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EXPERIMENTAL STUDY OF THE MECHANICS OF MOTION OF FLAPPING INSECT FLIGHT UNDER WEIGHT LOADING

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ABSTRACT

The results of this study are an evaluation of the mechanics of motion of a weight loaded *Manduca sexta* Hawkmoth during flight using accelerations recorded with an onboard sensory system. Findings indicate that these 'normal' flapping insects maintain relatively fixed body frequencies in both free and weight loaded flight, which correspond with the driving frequency, or wing beat frequency. Within the analysis, a presence of a harmonic body frequency at twice the wing beat frequency was also discovered. The conclusions from this study indicate an average excess muscle power of over 40mW available in free, unloaded flight. Stability robustness of these flapping insects in flight using the results of a large payload disturbance, 856mg or nearly half to one-third the mass of insect, is demonstrated, and their usefulness as platform for cyborg MAV (CMAV) development is presented.

INTRODUCTION

A significant amount of engineering and biological research has focused on developing an understanding of the mechanics of flapping flight [1-16], but little has been cited on the effects of this motion given the presence of disturbances, specifically weight loading [17-21]. This paper aims to provide further insights and reveal its impact on how a biological specimen adapts to such a disruption of its fundamental vehicle dynamics.

The study of flapping flight has many useful applications, from realizing the transition of forward to hovering flight, to understanding unsteady aerodynamic forces, to creation of biomimetic small-scale aircraft, such as flapping micro-air vehicles (MAVs). In examining the vast literature available on the subject of flapping flight [1-16], it is important to note the size and type of flapping motion that is under investigation. In this work, an experimental study is performed on the *Manduca sexta* Hawkmoth, where the physical properties of the male and female specimens tested are listed in Table 1, along with an overhead photograph of the insect in Figure 1.

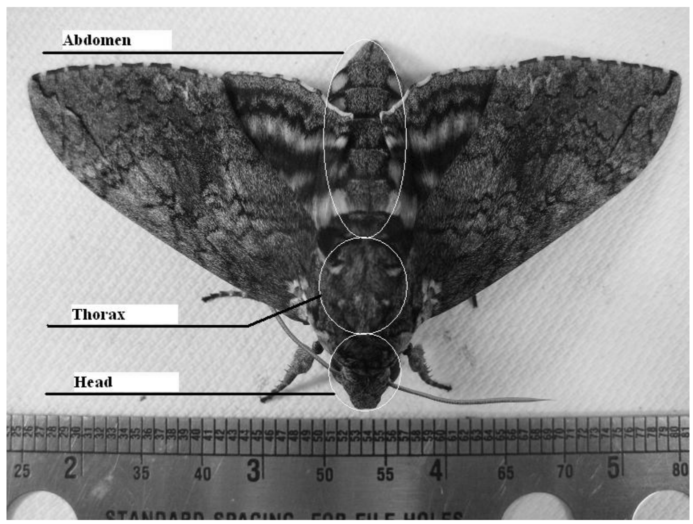

Figure 1. *Manduca sexta* Hawkmoth insect.

Table 1. Physical parameters of insects tested.

	Head mass	Thorax mass	Abdomen mass	Wing mass	Wing area
Female	127mg	833mg	1519mg	104mg	591.4mm^2
Male	123mg	678mg	650mg	76mg	449.6mm^2

These insects utilize 'kinematics of normal insect flight,' [17-18] as opposed to a 'clap-and-fling' method which insects such as Damselflies and butterflies implement. While it has been cited [17] that 'normal' flight produces 25% less lift than 'clap-and-fling' flight, the reasoning for selection of this species as a model in which to study the effects of weight loading in flapping flight are easily summarized; they are relatively large insects with a well studied literature on their free flight aerodynamic performance [22-23], are documented to have a capability of withstanding payloads that can harness sensory electronics [17,24], and are common test subjects as they can be obtained from many breeding facilities within the United States, see Carolina Biological Supply, the University of Arizona, and the Boyce Thomson Institute at Cornell University. The purpose of this study is to not only simply quantify weight loading flight but to also extend the methods by which insect aerodynamics can be conducted experimentally to incorporate onboard sensory data collection. Thus, since ‘clap-and-fling’ flight insects are far less understood in the literature and are incapable of carrying significant payloads in flight, such as for onboard electronics, this study decided to use the *Manduca sexta* species as a basis for testing of this new weight loading measurement technique.

