12-1-2012

Exploratory Structural Investigation of a Hawkmoth-Inspired MAV's Thorax

Luciano Demasi
San Diego State University

Anthony N. Palazotto
Air Force Institute of Technology

Alex C. Hollenbeck

Rauno Cavallaro

Recommended Citation

Demasi, L., Palazotto, A. N., Hollenbeck, A. C., & Cavallaro, R. (2012). Exploratory Structural Investigation of a Hawkmoth-Inspired MAV's Thorax. International Journal of Micro Air Vehicles, 4(4), 291–304. https://doi.org/10.1260/1756-8293.4.4.291

Exploratory Structural Investigation of a Hawkmoth-Inspired MAV's Thorax

Luciano Demasi[1], Anthony N. Palazotto[2], Alex Hollenbeck[3] and Rauno Cavallaro[4]
[1]Associate Professor, Department of Aerospace Engineering, San Diego State University
[2]Distinguished Professor Aerospace Engineering, The Air Force Institute of Technology
[3]Graduate Student at The Air Force Institute of Technology
[4]Ph.D. Candidate, Department of Aerospace Engineering, San Diego State University and Department of Structural Engineering, University of California San Diego

Received 18 July 2012, Accepted 5 November 2012

ABSTRACT
Manduca Sexta present excellent flight performances which make this insect an ideal candidate for bio-inspired engineered micro air vehicles. The actual insect presents an energetically very efficient thorax-wing flight system which needs to be fully understood for an effective design of artificial flying machines. This work discusses a preliminary finite element model which simulates the thorax-wing system and the muscles involved in the flapping motion. Both upstroke and downstroke conditions are statically analyzed with the application of load sets that simulate the contractions of the dorso-ventral and dorso-longitudinal muscles (indirect flight). Comparison with commercial software and experimental results is also presented and discussed.

1. INTRODUCTION
MICRO Air Vehicles (MAVs) present significant applications in the battlefield for military surveillance and reconnaissance missions. The Defense Advanced Research Project Agency (DARPA) [1] is pursuing the development of an insect-size MAV program. The dimensions of the MAVs will be smaller than 15 cm, relatively easy to produce, inexpensive, and highly capable. The small size requirement for the MAVs clearly identifies [2] the range of Reynolds numbers ($\leq 10^4$) at which the MAVs must operate. The biological flyers of that size use the flapping of the wings as the main mechanism to produce lift and thrust [3], [4]. It has been extensively shown that complex unsteady flow [3],[5], [6] is generated during a complete flapping cycle, including a strong leading edge vortex [7] which is responsible of the high lift [2], [8] observed during the downstroke. Other unsteady aerodynamic phenomena could be observed in some cases [9], where the two wings press together at the end of the upstroke generating vortices on the wings and lift. Dickinson [10], [11] discovered that wings translated backwards in a wake created in a preceding stroke present an enhancement of the lift. But understanding the complex flapping mechanism of biological flyers, important to effectively design artificial MAVs, also requires a detailed investigation of the structural features of the wing and the insect's body. Combes and Daniel investigated the flexural stiffness of the wing with particular emphasis [12] on the influence of wing venation. A qualitative finite element model of a Manduca Sexta's wing, including the membranes and veins, was developed. With the support of an experimental measurement of the flexural stiffness, Combes and Daniel found that there is a strong spanwise-chordwise anisotropy regarding the flexural stiffness (i.e., the spanwise bending stiffness is one or two orders of magnitudes larger than the chordwise bending stiffness). It was also investigated and discussed that the leading edge veins are the main reason for that anisotropy. In Reference [13] Combos and Daniel presented a simplified finite element model of the Manduca Sexta's wing and applied declining values of material stiffness in 12 strips oriented diagonally. The results they obtained were consistent with the measurements which showed a sharp decline of the flexural stiffness from the

base to the tip and from the leading edge to the trailing edge. Moreover, male and female of Manduca Sexta specie appear to have different flexural stiffness in their wings: the bending stiffness declines chordwise much more sharply in the males than in females.

The *hovering* flight requires a high flapping frequency which depends on the weight of the insect. It is well known [14] that, in order to maintain a fixed position in space (important in some surveillance missions in MAVs which mimic insects), the insect must be able to accelerate the wing in one direction (downstroke), decelerate it and reverse the motion (*supination*) [2], perform the upstroke, decelerate the wing again and then reverse the motion for the next downstroke (*pronation*). These accelerations and decelerations imply an increase/decrease of the kinetic energy of the wing. To increase the efficiency of flight and decrease the amount of energy [14] required to achieve the flapping motion, the wing must not be rigid: the structural deformation brings changes of the effective angle of attack, the vortex intensity, and the net force [4]. Moreover, insects do not present [15] muscles on the wings: they are passively deformed [16], [17] under the inertial and aerodynamic forces. The deformation is such that the overall aerodynamic performance and energy expenditure to maintain the flight are optimized. This explains for example, the complex flexural stiffness distribution [12], [13] over the wing. In reference [18] a computational fluid dynamic model of a flexible wing showed that the flexibility increases the force created at early downstroke, enhancing the aerodynamic efficiency. Moreover, the passive deformation of the wing is probably responsible for the stabilizing and delaying of the breakdown of the leading edge vortex [18]. The flexibility and anisotropy [12], [13] lead to wing twist and camber which change dynamically during the flight. The hawkmoth is discussed in Reference [19]. The flexibility of the wings may also involve some nonlinear structural geometric effects [13]. In particular, the wing behaves not symmetrically when loaded from the concave or convex part. In other words, the veins are pushed together with a consequent softening effect for the membrane between the veins (nonlinear softening effect) or are pulled further apart with a consequent stiffening of the membrane (nonlinear stiffening effect). Other important aspects of this passive deformation of the wing are related to the highly complex hinge connection with the insect's *thorax*. The wing must be able to experience significant torsional deformation especially during the supination and pronation phases [2] and this can be achieved thanks to the above mentioned anisotropy and to an appropriate set of boundary conditions which need to be properly understood. The bending asymmetry is for example possible by one-way hinges ([13],[16], and [18]) whose role needs to be further investigated.

An effective design of MAVs will try to reproduce the *essential* insects' biological features required for an efficient flight, with particular focus on the maximization of the payload (for example a small camera or other sensors) and minimization of the power required to flap the wings in forward and hovering flight.

These were, for example, the goals pursued in Reference [20], where ring-based resonators were used to minimize the energy expenditure for the basic movement of the wings, so that the work to be delivered by the actuators to accelerate and decelerate the wings is significantly reduced. This concept was stemmed by direct observation [21] of most insects' flight: a portion of their body, named *thorax*, hosts the *flight muscles,* which can contract at very high frequencies (necessary, for example, to maintain a fixed spatial position in hovering flight). This contraction is automatically adjusted [21] to the *natural frequency* of the whole flapping system. Part of the kinetic energy "lost" during the deceleration of the wings in the transition from the downstroke to the upstroke motions (and vice-versa), is stored in the form of elastic energy (deformation), with improved energetic efficiency. This has practical implications in the MAV design: one of the challenges is to provide an adequate endurance [1] that can be achieved by increasing the energetic performance and reducing the required power [14].

