Bio-inspired Thorax for Flapping-Wing Robotfly

Teo Wei Xiong[a], Lau Gih Keong[a], Li King Ho, Holden[b]
[a]Nanyang Technological University, School of Mechanical and Aerospace Engineering, 50 Nanyang Avenue, Singapore, Singapore 639798;
[b]Defence Science Organisation National Laboratories, 20 Science Park Drive, Singapore, Singapore 118230

ABSTRACT

Insects are impressive natural flyers. They fly with high agility and maneuverability by flapping their wings. Emulating their flight capability and flight mechanisms may provide a good start in the design of a micro air vehicle (MAV). In this paper, wing flappers are designed and developed with reference to the blueprint of the flight thorax of insects. The developed wing flappers consist of a thoracic frame structure as a flapping mechanism and a vibration motor as a driver. The bio-inspired thorax design is evaluated and its performances are compared with those of the flapping wing insects. The initial prototype demonstrates that the wing flappers are comparable to the insects in terms of the wingbeat frequency and body mass. The initial wing flappers can flaps at a flapping angle of 30°. In addition, simplified analytic model of the wing flappers are derived to optimized the design. Upon redesigned, an improved wing flappers can flaps at at a large flapping angle of 75°.

Keywords: Micro Air Vehicle; flapping wing insects; flight mechanisms; thorax

1. INTRODUCTION

Micro Air Vehicles (MAVs) have been a popular subject of research for the past two decades. Defence Advanced Research Project Agency (DARPA) began funding researches into MAV in the 1990s and since then, there have been several novel designs of MAVs proposed. MAVs have many applications for both the military and also civilian uses. Applications in military include reconnaissance and increasing situational awareness for the land soldiers without the need of heavy equipments and compromising stealth. For civilians, MAVs can be used in search and rescue operations where small and tight space makes it impossible for rescuers to move forward [10]. Therefore, the many benefits of a MAV have propelled increased interest in the design of a MAV.

The definition given by DARPA for a MAV is an aerial vehicle with a dimension of less than 15 cm in length, width or height. There are currently three possible types of MAV, namely the fixed-wing, rotary and the flapping wing design. Fixed-wing MAV adopts a conventional airfoil design, which is well understood in conventional aerodynamics. However, fixed-wing MAVs have poor maneuverability for indoor applications. Rotary and flapping wing designs provide better maneuverability but at the expense of heavy power consumption which results in a short endurance.

The remarkable flight capabilities of the animal kingdoms have lead to interest in studying their flight mechanisms and applying them in the MAV design. Several researchers have adopted this flapping wing design [1] [11] [12]. Design of a miniaturized MAV is challenging as there is a need to balance the size versus the function of each subsystems. There are several actuation methods to drive MAV, namely dielectric elastomers, and piezoelectric actuators, and electric motors [1]. Most large MAV designs adopts an electric motor, revolute joints and gears to generate wing flapping motion. These designs are subjected to friction loss and they may perform efficiently when they are miniaturized [13].

In this paper, we propose and develop an 'active' thorax to enable the wing flapping motion of a robotfly. The designs of thoracic frame structures are inspired by the insect thorax. They have similar shapes to morphology of insect thorax. However, the developed 'active' thorax is made of carbon-fiber reinforced polymer composite and it is driven a man-made actuator, such as an electric motor. This paper will first review the flight mechanism of the flapping wing insects and provide an idea of the performance we should expect from an initial design of the prototype. Then, we shall develop a bio-inspired flight mechanism design and the prototype to discuss on its feasibility for flight with respect to the

Active and Passive Smart Structures and Integrated Systems 2010, edited by Mehrdad N. Ghasemi-Nejhad,
Proc. of SPIE Vol. 7643, 76431P · © 2010 SPIE · CCC code: 0277-786X/10/$18 · doi: 10.1117/12.847419

properties of the frame structure. In the following section, a simplified analytical model of the frame structure will be discussed and parameters optimizing the frame properties will be identified. Lastly, an improved model of the frame structure will be fabricated to verify the optimizing parameters.

2. REVIEW ON FLAPPING WING INSECTS

Flapping wing insects have been suggested to first fly around 350 million years ago [2]. During the millions of years of evolution, flapping wing insects have undergone the process of natural selection and emerge with impressive wings, kinematics, aerodynamics, control and sensory systems with which no man-made machines are able to match. These impressive flight capabilities lead us to review the flapping wing insects' flight mechanisms and draw inspiration from them to design the frame structure for the robotfly. In this section, the flight mechanism of a typical flapping wing insect will be discussed. The review includes the muscular systems and the thoracic structure function in the wing flapping mechanism. The use of energy conservation in the flight mechanism will also be briefly covered as it will be a crucial element in the design of a functional robotfly. More detailed discussions in the insects' flight mechanism can be found in various papers [6] [7] [8] [15].