The main application for this research is to provide a basis for the effect of a payload to the mechanics of this species' flight and ultimately the amount of kinetic energy that can be harnessed from the flight using an onboard energy harvesting system, such as a piezoelectric structure or an electromagnetic generator [25-27]. By attaching an energy harvesting device to a flapping species, rechargeable power systems for items such as animal tracking tags can be extended in length for sensory data collection [28]. In addition to applications such as animal tag power harvesting, this research is involved in development of insect cyborgs for use as reconnaissance and surveillance CMAVs [29], where these *Manduca sexta* are implanted with onboard electronics like power harvesting structures [30-31]. These energy harvesting systems are used to recharge the power system that supply energy for flight steering mechanisms, which direct the insects to desired locations [32-33]. The effects of these structures' mass, and the energy absorption that incur with respect to the flight mechanics of the insects, are important in predicting the amount of sustained flight under such conditions. Thus, the importance of this study of weighted loading to the mechanics of the flight is important to the basis for CMAV development and is evident in its critical understanding for any application wishing to prescribe a given load to a flapping vehicle. To emphasize this more, a comparison with another loading study [34] shows the importance of such energy correlations. In that study, it is reported that human users of an energy harvesting backpack, which used a sliding mechanism to allow the load to bounce with each stride, experienced less fatigue than expected, based on the energy harvested and the efficiency of muscle. They suggested that this might be due to gait adaptation. The same might prove to be true of weight loading on flying animals but will be answered by analyzing the dynamic response. In conclusion, this paper provides further insight into the mechanics of motion for weight loading flapping for ‘normal’ insect flight and is compared with a study of the literature to show its contribution.

NOMENCLATURE

a_{max}: Maximum acceleration

f: Wing beat frequency

$m_{specimen}$: Specimen mass

m_T: Specimen mass plus payload mass

$P_{induced}$: Induced power output

$P_{min\ flight}$: Minimal power for flight

Q: Quality factor

Θ: Maximum muscle specific power output

Ξ: Ratio of unladen muscle mass to body mass

Φ: Body angle

Ψ: Ratio of muscle mass to total system mass, m_T

ξ: Damping ratio

σ: Standard deviation

Free Flight Mechanics

Before engaging in a study of a complex set of dynamics involving a system with flapping motion and loading parameters, this section provides a basis for the free flight of flapping insect mechanics. Traditionally the analysis of flapping flight has followed two paths of solvers, the large computational numerical methods, which have tended to make fewer assumptions about the structure of the wake, and the faster conventional methods, which typically have been limited to correction factors or disconnects in the theory when dealing with hovering or forward flight. The common thread between all of these methods though is an attempt to determine the induced power for flapping flight. The induced power, in conjunction with components like the inertial power, profile power and parasitic power, combine to form the mechanical power needed for flapping flight. A correct analysis of mechanical power then, in combination with an estimate of the power generation capability of these flapping insects, would provide an approximation for the maximum payload and energy harvesting that the insect could withstand in flight. To explain just some of the vast range of analyses presented in the literature for solving only the free flight induced power, for numerical analyses alone, heavy computational methods such as the lifting line theory [35], the panel method [36], and the vortex lattice method [37] are used. Conventional methods have included the momentum theory for a fixed wing [38], which is limited to fast forward flight approximations, the momentum theory for a rotary wing [39-40], which is good for both hovering and forward flight but requires a correction factor for the geometry of the wake, and the momentum jet estimate [41], which is limited to hovering and requires its own correction using quasi-steady vortex theory for wake periodicity. A promising but discontinuous conventional method that exists is the vortex ring theory [42], where a gap exists in the theory from hovering [43], which requires a wake evolution from rest, to forward speeds [44], where the wake geometry must be prescribed. A hybrid conventional method also exists known as an added mass of vortex sheets method [45], which contains the same accuracy as the vortex ring theory for hovering and the same accuracy as the momentum theory for fixed wing flight at fast forward velocities. All methods are to this day still being modified to account for all the dynamics that are observed experimentally, from parameters like the stroke plane inclination to the mean flapping angle. Each of these methods can be further examined for their validity through more experimental testing, like free flight from hovering to forward flight, and weight loading studies, which are discussed later in this paper.

Wing Motion

The motion of the flapping flight under investigation in this study is 'normal' flapping flight. Detailed descriptions and drawings depicting the flapping motion of sub wing beat mechanics for this type of flapping have been cited in the literature from many studies using high-speed cameras filming *Manduca sexta* flight [22]. The main considerations examined in those analyses comprised of the stroke plane angle and the body angle with respect to the horizontal plane. Other areas of interest were the wing beat frequency, amplitude, and sweep angles. The results of these experimental studies have given researchers multitudes of information for flapping vehicle dynamics, allowing them to compare their methods with these agile insect flyers' solutions.