2. BACKGROUND AND MOTIVATION OF THE PRESENT STUDY

As required by DARPA [1], the ideal MAV should be able to fly in small spaces and even hover, according to the designed mission. This is not achievable by conventional forward-flight fixed-wing types of air vehicles for those small dimensions. Flapping wing MAV is then a possible effective solution. The main challenge is to have a machine which is small, light, and energetically efficient so that the mass of the battery used to store the energy is not too large and the MAV can effectively carry a payload.

The Manduca Sexta is an insect with relatively small size that presents excellent flight performances [22] and is an ideal candidate for a biologically inspired engineered MAV [23]. One of the main components of the Manduca Sexta's flight system is the thorax (see Figure 1), which consists of a highly elastic exoskeleton made up of chitin microfibers embedded in a protein matrix [24],[25].

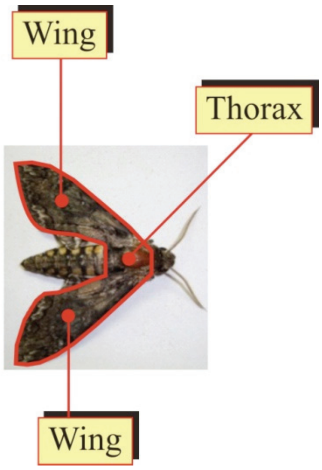

Figure 1. Hawkmoth (Manduca Sexta): Thorax and Wings.

If one investigates the thorax internally, one would find that it is predominately a mass of muscle structure both soft and hard [14]. Thus, the attempt at duplicating this material arrangement will be initially investigated in this paper. Some experimentation of the plate-like action has been carried out as a portion of the research done at AFIT [14] and further investigation is proceeding on the wing movement as an extension of the research. The paper herein is specifically interested in duplicating thorax's muscle action in the form of springs and plates. It is recognized that many of the assumptions made are very preliminary and thus will have to be modified in the future, but an interest is to characterize realistic flapping of the wing. If the static movement is similar to the actual movement then future iterations will allow for a better appreciation of the dynamic features.

3. DESCRIPTION OF THE MATHEMATICAL MODEL

The *thorax* is the portion of the insect's body that presents several biological important functions. Most of these functions do not have practical interest because they are strictly related to the biological survival of the Hawkmoth. From an engineering view point, it is relevant to observe that the thorax (see Figure 1) plays an important role in the flapping motion of the wings and subsequently, in the insect's flight. In particular, the thorax hosts the *flight muscles* [21],[24]. Contraction of these muscles deforms the thorax and this, in conjunction to a quite complex deformation of the wing-thorax junction, allows the movement of the wing. For example, Figure 2 presents the contraction of the *Dorso-Ventral Muscles* (DVMs) that causes a displacement of the *tergal plate*. This displacement determines an upward motion of the wings (upstroke). Similarly, a compression of the *Dorso-Longitudinal Muscles* (DLMs) changes the curvature of the tergal plate and the complex wing-thorax junction makes the wing rotate downward. This is the so-called downstroke motion. It has been extensively investigated [2] that flight at low Reynolds number (e.g. viscosity is important and cannot be neglected as it happens for most of the classical aeronautical applications, at least outside the boundary layer) is very effective for insects if the wings perform a *non-symmetric* flapping motion: the upstroke and downstroke phases are not symmetric with a net generation of force.

One of the key features that need to be reproduced in low-Reynolds-number flight mechanics is the complex wing-thorax hinge mechanism that effectively allows the flapping of the wing. The features that are strictly required to achieve the flight should be enhanced and used in a man-made MAV.

The goal of this effort is *not* to model the actual Manduca Sexta's thorax and its connection with the wing. The main purposes of the present investigation are listed below:

- Identify the key structural components that need to be properly simulated to *replicate the main features* of Manduca Sexta's extraordinary flight ability with an artificial MAV. This could have a strong impact for civil applications such as investigations of dangerous scenarios that follow, for example, a nuclear disaster. Military use would also be invaluable because it could allow reconnaissance especially when natural obstacles (e.g., hills or forests) would place the life of soldiers at risk.

- Understand which parts of the thorax play a more significant role in the complex deformation that takes place to ensure the downstroke and upstroke motions of the wing. For example, from Figure 2 it could be inferred that the elastic deformation (with consequent energy storage) of the Tergal Plate is essential to achieve the desired MAV's efficiency.
- Investigate if it is possible to design a MAV's thorax based as much as possible on a linear behavior, so that the engineering prediction is facilitated. This should be achieved without penalization of the flight performance of the MAV. It is true that the design of a *bi-stable* configuration, as far as the Tergal Plate is concerned, would increase the chance of reducing the amount of energy that needs to be carried by the MAV. However, this possibility is not going to be analyzed in the present work.
- Create a Finite Element Model that is capable of qualitatively representing the main wing-thorax interaction during the flight. This means that the model should be able to obtain the upstroke and downstroke motions with a contraction that in nature takes place in the dorso-ventral and dorso-longitudinal muscles.

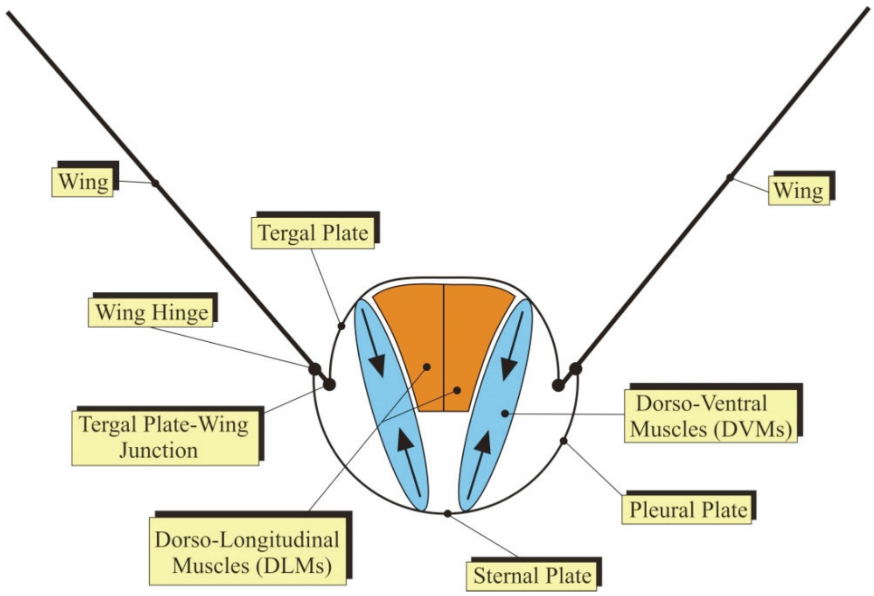

Figure 2. Hawkmoth (Manduca Sexta) and Upstroke Motion: Terminology.

