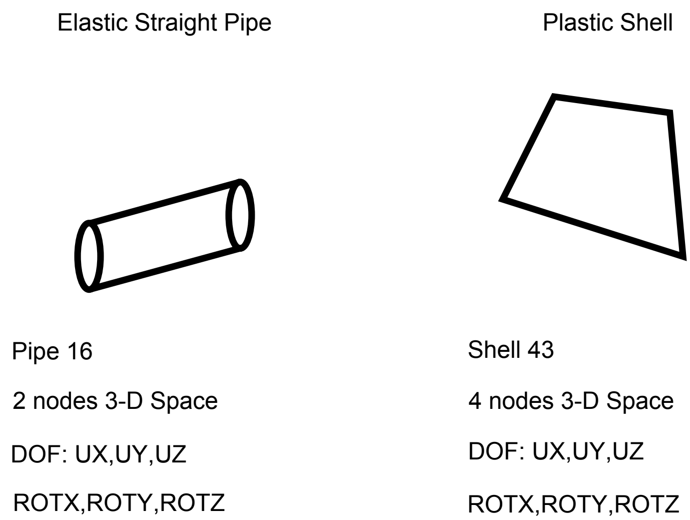

Figure 5 The plastic shell and elastic straight pipe properties.

elements (plastic shell43 with 4 nodes) as ‘membranes’ (each with three translatorial and three rotational degrees of freedom per node).

The reason of selecting these elements, were special characteristics and similarity of their properties with veins and membranes as mentioned above. The properties of related to plastic shell and elastic straight pipe have shown in Fig. 5. these elements were best choice for presenting dragonfly wing characteristics.

3.1. BOUNDARY CONDITIONS

As shown in Fig. 6, the wing joint was assumed to be clamped (constrained in Ux, Uy, Uz, ROTx, ROTy, ROTz).

3.2. MATERIAL PROPERTIES

Main constituent material of wing, including vein and membrane is chitin. The chitin of veins and membranes was modeled as an isotropic material [15] with a Young's modulus of 7.5 GN/m^2 [20]. The Poisson's ratio was assumed to be 0.3 [21]. We consider wing density as 1200 Kg/m^3 [16].

3.3. MODELING

At first, we designed a precise model of forewing of dragonfly. We considered total thickness of wing in all parts 3e-03 mm.

The related image of forewing and its model have been shown in Figs. 7, 8.

As mentioned above, we considered the vein networks. The vein modeled by pipe elements and membranes by shell elements. The membrane thickness was 3e-03 mm in all points and the veins were in form of tubular elements with external diameter of 135e-03 mm and wall thickness was 25e-03 mm.

3.4. CHARACTERISTICS OF MODEL

In summary, the specifications of dragonfly wing are as follow:

a) Three-dimensional model.
b) Wing joint as a clamp.

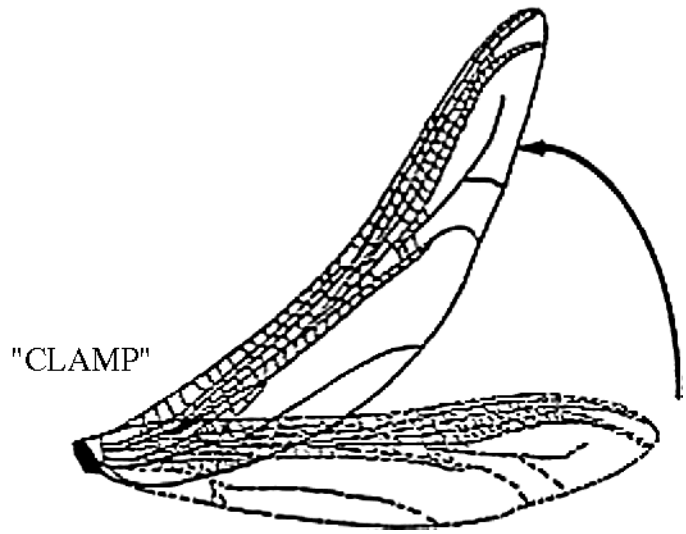

Figure 6 Deflection of dragonfly wing and its clamped joint.