A relevant set of results for this weight loading study in this paper, derived from these studies, was that when the *Manduca sexta* species increased their flight speed from 0 to $5ms^{-1}$, which was induced in the experiments by a varying wind tunnel airflow, the stroke plane angle increased from approximately 15 ± 5^o to 53 ± 5^o and the body angle decreased from 38 ± 5^o to 23 ± 7^o. However, with this pitching motion, a clear correlation for change in the wing beat frequency with increasing speed was not seen. The wing beat frequency showed a range of frequencies from approximately 25-26Hz, if one can disregard an outlying frequency of 23Hz from one of the studies of one female specimen, in which no further statistical proof that this was indeed a true correlation for all female *Manduca sexta* Hawkmoths has been presented thus far. Those findings are potentially useful to this study, because they represented a reaction of the insects to a disturbance on their flight. The results indicated that the insects, with an increasing wind speed within their actual flight speed capabilities, changed their effective angle of attack to compensate. Adding to these studies, the next section describes the motion of the body, rather than the wings, for free flight, in order to understand further the energetics involved in *Manduca sexta* hovering.

Free Flight Body Tracking

For the tracking of body motion in hovering free flight, a Redlake high-speed camera filming at 250 frames-per-second was used. The imagery is post-processed using a custom motion tracking code written in MATLAB, which has been previously documented in the literature [29]. Other more sophisticated image processing techniques are also well documented for not only body tracking but general point tracking [23] and wing-plane following [46]. The results for hovering motion of the body are presented in Figures 2-3, displaying the longitudinal and transverse motion. The amplitudes can be seen to vary from ±2-3mm in the horizontal direction to ±3-4mm in the vertical direction.

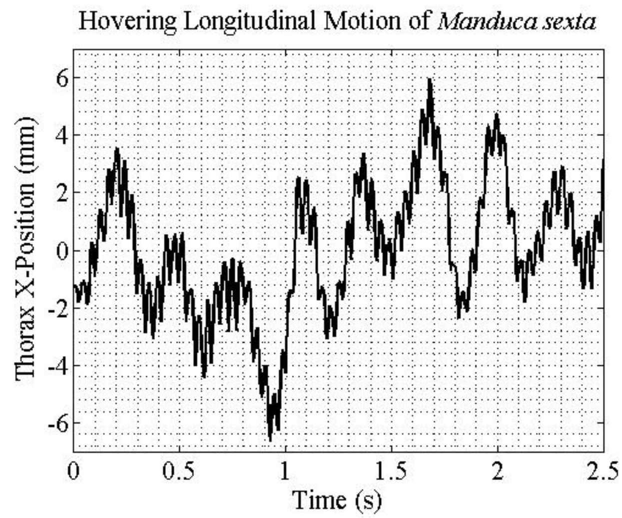

Figure 2. Longitudinal motion during hovering.

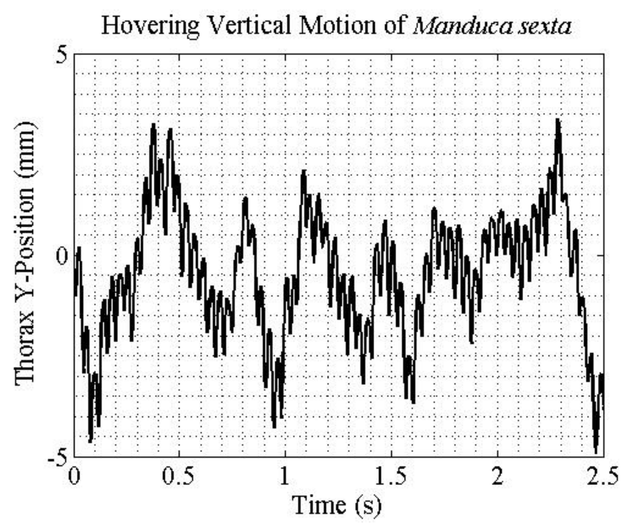

Figure 3. Vertical motion during hovering.

From Figures 2-3, a confirmation of the wingbeat frequency was made by analyzing the coupled body motion. Using Welch's averaged modified periodogram method of spectral estimation [47-49], a system identification was performed with MATLAB's Signal Processing Toolbox. The resultant of the data analysis was a power spectral density (PSD) estimate based off using a Hamming window technique for a given subset of the data and supplying the sampling frequency value, 250Hz. The following *Manduca sexta* insect phenomena for body motion under zero-payload, hovering flapping flight was then found, see Figures 4-5.