The simplified finite element model does not reproduce any material anisotropy that is typical of the real insects [24],[25]. Moreover, the thickness distributions are assumed constant on large parts of the thorax (for example, on the Tergal Plate) and the material is assumed to be homogeneous on the different parts included in the model. The static analysis is investigated in this work from both a computational and experimental [14] points of view. The goal is to reproduce the flapping mechanism from a qualitative prospective. Thus, the geometry is simplified without removing the significant features of the Manduca Sexta (see Figure 3). Figure 3 shows the geometrical representation of an actual Manduca Sexta modeled as an assembly of surfaces. The thickness is taken into account in the finite element model only when the finite element shell properties are defined.

The present finite element model is created by meshing only half of the geometry because the analyzed conditions will present symmetry about the longitudinal plane.

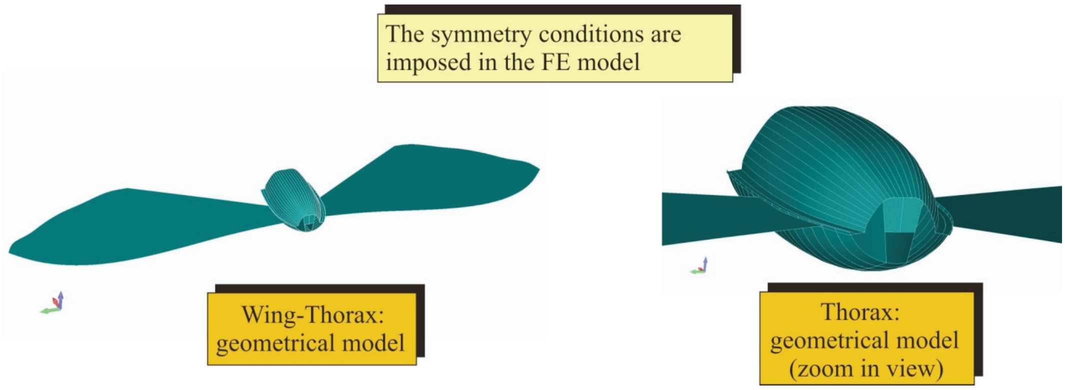

Figure 3. Geometrical Model of the Thorax-Wing System.

Figures 4, 5, 6, and 7 present the FE model. The complex hinge mechanism is connected to both the wing and Tergal Plate. The curve connecting the wing and the junction is called *external hinge curve*. The curve connecting the junction and the Tergal Plate is named *internal hinge curve*. The wing-thorax junction is modeled as follows:

- The *relative rotation* between the wing and the *external hinge curve* is allowed. This is accomplished by the adoption of "rigid" elements (*multifreedom constraints*). Figure 6 shows the curves on the hinge area.
- The *relative rotation* between the internal hinge curve and the Tergal Plate is allowed.
- The *relative translational displacements* in correspondence of the external and internal hinge curves are *not* allowed.

In Figure 4, it is possible to see the different parts: Tergal Plate, Pleural Plate, Sternal Plate, Wing, and joint areas. These components have been simulated with plate elements. Additional plate elements have been used to create the necessary supports for the application of the axial load required to simulate the DLM contraction (which takes place during the downstroke motion).

The boundary conditions adopted to take into account the symmetry of the model and so save computational time, are also imposed and the Sternal Plate is fixed at the curve shown in Figure 5.

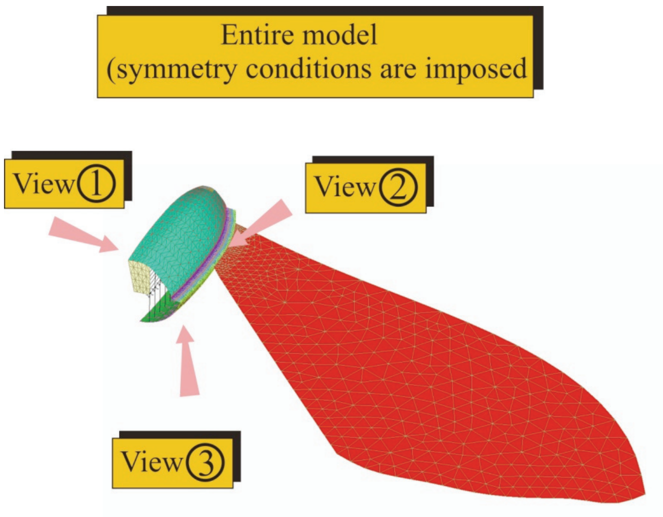

Figure 4. Finite Element Model: of the Thorax-Wing Mechanism.

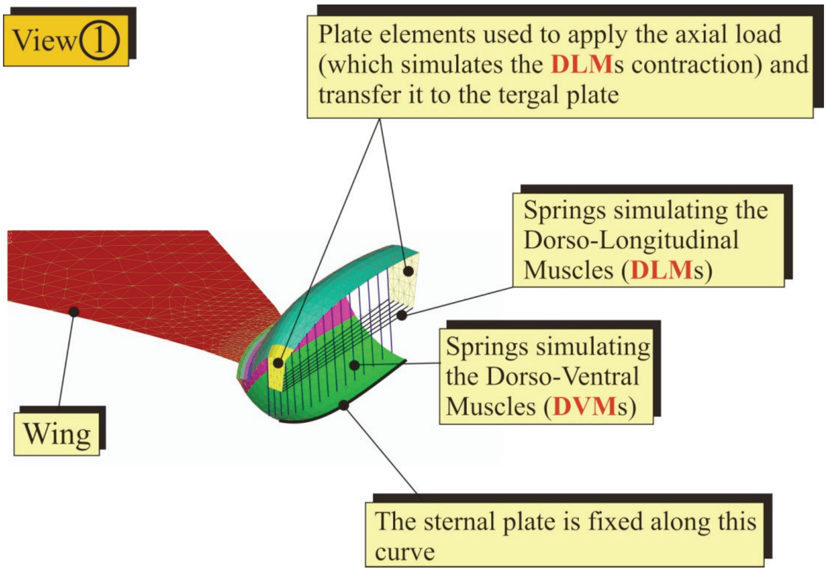

Figure 5. Finite Element Model: of the Thorax-Wing Mechanism.