2.1 Insects

The impressive flight capabilities of an insect are powered by the flight muscles which fills the thorax. The number of flight muscles varies in different species of insects from 9-12 pairs of muscles in cockroaches, locusts and karydids to 4 or 5 pairs of muscles in flies and only 2 pairs in bees [3]. Flights muscles in insects can be categorized into power muscles and control muscles. As the name suggest, power muscles are required in driving the oscillation of wings while the control muscles are required to provide the continuous adjustments of the wing stroke amplitude and angle of attack. The control muscles are important in maintaining flight stability and executing sharp turns and maneuvers. In general, in advanced fliers such as honeybee, control muscles are more important than power muscles and thus more in number as compared to primitive fliers such as locusts [3]. The power muscles which drive the oscillation of wings can be further classified into direct and indirect muscles which are defined by its method of actuating wing oscillation.

Figure 1 shows the cross section of a half thorax with the various features of the thorax highlighted. Direct muscles are attached directly to the wing base and its contraction will result in a downward movement in the wing. Therefore, direct muscles are also known as wing depressors. Indirect muscles are connected to the dorsal plate of the thorax or also known as the tergum. Contraction of the indirect muscles changes the shape of the thorax structure and this result in an upward motion of the wing. Wing flapping due to contraction of the indirect muscle can be visualized as a lever system where the contraction is viewed as the downward effort on the lever resulting in an upward load of the wing as shown in the Figure 2. Therefore, wing oscillation is a result of both the direct and indirect muscles contracting and relaxing alternately.

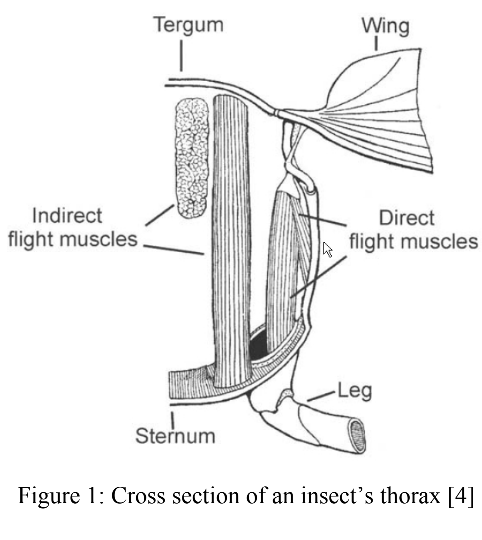

Figure 1: Cross section of an insect's thorax [4]

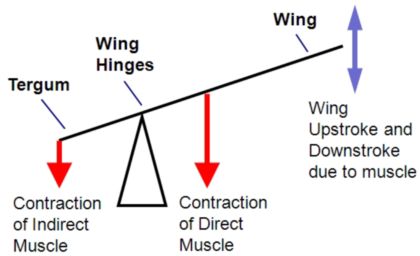

Figure 2: Simplification of insect wing actuation by indirect muscles

2.2 Flight parameters

Flight capabilities of a flapping wing insect can be quantitatively described using a few flight parameters, namely, the wing stroke amplitude, wingbeat frequency, and body mass. These parameters could serve for assessing the performance of a MAV design. Wing stroke amplitude is the flap angle between the two half strokes. Insects display a wing stroke ranging from 70^0 to 130^0 [6]. On the other hand, the wingbeat frequency generally ranges between the range from 20Hz to 40Hz for larger insects such as the odonata and orthopteroid insects, whereas it ranges above 100Hz for smaller insects such flies [6]. Body mass of insects ranges from 20-30µg for small insects to approximately 10g for a large insect [7]. The wingbeat frequency is related to the body mass such that the frequency (f) decreases with mass (m) at a power scale of -0.24 (i.e. $f=m^{-0.24}$) [7].To emulate the insects, a MAV design is generally desired to achieve a wing stroke of 120° at comparable wingbeat freqeuncy [1] [2]. Often, the MAV are compared with insects in terms of the wingbeat frequency and the body mass, such as shown in Figure XII.

2.3 Elastic storage

MAV requires massive amount of energy for hovering flight. In comparison, insects are far more energy efficient to perform the flight [14]. This is because insects can store and recovered elastic energy in the deformed thorax during the wing flapping, beside recovering energy from the vortices through their wing [8]. In this paper, we will discuss the use of elastic storage in the deformed thorax. The wing hinges of insects often contains protein resilin which are of high toughness and thus have the ability to absorb energy [9]. During the wing stroke, the kinetic energy of the wing is converted to the elastic energy by stretching and deforming the thorax. Upon reaching the end of the half stroke, this elastic energy is released and thus provides the energy to accelerate the wing in the opposite direction. Therefore, insects are able to achieve better energy efficient flight through this mechanism.

3. ROBOTFLY FLIGHT MECHANISM DESIGN

Guided by flight mechanism and thorax morphology of insects, we shall develop a thorax design with the following characteristics:

1) The thorax should employ the use of compliant mechanisms as joints which improve the energy efficiency of the robotfly by reducing friction loss and also through the use of energy storage [1].