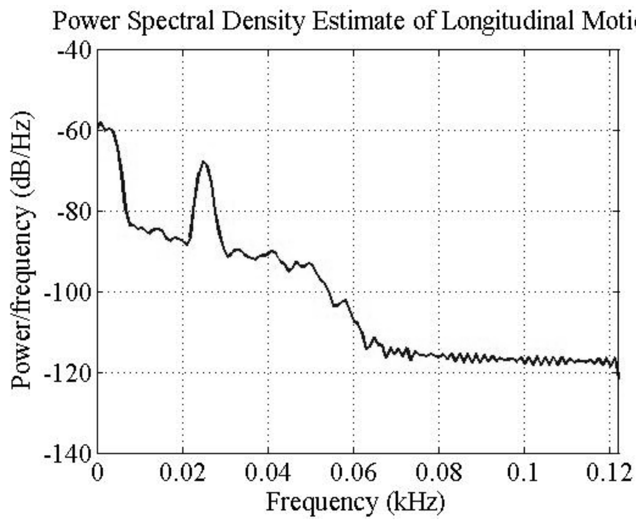

Figure 4. Hovering motion longitudinal frequencies.

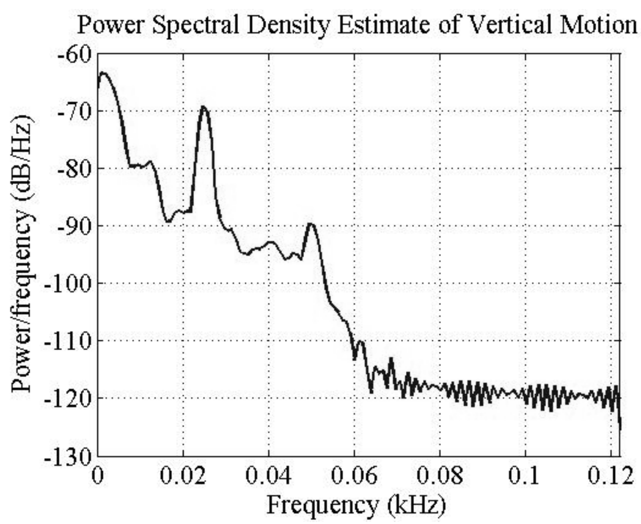

Figure 5. Hovering motion vertical frequencies.

Both the longitudinal and vertical components of the flight have a shared frequency peak of 24.79Hz, with a bandwidth of approximately 6.67Hz. This peak frequency lies just below that of documented mean wing beat frequencies for *Manduca sexta*, 25-26Hz [22]. Reasoning for the lower value, assuming it signifies the wing beat, or driving, frequency for the motion, can be explained by either variation of wing beat frequencies within the species or slight error in the data processing of the imagery. In any case, the body experiences directly both a longitudinal and vertical coupling to what appears most likely to be the wing beat frequency, inferring it as a linear relationship. In addition, the vertical component reveals a second distinct peak at nearly precisely double the wing beat frequency. This appears to be a harmonic that is occurring with the flapping dynamics with respect to the coupled body motion. To see if any of these dynamics are affected by the influence of added mass to the system, the next section investigates previous weight loading studies on flapping flight and presents additional findings from this research's weight loading study.

Weight Loading Flight Mechanics

To understand better the need for more information on weight loading flight, a background of the limited literature on loaded flight and muscle energy studies of flapping flight is provided here, along with the contributing results from this study.

Maximum Lift Studies

A select number of weight loading flight studies exist in the literature, in which biologists typically observed the maximum weight that could be attached onto a species before it was no longer able to achieve lift. One such study that truly enlightened this topic area was performed by Marden [17], who studied the lift characteristics for 49 species of insects, 9 species of birds, 3 species of bats, and 5 species of dragonflies. In that work, Marden examined an effect he defined as "marginal flight muscle ratio" Ψ, which is the ratio of flight muscle mass to total flying mass, including additional loading, at which an animal could just barely take off. Marden determined this ratio to be approximately .16 across all taxa in his study, including vertebrate and invertebrate fliers and whose members varied in mass from 19mg to 267g, a remarkably consistent result, considering a mass variation of several orders of magnitude. For *Manduca sexta* the exact number was Ψ equal to 0.158. Individual species have un-laden muscle mass to body mass ratios Ξ ranging from just below .16 to above .56, once again for *Manduca sexta* this number was 0.17 to 0.436, with a mean Ξ of 0.336. The difference between these two ratios represents the amount of power, scaled by mass, that may be extracted while still allowing the animal to fly. This particular study however does not give any useful conclusions to the dynamic impacts of such loading. It does however provide a useful upper bound for weight loading while maintaining flight for a range of insect species, which is relevant to animal tag mass constraints and any other devices that a researcher may be planning on attaching to a flapping animal.