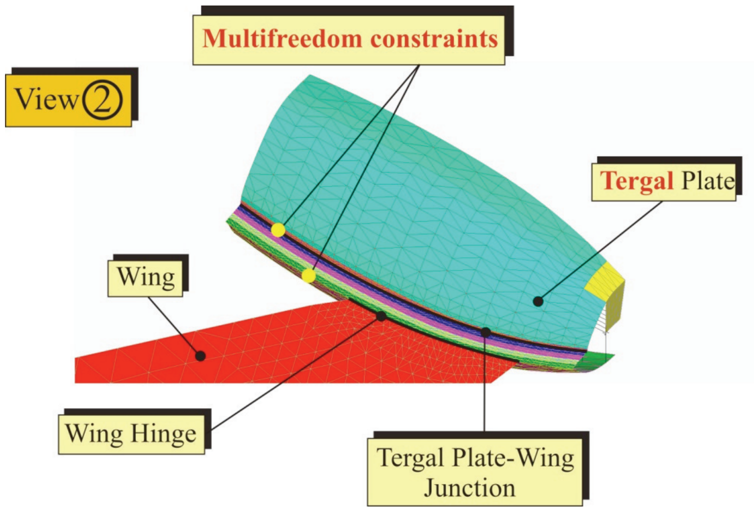

Figure 6. Finite Element Model: of the Thorax-Wing Mechanism.

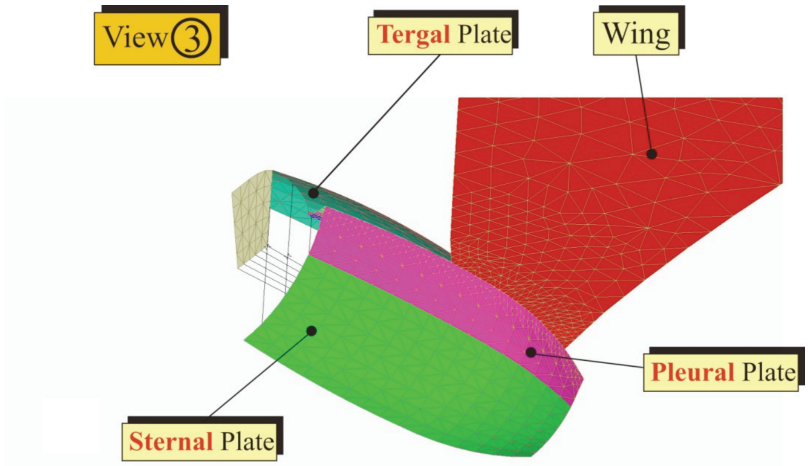

Figure 7. Finite Element Model: of the Thorax-Wing Mechanism.

Figures 8 and 9 present the simplified simulation of the flight muscles. This is accomplished by adopting *linear translational springs*. The value of the stiffness of the springs does *not* reflect the actual stiffness of the muscles of the insect. The stiffness has been selected after a tuning of the FE model. In particular, the stiffness of the springs was varied starting from a relatively low value and gradually increased. The comparison of the upstroke angular rotation of the wings (discussed later in the present work) resulting from the DVMs simulated contraction, was compared with the experimental results. The spring of the stiffness that provided the best correlation with the available experimental data was selected. Additional numerical investigations showed that the major role played in the deformation of the hinge area is due to the plate elements rather than the springs used to simulate the muscles.

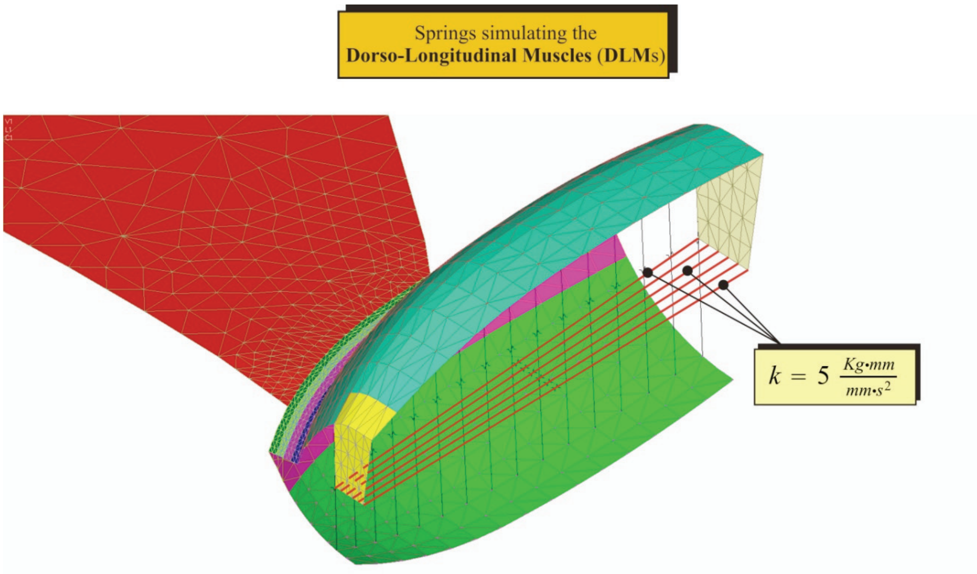

Figure 8. Simulation of the Dorso-Longitudinal Muscles (DLMs).

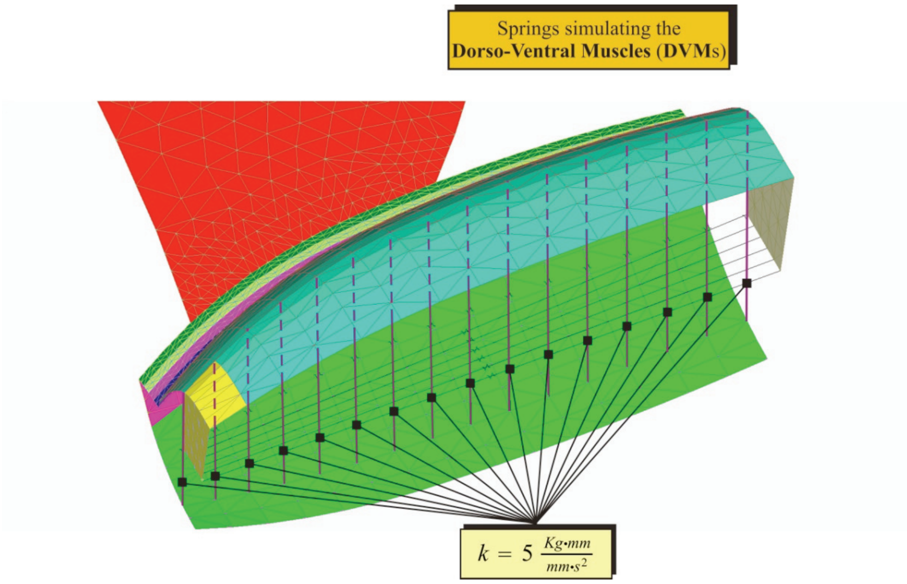

Figure 9. Simulation of the Dorso-Ventral Muscles (DVMs).