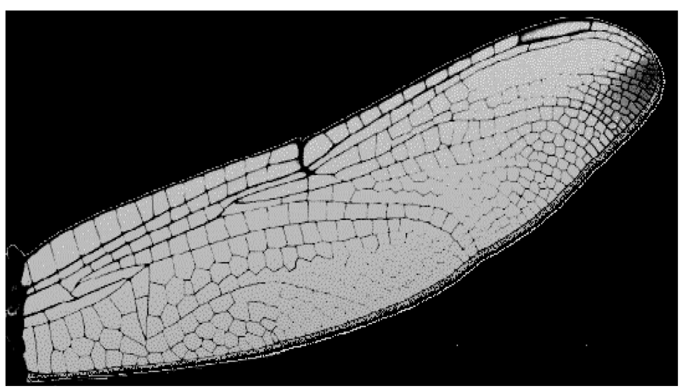

Figure 7 Image of *Odonata Libellulidae* dragonfly wing.

c) All veins modeled by pipe elements with the same cross-section (ring-shaped; outer diameter, 0.135 mm; wall thickness, 2.5e-02 mm).
d) All membranes modeled by shell elements (thickness of anywhere, 3e-3mm)
e) The chitin of veins and membranes was modeled as an isotropic material with a Young's modulus of 7.5 GN/m^2, Poisson's ratio 0.3 and density 1200 Kg/m^3.

4. RESULTS

In above mentioned condition, natural frequencies of dragonfly wing calculated with ANSYS software. First four natural frequencies and corresponding mode shapes are shown in Figs. 9(a)–(d).

These results that given from numerical analysis compared with those obtained from experimental methods that Zeng et al. [12] and Chen et al. [13] employed.

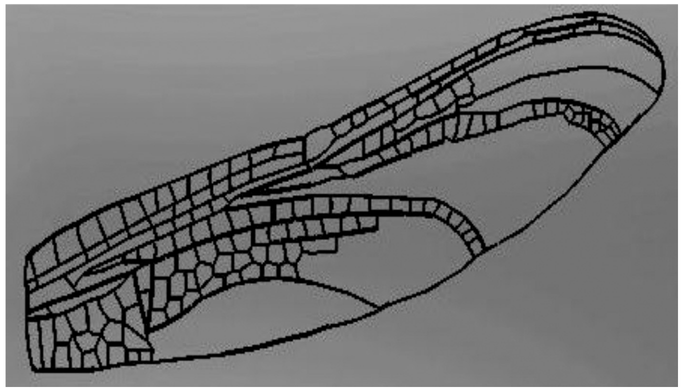

Figure 8 Model of dragonfly wing.

Results from present analysis indicate that the fundamental natural frequency of dragonfly wing is about 181.12 Hz. Chen et al. [13] clarified the role of the inertial force on the wing deformation during insect flight by simplifying the wing structure into a simple mass-spring system under harmonic external force FSinωt, where F is the magnitude of the external force. The ratio between dynamic deformation amplitude X_d and static X_s, also called magnification factor, is [22]:

$$\frac{X_d}{X_s} = \frac{1}{1-(\omega/\omega_n)^2}, \quad (1)$$

Where ω_n is the natural frequency of mass-spring system, also the first natural frequency of dragonfly wing. The average flapping frequency (ω) of dragonfly wing is about 27 Hz; therefore, the flapping frequency is about 15% of fundamental natural frequency (181.12Hz). By substituting natural frequency (ω_n) and flapping frequency (ω) into Eq. (1) the magnification factor is estimated to be 1.02 at this frequency ratio. It means that inertial force of the wing is negligible compared to the elastic force during flapping flight.

By observation of mode shapes of the dragonfly wing, we conclude that these mode shapes contain bending and twisting deformation. It can be seen that in the first mode shape of natural frequency the effect of bending deformation much more than twisting deformation.