Many follow-up studies [19-21] were later performed testing Marden's results, in which correlation of muscle mass to load carrying capacities were found. Another theory about the actual muscle power output did arise within these subsequent studies from Ellington [18], in which he claimed that Marden's results were valid only for an estimate of the induced power and not the total muscle power. The reasoning behind this claim was that while the power induced was sufficient for lift, inertial power to flap the wings would be substantial at high wing beat frequencies. In examining it even further, if the flight muscles were modeled as elastic, the data from such tests would still be insufficient for determining profile power. Instead, Ellington re-examined Marden's study using other relations of induced power to components of flight power [50-55] to find that a better conclusion was to use a maximum muscle-mass specific power (MMSP), rather than a body-mass specific power, to correlate lift capabilities. Using that analysis it was found that induced power varies with MMSP as $m^{0.13}$ and not $m^{0.08}$ according to Marden's findings.

In the weight loading study described in the next section, a weight is applied to a female and male *Manduca sexta* Hawkmoth, which according to Marden [17] have a mean Ξ of 0.336 with a weight of approximately 1.57 to 2.58g. If it is assumed that the flight muscle is in aerobic operation, with approximately a maximum muscle power output Θ of 100W/kg [18], then the induced power output range for the two *Manduca sexta* specimens tested is predicted to be roughly 52.8mW to 86.8mW and requires at minimum 25.1 to 41.3mW for flight respectively. This information is useful as it incorporates estimates for power consumption with our dynamic motion study. To derive these values, Equations 1-2 were used, where $m_{specimen}$ is the actual mass of the specimen without any added payload.

$$P_{induced} = \Xi \Theta m_{specimen} \tag{1}$$

$$P_{\min\ flight} = \Psi \Theta m_{specimen} \tag{2}$$

If one examines though the wide variance in any of the variables, one will see that the range for induced power output ($P_{induced}$) and minimum power for flight ($P_{min\ flight}$) can vary significantly as well. As long as Ξ > Ψ though, the insect will be capable of flight from an energy standpoint. The exact quantitative difference is essentially highly dependent upon the amount of muscle present, as predicted by Ellington [18], and in so, using Marden's predictions may be underestimates of their actual power if Ellington's theory [18] is correct. Another estimate given by Ellington [24], is on the 'quality' Q of this species, which was reported at a value of 10 for *Manduca sexta*, which translates to these insects having an excess of 37.2% of their energy available during free flight. Given all of these studies, it is thus concluded that a payload device needs to be constrained to a maximum mass of 584 to 960mg to allow for this species to achieve flight and make recordings to verify and augment these weight loading flight findings.

Weight Loading Flight Accelerations

While the estimates of total flight muscle power approximated previously are useful for placing a bound on the maximum amount of loading a flying insect can withstand, they say nothing about the actual mechanics of the loaded fliers, especially the motion of the body and any corresponding wing beat alteration. To explain further, if the body is assumed to undergo simple harmonic oscillation in response to the wing beats, then the total system mass m_T, which is the sum of the specimen's mass and the added payload, the peak body acceleration a_{max}, the wing beat frequency f, and the damping ratio for energy of each wing beat cycle ξ, can be derived to solve for the relationship between the average power during a wing beat cycle P_{avg}, see Equation 3. As shown in Equations 4-5, the derivation for Equation 3 involves using the formula for a harmonic inertial power generator and the relationship of the quality factor Q to the damping ratio ξ [56].

$$P_{avg} = \frac{Q m_T a_{max}^{\ 2}}{4\pi f} \tag{3}$$

$$P_{generator} = \frac{m_T a_{\max}^2}{8\pi f \xi} \tag{4}$$

$$Q = \frac{1}{2\xi} \tag{5}$$

A quick glance at the variables in Equation 3 indicates that all but the maximum accelerations have been verified in the literature, which if attainable would then provide a true estimate of the average power output at maximum loading. Going over each of the known parameters for clarity, the wing beat frequency has been measured for a variety of flying animals, in which *Manduca sexta* have been measured with a mean wing-beat frequency while hovering at approximately 26 Hz with a standard deviation σ of 3.4% [22] and a measured free flight body vibration frequency of 24.8Hz, found in this study. The mass has been recorded for each specimen in this and the other studies [17-21] and the quality factor is estimated using Ellington's published value [24].