Figures 10 presents the material properties adopted for the thorax structural model. The actual insect's thorax is definitely not isotropic [24,25]. However, the nano-indentation [14] experimental procedure evaluated an average elastic modulus for the Tergal Plate of 5.1GPa. The FE model adopted that elastic modulus also for other parts of the thorax (see Figure 10). The wing and the junction (see Figure 10) are simulated with higher values for the elastic moduli to make the wing almost a rigid part (compared to the thorax). This is not the case of the real insect, as previously discussed. More advanced structural models of the wing can be created allowing the necessary flexibility, important in the aeroleastic computations and for energetic efficiency. As far as the thickness of the different thorax's parts is concerned, only the thickness of the Tergal Plate [14] was experimentally measured. This thickness was assumed to be a constant quantity. For the other parts (e.g., Pleural Plate and Sternal Plates) there was no experimental data and several assumptions (reported in Figure 10) were made.

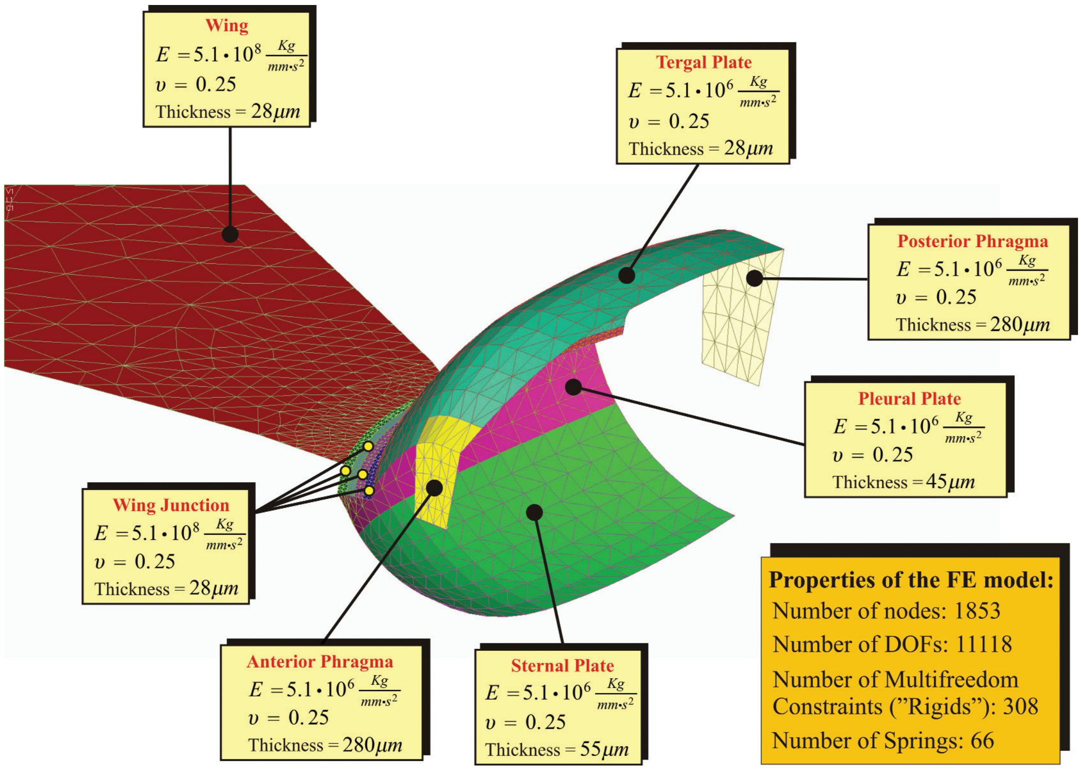

Figure 10. Finite Element Model: Material and Structural Data.

About Poisson's ratio, a value of 0.49 has been measured for some biological materials [12], [26]. Numerical tests were performed in reference [12] to investigate the effects of Poisson's ratio of the wing. No significant sensitivity of the results was found. In this work Poisson's ratio of 0.25 has been selected for all the modeled parts (see Figure 10). This choice is not directly linked to the actual (mostly unknown) material properties and has a certain degree of arbitrariness. But, as previously discussed, this model does not have the goal to reproduce the actual insect's properties, but only to provide insights which can have a direct application on the design of MAVs. A convergence test, related to the size of the structural mesh, has been performed and the resulting model is the one depicted in Figure 10. More than eleven thousand degrees of freedoms were necessary for satisfactory numerical performance. Particularly important in the investigation has been the junction area: a more refined mesh was required for accurate results.

It should be noted that the finite element model focuses on the thorax and wing hinge representations. Thus, the wing has been represented with a relatively rigid isotropic surface (see Figure 10). In the actual Manduca Sexta's wing there is a substantial flexural anisotropy, as extensively discussed in References [12] and [13], and this will be included in more detailed models tailored for aeroelastic investigations and energy efficiency evaluations.

The different colors represent the mathematical properties adopted in the finite element model. The adoption of colors was useful in the testing phase of the model. For example, the hinge area (see Figures 6 and 10) was initially modeled with 5 different properties which presented different elastic moduli. In the final model, the mathematical properties were maintained. However, the FEM properties are the ones shown in Figure 10. That is it: different mathematical properties may represent a single FEM property. For example, in Figure 10 it is clearly shown that at the hinge location a single FEM property is adopted ("wing hinge" in Figure 10) whereas there are 4 mathematical properties (the different colored zones).

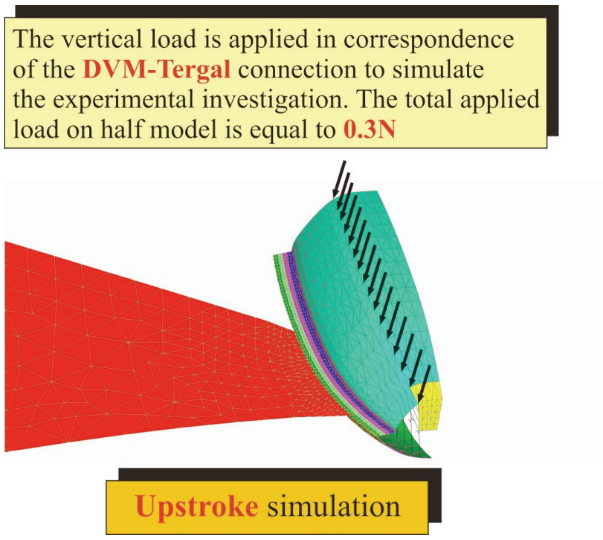

Figure 11. Static Loads Applied to Simulate the Upstroke Motion (Contraction of the DVMs).

The *upstroke motion* takes place passively from a contraction of the dorso-ventral muscles. In the present model the contraction is simulated with a static application of a load in correspondence of the muscles (see Figure 11 for the indication of the applied forces and Figure 9 that presents the location of the DVMs).