2) The thorax should have a low weight to reduce the payload during flight.

3) The thorax design should produce the required wingbeat frequency and wing stroke amplitude to sustain flight.

3.1 'Active' Thorax Prototype Design

We propose a frame design which imitates the functions and morphology of an insect's thorax and its indirect flight muscles. Figure 3 illustrates the design of the frame. The design has a flat tergum and wing roots connected to an arc-shape sternum through flexural joints. Two joints connect the wing root to the sternum and the tergum respectively. Both joints are clustered near one end of the wing root. One joins the end of wing root to the end of the tergum while the other joins the end of sternum of an adjacent point to the same end of wing root. A wing can be attached parallel to the wing root and the thorax can house an actuator which applies a 'pull force' to the tergum. However, we shall first consider the design without wing attached to show that the flight mechanism is feasible.

The design works on the principle of a “lever” mechanism. Zooming to a half of the thorax, the wing root is pivoted to the base through a fulcrum of a compliant joint. The wing root is brought into rotation when a load is applied onto the tergum that connects to one end of the wing root through another compliant joint. In this way, the wing root can rotates to flap a wing.

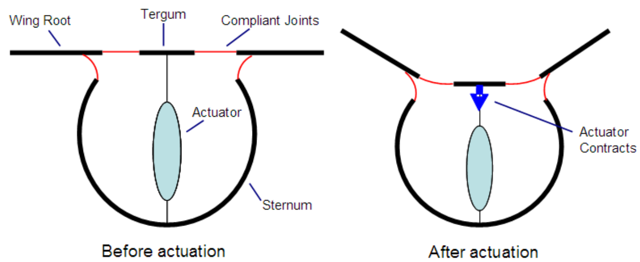

Figure 3: Design of bio-inspired structure

3.2 Prototype Fabrication

The thoracic frame is made of carbon-fibre-reinforced epoxy (CFRE) composite and a polyimide film. It is realized using the composite hand lay-up method. The thoracic frame comprises of rigid segments and compliant hinges. Rigid segments, which include the sternum, tergum and wing roots, are the CFRE-reinforced regions of polyimide. The flexural joints are defined over the un-reinforced regions of polyimide. The adopted carbon fiber fabric is 0.27mm thick with 2mm wide by 2mm long interweaved strands. Epoxy is the matrix material for the composite. Polyimide films (Kapton of DuPont) bonds well to epoxy. In the design phase, a 50 µm thick polyimide film is used. Varying thickness of the Kapton® films allows the adjustment of the flexure stiffness.

Figure 4 shows the fabrication steps for making the thorax. The prototype is built in two parts. A 27mm diameter Polyvinyl Chloride (PVC) pipe is used as the mold for the sternum while a flat glass base is used as the mold for the tergum and wing roots. Polyvinyl Alcohol (PVA) is applied as the release agent on the pipe and glass base prior to building up the layers. Epoxy is then spread onto the carbon fiber fabrics and allowed for an initial cure before cutting into the desired length. The design has the following dimensions shown in Figure 4. The pair of compliant joints between the tergum and wing root is 3mm long while the pair between the sternum and wing root is 5mm long. Both parts are left to cure fully before joined together using another piece of CFRE between them.

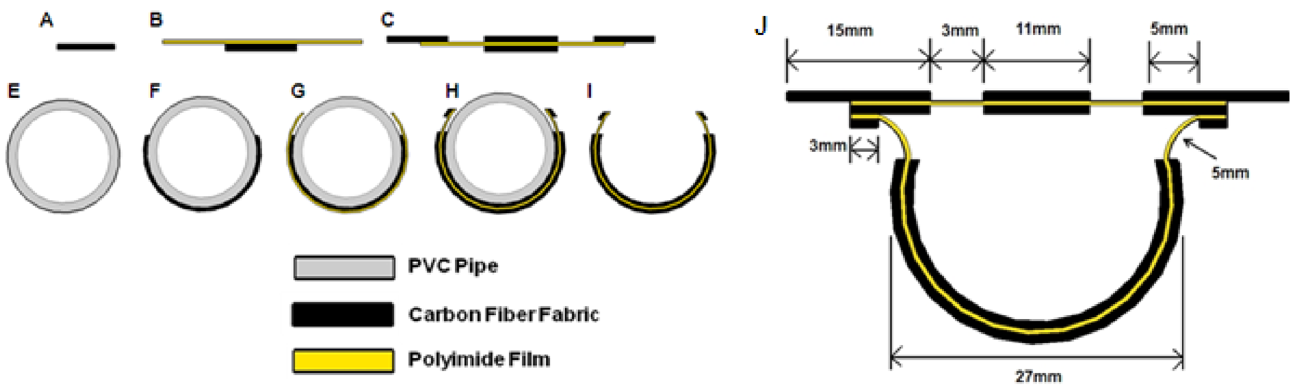

Figure 4: Fabrication steps for a thorax design with round sternum (‘belly’)

3.3 Results

Figure 5 shows a prototype of the thorax design. Some simple tests are devised to measure the resonance frequency and amplitude of the oscillating thorax. The thorax oscillates under the excitation by a small vibration motor, which carry a rotating unbalance mass and induces an unbalance force. The motor is attached to the top of the tergum as seen in Figure 8 and Figure 9. The rotation frequency of the motor can be controlled by varying the input voltage. When the rotation frequency coincides with the natural frequency of the thorax, the thorax will vibrate in resonance.