So, for this paper's experimental weight loading study, maximum accelerations are needed in order to complete Equation 3 and are achieved by recording with a tri-axial accelerometer, a Bosch BMA150, and logging the data to a small microprocessor, a Texas Instrument MSP430, creating a new method for weight loading studies via an onboard acceleration logger. The logger itself acted as the mass at 856mg and allowed quantitative measurements of weight loading flight and gain information on the maximum acceleration and frequencies. While the logger exceeds the minimum bound recommended for the device weight, the two specimens studied were able to carry the load and sustain flight, proving the variance for such bounds as only being appropriate as an estimate. The logger measures the actual acceleration experienced by the insect's body to upwards of ±8g. Figures 7-8 show the top and bottom of the logger design, which can store acceleration measurements onto flash memory for a total of 50 seconds of flight at a 200Hz sampling rate.

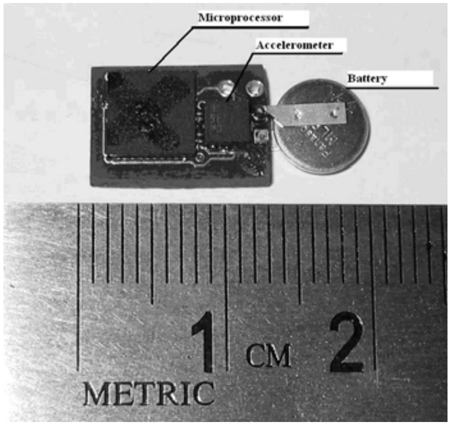

Figure 6. Bottom side of acceleration logger.

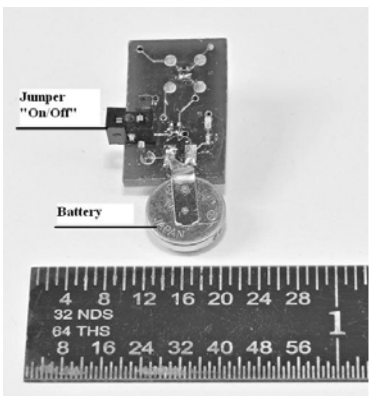

Figure 7. Top side of acceleration logger.

The logger is attached using a Velcro design, where the underside of the logger has one side of the Velcro and the specimen contains the other half, which is placed on its dorsal thorax. The application of the Velcro to the insect involves a multi-step process. First the moth is placed in a refrigerator for 5-10 minutes to lower its internal temperature enough to prevent movement but still allow it to come back to temperature without affecting its flight. While the moth is "chilled," a scalpel is used to remove the hair on the dorsal thorax. The Velcro is then placed onto the thorax with the assistance of a small amount of biocompatible adhesive, Loctite 454. After the insect is given one full day to recover, it is then placed under lighted conditions for 24 hours. After the 24 hour light exposure, it is placed in complete darkness for 20 minutes. A small amount of light is then turned on to encourage flight. Since the moths are primarily active during sunrise and sunset, this long period of inactivity allows for them to be most active when the experimentalist wants to observe them in flight. With the moths flying very actively at this point, the acceleration loggers are attached and the jumper switch is connected to record the flight. Figure 8 shows a moth with the acceleration logger attached.

Figure 8. *Manduca sexta* with acceleration logger.

From the acceleration logger, the following accelerations were recorded for both the female and male specimens, shown in Figures 9-10. From these accelerations, the following statistical data can be gathered; for the female specimen, the x-axis experiences a σ of 0.67g, while the y-axis undergoes 0.55g, and the z-axis has 0.94g. For the male specimen, the x-axis experiences a σ of 0.54g, while the y-axis undergoes 0.60g, and the z-axis has 0.98g. All values are therefore approximately the same between the two genders, despite their differences in size.

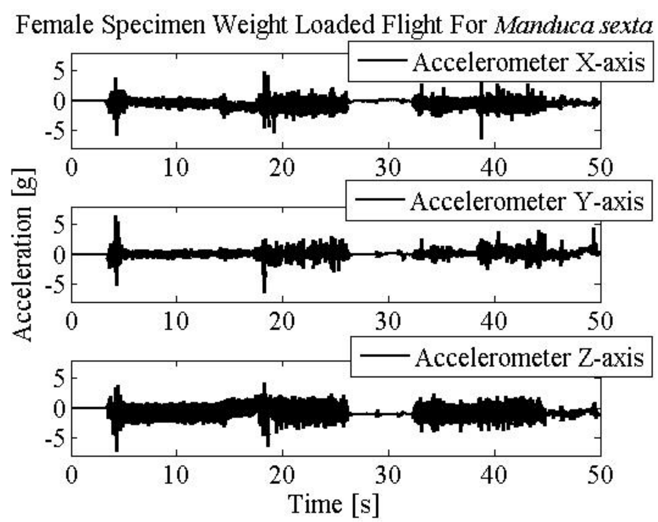

Figure 9. Body accelerations experienced by the female *Manduca sexta* specimen under weight loading flight.