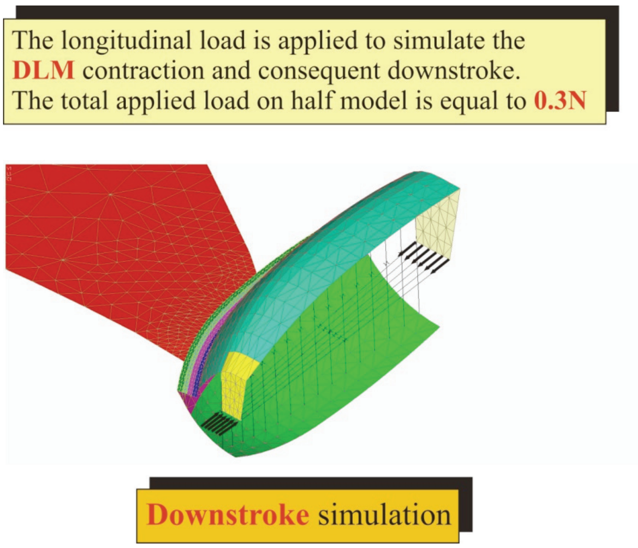

Figure 12. Static Loads Applied to Simulate the Downstroke Motion (Contraction of the DLMs).

The *downstroke motion* takes place thanks to the contraction of the DLMs. This is simulated with the static application of a set of axial forces, as shown in Figure 12.

4. EXPERIMENTAL DETERMINATION OF THE ROTATION ANGLE IN THE UPSTROKE PHASE [14]

The concept used for the experiment is depicted in Figure 13. The basic setup for the static load experiment (Figure 14) can be applied to nearly any current or future flapping-wing MAV design. Of course, this experiment could easily be reworked for use on other insects. The experimental curve reported in Figure 15, and used for comparisons with the present FE capability, has been obtained by fitting all the points experimentally determined.

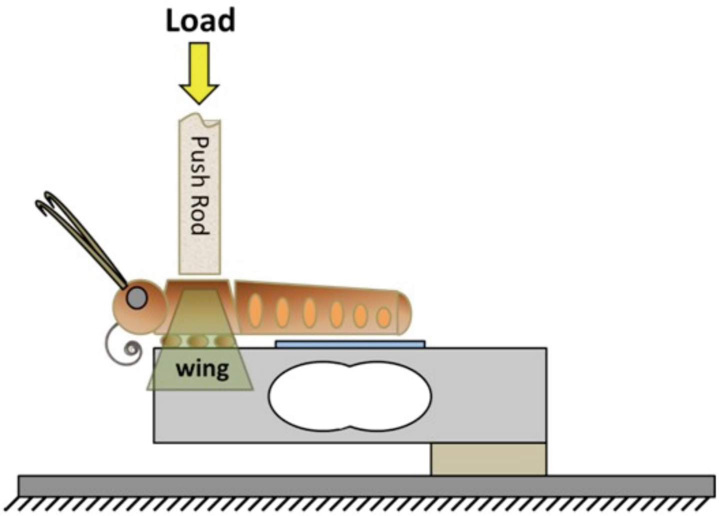

Figure 13. Depiction of cantilever beam load cell with moth [14]

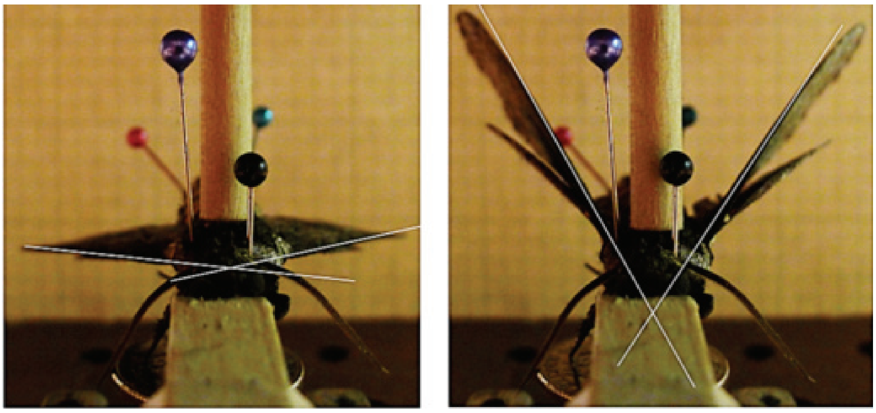

Figure 14. Experimentally-Induced Upstroke with a Static Compression of the Tergal Plate [14]

5. NUMERICAL EVALUATIONS AND COMPARISONS WITH EXPERIMENTAL DATA

The experimental investigation [14] (see also Section 4) generated some points that were fitted with a parabolic curve. In particular, the change of angle between the displaced configuration and the condition at rest was investigated. The experimental results were obtained from different actual insects and, therefore, include all the structural nonlinearities. In the present finite element model the nonlinearities are not included and the real material and thickness distributions are not the ones the Manduca Sexta possesses. For that reason, it is not reasonable to expect a perfect match with the experimental data (see Figure 15). The tuning of the model (e.g. spring values) helped to match the order of magnitude of the rotation angle of the upstroke motion. The present results were obtained by using an in-house triangular shell element based on the formulation presented in Reference [27]. This paper focuses on the linear static response. Thus, the geometric stiffness matrix has been zeroed out in the calculations, leaving only the elastic contribution. This finite element capability can handle the case of multilayered composite structures and will be used in the future for more detailed models of the thorax. The results have been validated against NASTRAN and excellent correlation, was demonstrated. A small difference in the results can be observed. This is due to the different adopted finite elements (CTRIA3 in the case of NASTRAN; for the present shell element see Reference [27]). It has also been verified that the amount of elastic energy, corresponding to the upstroke numerical simulation, correlates very well with the experiment. Indeed, this could be directly realized if it is first observed that the displacements of the thorax in correspondence of the applied loads (which simulate the DVM's contraction) are directly related to the wing's angular displacement, and, second, if it is realized that the areas below the experimental and present curves in Figure 15 are comparable.

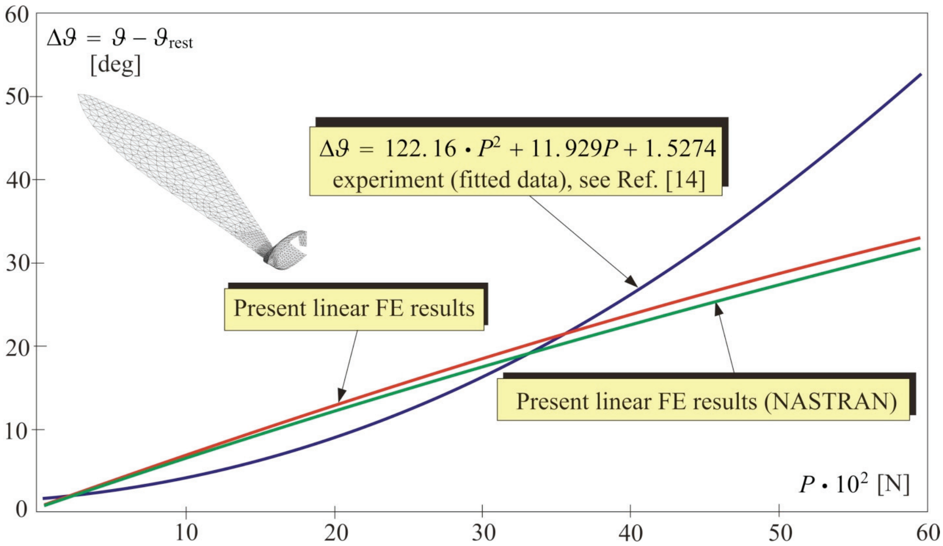

Figure 15. Static Load Simulating the DVMs Contraction (Upstroke Motion): Change of the Wing's Angle Measured From the Position at Rest and Comparison with Experimental Data

Figure 16 shows the upstroke rotation corresponding to an applied load (referred to the entire model and not just half of it) $P = 0.6N$ (see also Figure 11 for the graphical interpretation of the load causing the upstroke motion).