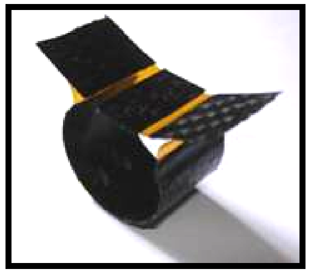

Figure 5: Fabricated prototype

A strobe and a camera are used in the experiments to measure the stroke angle and wingbeat frequency. Flashes of light emitted by the strobe were used to illuminate the oscillating thorax. Frequency of the strobe light is adjustable. When the strobe frequency coincides with the driving frequency, an oscillating thorax will appear ‘motionless’. In other words, the oscillatory motion is ‘frozen’ and captured in the video under the strobe illumination. In this way, the wing stroke amplitude and the displacement of the tergum of the oscillating thorax can be visualized and determined as for a static displacement. In addition, resonance frequency of the thorax structure can be identified with the help of the strobe. At resonance, the driving frequency at which the thorax vibrates most excessively can be measured from the strobe frequency. The measurement results, together with design parameters, are shown in the Table I.

Table 1: Properties of prototype frame structures

Parameters	**Magnitude**
Diameter of Frame	27 mm
Mass of frame	≈1.979g
Mass of frame with actuator	≈4.429g
Stiffness	65.4 N/m
Resonance Frequency	20 Hz
Wing Stroke Amplitude	30 degrees
Tergum Displacement	5 mm
Static Amplification Factor	6 degrees/mm

The static amplification factor is defined as the flap angle of wing root per unit tergum displacement. It indicates how effective the design is for wing transmission. Tergum stiffness is a useful parameter for actuator selection. It is obtained by loading the tergum and measuring the resulted displacement. Figure 6 illustrates the variation of tergum displacement with mass added to the tergum. The load deformation in both downwards and upwards tergum displacement is found to be the same.

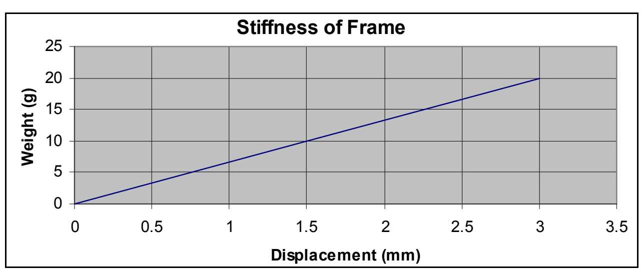

Figure 6: Plot of tergum displacement with loading

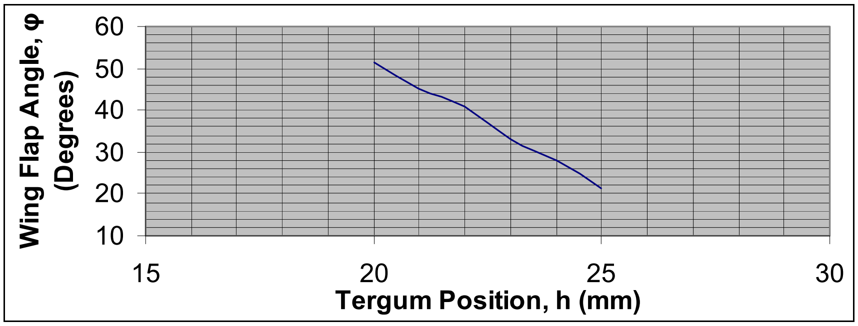

Figure 7: Variation of Wing Flap Angle with tergum displacement at 20 Hz

When resonating at 20 Hz, the prototype thorax exhibits a wing stroke of 30°, about a quarter of the insect wing stroke amplitude. Figure 8 shows the progressive motion of the wing root and tergum capture in the video. Figure 7 plots variation between the wing flap angle and the position of the tergum and is shown to be approximately linear. Resonance frequency of the thorax at which the wing flap is compared to the wingbeat frequency of insects with respect to the mass. Figure 15 shows that mass of the frame structure with the actuator and its wingbeat frequency are comparable with those of large insects.