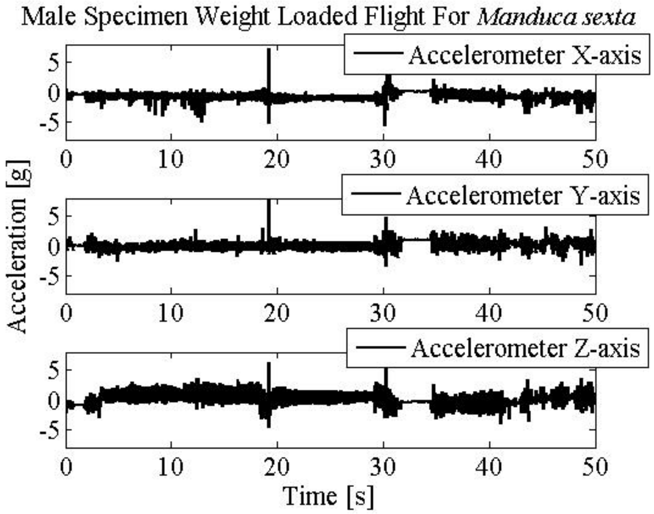

Figure 10. Body accelerations experienced by the male *Manduca sexta* specimen under weight loading flight.

These acceleration values are not however the exact accelerations with respect to a fixed coordinate frame, as they correspond to the accelerometer's coordinate references which are dependent on the body angle during flight Φ, which has been reported previously to range from 16^o to 43^o [22].

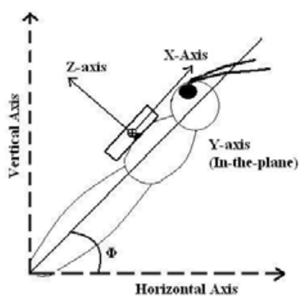

Figure 11. Body angle correction of true accelerations.

With knowledge of the angle Φ, a rotation about the y-axis can be performed using a rotation matrix $R_y(\Phi)$, see Equation 6, to find the fixed coordinate frame accelerations. To achieve this exact correction angle, another sensory input would be needed, such as a high-speed camera or an inclinometer to confirm the body angle with the data, see Figure 11. For our application though, of ultimately attaching energy harvesting devices, this rotation is not necessary as the accelerometer's reference frame would then become the energy harvester's reference frame, assuming the same orientation.

$$R_y(\Phi) = \begin{bmatrix} \cos(\Phi) & 0 & -\sin(\Phi) \\ 0 & 1 & 0 \\ \sin(\Phi) & 0 & \cos(\Phi) \end{bmatrix} \quad (6)$$

While Figure 11 indicates the need for a correction angle Φ for fixed reference frame correlations, the data collected for the x and z axes still provide the components for the longitudinal and vertical motion to be compared with the free flight data. Y-axis measurements provide correlations to yaw and roll. Using then the time history data from all three axes, a PSD estimate is performed again for each axis, in order to locate the dominate body frequencies under weight loading flight. Following the same data analysis as previously performed in the Free Flight Body Tracking section, Figures 12-13 are created showing the results for the female and male specimens.

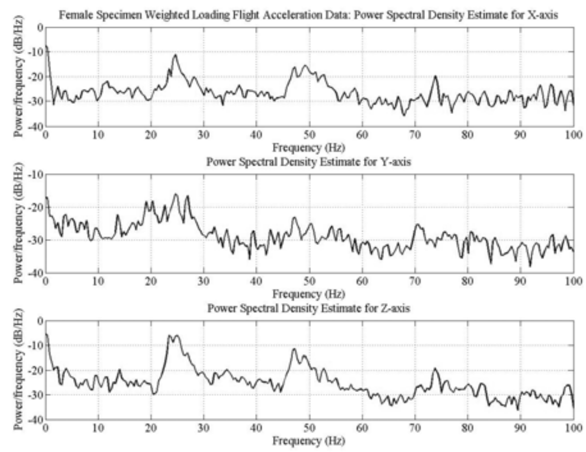

Figure 11. Female specimen's weight loading flight frequencies.