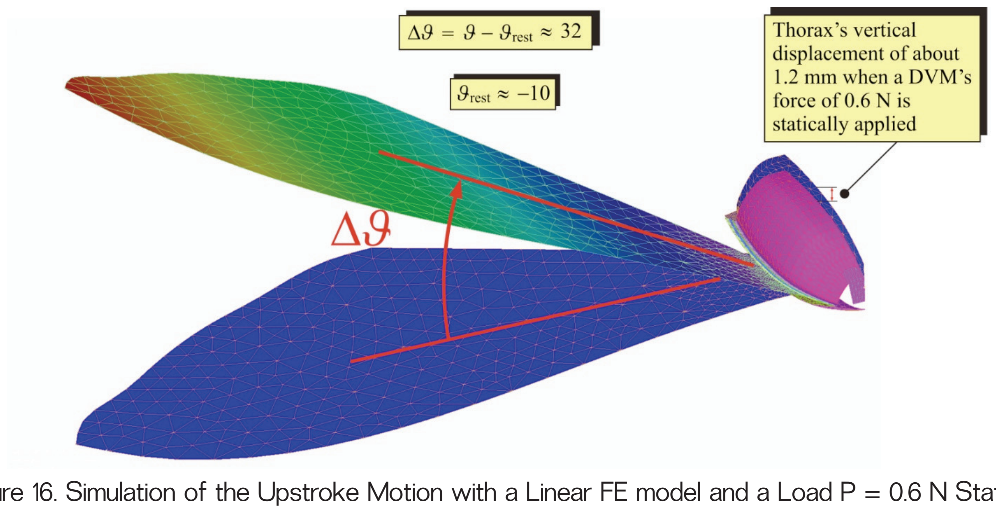

Figure 16. Simulation of the Upstroke Motion with a Linear FE model and a Load P = 0.6 N Statically Applied to Simulate DVM's Contraction

Figure 17 presents the downstroke rotation obtained with the in-house code and the NASTRAN commercial software. For that simulation no experimental investigation was available. However, it should be noted that the FE model presented here can capture the downstroke motion of the actual insect from a qualitative point of view only. This is normal, since the goal is not to model the real Manduca Sexta but just learn from it and use the knowledge for engineering purposes.

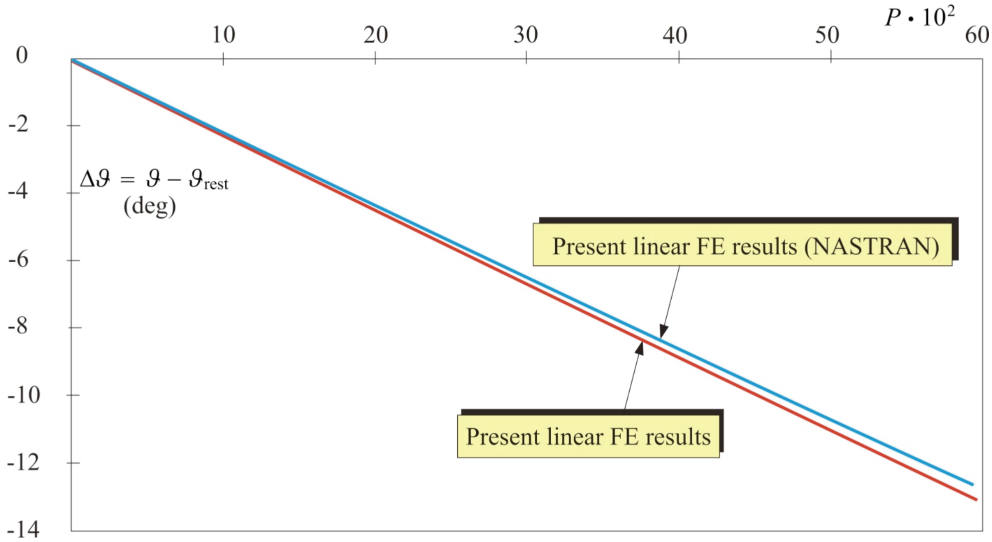

Figure 17. Static Load Simulating the DLMs Contraction (Downstroke Motion): Change of the Wing's Angle Measured From the Position at Rest

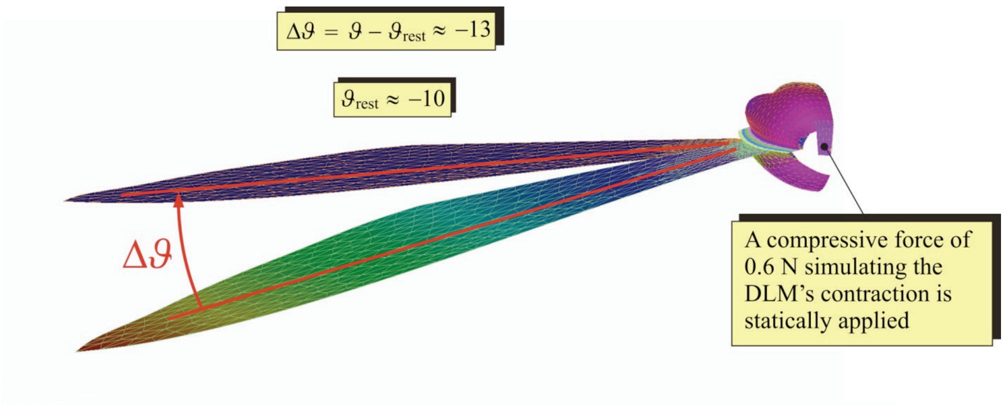

Figure 18. Simulation of the Downstroke Motion with a Linear FE model and a Load P = 0.6 N Statically Applied to Simulate DLM's Contraction

Figure 18 shows the rotation of the wing corresponding to the downstroke motion consequent of a compressive force simulating the contraction of the DLMs (see also Figure 12).

6. CONCLUSION

A preliminary finite element model of the Manduca Sexta flight system (thorax and wing) has been presented. The goal of this effort was to understand and quantify the complex effect of the thorax's muscles during the upstroke and donwstroke motions of the wing. Experimentally evaluated values for the thickness and elastic modulus of the upper portion of the thorax (tergal plate) have been adopted to simulate the correct order of magnitude of the actual insect's response.