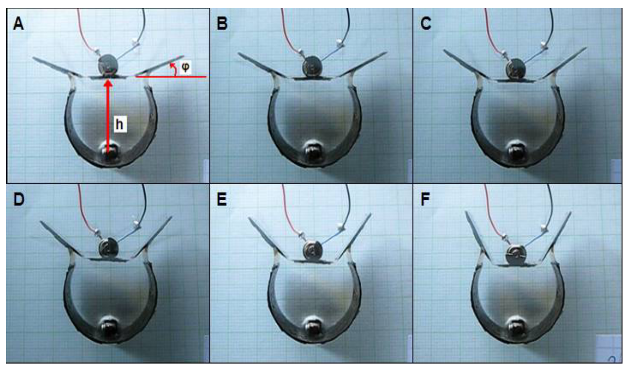

Figure 8: Symmetric flapping motion of frame structure at 20 Hz

Videos in Figure 9 show that the vibrations become asymmetric as the rotating frequency of the unbalanced mass goes slightly beyond its resonating frequency of 20 Hz but below 22 Hz. The asymmetric vibration is due to the use of rotating unbalanced mass, which does not only cause a vertical oscillatory motion, but also a horizontal oscillatory motion. Also, unequal length between the joints for the thorax prototype and undesired resonance modes may also attribute to such asymmetric vibrations.

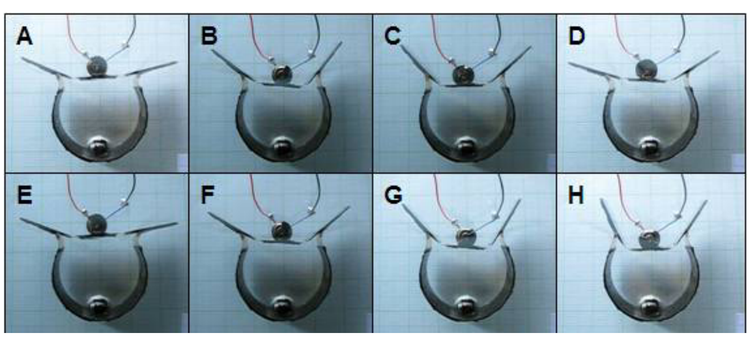

Figure 9: Asymmetric flapping motion of frame structure at above 20-22 Hz

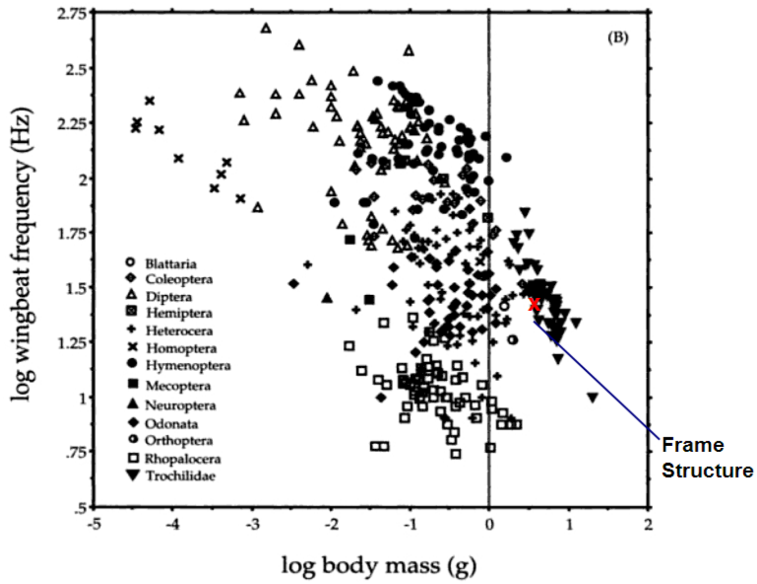

Figure 10: Plot of insects' wingbeat frequency and body mass compared to the frame structure [7]

4. IMPROVED DESIGN

In the previous section, a prototype of the robotfly thorax is demonstrated to flap with an angle of 30° at a frequency of 20 Hz. However, upon attaching a wing to the wing roots, the prototype is incapable of flapping well. Its resonance frequency and wing stroke amplitude decrease drastically. In view of these, we need to improve the design of the robotfly thorax in order to increase the resonance frequency and wing stroke amplitude upon loaded with wings. To do so, we shall first develop a simple analytical model to understand the influence of various design parameters on the resonance frequency.

4.1 Simplified Analytical Model

For a robotfly thorax, wing stroke angle and frequency are measured directly from rotary motion of the wing roots. With reference to the configuration of the thorax, a wing root is supported on a compliant joint at an intermediate point on the wing root. One end of the wing root is connected to the tergum on which a vibration motor is mounted, whereas the other end could carry a wing. The wing root on the compliant joint in Figure 11 can be idealized as a rigid lever on a fulcrum with a torsional spring, as shown in Figure 12. Such an idealization serves well to formulate a mathematical model to predict motion of the wing root. The mathematical model will be very useful to guide the thorax design.