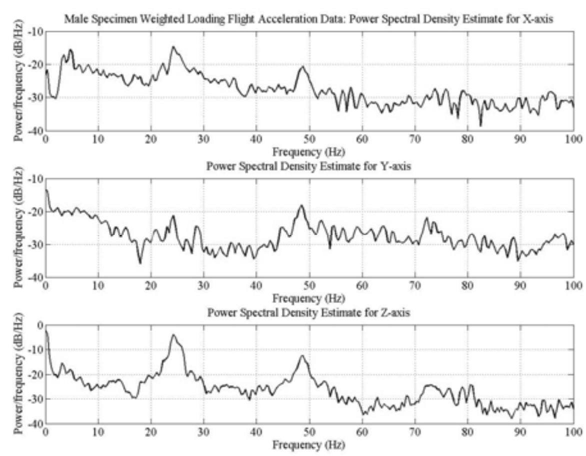

Figure 12. Male specimen's weight loading flight frequencies.

The PSD estimates for the weight loading study indicate that a nearly shared body frequency peak exists for the x and z axes for both specimens, 24.61Hz for the female and 24.22Hz for the male. These results indicate that the body frequency is nearly maintained between free and weight loading flight. The bandwidth for the loaded flight body frequencies was found to be 4.68Hz for both genders, which means that there is significant overlap between the free and weight loading flight frequencies, so much so that the slightly lower values for weight loading flight body frequency cannot be definitively considered as a reduction. The interesting finding is that the apparent ability to control the body frequency bandwidth had been narrowed from 6.67Hz to 4.68Hz from free to weight loading flight, a 30% reduction in body frequency variation. A second shared frequency exists between the two axes at once again nearly precisely twice the first shared frequency, 47.27Hz for the female and 48.83Hz for the male. The remarkably similar results from both the free flight and weight loading study, using two different forms of sensory data collection, image processing of high-speed camera footage and onboard acceleration logging, can conclude that the *Manduca sexta's* flight capabilities are remarkably stable given large disturbances and that the amount of available power for flight far exceeds the minimum requirements to achieve flight. In fact, using these results, the average power, calculated using Equation 3, for the female was approximately 85mW and the male was 66.3mW. These values differ from Marden's Equation 1 estimate by 2.1% for the female specimen and 25.6% for the male specimen. This is not surprising though, given the variance of nearly 29.8% in Equation 1's estimate based on the difference between the mean and true value for Ξ. These average power values when compared with the minimum power needed for flight, Equation 2, indicate that the female specimen has at least 43.7mW of excess available power in free flight and the male has at least 41.2mW available, allowing them to achieve lift and stabilize flight under a large disturbance, such as a payload loading of 856mg. The data from the y-axis is not as clear as the other two axes though, but it does show some correlations with the same body frequencies to the other two axes, which infers that a linear coupling exists between the three-axes, which present a theory that a linear relationship of the body motion to the driving force, or wing beat frequency, exists.

Discussion

With all the variation cited in the literature in trying to analyze biological behavior, specifically in this study of flapping flight characteristics, there arises some difficulty when trying to specify the parameters of a flapping vehicle analytically, thereby proving the case more for an experimental study of weight loading to be performed to observe the dynamic effects. A major improvement in this study lies with actual measurements of the accelerations experienced by the body during flapping flight using onboard sensory data. These accelerations can then be examined with the total system masses to generate precise forces experienced and average power output estimates. Traditional methods of analyzing flapping motion using high-speed camera imagery require the use of derivatives for acceleration measurements, which are extremely difficult to achieve due to issues with spatial and temporal resolution for high accuracy. While this new solution is only applicable to weight loading flight, it does provide further insight into the magnitudes of the accelerations experienced, the coupling of the body motion to the wing beat frequency, and the robustness of maintaining flight conditions, not only between both genders but also in the presence of large disturbances. For MAV development, these 'normal' flappers exhibit an energetic flight platform for CMAV energy harvesting development and provide a wide payload range for adding other onboard electronics.

Future Direction

A second generation of lighter acceleration loggers, with thinner circuit boards and smaller battery size, are under development to allow for a larger percentage of flapping insects to be studied for their weight loading flight characteristics. In addition, a two high-speed camera system filming at 250 frames-per-second and recording at an 800x800 resolution is also being implemented to correlate the accelerations with position and body angle data to achieve fixed reference frame correlations between specimens and gain sub wing-beat information. The final goal of these future studies is to not only document the mechanics of weight loading flight but to also implement energy harvesting devices and study the effects of these energy absorbers on flight mechanics.

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