The representation of the complex hinge mechanism that connects the wing to the thorax was capable of successfully representing both the upstroke and downstroke motions. The downstroke and upstroke were induced by statically applied loads simulating the contraction of the muscles (dorso-ventral muscles in the case of upstroke and dorso-longitudinal muscles in the case of downstroke). The muscles were modeled with translational elastic linear springs.

Future investigations will present more sophisticated models for the hinge, to allow the large torsional deformations of the wing typical of the supination and pronation phases. Moreover, one-way hinges will also be adopted for a more realistic simulation of the actual flight conditions.

7. ACKNOWLEDGMENTS

The first and fourth authors acknowledge the support by San Diego State University (College of Engineering). The second and third author would like to thank Dr Douglas Smith of AFOSR for his support.

REFERENCES

[1] DARPA Selects Micro Air Vehicle Contractor," *US Department of Defense Reloase*, 12 Dec 1997, No. 676-97, http://www.defense.gov/releases/release.aspx?releaseid=1538

[2] Ho, S., Nassef, H., Pornsinsirirak N., Tai Y. C., and Ho, C.M., "Unsteady Aerodynamics and Flow Control For Flapping Wing Flyers" *Progress in Aerospace Sciences*, Vol. 39, 2003, pp. 635–681.

[3] Kim, J. O., and Kim, C., "Computational Investigation of Three-Dimensional Unsteady Flowfield Characteristics Around Insects' Flapping Flight" *AIAA Journal*, Vol. 49, No. 5, May 2011, pp. 953–968.

[4] Lee, K.B., Kim, J. O., and Kim, C., "Aerodynamic Effects of Structural Flexibility in Two-Dimensional Insect Flapping Flight" *Journal of Aircraft*, Vol. 48, No. 3, May-June 2011, pp. 894–909.

[5] Tanaka, H., Whitney, J.P., and Wood, R.J., "Effect of Flexural and Torsional Wing Flexibility on Lift Generation in Hoverly Flight" *Integrative and Comparative Biology* , Vol. 51, No. 1, 2011, pp. 142–150, DOI: 10.1093/icb/icr051.

[6] Shyy, W., Lian, Y., Tang, J., Viieru, D., and Liu, H., "Aerodynamics of Low Reynolds Number Flyers" *Cambridge University Press* , ISBN-13 978-0-521-88278-1

[7] Ellington, C., Van Den Berg, C., Thomas, A., "Leading-Edge Vortices in Insect Flight" *Nature*, Vol. 384, No. 6610, 1996, pp 626-630

[8] Liu, H., and, Kawachi, K., "A Numerical Study of Insect Flight" *Journal of Computational Physics*, Vol. 146, 1998, pp 124-156, doi:10.1006/jcph.1998.6019

[9] Weis-Fogh, T., "Quick Estimates of Flight Fitness in hovering Animals" *Journal of Experimental Biology,* Vol. 59, 1973, pp. 169-230

[10] Dickinson, M.H., and Gotz, K.G., "Unsteady Aerodynamic Performance of Model Wings at Low Reynolds Number" *Journal of Experimental Biology*, Vol. 174, No. 1, 1993, pp 45-64

[11] Dickinson, M.H., Lehmann, F., and Sane, F., "Wing Rotation and the Aerodynamic Basis of Insect Flight", *Science*, Vol. 284, No. 5422, 1999, pp 1954-1960

[12] Combes, S.A., and Daniel, T.L., "Flexural Stiffness in Insect Wings. I. Scaling and Influence of Wing Venation" *Journal of Experimental Biology*, Vol. 206, 2003, pp 2979-2987

[13] Combes, S.A., and Daniel, T.L., "Flexural Stiffness in Insect Wings. II. Spatial Distribution and Dynamic Wing Bending Venation" *Journal of Experimental Biology*, Vol. 206, 2003, pp 2989-2997

[14] Hollenbeck, A.C., "Evaluation of the Thorax of Manduca Sexta for Flapping Wing Micro Air Vehicle Applications" *Master Thesis, Air Force Institute of Technology*, 164 pages

[15] Wootton, R.J., Herbert, R.C., Young, P.G., and Evans, K.E. "Approaches to the structural modelling of insect wings" *Phil. Trans. R. Soc. Lond. B*, Vol. 358, 2003, pp 1577-1587

[16] Wootton, R.J., "Support and Deformability in Insect Wings" *J. Zool B*, Vol. 193, 1981, pp 447-468

[17] Brodsky, A.K "The Evolution of Insect Flight" *New York, NY: Oxford University Press*

[18] Nakata, T., and Liu, H., "Aerodynamic Performance of a Hovering Hawkmoth with Flexible Wings: a Computational Approach" *Proceedings of the Royal Society B*, Vol. 279, 2012, pp 722-731, DOI:10.1098/rspb.2011.1023

[19] Wu, G., and Zeng, L., "Measuring the Kinematics of a Free-Flying Hawk-moth (Macroglossum Stellarum) by a Comb-Fringe Projection Method" *Acta Mech. Sin. B*, Vol. 26, 2009, pp 67-71, DOI:10.1007/s10409-009-0306-y

[20] Bolsman, C.T., Goosen J.F.L., and Van Kuelen, F., "Insect-Inspired Wing Actuation Structures Based on Ring-type Resonators" *Active and Passive Smaar Structures and Integrated Systems*, Vol. 6928, 69281I, 2008, DOI:10.117/12.776084

[21] Wootton, R.J., "The Insect Flight Scheleton: Towards a New Technology?" Paper AIAA 2006-36

[22] Willmont, A.P., and Ellington, C.P., "Mechanics of Flight in the Hawkmoth Manduca Sexta I: Kinematics of Hovering Forward Flight" *Journal of Experimental Biology*, Vol. 200, 1997

[23] Deleon, N.E., and Palazotto, A., "The Evaluation of a biologically Inspired Engineered MAV Wing Compared to the Manduca Sexta Wing Under Simulated Flapping Conditions" *International Journal of micro Air Vehicles,* in press

[24] Khan, Z.A., and Agrawal, S.K., "Optimal Hovering Kinematics of Flapping Wings for Micro Air Vehicles", *AIAA Journal*, Vol. 49, No. 2, 2011, pp. 257-268

[25] Dudley, R., "The Biomechanics of Insect Flight, From Function and Evolution" *Princeton Univ Press*, Princeton, NJ, 2002

[26] Wainwright, S.A., Biggs, W.D., Currey, J.D., and Gosline, J.M. "Mechanical Design in Organisms" *Princeton Univ Press*, Princeton, NJ, 1982

[27] Gal, E., and Levy, R. "The Geometric Stiffness of Triangular Composite-Materials Shell Elements" *Computers and Structures*, Vol. 83, 2005, pp 2318-2333