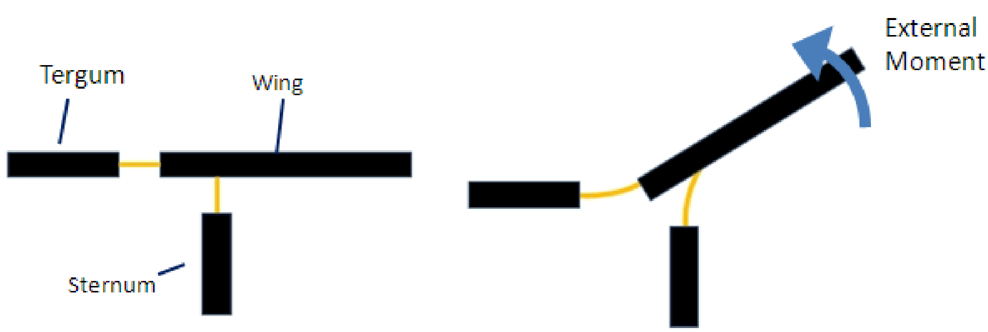

Figure 11: Compliant joints and wing mechanism

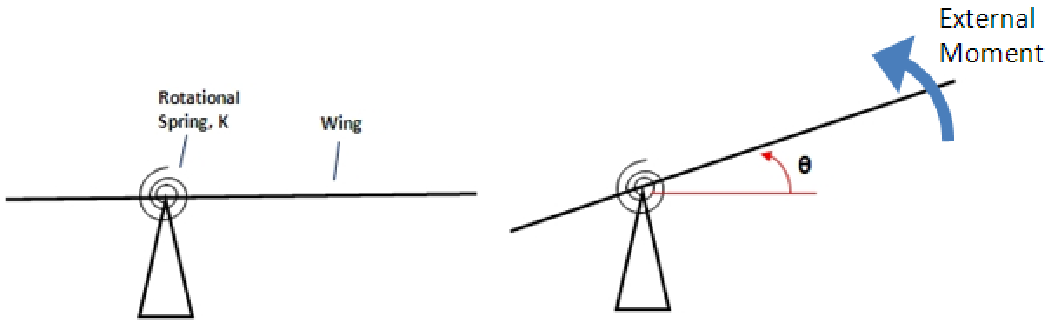

Figure 12: Simplified analytical modeling of 'active' thorax

During free vibration, the wing root vibrates with zero external moment. Based on the idealization and applying Netwon's second law, a differential equation of motion is formulated to predict the free vibration of a wing root:

$$J\ddot{\theta} + (k_1 + k_2)\theta = 0\,, \tag{1}$$

in which J is the rotational moment of inertial of the wing root and contribution from both the mass of the tergum and the vibrator; k_1 and k_2 are the rotational stiffness of the two compliant joints.

The rotational stiffness of the compliant joints are related to the hinge geometry and material properties such that

$$k_1 = \frac{E_1 I_1}{L_1}\,,$$

$$k_2 = \frac{E_2 I_2}{L_2}\,,$$

in which E_1 and E_2 are Young's modulus of the constituent material, I_1 and I_2 are the areal moment of inertia of the cross sectional area, L_1 and L_2 are the length of the two hinges respectively. The rotational stiffness is proportional to the elastic modulus of the flexural material and the area moment of inertia while inversely proportional to the length of the joints.

Solving the differential equation leads to the natural frequency of the system, with an expression as in Equation (2):

$$\omega = \sqrt{\frac{(k_1 + k_2)}{J}} \tag{2}$$

From Equation (2), we observe that square of the resonance frequency is proportional to the stiffness of the joints and inversely proportional to the rotational inertial of the wings. Through the analytical estimation, it was shown that the resonance frequency can be increased by increasing the joints stiffness and decreasing the rotational inertial of the thorax and its wing. In order to increase the resonance frequency and flapping angle, the joints stiffness and rotational inertia need to be optimized.

For a vibrator with a rotating unbalance mass, the input force is a sinusoidal function as below:

$$F(t) = m\omega^2 e \sin(\omega t), \tag{3}$$

where F(t) is the actuating force, m is the unbalance mass, ω is the rotating frequency, e is the eccentricity of the unbalance mass and t is the time in oscillation.

Increasing the rotation frequency of the rotating unbalance mass actuator will increase the force output. In the experiment, the stiffness of the system is shown to be linear. Therefore, an increase in the force acting on the tergum will increase the wing stroke amplitude. On the other hand, stiffness of the thorax influence both the wing stroke amplitude and the wingbeat frequency. An increase in the stiffness may compromise the static amplification factor but increase the resonant frequency. Hence, there may be an optimum stiffness at which resonance frequency and wing stroke amplitude are adequately high.

4.2 Areas of improvement

Based on the discussion above, it is noticed that a proper sizing of the thorax design can improve the flap angle and natural frequency. The sizing affects the joint stiffness and the wing rotational inertia. However, the achievable sizes of the joint or the wing are limited by the fabrication process and the materials used for the joints and wings.