Tab. 1. shown the number of mode shapes, their natural frequencies and the kind of deformations on these mode.

These results that based on numerical method have an advantage in comparison with experimental methods that performed previously [12, 13]. In other words, there are no damping effects due to aerodynamic forces in this analysis.

The comparison of results from present analysis with those from experimental methods that conducted I n non-vacuum chamber, we can estimate damping ratio of surrounding air. If the samples that used in both numerical and experimental methods be same, damping ratio can calculated with this formula:

$$\text{Damping Ratio} = \frac{\omega_N}{\omega_E} \quad (2)$$

That ω_N, is numerical natural frequency and ω_E, is experimental natural frequency.

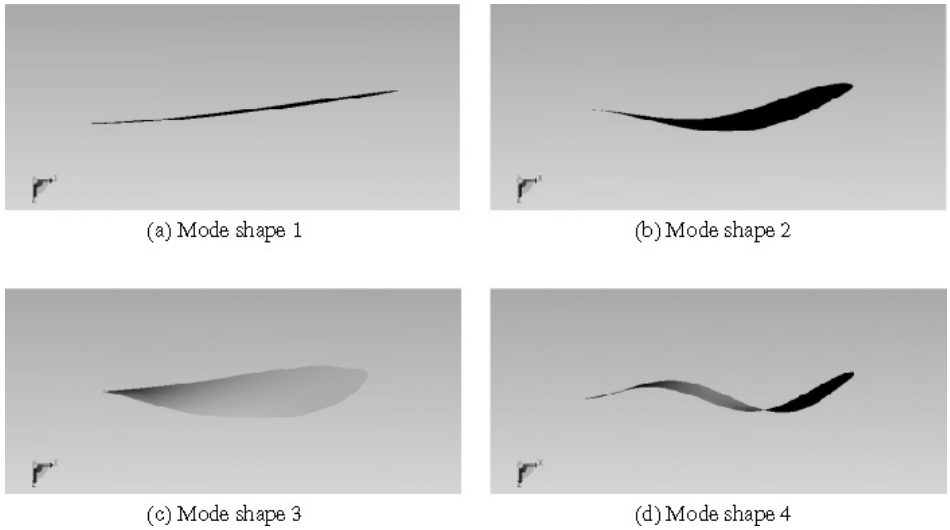

Figure 9a Mode shape 1. (b) Mode shape 2. (c) Mode shape 3. (d) Mode shape 4.

Table 1 Number of mode shapes – natural frequencies – kind of deformations

Number of Mode Shape	Natural Frequency (Hz)	Kind of Deformation
1	181.12	Bending
2	313.28	Bending + Twisting
3	390.14	Twisting
4	446.31	Bending + Twisting

5. CONCLUSION

The present work studies the micro structure and material properties of dragonfly wing and analyzed natural frequencies and mode shapes of it (based on forewing of *Odonata Libellulidae*).

Three-dimensional data obtain by probing a wing surface, served as a basis for constructing a numerical precise model base on finite element method.

Various wing aspects were used to construct the model: the joint became a clamp. The wing veins were implemented as pipe elements, the membranes as shell elements. Chitin was defined as an isotropic material.

The following results were obtained from a non-linear analysis carried out in several stages:

- The fundamental natural frequency of dragonfly wing is estimated about 181.12 Hz.
- Some mode shape contain bending, some twisting and the others combination of bending and twisting deformation. It is observed that bending deformation obtains the fundamental mode shape.
- Damping ratio of the wing can be calculated with numerical resonance frequency divided by experimental resonance frequency for same wing.
- By using natural frequency obtained from this study and determination of damping ratio of the wing , we can provide a guide to the biomimetic designs

of the micro air vehicles. It should be noted that insect wings are highly functional and largely optimized structures in order to coordinate with their flight Characteristics.
- By using the magnification factor of dragonfly wing we can understand that inertial force of the wing is negligible compared to the elastic force during flapping flight.

REFERENCES

[1] R.J. Wootton, Support and deformability in insect wings, Journal of Zoology 193 (1981) 447–468.