The previous design of thorax with a diameter of 27 mm and a mass of 4.43 gram display a low natural frequency when loaded with wings. However, it is possible to raise the natural frequency by sizing the thorax design down, which reduces the rotational inertia and increases the stiffness. In an improved design (as shown in Figure 13), the thorax is half the initial size but have an enough area to mount the vibrator. Lengths of the compliant joints are reduced in order to increase the joint stiffness. In addition, sternum of the thorax is now altered to two vertical side walls which allow easy mounting onto a test platform. This vertical sternum overcomes the sideway instability of the previous sternum design of a circular shape. Furthermore, the improved thorax design incorporates two wing spars, which will later be used for air foil mounting. The wing spars are bonded to the wing roots. The wing spars are made of carbon fiber rods and bonded to the wing roots. The wing spar is designed to have a higher natural frequency than the thorax's.

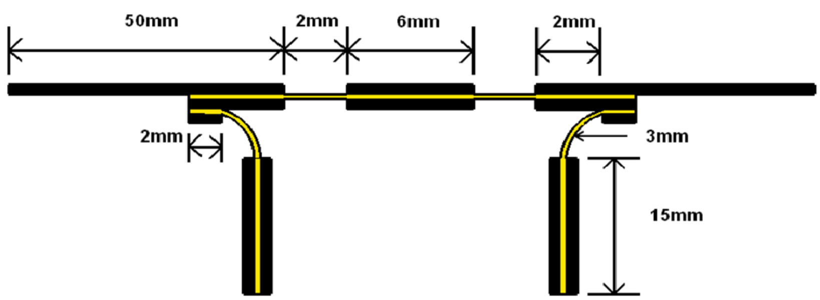

Figure 13: Dimensions of improved 'active' thorax

In the fabrication of the prototype, wet hand lay-up was used to build the rigid composite components of the thorax. This method of fabrication produces heavy composites and is difficult to control the epoxy content and dimensions down to the millimeters range. The use of interweaved cross directional carbon fiber fabrics also introduce redundant weights and thus increased rotational inertia. By using unidirectional carbon fiber pre-pregs, the fabrication process is improved to and capable of making a compact and lightweight thorax. Use of the pre-pregs significantly reduces the additional weight incurred from excess epoxy content and fabrics in the cross direction. In addition, the improved fabrication process also adopts vacuum bagging of the composite layup in order to ensure uniform weight distribution and remove excess epoxy.

4.3 Improved thorax design

Figure 14 shows a prototype of an improved thorax design. The vertical bases of the thorax are mounted on a mouldable rubber platform for support.

Figure 15 shows the progressive motion of the improved thorax when actuated by the vibrator. The improved thorax demonstrates an increase in the performance even though a wing spar is attached. The resonance frequency had increased slightly to 23 Hz while the wing stroke amplitude had been increased significantly to 75°. The weight of the frame with wing spar is also reduced significantly to 0.379 g with the use of better materials, fabrication methods and smaller dimensions.