[2] R.J. Wootton, Functional morphology of insect wings, Annu. Rev. Entomol. 37 (1992) 113–119.

[3] C.P. Ellington, The aerodynamics of hovering insect flight. I–VI. Philos. Trans. Roy. Soc. London B, Biolog. Sci. 305 (1984) 1–181.

[4] C.P. Ellington, The aerodynamics of hovering insect flight. III. Kinematics, Philos. , Philos Roy Soc London Ser B 305 (1984) 41–49.

[5] R. Ennos, The inertial cause of wing rotation in Diptera, J. Exp. Biol. 140 (1989) 161–169.

[6] R. Ennos, The importance of torsion in the design of insect wings, J. Exp. Biol. 140 (1988) 137–142.

[7] R. Ennos, Comparative functional morphology of the wings of Diptera, Zoological Journal Of The Linnean Society 96 (1989) 27–47.

[8] Antonia B. Kesel, Ute Philippi, Werner Nachtigall. Biomechanical aspects of the insect wing: an analysis usingthe finite element method, Computers in Biology and Medicine 28 (1998) 423–437

[9] T. Wagner, C. Neinhuis, and W. Barthlott. Wettability and contaminability of insect wings as a function of their surface sculptures, Acta Zool. 3 (1996) 213–225.

[10] S.A. Combes, T.L. Daniel, Flexural stiffness in insect wings I. Scaling and the influence of wing venation, Journal of Experimental Biology 206 (2003) 2979–2987.

[11] R.J. Wootton, Functional morphology of insect wings, Annu. Rev. Entomol. 37 (1992) 113–140.

[12] L. Zeng, H. Matsumoto, S. Sunada, T. Ohnuki, K. Kawachi, Two-dimensional noncontact measurement of the natural frequencies of dragonfly wings using a quadrant position sensor, J. Optical Engineering 34 (1995) 1226–1231

[13] J.S. Chen, J.Y. Chen, Y.F. Chou, On the natural frequencies and mode shapes of dragonfly wings, J. Sound and Vibration 313 (2008) 643–654.

[14] X.S. Wang, Y. Li, Y.F. Shi, Effects of sandwich microstructures on mechanical behaviors of dragonfly wing vein, J. Composites Science and Technology 68 (2008) 186–192

[15] R.J. Wootton, Geometry and mechanics of insect hindwing fans- a modeling approach, Proc Roy Soc London B 262 (1995) 181–187.

[16] R.J. Wootton, K.E. Evans, R.C. Herbert, C.W. Smith, The hind wing of the desert locust (schistocerca gregaria forskal), I. Functional morphology and mode of operation, J. Exp. Biol. 203 (2000) 2921–2931.

[17] C.W. Smith, R.C. Herbert, R.J. Wootton, K.E. Evans, The hind wing of the desert locust (schistocerca gregaria forskal), II. Mechanical properties and functioning of the membrane, J. Exp. Biol. 203 (2000) 2933–2943.

[18] A.C. Neville, Biology of the arthropod cuticle, Zoophysiology and Ecology, (W. S. Hoar, J. Jacobs, H. Langer, and M. Lindauer, eds.), Springer Verlag, Berlin vol. 4–5 (1975) 1–448.

[19] B.K. Filshie, Fine structure of the cuticle o insects and other arthropods, In: King R.C., Akai H., editors, Insects ultrastructure, New York: Plenum Press 1 (1982) 281–312.

[20] P. Kreuz, , A. Kesel, , M. Kempf, , M. Göken, , H. Vehoff, and W. Nachtigall, Mechanische Eigenschaften biologischer Materialien am Beispiel Insektenflügel. BIONA Rep. 14 (1999) 201–202.

[21] F. Song, K.W. Xiao, K. Bai, Y.L. Bai, Microstructure and nanomechanical properties of the wing membrane of dragonfly, Mat. Sic. Eng. A, 457 (2007) 254–260.

[22] S.S. Rao, Mechanical Vibration, Addison-Wesley, New York, (1995).