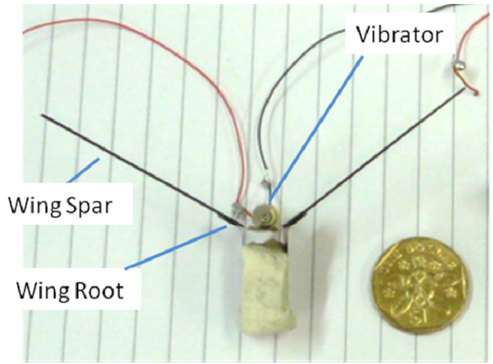

Figure 14: A prototype of the improved thorax design

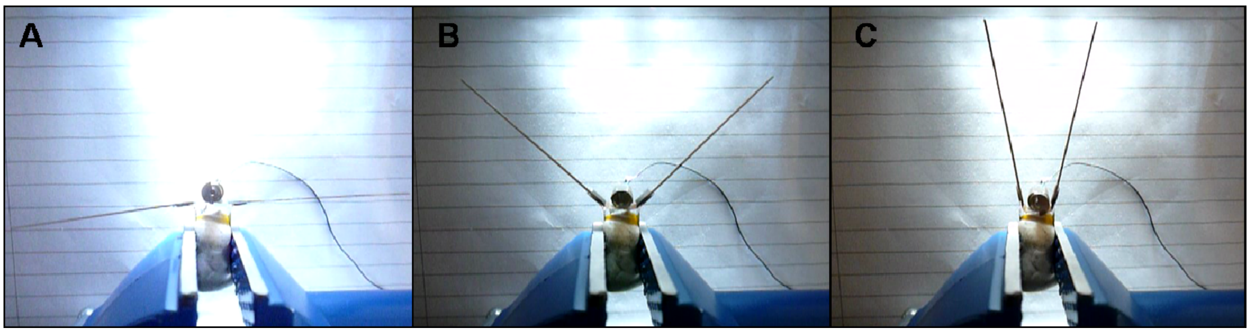

Figure 15: Progressive motion of improved 'active' thorax

5. CONCLUSION AND FUTURE WORK

In this paper, we presented a thoracic frame structure for wing transmission, mimicking the insect thorax. The proposed frame structure was successfully fabricated using carbon-fibre-reinforced epoxy on polyimide laminate. The prototype of 'active thorax' demonstrates wing flap at a stroke amplitude of 30° at a resonance frequency of 20Hz. Wing beat frequency and mass of the design are comparable to those of large insects. This prototype proves that the design concepts work for a flapping wing MAV. However, the addition of the wing results in significant decrease in resonance frequency and wing stroke amplitude. Optimization of the joints stiffness and rotational inertia by using better materials, fabrication methods and varying the thorax dimensions produces significantly better results. The improved design with wing spars demonstrates a wing stroke amplitude of 75^0 and resonance frequency of 23Hz. The ability of the bio-inspired flight mechanism to produce comparable wing stroke amplitudes and wingbeat frequency to insects illustrates the potential of developing an MAV which is capable of flight. Furthermore, the low power requirement of the actuator reduces the power and energy problem in most MAV design. Future work will include improving the fabrication techniques to achieve better control in frame dimensions, improving the wing stroke amplitude, reducing the thorax dimensions and weight to miniaturize it further, experimenting with alternative actuators, analytical modeling of the thorax to better understand the static and dynamic properties of the flapping mechanism and lastly attaching wings to perform tethered or assisted flight test.

ACKNOWLEDGEMENT

The first author would like to express his deepest gratitude to Asst/P Lau Gih Keong, project supervisor from NTU School of MAE and Adj Asst/P Li King Ho, Holden, project supervisor from DSO National Laboratories for all the assistance and advice given. The author would like to thank Casper T. Bolsman and the technicians from Delft University of Technology for the help provided in performing the experiments during the exchange program in Delft, The Netherlands. The author would like to thank Du Pont Company (Singapore) Pte Ltd for providing the Kapton®

films in this research. We wish to acknowledge the funding support for this project from Nanyang Technological University under the Undergraduate Research Experience on Campus (URECA) programme.

REFERENCES

[1] Robert J. Wood, "The First Takeoff of a Biologically Inspired At-Scale Robotic Insect," IEEE Transactions on Robotics, vol. 24, no. 2, April 2008, pp. 341-347.
[2] C. P. Ellington, "The Novel Aerodynamics of Insect Flight: Applications to Micro-Air Vehicles," The Journal of Experimental Biology, vol. 202, issue 23, 1999, pp. 3439-3448.
[3] Jim O. Vigoreaux (Ed.), Nature's Versatile Engine: Insect Flight Muscle Inside and Out, 1st ed. Austin, Texas: Springer and Landes Bioscience, 2006
[4] Snodgrass RE. Principles of Insect Morphology, New York: McGraw-Hill Book Co., 1935
[5] Fritz-Olaf Lehmann, "Aerial Locomotion in Flies and Robots: Kinematic control and aerodynamics of osciilating wings," Arthropod Structure & Development, vol. 33, 2004, pp. 331-345.
[6] R. F. Chapman, The Insects: Structures and Function, 4th ed. New York: Cambridge University Press, 1998.
[7] R. Dudley, The Biomechanics of Insect Flight: Form, Function, Evolution, Princeton: Princeton University Press, 2002.
[8] Michael H. Dickinson, Claire T. Farley, Robert J. Full, M.A.R. Koehl, Rodger Kram and Steven Lehman, "How Animals Move: An Integrative View," Science, vol. 288, no. 5463, April 2000, pp. 100-106
[9] Michael H. Dickinson and Michael S. Tu, "The function of Dipteran Flight Muscles," Comparative Biochemistry and Physiology, vol. 116, no. 3, March 1997, pp. 223-238
[10] Srijya Mohan and G. Sridharan, "Emerging Technologies for Micro-Unmanned Air Vehicles," Defence Science Journal, vol. 51, no. 3, July 2001, pp. 223-228
[11] Casper T. Bolsman, Bjorn Palsson, Hans F.L Goosen, Rob H. Munnig Schmidt and Fred van Keulen, "The Use of Resonant Structures for Miniaturizing FMAVs," 3rd US-European Competition and Workshop on Micro Air Vehicle & European Micro Air Vehicle Conference and Flight Competition, Toulouse, France, September 2007
[12] Casper T. Bolsman, Johannes F. L. Goosen and Fred van Keulen, " Insect-inspired wing actuation structures based on ring-type resonators,"Active and Passive Smart Structures and Integrated Systems 2008, San Diego, California, USA, March 2008
[13] Seah H. McIntosh, Sunil K. Agrawal and Zaeem Khan, "Design of a Mechanism for Biaxial Rotation of a Wing for a Hovering Vehicle," IEEE/ASME Transactions on Mechatronics, vol. 11, no. 2, April 2006, pp. 145-153
[14] Micheal H. Dickinson and John R. B. Lighton, "Muscle Efficiency and Elastic Storage in the Flight Motor of Drosophila, Science, vol. 268, no. 5207, April 1995, pp. 87-90
[15] R.J. Templin, "The spectrum of animal flight: insects to pteosaurs," Progress in Aerospace Sciences, vol. 36, 2000, pp. 393-436